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AN INVESTIGATION INTO THE USE OF THERMAL MASS TO IMPROVE COMFORT IN BRITISH HOUSING

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ABSTRACT

The UK Government has set ambitious targets for reducing energy use in buildings, including the target for all new homes to be zero-carbon by 2016. In addition, the government is committed to promote Modern Methods of Construction (MMC) as a solution for the shortage in housing that the country has been experiencing for a number of years. MMC have the potential to meet the new stricter building regulations and produce better quality homes that may use less energy for space heating but may also create homes that are more susceptible to overheating. Hence the paradox lies on the fact that a rising demand for cooling may be a result of the effort to reduce energy demand for heating.

This innovative research evaluates eight different construction methods built to meet the proposed targets and demonstrates by means of computer simulations and field monitoring that overheating in British homes may be a serious current issue if it is not accounted for during the design and construction of houses and that it will be a major problem in the future, when most of the houses built now will still be in use. It also shows that traditional heavyweight thermal mass integrated in a dwelling envelope may help overcome the issue but it presents limited benefits in highly insulated buildings and its integration may jeopardise some of the benefits of MMC constructions. Therefore the use of solutions such as Phase Change Materials (PCM) and Earth-Air Heat Exchangers (EAHE) may become of more importance in the near future.

These strategies have been assessed by means of computer simulation, laboratory and field experimental work and have been shown effective. Two real life applications where these strategies are combined, the Stoneguard House and the BASF House, both part of the Creative Energy Homes project, have been investigated. The houses were appraised not just in today’s climate but also in the future, taking into account some of the potential effects of climate change. In addition, a novel type of low-energy space conditioning system has been proposed by the author and tested with positive results. The hybrid system integrates PCMs and EAHEs aiming to overcome the limitations of both strategies and to provide occupants with a pleasant alternative to the conventional air-condition systems.

Keywords: Modern Methods of Construction (MMC), Lightweight Buildings, UK Housing Crises, Thermal Performance of Dwellings, Low-energy Houses, Thermal Mass, Earth to Air Heat Exchangers (EAHE), Phase Change Materials (PCM), Low-energy space conditioning

PREFACE

> *"The mother art is architecture. Without an architecture of our own we have no soul of our own civilisation."*
> Frank Lloyd Wright (1987: p. 31)

I have been asked why, as an architect, I have chosen to cross the line and learn aspects of building engineering and physics. Part of the reason is because I am curious, partially it is because I cannot easily accept knowledge I do not fully comprehended, partially it is sheer fascination for the complex simplicity of reality but most importantly it is because I like to be in control of my design.

I believe that architecture is the closest to a piece of functioning art that anything can be. But if architecture is the art of building then knowing the nature of materials, the behaviour of heat and fluids, the response of a proposed strategy, the performance of a technology and everything else that is part of that art is absolutely vital. Without this understanding there is no design freedom and just by knowing it an architect is completely in charge of the design.

Some may say it may limit architectural creativity. I say it should inspire it, produce visionary work and instigate the search for new solutions for the puzzle. It should inspire results that are not just beautifully designed but also functional, efficient and pleasing. It should generate outcomes that create awe, tantalize the senses, evoke delight and support life styles. Fully operational interactive inhabitable and beautiful pieces of art.

I certainly believe that this work has made me not just a better designer but also a freer architect and I hope it will inspire others to pursue similar paths with no fear of crossing the line.

ACKNOWLEDGEMENTS

> *"The journey is the reward."*
> Chinese Proverb

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This was unquestionably the hardest work I have every completed and definitely the first of many. Thank you with all my heart.

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LIST OF ACRONYMS

ACH: Air Changes per Hour (unit)

BB: Brick and Block full fill cavity wall

BRE: Building Research Establishment

CEH: Creative Energy Homes

CIBSE: Chartered Institution of Building Services Engineers

CLT: Cross laminated timber wall

CSH: Code for Sustainable Homes

DER: Dwelling Emission Rate

DSY: Design Summer Year

EAHE: Earth to Air Heat Exchanger

EPS: Extruded Polystyrene

EST: Energy Saving Trust

HLP: Heat Loss Parameter

ICF: Insulated Concrete Formwork

MMC: Modern Methods of Construction

PCM: Phase Change Material

PCP: Precast concrete panel wall

PHPP: Passive House Planning Package

PMV: Predicted Mean Vote

PPD: Predicted Percentage Dissatisfied

PUR: Extruded Polyurethane

RIBA: Royal Institute of British Architects

SAP: Standard Assessment Procedure

SB: Solid Concrete Block wall

SF: Steel frame wall

SIPs: Structurally Insulated Panels

TER: Target Emission Rate

TF: Timber frame part fill cavity wall

UK: United Kingdom

UKCIP: UK Climate Change Impacts Programme

NOMENCLATURE

A = area of material (m^2)

C = specific heat capacity of material (kJ/kg^oC)

C_{air}= specific heat capacity of air (1.012 kJ/kg^oC)

Cd= metabolic conduction (W)

COP = coefficient of performance

Cv= convection including respiration (W)

D = thermal diffusivity (m^2/s)

EI= system energy input (kW)

EO= system energy output as cooling or heating (kW)

Ev= evaporation including respiration (W)

K = conductivity ($W/m\ ^oC$)

L = thickness of material (m)

M = mass of material (kg/s)

M= metabolic heat production (W)

M_{air}= mass of air (kg/s)

P = time period for one cycle (s)

q = heat flux (W/m^2)

Q = quantity of energy input/output (kW)

Q_{EAHE} = quantity of cooling or heating energy EAHE (kW)

ρ = reflectivity

R = resistance or R-value ($m^2\ ^oC/W$)

r = resistivity ($m\ ^oC/W$)

Rd= net radiation exchange (W)

R_T = ratio of temperature variation

τ= transmissivity

T_1 = initial temperature (^oC)

T_2 = final temperature (^oC)

$T_{comfort}$= operative comfort temperature in free running buildings (^oC)

T_{earth} = undisturbed earth temperature (^oC)

$T_{external}$= external monthly average temperature (^oC)

T_{in} = temperature in the pipe's inlet (^oC)

$T_{in,max}$ and $T_{in,min}$= maximum and minimum temperature in the pipe's inlet (^oC)

T_{out} = temperature in the pipe's outlet (^oC)

$T_{out,max}$ and $T_{out,min}$= maximum and minimum temperature in the pipe's outlet (^oC)

U = conductance or U-Value ($W/m^2\ ^oC$)

V = volume of material (m^3/s)

α= absorptivity

$\Delta h_{fusion/evaporation}$= specific latent enthalpy (kJ/kg)

Δh_{latent} = specific latent enthalpy of water (kJ/kg)

ΔS= change in stored heat (W)

ΔT = temperature difference (^oC)

$\Delta T/\Delta x$ = temperature gradient (ºC/m)

ΔT= temperature difference (^oC)

ε = thermal effusivity (j/m² ºC)

ε_{EAHE} = overall EAHE efficiency

ρ = density of material (kg/m^3)

INTRODUCTION

INTRODUCTION

> *"To approach sustainability in architecture we need to engage more with materials, practices, design, intentions, reception."*
> Graham Farmer, seminar 'Thinking through Technology', 27th of February 2009 at the University of Nottingham

> *"Architecture begins when you place two bricks carefully together."*
> Mies van der Rohe (Quoted at the New York Herald Tribune, 28 Jun 1959)

Half of humanity now lives in cities, and within two decades, nearly 60 per cent of the world's people will be urban residents. Out of those, it is estimated that more than one billion people live in inappropriate houses. Cities are still growing and growth rates are highest in the developing world, which absorbs an average of 5 million new people every month. In less developed countries up to two thirds of urban population is believed to live in poor quality and overcrowded houses. In the developed world there is still quite a large percentage of low-income households, usually between 15 and 20% (UN-HABITAT, 2008: p. iv).

Buildings are not just the major economical sector in the world but also the shaper of citizen's lives and the soul of a civilisation. On the other hand they are major contributors of environmental damage, from the sourcing of raw materials through the energy used for their functioning and to the disposal of their elements once their life cycle come to an end. Almost half of the UK's carbon emissions come from the use of buildings, and houses alone account for more than 30% of all primary energy demand (DTI, 2005: p. 1- 25; Association for the Conservation of Energy, 2007: p. 1-4).

Climate change is now widely accepted and a warming climate over the next century seems inevitable. The current set of UK government climate scenarios indicates that increases on the mean daily maximum temperature may be up to 9.5^{o}C and the warmest day may increase up to 12.3^{o}C (Jenkins, Murphy et al., 2009: p. 6-7). Those predictions can already be illustrated by facts. Since the mid 1980s the average UK surface air temperature has warmed by about 1°C, about twice the global warming trend averaged, and as a consequence, summers warmer than the 1971-2000 average are now frequent. Furthermore, the chance of exceptionally warm summers, such as experienced in 2003 or 2006, has increased (Met Office, 2007 ; Jenkins, Murphy et al., 2009: p. 5). According to Euro surveillance an estimated 22,090 excess deaths occurred in England, Wales, France, Italy and Portugal during or immediately after the heat wave of the summer 2003 (Santamouris, Pavlou et al., 2007: p. 859-861).

The years 2008 and 2009 have been unusual for the British economy as it faced the effects of the credit crunch, property prices have fallen and a large quantity of them can be seen available in the market. This masks an underlying problem in the long term housing supply which has not met its demand for many years. As a consequence, the government is committed to increase the rate of house-building by 50,000 dwellings over the next decade (Milne, 2005). Simultaneously, since 2007 an ambitious target has been set for all new houses to meet net carbon dioxide emissions (zero carbon) from 2016 in an attempt to tackle climate change and meet the targets set by the Kyoto Protocol that came into force in 2005 (Department for Communities and Local Government, 2008).

In order to deliver more houses of better quality at a faster rate, the government and its agencies are prioritising the modernisation of the housebuilding sector through the promotion of Modern Methods of Construction (MMC). Stricter building regulations and new building standards (such as the Code for Sustainable Homes) have also been implemented to support more efficient housing construction. The University of Nottingham is at the forefront of the research on these issues with the creation of the Creative Energy Homes, a project mainly sponsored by industry, which aims to stimulate sustainable ideas in housing design and promote MMC.

Inappropriate design of buildings combined with heat island conditions in dense urban areas, the effects of climate change and cultural changes related to an improvement of living standards mean that in places such as the United States of America, up to 80% new homes have air-conditioning systems, and around the world this number is almost 46% resulting in peak electricity load problems to utilities and rising energy costs. Energy demand for cooling of dwellings accounted for 6.4% of the total electricity demand of the 30 member countries of the Organisation for Economic Co-operation and Development[1] in 2000 and experienced a growth of 13% from 1999 to 2000 (Santamouris, Pavlou et al., 2007: p. 860). No up-to-date numbers were found but all authors are in consensus when it comes to energy use for cooling: it will rise and it is likely to rise proportionally to the rise in temperatures. It is evident that passive architectural design and cheaper and healthier alternatives to conventional air-conditioning have to be adopted. For historical reasons, in the UK very little or no attention has been given to the cooling of dwellings. With the temperatures getting warmer there is a greater risk of overheating inside the buildings and in the UK the houses are particularly vulnerable to the impact of this as most of them rely on natural ventilation alone to avoid summer overheating.

The paradox lies on the fact that the rising risk of overheating is a result of the effort to reduce energy demand for heating in the last few decades. Changes in building regulations meant an increase on insulation levels that reduced the heating season and created buildings that are much more sensitive to any alteration in energy inputs, especially if they are built using certain common MMC configurations that do not incorporate thermal mass. A highly insulated building with low levels of thermal mass tends to be more thermally

[1] More information can be found at www.oecd.org [Accessed on the 26th of September 2009]

responsive in shorter periods of time (i.e. quickly getting too hot or too cold). It is likely that as a response more home owners in the UK will seek to install air-conditioning as it is generally within economic reach. The use of air conditioning in the UK is rising by 8% per year (Littlefair, 2005: p. 11), a situation that could lead to six million extra tones of carbon emissions per year by 2020 as a typical electrical air-conditioning unit causes a carbon dioxide emission of around 0.27kg per kWh of cooling. The need for air-conditioning in homes is in all aspects an unwanted scenario but probably an evitable one in the UK if houses are designed considering the risk of overheating.

Generally, thermal mass refers to a material's capacity to absorb, store and release heat. Since ancient times, man has used thermal mass to regulate their thermal environment by using caves, holes in the soil or stone and brick as construction materials. Well applied, thermal mass can help control the indoor temperature of a building. However, the recent promotion of MMC to build houses has triggered a new discussion on the value of having thermal mass in British houses. Various works have suggested that well insulated houses with low levels of thermal mass could result in substantially higher and uncomfortable room temperatures (Athienitis and Santamouris, 2002 ; Orme and Palmer, 2003 ; Dunster, 2005). All of these works are now out-of-date if the new targets set in 2007 are considered.

In view of these facts, many factors have originated and driven this work: to find solutions for better quality homes that provide occupants with accessible means to live in a healthier environment that may not depend on conventional air-conditioning systems, to investigate the possibilities of using modern means of construction to achieve that aim at a faster rate than by traditional means and to support the reduction of carbon dioxide emissions from dwelling space conditioning by exploring low-energy strategies.

This thesis investigates the thermal performance of MMC constructions when compared to conventional construction methods and proposes Earth Air Heat Exchangers (EAHEs) and Phase Change Materials (PCM) as potential solutions for integrating thermal mass in housing without hindering the benefits of MMC. It makes use of two case studies, the Stoneguard House and the BASF House, both part of the Creative Energy Homes project, to examine those issues. The houses are considered not just in today's climate but also in the future, taking into account the potential effects of climate change.

The novelty of this work lies not only on the examination of the benefits of thermal mass in today's cultural and political scenarios and current and future climate scenarios but also in the in depth study of EAHEs and PCMs and the development of an innovative hybrid system that integrates both strategies. The work is up-to-date with regulations, strategies and, especially, with the assessment of the recently built houses used as case studies. In addition, the topic is very current and the practical approach taken means that, even though the result is a piece of academic research, it is easily translated to the fast-moving construction industry.

The thesis' structure was divided into a literature review that is in itself mostly new, the development of computer simulations to study MMC elements, the study of each case study (by computer based simulations and on-site testing) and the experimentation of the proposed hybrid system. The chapters were divided as follows:

Chapter 1: Introduces the issues of housing shortage, promotion of the use of MMC and the search for zero-carbon housing, establishing the scene for the development of this study.

Chapter 2: Provides a background study on heat transfer in buildings and the properties that influence thermal mass and heat storage. It looks into common construction materials and traditional means of exploring thermal mass in building.

Chapter 3: Presents EAHEs as unconventional means of exploiting thermal mass to store heat, reviewing properties and design considerations as well as existing systems. It is the first time this kind of system is appraised in such depth.

Chapter 4: PCMs come as the second of the unconventional means of storing heat in building elements for later utilisation. Properties, characteristics, existing applications and problems are covered and important considerations for PCM usage are raised. PCM is a 'hot topic' in industry the moment as it promises to completely substitute usual high thermal mass materials in a lightweight form.

Chapter 5: By using mathematical calculations and extensive computer simulation, this chapter investigates the thermal storage capacity of common construction methods updated to meet current requirements of energy efficiency and the resultant influence they have on a building's thermal performance.

Chapter 6: The Stoneguard House is examined by means of computer simulation and analysis of data of the EAHE built by the author for the house. The dwelling is also simulated in future weather scenarios.

Chapter 7: A critical evaluation of the data collected at the BASF House over the summer of 2009. The house was dynamically simulated now as well as in future warmer climates scenarios and the results were compared with real data collected on site. The house's EAHE and PCM boards were also evaluated.

Chapter 8: A novel hybrid system incorporating EAHEs and PCMs is proposed by the author and tested by means of laboratory and outdoor experimentation in purposely built rigs. This is a very significant chapter of the thesis and includes a series of experiments undertaken to prove the functioning of this low-energy alternative to space conditioning.

Despite being complete, this thesis opened many doors and the research that it has started is an on-going work to be constantly updated.

1 HOUSING CONSTRUCTION IN THE UK

In order to address the climate change contribution from the domestic sector, the UK government has stated that every new home needs to be zero-carbon by 2016. Simultaneously, a crisis in the housing construction market has lead to a push towards the use of innovative building techniques which have the potential to construct better quality houses faster than traditional methods. This chapter introduces these issues that established the scene for the development of this study as part of the Creative Energy Homes project also described in this section.

1 HOUSING CONSTRUCTION IN THE UK

> *"For a generation, the supply of new homes has not kept up with rising demand. (…) That is why the Government is now setting a new housing target for 2016 of 240,000 additional homes a year to meet the growing demand and address affordability issues. The level of housing supply needs to increase over time towards this target and we believe that a total of three million new homes are needed by 2020, two million of them by 2016.*
>
> *We don't just want to build more homes. We want them to be better homes, built to high standards, both in terms of design and environmental impact and homes that are part of mixed communities with good local facilities. Our new homes need to be part of the solution to climate change; not part of the problem."*
>
> (The Secretary of State for Communities and Local Government, 2007: p. 5, 7, 9)

> *"In the consultation Building a Greener Future, we proposed an ambitious target to achieve zero carbon new homes by 2016, as a significant contribution to our goal to reduce overall carbon emissions by 60 per cent by 2050."*
>
> (Department for Communities and Local Government, 2007a: p. 25)

In the current scenario of falling house prices due to the credit crunch and large availability of properties in the market, it might seem inappropriate to talk about a housing shortage in the UK. However, there has been for many years a fundamental problem in the country's housing supply and its much larger demand. Britain is heading for a property shortage of more than a million homes by 2022 unless the current rate of house building is dramatically increased. Thus the government has decided to increase the rate of house-building from 150,000 per year to 200,000 over the next decade (Milne, 2005).

According to Barker (2006), there are a series of short-term and long-term factors playing their part in this crisis. It is a consequence of housing market price levels over the years, with an increase on house prices for many years before the credit crunch, a lack of affordable and social housing, policy constraints, land availability and other issues. The report also points out that if house building was to take-off in the UK, skills shortages are likely to come into play.

At the same time, in July 2007 the government's "Building a Greener Future: Policy Statement" announced that all new houses will have to be zero carbon from 2016. A zero carbon house is one whose net carbon dioxide emissions (taking account of emissions associated with all its energy use) is equal to zero or negative across a one year period. In December 2008 the government defined zero carbon houses by an approach based on (Department for Communities and Local Government, 2008):

- High levels of energy efficiency in the fabric of the home.
- A minimum level of carbon reduction to be achieved onsite or through directly connected heat.
- A list of allowable solutions for dealing with the remaining emissions (including from appliances).

In July of 2007, the Communities and Local Government published "Homes for the future: more affordable, more sustainable", the UK government's green paper focused on addressing the issue of the shortage in housing supply (Department for Communities and Local Government, 2007b). The Government has set a target for two million new well-designed and greener homes to be built before the zero carbon targets come into effect in 2016, and for a further million to be built afterwards.

Currently, almost half of the UK's carbon emissions come from the use of buildings, so there has never been a more important time to encourage the implementation of energy efficient strategies in construction. Domestic energy use alone accounts for more than 30% (Figure 1-1) of all primary energy demand, which is an increase of 26% since 1970 and 17% increase since 1990 despite the implementation of much tighter building regulations. Around 60% of that energy used in British houses is for space heating (Figure 1-2) even though the application of insulation in new and existing houses has become widespread (DTI, 2005: p. 1- 25; Association for the Conservation of Energy, 2007: p. 1-4).

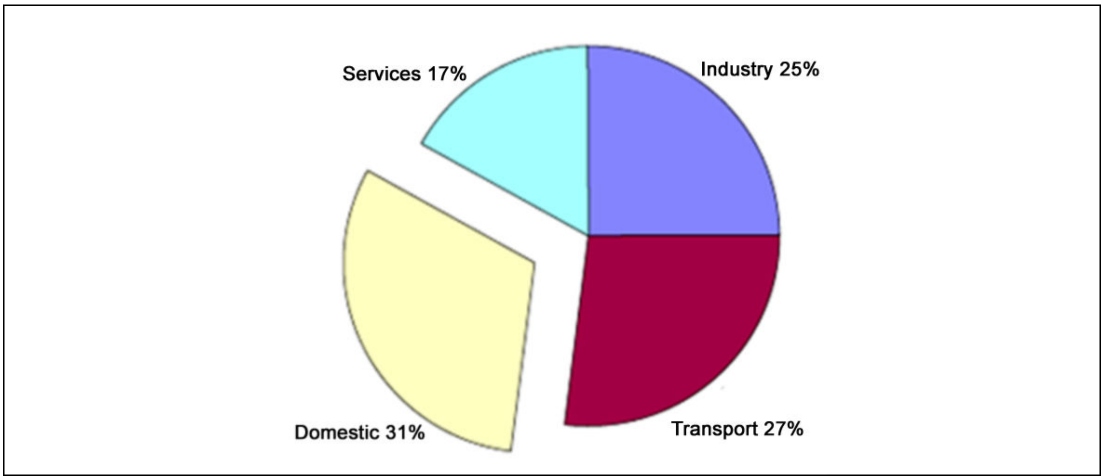


Figure 1-1: Primary energy consumption per sector (DTI, 2005: p. 11; Association for the Conservation of Energy, 2007: p. 1)

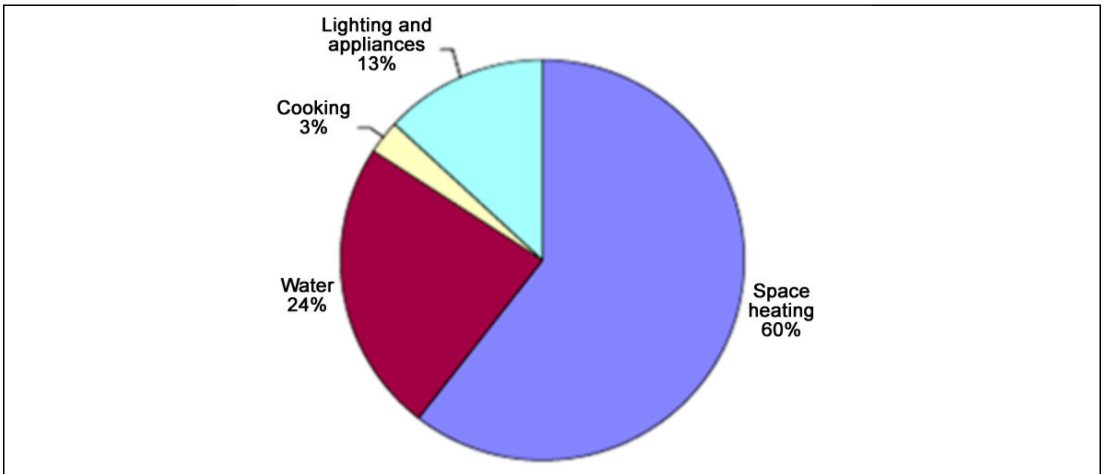


Figure 1-2: Domestic final energy use (DTI, 2005: p. 23; Association for the Conservation of Energy, 2007: p. 2)

The government and its agencies are prioritising the improvement of the quality of the houses to be built so the zero carbon targets can be met. One of the ways of doing that is by supporting the modernisation of the housebuilding sector through the promotion of Modern Methods of Construction (MMC) and the other way is by supporting more efficient housing construction through the implementation and promotion of building standards such as the Code for Sustainable Homes.

This chapter discusses these issues and sets the scene for the work developed in the University of Nottingham as part of the Creative Energy Homes project where a number of experimental eco-houses were constructed to trial and test different construction solutions and sustainable energy technologies.

1.1 METHODS OF HOUSE CONSTRUCTION IN THE UK

The British housing industry is known for being very conservative possibly as a response to the traditionalist thinking from the demand side. The houses have not seen much change either in their aesthetic or their layout for the last 100 years. The Eon House, in Figure 1-3, is a good example: whilst cars have changed immensely in that time, houses are still quite similar. In the UK, traditional constructive methods are usually understood as a structure where the internal load bearing leaf of the walls is of masonry (normally brick or block) and the external leaf, tied to it by steel ties, of either brick of block. This type of cavity wall was just adopted since the 1920s and just houses built since the 1970s energy crisis are likely to have received an insulating material in between the layers (Hens, Janssens et al., 2007). Before cavity walls, solid single skin walls were the most common constructive method. Typical traditional materials include dense concrete blocks, lightweight aerated (aircrete) blocks, stone and various types of bricks. Chapter 2 studies the thermal characteristics of these materials and in Chapter 3 typical walls are illustrated and compared to MMC walls.

Figure 1-3: The Eon house built to 1930's style as part of the Creative Energy Homes Project and a 1930's Austin 7 (Photo taken by the project's manager, Dr Mark Gillott, and sourced from the Creative Energy Home's website[2])

The traditional approach to building design is characterised by a fragmented process where little contribution is seen by key contractors and specialist suppliers at the briefing, design

[2] www.creative-energy-homes.co.uk [Accessed on the 22nd of July 2009]

and cost-planning stages which is one of the main causes of additional cost and contractual conflict commonly found in this type of construction (Stirling, 2003: p. 5).

Despite the growth on the use of MMC, traditional methods of construction are still the most widely used method in the UK. However, the shortage of skilled labour, environmental concerns and the need to speed up house construction are slowly pushing the industry away from the traditional techniques and closer to MMC techniques. Nevertheless these are not yet extensively established, as is shown in the next sections.

1.1.1 What are the Modern Methods of Construction?

MMC is a collective term used to describe a number of aspects of construction. MMC is being defined by industry in terms of activities and outcomes as well as products, which mean people and processes engaged to search for improvements in the delivery and performance of construction (Energy Saving Trust, 2005 ; Fawcett, Allison et al., 2005 ; Ross, Cartwright et al., 2006). The MMC constructive methods can be classified as:

1. Off-site manufacture:

- Volumetric: factory produced three-dimensional units that can be in a variety of forms such as empty shells or fully complete with services, internal features and external finishes. This presents limitations as the large units have to be transported assembled.
- Panellised: factory produced flat panels assembled on site to create a three dimensional structure. It can be in the form of open panels (a skeletal structure only) or closed panels (including services, openings and finishings). The panels can be made of timber, steel or structurally insulated panels (SIPs). Panellised systems offer few restrictions on room size and layout so allow the designer to have flexibility. The panels are easy to transport as they can be stacked flat.
- Hybrid: combination of volumetric and panellised to create three-dimensional pods, typically areas with are normally repeatable such as kitchens and bathrooms. Generally the pod would have complete services ready to be plumbed in and would be closed by panels.
- Sub-assemblies and components: factory produced items not regarded as a full system but that can replace parts of the structure usually made on site.

2. Non off-site manufacture: innovative site-based forms of construction i.e. insulated concrete formwork (ICF), tunnel form and calcium silicate blocks. These methods depend more on on-site labour and tend to use recyclable and/or sustainable materials in modern process.

These methods can be used in many different ways and be exposed as, for example, an expressive frame or hidden behind claddings and other finishings. In any case MMC can be used to create high quality architecture and efficient buildings. With care on the assembly, MMC buildings can achieve excellent air-tightness. Examples of typical MMC walls are illustrated in Chapter 3. According to the Building Research Establishment (BRE), the form and extent of the use of MMC in a project depend on (Stirling, 2003: p. 3):

- The type of project: ‘Is there duplication or replication?’
- The type of client: ‘Is the client a one-off or repeat client?’
- The relationships and contractual arrangements

MMC have the ability to shorten the supply chain by allowing the architect to send computerised drawings straight to the factory as opposed to sending it to a contractor who would send it to a subcontractor and/or the supplier. A shorter supply chain means less risk of mistakes in the process as decisions do not have to be re-addressed several times. However, it also means a much bigger responsibility for the architect.

Nick Whitehouse, an experienced engineer from Terrapin (a UK company that started using MMC in 1949 by developing prefabricated bungalows to solve the problems of post-war housing[3]) specialised in MMC houses, mentioned in a seminar at the University of Nottingham in 2009 that the Royal Institute of British Architects (RIBA) does not embrace the requirements for off-site construction despite the fact that the sector grows year by year. In addition, not much data on MMC buildings’ performance can be found because developers do not wish to expose the results so the full long term benefits of MMC cannot be quantified. Terrapin claims that their products can achieve certifications and all regulated requirements.

The use of MMC may have the following advantages:

- Much shorter time on-site and so less disturbance to local residents
- Smaller number of on-site workers
- Less need for skilled labour on site
- Improved on-site health and safety
- Great waste reduction on assembly on site
- Great waste reduction in fabrication as raw materials can be recycled
- Fewer deliveries and less need for on-site storage
- Construction less dependent on weather conditions
- A more predictable construction programme
- Cost and time certainty
- Possibility of having a prototype before the full building construction

[3] More information can be found at www.terrapin-ltd.co.uk [Accessed on 17th of July 2009]

- Improved quality of each element so less risk of infiltration in the building's envelope
- Reduction on snagging
- Smaller risk of on-site faults
- Improved insulation in the same element thickness
- Less infiltration through the building envelope as it is less dependent on on-site labour
- An Integrated supply chain that involves manufacturer and suppliers in the early stages of the design, ensuring their skills and knowledge are embedded in the project

MMC techniques have a long list of advantages. However, there is an important aspect which can be a potential disadvantage for MMC: the thermal performance. This is what is being investigated in this work.

1.1.2 A Push Towards Modern Construction Techniques

> *"BERR, Communities and Local Government, and their delivery agents, have sought to prioritise improved efficiency in the housebuilding sector across all forms of construction. There is also a continued focus on modernising construction processes to build more, better quality homes in less time. Government believes that, although not a panacea, modern construction techniques have an important role to play in delivering the step change needed in housing supply."*
>
> (Department for Communities and Local Government, 2007b: p. 100)

As a response to the housing crisis the government is committed to promoting the use of MMC in home building (Fawcett, Allison et al., 2005). The idea is to accelerate housing provision to achieve a better balance between housing availability and demand. The Office of the Deputy Prime Minister defines MMC as "a process to produce more, better quality homes in less time" (Fawcett, Allison et al., 2005). Most of the important British agencies related to construction and/or sustainable development have published MMC supportive material.

The English Partnerships[4] and the Housing Corporation[5] have attributed the success they achieved in driving up the quality of new social and private housing for sale to greater use of MMC (Department for Communities and Local Government, 2007b). One of the English Partnerships' aims is to promote the use of MMC to "achieve high-quality, well-designed, sustainable places for people to live, work and enjoy". They have been working with the

[4] English Partnerships is the national regeneration agency, a non-departmental public body supporting sustainable growth in England and working with partners such as the Housing Corporation. More information can be found at www.englishpartnerships.co.uk [Accessed on the 21st of July 2009]

[5] Housing Corporation was a government agency that funded new affordable homes and regulated housing associations in England. The Housing Corporation closed in 2008 but two new agencies were created, the Tenant Services Authority and the Homes and Communities Agency. More information can be found at www.housingcorp.gov.uk [Accessed on the 21st of July of 2009]

construction industry to research the benefits of MMC and have been setting up a number of projects to promote it: the Design for Manufacture Competition (high-quality homes for £60,000), the Smartlife project in Cambridge (testing the use of different MMC techniques on a single real development site), the Greenwich Millennium Village, the Housing Partnership, and the London-Wide Initiative. They have also built their own three-storey townhouse, The Summit House, to "demonstrate how MMC can be used to create a property that provides a flexible and enjoyable home as well as meeting the EcoHomes Excellent standard[6]". The housing associations are being strongly encouraged by the Housing Corporation to use MMC (Energy Saving Trust, 2005: p. 3).

The National Audit Office (Fawcett, Allison et al., 2005) published a study claiming that a greater use of Modern Methods of Construction (MMC) to build houses in the UK could mean that:

- Four times as many homes can be built with the same on-site labour
- On-site construction time can be reduced by over a half
- Building performance can be at least as good as traditional build
- A reasonable degree of cost comparability can be achieved depending upon the approach adopted

The report also mentions that good risk management is even more important than in traditional methods of construction, that close liaison with local authorities is essential and that the benefits of MMC might be wasted if the construction is not well planned. The BRE reported that MMC components can have a major impact on the construction process and mean reduction of time and enhancement of quality (Stirling, 2003). It also says that the use of MMC presents opportunities for reducing the impact of a development and has the same visual attributes as a traditional building.

A number of agencies have been created to support the development and integration of MMC in construction, independent or supported by the government. For example, the Buildoffsite[7] has as its primary activity to promote the benefits of off-site solutions for the new build, extension and major refurbishment sectors. It has published guides (Buildoffsite, 2006 ; Ross, Cartwright et al., 2006) on MMC techniques and has created a registration scheme to aid companies that supply MMC products. The registration scheme is "a process based assessment scheme designed to benchmark offsite construction organisations against best

[6] In April 2007 the Code for Sustainable Homes (described in section 1.2) replaced Ecohomes for the assessment of new housing in England

[7] Buildoffsite is an industry-wide campaigning non-profit organisation supported by the government that promotes greater uptake of offsite techniques by UK construction. It is composed of an alliance of clients, developers, designers, contractors, manufacturers, suppliers, government, advisors and researchers. More information can be found at www.buildoffsite.com [Accessed on the 22nd of July 2009]

practice in terms of competency, methodology and safety". Despite all the promoting and exposure, and the long list of advantages on its use, MMC is not yet the main method used in Britain- in fact it is still scarcely used as discussed in the next section.

1.1.3 MMC: Acceptance and Applicability

> *"Our plans will make big demands on the industry. Is the industry up for the step change that will be required, has it got the capacity? (…) When the rest of industry zealously minimises processes to cut down costs and minimise the risk of mistakes, it is curious that the housebuilders remain wedded to the technology of the past. We see MMC as a key component to stepping up performance. Too few new homes in the UK are built this way and our performance is not as good our neighbours on this. In Germany a third of new homes are built on the basis of off-site manufacture, but our industry has been very, very slow to respond to that."*
>
> Former housing minister Keith Hill for the Housebuilding News (Design and deliver, 1st of September of 2004)[8]

> *"How will we deliver three million zero carbon homes that are better designed, faster to build, and more cost effective than ever, whilst tackling affordability problems?"*
>
> Publishing director Ben Roskrow for the Housebuilding News (Editorial 3 - Housebuilder Media, 9th of November of 2007)[9]

Whilst the government seems committed to support a wider spread of MMC, the construction industry and the general public seem to be very slow at accepting and implementing it. A very particular aspect of the English housing market is the consumer resistance to prefabricated houses and housebuilders refusal to expand their skills.

According to Hughes (Hughes, 2000a ; Hughes, 2000b), due to demographic shifts and population's lifestyle change, houses have become smaller and necessarily more adaptable to suit occupants. In addition, due to an increasing awareness of environmental issues, more importance has been given to regulatory frameworks. The result of all this pressure on the construction industry combined with the need for more homes which are fundamentally affordable and efficient is the gap between need and provision previously mentioned. In addition, despite a general dissatisfaction with speculative housebuilding, there is a resistance to innovate. However, it is widely recognized, among designers and housebuilders that the only way to bridge that gap is by innovation.

Hughes also mentioned that it is easier to find innovative construction methods being used in social housing which is a public that exerts less influence in the market and expects less choice. Social houses are usually coordinated by housing associations who are more worried about quality as (differently from the speculative housebuilders) they are usually involved in the running and maintenance of the properties as well as construction. Housing associations are likely to be demanding clients whilst the speculative house client is typically

[8] Available at www.house-builder.co.uk/news/articles/2004-09-01/design-and-deliver.html [Accessed on 20th of July 2009]

[9] Available at www.house-builder.co.uk/news/articles/2007-11-09/editorial-3-ben-roskrow-publishing-director-housebuilder-media.html [Accessed on 20th of July 2009]

inexperienced. Hughes has developed a thorough study on the acceptance of steel frame houses by the public [10] and found that the biggest concerns of the population in relation to steel frame houses are financial matters (capital cost and difficulty getting a mortgage), adaptability and performance issues.

Considering that steel frame can easily perform as well as or better than a house constructed in a traditional way and that it can possibly be much easier and cheaper to adapt (removed panels could be reused) the results of the survey show a lack of knowledge of the technique. This suggests that there is room for a marketing campaign supported by good constructed examples to tackle the resistance to this type of construction. The Stoneguard House, which is detailed in Chapter 6, aims to be one of those good examples.

In 2003 the BRE suggested that since the post-war period MMC has acquired negative connotations but “with developments in lightweight, high strength materials and modern production techniques, prefabrication has much to offer today’s construction industry” (Stirling, 2003: p. 1).

In 2005, the Buildoffsite commissioned the Mtech Group, with the support of Loughborough University to conducted a survey with the intention of defining how MMC has been applied in practice and what should be expected in the near future (Pan, Gibb et al., 2005). They approached the top 100 housebuilders in the UK with key questions to identify their attitudes towards MMC, establish to which extent MMC is being applied, the drivers and barriers of the technique and its potential trends. It was found that, despite having extensive documentation, some MMC techniques are hardly used and generally more employed for apartment construction rather than houses. Moreover, to that date MMC accounted for only 3.6% of new buildings and it was mainly utilised in kitchen and bathroom pods and external walls. Nevertheless, 64% of housebuilders believe industry needs to use more MMC and 58% of them intended to utilise more of it in the near future (Figure 1-4 and Figure 1-5).

The survey also found that, for housebuilders, the most important drivers for more extensive MMC use were skill shortage, cost and time certainty, high quality and minimal on-site time. Health and safety, sustainability and client’s influence were largely ignored. Top listed barriers were the higher capital cost, the difficulty to achieve economy of scale the complex interface between systems and the inability to freeze the design at an early stage. The work also reports that 71% of the housebuilders considered MMC from the design stage but were not satisfied with its performance. This might be a reflection of the low up-take of the techniques, a general lack of knowledge on MMC and the traditional ‘risk adverse culture’ as there were no performance figures to justify that statement.

[10] Available at www.foursteelwalls.co.uk/survey.html [Accessed on 20th of July 2009]

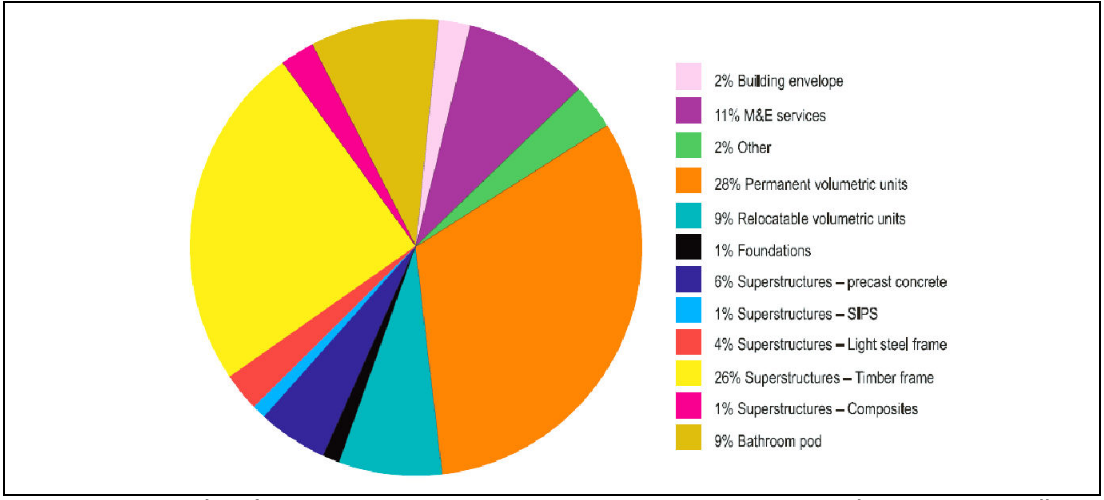


Figure 1-4: Types of MMC technologies used by housebuilders according to the results of the survey (Buildoffsite, 2008: p. 11)

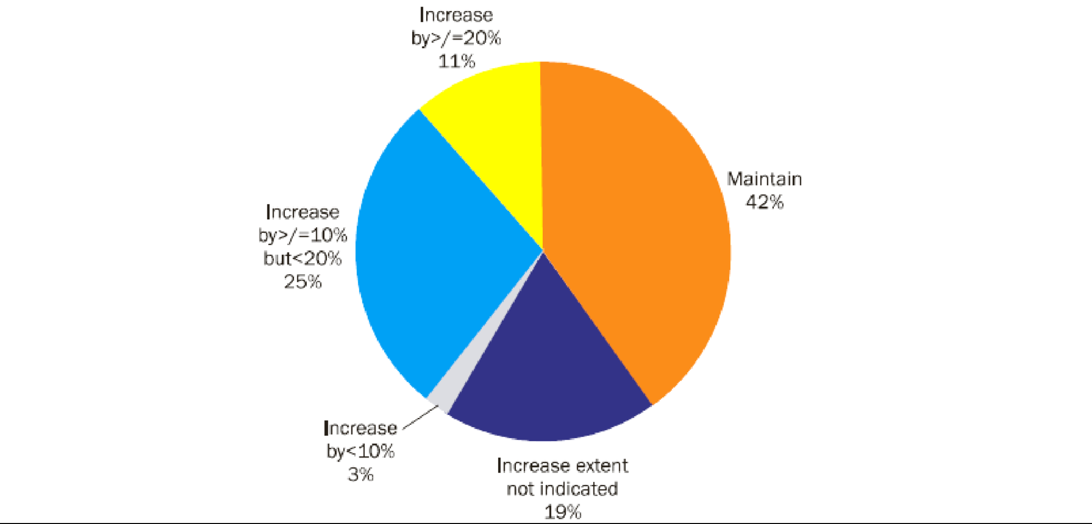


Figure 1-5: The trend of future use of MMC in the top 100 housebuilders (by volume) according to the results of the survey (Pan, Gibb et al., 2005: p. 5).

The Housing Corporation funded CABE (2006) to address the other criticism that MMC usually receives: it does not allow for flexibility of design. The research focused on the implications of the use of MMC on the quality of design of nine social housing schemes aiming to define to what extent the use of MMC has affected their design. The findings demonstrate that there is no direct correlation between the use of MMC and quality design. Another relevant observation from this report is that funding mechanisms should be adjusted to accommodate the higher cost of the designer in MMC schemes as it requires significantly longer design time at early stages of the project.

In 2007, the Housing Corporation and the English Partnership published a report which illustrates how quickly the use of MMC has been growing. The report states that 41% of affordable homes last year were built using modern approaches, against a government target of 25% (Housing Corporation and English Partnership, 2007: p. 4). Their quality indicators show that properties built between 2000 and 2006 using MMC provide better homes than those built using conventional building techniques as can be seen in Figure 1-6.

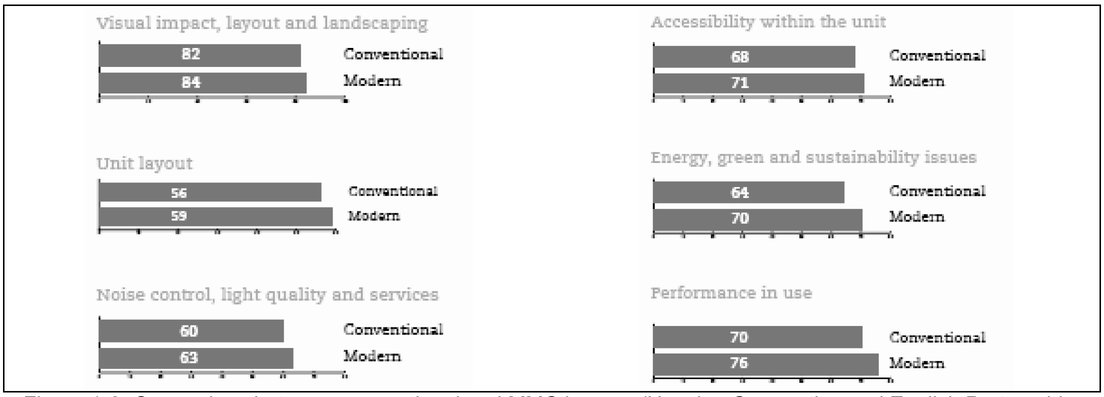


Figure 1-6: Comparison between conventional and MMC houses (Housing Corporation and English Partnership, 2007: p. 21)

In 2008 the government released a report indicating a growth of 20% in MMC permanent buildings between 2000 and 2005 and forecasted a growth of 24% between 2005 and 2009 (Department for Communities and Local Government, 2008: p. 9). They forecasted steel frame to have a greater growth between all MMC materials, 23% between 2005 and 2009. It states that “innovative construction products and techniques will have a significant role in meeting the current and future levels of housing demand”.

In the Buildoffsite 2008 yearbook the organization states that three years before the market for off-site solutions in the UK was worth £2 billion a year and had grown to more than £6 billion by 2008 (Buildoffsite, 2008: p. 3) with “many of the leading main contractors looking to deliver 25% plus of their new build programmes through the use of off-site solutions”. The organisation aims to achieve a target of doubling the use of off-site solutions by 2010 with a tenfold increase by 2020.

It is interesting to notice that, from the house owner’s side the most important concerns included difficulties in obtaining a mortgage, flexibility and performance concerns whilst from the housebuilder’s side the top concerns were higher capital cost, economy of scale, complex interface between systems and inability to freeze the design at an early stage. Housebuilders listed high quality as a motivation to use it and also expressed dissatisfaction with performance but without specifying why. Since the focus of most of the published works was on financial or social matter with very little concern about the performance of MMC houses, particularly if thermal comfort is considered, these concerns might be attributed to the low level of application of the technique and a lack of knowledge. It should be pointed out that most of the respondents of both surveys had no personal experience with MMC so were probably influenced by external views.

It seems unfair to state satisfaction or dissatisfaction with a technique which has not yet been fully assessed as it is very rare to find long term (or even short term) monitoring of MMC houses. That is one of the problems that the University of Nottingham is aiming to address through the Creative Energy Homes project presented later in this chapter. Through her on-site work experience in the project, the author of this work learnt that most housebuilders are supportive of the traditional methods of construction simply because they know how to do it. Consequently, in order to achieve any changes in the industry firstly this lack of understanding should be addressed so designers and builders can share the same goal and build faster and better quality houses.

1.1.4 MMC and Thermal Comfort

> *"When compared to lightweight dwellings, the thermal mass in masonry and concrete construction can provide significant year-round operational savings if designed appropriately. For example, research has shown that a typical two-bed semidetached house in south east England that fully utilises its thermal mass is likely to save around 14 to 33 tonnes of CO2 over the 21st century."*
>
> The Concrete Centre in the report 'Thermal mass for housing' (2006)

> *"Occupants really like the houses we made but they do find that they have to ventilate a lot, especially bedrooms."*
>
> Nick Whitehouse from Terrapin Off-site Construction in a seminar at the School of the Built Environment, University of Nottingham, 2009

The expressed concerns on the thermal performance of MMC houses might be justifiable. Most MMC construction methods use off-site manufactured lightweight materials, which have a small heat storage capacity, to produce highly insulated and air-tight buildings. This combination of factors can achieve a reduction on the heating loads of the dwelling but is more likely to present overheating due to the lack of thermal mass therefore escalating the necessity for air-conditioning. This statement is qualified by review of existing work and further work undertaken by the author later in this thesis.

Generally the term thermal mass is used for any material that is capable of storing heat. The use of thermal mass is essential to control internal temperature peaks and fluctuations. The concept of thermal storage in buildings is explored further in Chapter 2. Traditionally, the construction materials used for heat storage in buildings are concrete, adobe, stone and bricks. However, these materials are heavyweight and generally used for on-site construction and assembly which defeats the benefits of using MMC.

The increasing levels of insulation and potential decrease on level of thermal mass may result in not just summer overheating but also spring and autumn according to a study published by FaberMaunsell (Orme and Palmer, 2003). They have dynamically simulated four house types to identify degree hours[11] above 27°C and peak temperatures in addition to the influence of each possible measure to mitigate the problem. None of the measures (thermal mass, night cooling, solar shading and reduced internal gains) was found to completely eliminate the issue but a combination of them could lessen it by 80%. Night time

[11] Degree hour is the deviation of the hourly temperature from a standard temperature, positive if above and negative if below.

ventilation combined with high thermal mass was found to be most effective in preventing overheating. They also concluded that “balanced mechanical ventilation at levels appropriate for the maintenance of good indoor air quality is not able to mitigate overheating in dwelling with high thermal mass”.

The Energy Saving Trust (EST) has published a design guide to avoid overheating in houses in the UK which “is, paradoxically, a result of efforts over the last few decades to reduce energy demand” (2005). According to the report, the increasing levels of insulation mean that internal temperatures are more sensitive to changes but that could be mitigated by applying thermal mass and/or other design options. The study found that the addition of thermal mass in a lightweight house could greatly reduce the number of degree hours over 27^{o}C.

The report produced by Ove Arup & Partners and Bill Dunster Architects (2005) described the potentially poor performance of thermally lightweight construction and how, when other parameters are kept the same, constructions with high thermal mass were able to absorb more solar radiation and regulate internal temperatures. This is an especially concerning matter when climate change and global warming are taken into account (an exploration of this subject can be found in Chapter 5). The report provides strong evidence that lightweight homes might not be as sustainable in the long term as heavyweight constructions.

On behalf of the BRE, the EST produced a report discussing the problem of overheating in urban houses in the UK which have restricted possibilities of natural ventilation due to noise, pollution and urban heat island effect (EST, 2005). With the average temperature in the UK at risk of rising as much as 5^{o}C by 2080 (Hulme, Jenkins et al., 2002: p. V) in addition to recorded rises of 3^{o}C due to the urban heat island effect, overheating in urban houses is of big concern. Thousands of deaths have been attributed to overheating in the past few years (EST, 2005: p. 19). The study monitored an apartment in London that was found to overheat during June 2003. It also tested two houses, one of traditional brick and block construction and another of timber frame. The latter was found to be 2 to 4^{o}C hotter than the first with the same occupancy pattern. Another study found that the use of passive measures such as shading, night time ventilation and thermal mass can reduce the potential for overheating as the climate changes.

The concrete industry has published various works to support the theory that thermal mass is vital in any building. They claim that a high mass building always perform better thermally than a lightweight building and that the heavier the better (Hacker, Saulles et al., 2006).

Nonetheless, the MMC industry states that “most framing systems- both steel and concrete- have about the same effect on a building’s energy consumption” (Gorgolewski, 2007). The article claims that the glazing-to-wall ratio, U-Value and other aspects are far more important factors affecting energy use than thermal mass. They say thermal mass can have some benefits but its impact is complex and difficult to predict.

An alternative might be to mix construction types to make a hybrid building, e.g. by having a high thermal mass core (for example concrete) and a low thermal mass shell (for example timber frame). This approach has not been examined in depth by many authors but Mendonca and Braganca (2006) have studied a mixed weight solution using test cells and found that it “allowed significantly less environmental cost in comparison to a conventional heavyweight constructive solution”. The definition of hybrid construction is arguable in itself as some of the tradition construction in the UK might be considered hybrid by having brick or stone walls with timber floors.

There has always been a debate about the thermal performance of MMC buildings against heavyweight traditional buildings. Some works are supported by computer simulations but some don’t even go as far as that and none have presented measured data to support their claims. Nevertheless there is an issue to be investigated and work to address it is described in Chapter 5, 6 and 7. There is also scope for the implementation of innovative techniques that can add the benefit of the thermal mass without adding the extra weight that would defeat the benefits of MMC. Two of those techniques are being proposed and applied in this work, Earth to Air Heat Exchangers (Chapter 3) and Phase Change Materials (Chapter 4).

1.2 HOUSING STANDARDS

> *"We characterised the debate about sustainable architecture as exhibiting a tension between the proliferation of ideas associated with 'nature' and a corresponding urge to fix and define a 'best practice' design approach to sustainable architecture."*
>
> (Guy and Moore, 2005: p. 221)

> *"The production of environmental programmes and building codes is, of course, not entirely a matter of science. Rather, it is a highly social and contentious process in which some interests are suppressed and others are reinforced. (…) Standardised codes represent, to one degree of another, the negotiated interests of industry, government and environmentalists. Building codes can then be understood as temporary resolution of social conflicts that are, in turn, materialized as buildings."*
>
> (Guy and Moore, 2005: p. 52)

> *"Standards should not be the aim but the start of a design."*
>
> Dr Sergio Altomonte at the PLEA conference 2009, 24th of June in Quebec, Canada

Building codes are essentially documents providing guidance to those less experienced in the design and construction of buildings as well as on the targets to be met by the design brief. They usually offer a set of rules providing a standard approach for a range of situations so they are frequently seen as inflexible and restrictive.

The UK regulations apply to new buildings and refurbishments of existing buildings, whether domestic, commercial or industrial, and promote standards for all the building's construction aspects, energy efficiency and accessibility for all people. The British technical guidance is organised in parts, from 'A' to 'P'[12]. This work is just concerned with Part L which deals with conservation of fuel and power in buildings and more specifically with Part L1A which is for new dwellings. The first code of practice in the UK was published in 1948 and evolved to today's current building regulations that include the Part L1A 2006 (Department for Communities and Local Government, 2009).

Part L1A 2006 sets the minimum standards that all new homes have to meet and is now being reviewed to address the government's target for energy efficient homes via the zero carbon new homes policy. The review document is based on a 2008 consultation and contains the proposed text of the 2010 Approved Document (Department for Communities and Local Government, 2009).

As this work is looking into thermal performance it focuses only on the limiting fabric parameters proposed by the code. The proposed Approved Document 2010 does not change the U-Values established in 2006 (a detailed explanation of the meaning of U-Values can be found in Chapter 2) because "improving U-Values may not always be the most effective way to improve energy efficiency" (Department for Communities and Local

[12] More information can be found at www.planningportal.gov.uk/england/professionals /en/1115314110382.html [Accessed on 22nd of July 2009]

Government, 2009: p. 31). Figure 1-7 shows the limiting U-Values and air permeability (concept also explained further on in the work) as set by Part L1A 2006.

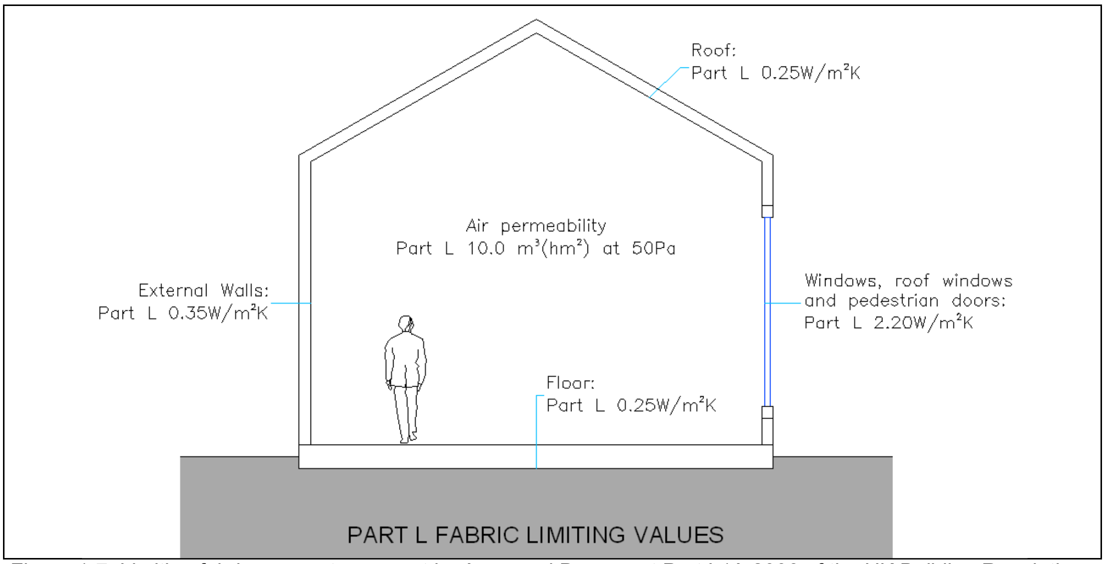


Figure 1-7: Limiting fabric parameters as set by Approved Document Part L1A 2006 of the UK Building Regulations

The annual energy savings of the house should be estimated using the Standard Assessment Procedure (SAP) to demonstrate compliance with Part L. The current version is SAP 2005[13] but that is currently under revision (SAP 2009), and is anticipated to come into operation in 2010. SAP uses the values Dwelling Emission Rate (DER), Target Emission Rate (TER which is based on a notional building) and Heat Loss Parameter (HLP) to assess a dwelling. The HLP combines the impact of both external surface area, insulation value of construction and airtightness. These values are the foundation of the Code for Sustainable Homes (CfSH) explained in the next section (Department for Communities and Local Government, 2008).

Building Regulations do not oblige a designer to make a sustainable building, it simply sets minimum standards. In order to address the government's zero carbon targets, a number of voluntary building standards have been launched. It is not likely that such voluntary schemes will become regulations in the future. However, for new housing, the CfSH was an aspirational standard to encourage homes to be built to higher standards of sustainability until 2007 when it became compulsory. Figure 1-8 shows the current timeline for zero carbon policy according to UKGBC[14].

[13] More information can be found at www.bre.co.uk/sap2005 [Accessed on the 22nd of July 2009]

[14] United Kingdom Green Building Council (UKGBC) is an independent, membership-based, non-profit organisation committed to improve the sustainability of the built environment. More information can be found at www.ukgbc.org [Accessed on the 22nd of July 2009]

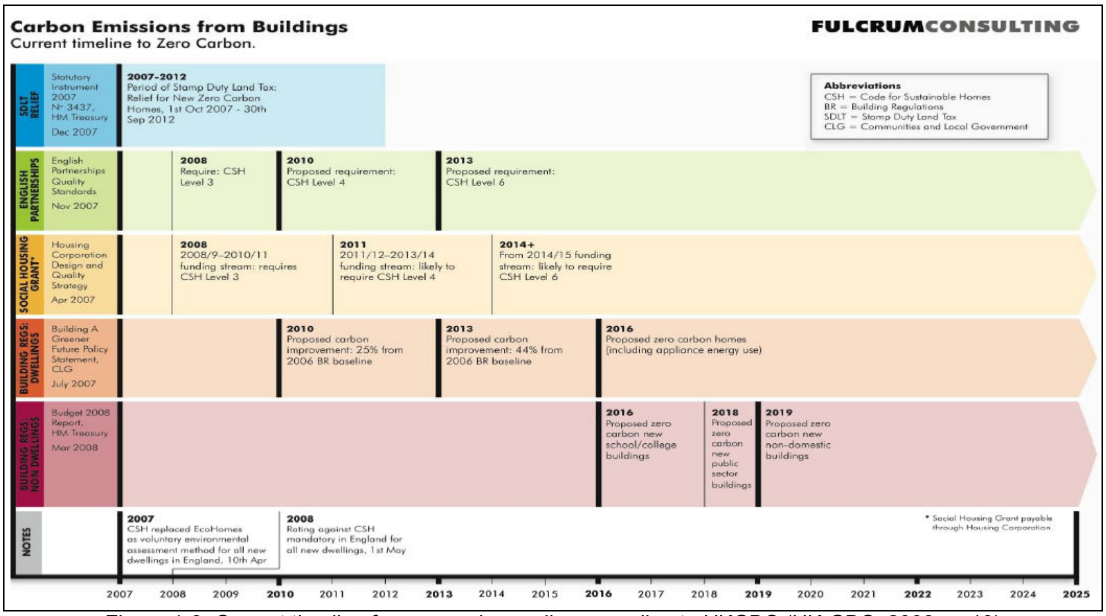


Figure 1-8: Current timeline for zero carbon policy according to UKGBC (UK-GBC, 2008: p. 13)

The CfSH has received a lot of criticism since its launch, especially for being ‘inflexible’ with innovative design feautures and for not taking passive design measures into account directly. However, it is a valuable tool as explained in the next section.

1.2.1 The Code for Sustainable Homes

> *“When the Code for Sustainable Homes first came out people spotted a lot of flaws so it had to be re-written. It doesn’t matter, what matters is that it caused a huge impact in industry and got people together to talk about the raised issues.”*
>
> Bill Gething from Feilden Clegg Bradley Studios at the EDUCATE Workshop, 8th of June of 2009 in Nottingham, UK

The Code for Sustainable Homes (CfSH) was launched in December 2006 and made available in April 2007 but just became a mandatory rating in April 2008. It was made mandatory to stimulate consumer choices and it replaced all other ratings including the EcoHome[15]. All houses funded by the government or its agencies such as the Housing Corporation and the English Partnerships also need to meet the CfSH. Regulations propose that those selling new homes will be required to provide information (a CfSH Certificate) to any buyer on the sustainability of the home (Department for Communities and Local Government, 2008: p. 5).

The code is a measure of the environmental performance of a building throughout its life. It aims to recognise best practice and encourages better than minimum building regulations. It looks over the nine categories of environmental sustainability listed below, applied at the

[15] The EcoHome rating system is still valid for Scotland and Ireland

level of an individual dwelling type through a two stage process. The final certification comes at a post construction review (Department for Communities and Local Government, 2009).

Table 1-1: Code for Sustainable Homes categories and level of flexibility (Department for Communities and Local Government, 2009: p. 7)

Categories	**Flexibility**
Energy and CO2 Emissions Water	Minimum standards at each level of the Code
Materials Waste Surface Water Run-off	Minimum standards at entry level of the Code
Pollution Heath and Wellbeing Management Ecology	No minimum standards

Table 1-2: Code for Sustainable Homes improvement over Building Regulations Part L (Department for Communities and Local Government, 2009: p. 11)

Code level	**Improvement over Part LA1 (Percentage reduction in DER over TER)**	**Total points score out of 100**	**Equivalent EcoHome rating**	**Other Equivalent rating**
1	10%	36	Pass	Energy Saving Trust Good Practice
2	18%	48	Good	
3	25%	57	Very good	Energy Saving Trust Best Practice
4	44%	68	Excellent	Similar to Passivhaus Standard (next section)
5	100%	84		
6	Full zero carbon	90		

Its minimum mandatory standards cover energy, water, materials, waste and surface water run-off. Each issue should be assessed against a performance target and awarded one or more credits. The rating system is divided in 6 levels as it can be seen in Table 1-2 and is indicated by ‘stars’ to communicate the overall sustainability performance of the house. One star is the entry level (above the level of the Building Regulations) and six stars is the highest level (reflecting exemplar sustainable design).

The CfSH does not directly account for passive design measures which can potentially make a building more efficient. It relies on the result of the SAP assessment which does account for better airtight and insulated fabric for example but currently excludes certain passive features such as sunspaces (explained in Chapter 2). Moreover, SAP gives a better rating for houses with highly efficient mechanical systems rather than passive low-energy systems. This will be demonstrated in Chapter 6. However, achieving a rating that can perfectly account for features which are not easily measurable is an impossible task. Even the use of dynamic simulation software (discussed in Chapter 2 and 5) cannot offer an accurate and credible result if not properly manipulated and their use is still limited to few specialised professionals. CfSH does its job when it comes to providing the general public with information on a house's probable performance in a glimpse and to provide a measure for comparison between houses.

In practice these percentages are difficult to apply. Sue Wolff (technical director from Foreman Roberts consultancy[16]) suggested in a talk given in the 'Symposium Towards Zero Carbon Sustainable Homes' at University of Nottingham (2008) some examples of how the levels could be achieved. For instance, to reach level 3 there would be a need to improve the fabric insulation, minimize thermal bridging, improve airtightness and install a heat recovery system with 85% efficiency. She suggested that, in order to reach level 3, the limiting U-values would have to change to:

- Walls: 0.25 $W/m^2 K$
- Roof : 0.13 $W/m^2 K$
- Floor: 0.20 $W/m^2 K$
- Windows and doors: 1.5 $W/m^2 K$

In terms of improvement of airtightness, her suggestion was a change from the $10m^3/hm^2$ at 50Pa of the building regulations to a $3m^3/hm^2$ at 50Pa. Almost 70% of homes in a recent survey just passed current requirement of $10m^3/hr/m^2$. Stephen (2000) looked into the BRE database of air leakage rates in UK dwellings (471 dwellings and 87 large panel system flats) covering a range of dwelling types and age and found that the mean value was $11.5m^3/hm^2$ at 50Pa, above Part L standards. He found no relationship between dwelling age and infiltration rates but it was clear that the ones built using traditional methods of construction (solid masonry and cavity masonry) were much leakier than the ones built using MMC. He concluded that there is considerable scope for improvement in the airtightness of British dwellings, old and new, as they are in average much leakier than many other countries.

Assuming that the percentages in Table 1-2 could be directly applied to the fabric limiting parameters, a diagram was produced (Figure 1-9) showing indicative values that would be potentially required to achieve different CHS levels in comparison to Part L 2006.

[16] More information can be found at www.foremanroberts.com [Accessed on the 22nd of July 2009)

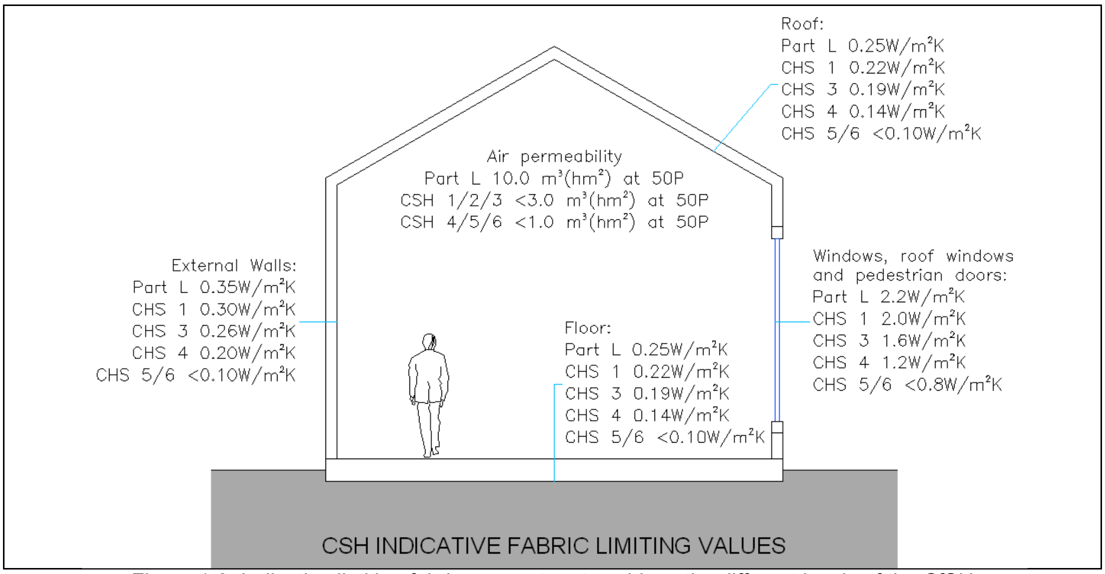


Figure 1-9: Indicative limiting fabric parameters to achieve the different levels of the CfSH

Higher standards of airtightness practically demand highly efficient mechanical ventilation systems to accomplish desired air quality and thermal comfort. In the UK, due to the milder climate and lifestyle matters, it is the author's belief that a good design well-thought throughout, considering natural ventilation strategies is more suitable than a mechanical system (Schiano-Phan, Rodrigues et al., 2008). Consequently, there would be a limit to the maximum desired airtightness standard.

The final aim is to achieve CfSH level 6 for all new housing in the country. From CfSH level 4, the improvements mean not just the incorporation of traditional passive solar features but also the reduction of the heating requirement to the point where a traditional heating system is almost no longer required. As shown in Table 1-2, CfSH level 4 is approximately equivalent to Passivhaus standard which is discussed in the next section.

1.2.2 The Passivhaus Standard

> *"But along came the tenants."*
>
> Ulla Janson, presenting the "Experiences from the New Swedish Passive House project" on the application of Passivhaus standards in Swede, at the PLEA 2009, 24th of June in Quebec, Canada

The German term 'Passivhaus' (passive house in English) refers to a specific construction standard firstly created in Germany for residential buildings[17]. The Passivhaus define passive houses as "buildings, in which a comfortable temperature in winter as well as in summer can be achieved with only a minimal energy consumption" (Passivhaus Institute, 2007: p.1).

17 The 'Passivhaus Institut' is a German independent research institution focused on efficient energy use in building. More information can be found at www.passivehouse.com [Accessed on 23rd of July 2009].

In 1991 Wolfgang Feist and Bo Adamson applied the passive design approach to a house in Darmstadt, with the objective of providing a show case low energy home at reasonable cost for the German climate. The design proved successful both in terms of energy consumption and comfort such that the same passive systems were applied again in a second construction in 1995 in Groß-Umstadt. By 1995, based on the experience from the first developments, Feist had codified the Passive Design of the Darmstadt and Groß-Umstadt homes, into the Passivhaus standard (Passivhaus Institute, 2007). The standard fundamentally consists of three elements: an energy limit (heating and cooling); a quality requirement (thermal comfort); a defined set of preferred passive systems which allow the energy limit and quality requirement to be met cost-effectively. It already featured all characteristics of what is today known as the current German Passivhaus standard: very good insulation, including reduced thermal bridges and well-insulated windows, good air tightness and a ventilation system with highly efficient heat recovery.

The five points that define the current German Passivhaus Standard for Central European Countries are (Passivhaus Institute, 2007):

- Heating criterion: The useful energy demand for space heating should not exceed 15 kWh per m² net habitable treated floor area per annum.
- Primary energy criterion: The Primary Energy demand for all energy services, including heating, domestic hot water, auxiliary and household electricity, should not exceed 120 kWh per m² net habitable floor area per annum.
- Air tightness: The building envelope must have a pressurization test result according to EN 13829[18] of no more than 0.6ACH at 50 Pa (approximately 0.4m^3/hm² at 50Pa[19]).
- Comfort criterion room temperature winter: The operative room temperatures should be kept above 20°C in winter, using the above mentioned amount of energy.
- All energy demand values are calculated according to the Passive House Planning Package (PHPP) and refer to the net habitable floor area, i.e. the sum of the net floor areas of all habitable rooms.

The PHPP defines a set of criteria to be used for calculations of the house's energy efficiency as well as giving specific weather data to be used. Some of the criteria, which are relevant further on in this work, are listed below:

- Thermostat temperature: 20°C without lowering of temperature at night.
- Internal heat sources: 2.1 W/m².

[18] EN 13829: European Standard for Thermal Performance of Buildings and Determination of Air Permeability of Domestic Buildings by Fan Pressurization Method

[19] The Passivhaus website does not specify a number but says "less than 1m^3/hm² at 50Pa" available at www.passivhaus.org.uk/index.jsp?id=669 [Accessed on the 23rd of July 2009]

- Occupancy: 35m²/person, deviant values may be used in the range of 20-50m²/person.
- Average air flow rate 20-30m³/h per person; use at least an air change rate of 0.3ACH for the room volume.

For Central European climates these rules for house design and consequent energy efficiency resulted in the possibility of simplifying the heating system. The whole heat distribution system could be reduced to a heat recovery system. This fact renders high energy efficiency cost-effectively: considering the lifecycle cost of the building, a Passivhaus need not be more expensive than a conventional new dwelling. In total more than 8.000 houses conforming to the current Passivhaus standard have now been built in Germany and elsewhere in central Europe. According to the institute, “Contemporary construction is quite airtight therefore the air replacement from infiltration is not sufficient. Ventilating by opening windows is not a convincing strategy either. Getting a sufficient volume of fresh air is not just a question of comfort, but a requirement for healthy living conditions. Therefore mechanical ventilation is the key technology for all new construction as well as refurbishment of existing buildings”[20].

Together with a set of suggestions to achieve better energy efficiency in the houses (such as optimum orientation, exposure to solar radiation, compact building form, etc[21]), the institute suggests construction standards for extra insulation: minimum U-Value ≤ 0.15W/m²K or desired U-Value ≤ 0.1 W/m²K for all opaque elements, and a U-Value around 0.8 W/m²K for windows and doors. That is comparable to somewhere in between CfSH levels 4 and 5/6 as shown in Figure 1-10.

Ulla Janson, in the “Experiences from the New Swedish Passive House project”, suggested that Passivhaus does not only mean one ‘type’ of architecture but also expected results can just be achieved if both, project leaders and carpenters, are familiar with the concept. In addition, the occupants have to understand the house and be able to use it efficiently (Janson, 2009).

[20] Source: www.passivhaustagung.de/Passive_House_E/passivehouse.html [Accessed on the 23rd of July 2009]
[21] More information at www.passivehouse.com, Passive House Checklist [Accessed on the 23rd of July 2009]

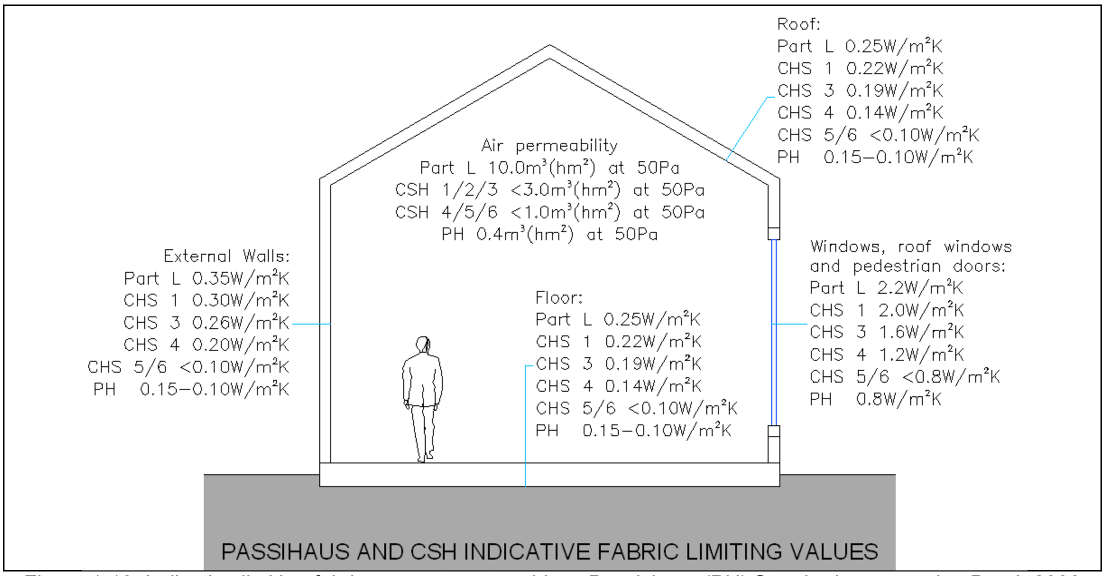


Figure 1-10: Indicative limiting fabric parameters to achieve Passivhaus (PH) Standard compared to Part L 2006 and CfSH

Defining a standard for low energy homes has offered a number of advantages both for the building industry as a whole and the German market in particular. In fact it has been a major reason for the explosion of the construction of low energy homes in Germany. To most professionals in Germany and to many people in the general public a Passive House now equates with the Passivhaus standard but its applicability elsewhere in Europe has yet to be tested. That was the starting point of the proposal made for the BASF House (Chapter 7).

The Passivhaus standard is a successful standard but was born to respond to the requirements of relatively cold central Europe. The requirements of the Passivhaus standard might be over engineered in milder climates such as the UK and needed to be adjusted for warmer European climates. That was the reason for the creation of the Passive-on project discussed in the next section. The requirement to limit the permeability of the building envelope so drastically makes an implicit need for an active air ventilation system which might not be adequate in milder climates.

1.1.1 The Passive-on Project

Given the success of the Passivhaus standard in central Europe it was expected that a debate would be raised considering if it was adequate for other climates. The Passive-on[22] project has been supporting the design of passive houses and exploring how to adapt the Passivhaus standard born to the requirements of a generally colder central European climate to the needs of a warmer climate. However, whilst in central Europe passive design is increasingly associated with the Passivhaus standard, this is not necessarily the case in

[22] More information can be found at www.passive-on.org [Accessed on the 23rd of July 2009]

southern Europe (e.g. Spain, Italy, Portugal and Greece). Here to most architects and general public, a passive house generally means any house constructed in line with the principles of passive solar design. Furthermore many professionals in the field disagree with associating the generic word “passive” with a specific building standard, which proposes an active ventilation system (Passive-on, 2007a).

The Passive-on consortium has formulated a revised proposal for the application of the Passivhaus standard in Warm European Climates, which takes into account the climatic as well as the philosophical issues mentioned above. The additional and amended points that define the proposed Passivhaus Standard for Warm European Climates are:

- Cooling criterion: The useful, sensible energy demand for space cooling does not exceed 15kWh per m² net habitable floor area per annum.
- Air tightness: If good indoor air quality and high thermal comfort are achieved by means of a mechanical ventilation system, the building envelope should have a pressurization test result according to EN 13829 of no more than 0.6ACH at 50 Pa (approximately $0.4m^3/hm^2$ at 50Pa). For locations with winter design ambient temperatures above 0°C, a pressurization test result of 1.0ACH at 50Pa (approximately $0.7m^3/hm^2$ at 50Pa) is usually sufficient to achieve the heating criterion.
- Comfort criterion room temperature summer: In warm and hot seasons, operative room temperatures remain within the comfort range defined in EN 15251 [23]. Furthermore, if an active cooling system is the major cooling device, the operative room temperature should be kept below 26°C.
- Removal of the requirement for active ventilation; passive or active ventilation should guarantee sufficient air quality.

These adaptations make the Passivhaus standard for warm climates a performance standard rather than a prescription. Simulation studies (Passive-on, 2007b ; Passive-on, 2007c) have shown that effective low energy homes can be built without the need for active ventilation systems and with less rigorous building envelope criteria than defined by the Passivhaus standard. This is demonstrated by the BASF House (Chapter 7). The Passive-on project also compares the proposed standard to a new construction built to current building regulations in each country and concludes that a typical Passivhaus requires only 15 to 25% of the energy required to heat a standard new construction (Table 1-3),

[23] EN15251: European Standard for Indoor environmental criteria for design and calculation of energy performance of buildings

Table 1-3: Heating and cooling energy demand for new homes constructed to the minimum building regulation standards and to the Passivhaus standard (Passive-on, 2007a: p. 4)

	Heating Demand (kWh/m^2/year)		**Cooling Demand (kWh/m^2/year)**	
	Standard	**Passivhaus**	**Standard**	**Passivhaus**
Germany	90	15	0	0
Italy	111	10.5	4.63	3
France	69.6	17.4	n/a	5
Spain	59	8.7	23.1	7.9
Portugal	73.5	5.8	32	3.7
UK	59	15	0	0

According to the Passive-on, building regulations need to adapt to support low energy housing. For example, high insulation levels mean that for the same land footprint as a standard house a Passivhaus will have less useful surface area so the council fees should be based on net not gross house volume. In addition, norms for summer indoor comfort levels should be relaxed by using adaptive comfort models (discussed in Chapter 5). This will ensure comfortable temperatures compatible with passive designs and make natural ventilation suitable for summer cooling. In line with the Passivhaus concept, the Passive-on project has identified for each country, partner to the project, a Passive Design which allows the requirements to be met cost effectively and practically, not forgetting the social and cultural side.

1.2.3 Thermal Mass and the Legislation

In 2005, the Energy Saving Trust report discussing the problem of overheating in urban houses in the UK stated that Building Regulations did not address the key issues related to overheating in British urban houses (EST, 2005). Since 2005, overheating is being taken into account by Part L but only for buildings other than dwellings. SAP, which is the standard assessment procedure for houses, just assumes a low level of thermal mass for all types of construction and may produce an indicative value to suggest overheating but this is not accounted for in the rating.

This assumption is currently being reviewed in the Proposals for amending Part L and Part F of the Building Regulations (Department for Communities and Local Government, 2009) so the new Part L to be launched in 2010 is expected to account for thermal mass. This will enable passive design features such as thermal mass to contribute towards Part L compliance and indirectly toward a better CfSH rating. Hopefully the revision will come as an incentive for more passive measures to be implemented in houses.

1.3 CREATIVE ENERGY HOMES PROJECT

The Creative Energy Homes[24] (CEH) is a unique research facility located on Green Close (latitude 52°94'N, longitude 1.20°W) at the Department of the Built Environment (DBE) on the University of Nottingham campus. The project aims to stimulate sustainable design ideas primarily using MMC and promote new ways of providing affordable, environmentally sustainable housing that are innovative in their design. The CEH has been awarded a number of prestigious prizes.

The project is mainly funded by industry through collaborations between the DBE and over 150 project sponsors/partners including main sponsors BASF, Roger Bullivant Ltd, Tarmac, Saint-Gobain and E.ON. There will be seven homes in total which will utilise a range of renewable energy and micro-generation technologies including solar thermal systems, ground-source and air-source heat pumps, biomass boilers, solar-photovoltaics, micro-wind and micro-CHP systems.

The homes include a lightweight steel framed dwelling (Stoneguard House, aiming to meet CfSH level 6), a home constructed using Insulated Concrete Formwork (ICF) and Structurally Insulated Panels (SIPs) (BASF House designed to meet CfSH level 4), an energy refurbishment project comprising a replica 1930s semi detached house (the E.ON House, to be refurbished to a zero-carbon standard), a pair of masonry constructed semi detached homes (the Tarmac Houses, CfSH levels 4 & 6), the Millennium Ecohouse finished in 2000 (before the discussed standards were created), a concrete house (Roger Bullivant) and potentially a timber framed house (The Nottingham HOUSE, Passivhaus & CfSH Level 6).

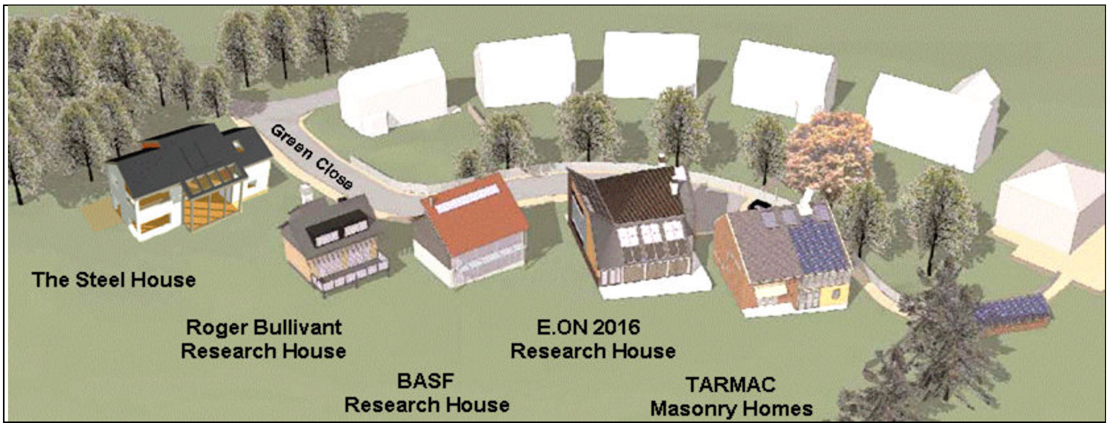


Figure 1-11: Artistic representation of the Creative Energy Homes project (courtesy of the project's manager[25])

[24] More information can be found at www.creative-energy-homes.co.uk [Accessed on the 24th of July 2009]

[25] Dr Mark Gillott, University of Nottingham. More information including contact details can be found at www.creative-energy-homes.co.uk [Accessed on 21st of July 2009]

This work concentrates on the thermal performance of two of the houses that were constructed using MMC techniques. The Stoneguard House (Chapter 6) is a steel frame home with an ICF basement with expected completion date around summer 2010. The BASF CfSH Level 4 House was completed in January 2008 (Chapter 7). The ground floor of the house was constructed using ICF and the first floor using lightweight SIPs building components. Both houses compromise alternative thermal mass solutions to help regulate internal temperatures as explained further in this work.

The E.ON house was built to enable the development and assessment of cost effective measures for reducing carbon emissions from ageing domestic properties. The property has been custom-constructed, with special planning permission, to the design of a typical 1930s semi-detached home using the building techniques and materials of the period. The house is already occupied and data collected over a 3 years period will inform and help to develop innovative solutions for improving the energy performance of older dwellings.

The Tarmac Houses are a pair of 3 bed, 5 person semi-detached homes that meets the minimum requirements of the CfSH Level 4 and 6 incorporating, where possible, masonry materials and existing industry best practice. Tarmac aims to demonstrate that masonry constructed homes can be sustainable, meet the code level requirements, be mass produced, visually appealing and affordable.

The Millennium Ecohouse was built and funded in 2000, by the housing developers David Wilson Homes (the only home that cannot be seen in Figure 1-11). The house was an experimental home used for research over a 3 years period. Currently, it is used as offices for the DBE staff. The remaining house listed is the Roger Bullivant House to be built using concrete and still in planning stage (no further information was available when this work was finished). The CEH site might also receive the latest development of the DBE, the Nottingham H.O.U.S.E. (Home Optimising the Use of Solar Energy[26]) which was design for the Solar Decathlon Europe competition[27] and mainly sponsored by Saint-Gobain. This is a timber framed terrace house with a courtyard, designed to meet CfSH level 6 and Passivhaus standards and to fit in a larger urban development.

Each new home will be fully monitored when occupied to provide researchers with both qualitative and quantitative data on environmental conditions, energy performance characteristics, micro-generation output and occupancy behaviour. The houses will have smart monitor display screens which inform the occupants, researchers, and visitors what the homes' environmental and energy performance characteristics are.

[26] More information can be found at www.nottinghamhouse.co.uk [Accessed on the 2nd of May 2010]
[27] More information can be found at www.sdeurope.org [Accessed on the 2nd of May 2010]

1.4 CONCLUSIONS

> *"The difference between target and truth [in building performance] is huge- we need to deal with the truth."*
> Bill Gething from Feilden Clegg Bradley Studios at the EDUCATE Workshop, 8th of June of 2009 in Nottingham, UK

> *"Truth is what stands the test of experience."*
> Albert Einstein

MMC is a term being used to describe a number of new construction methods that differ from the traditional brick and block constructions by being pre-manufactured, most of the times in a factory off-site.

MMC is relatively new in the UK and just recently its characteristics are being investigated in order to identify good practice, promote its wider use and encourage further development. Whatever the construction form or material, MMC has the potential to produce very energy efficient dwellings. However, just as in the traditional methods of construction, the energy efficiency of the finished dwelling depends heavily on good design and right material specification.

It is obvious that the use of MMC is in rapid expansion and should keep growing due to the strong driving forces. A crisis in the UK housing market and a lack of skilled construction labour are the strongest of those. MMC can provide better quality homes built at a much faster rate with less reliance on on-site labour. However, this means more dependence on good well-thought projects and significantly longer time at early stages of the design. Funding mechanisms and regulating institutions such as RIBA should adapt to this new reality to accommodate the higher costs of the designer. As a benefit, suppliers can get involved in the project in much earlier stages meaning more use of their skills and knowledge and less risk of mistakes on site. The use of MMC can cut through the usually long supply chain diminishing risks.

However, while the government and its agencies are supporting a wider use of MMC, there is still resistance from the builders and house owners which seems to be a result of lack of experience with the techniques involved and a lack of knowledge of the possibilities the method offers. The main barriers from the house owner's point of view are difficulties in obtaining a mortgage, a wrongly perceived lack of design flexibility and worries about the houses' performance. Builders worry about the higher costs of MMC construction, the complex interface between systems and the need for a time-consuming and more detailed design. Builders' apparent opposition to MMC might be just related to a fear of working using unknown/new skills and techniques and they do also express concerns with the performance of MMC but they do not have clear reasons to support their reservations. Consequently, in order to achieve any changes in the UK construction industry firstly this lack of knowledge should be addressed so designers and builders can share the same goal and provide the market with better houses at a faster rate.

The focus of most the published works associated with MMC was on financial or social matters and the few related to thermal performance of MMC houses do not include real life data. This is one of the issues that the University of Nottingham is intending to address through the CEH project. The project encourages MMC construction and is collecting long-term data to support research work on the subject. This work studies the thermal performance of two of its houses built using MMC techniques. Thermal performance of MMC houses is a controversial subject in need of further studies such as this thesis. The main issue at the centre of this discussion is the lack of thermal mass in MMC houses and how can this affect thermal comfort and energy use. In order to add the desirable thermal mass to both studied houses (the Stoneguard House and the BASF House) without adding extra weight, which would defeat most of the benefits of MMC, two innovative means were proposed: the exploitation of the ground's mass by the use of Earth to Air Heat Exchangers (Chapter 3) and the addition of latent heat storage by the use of Phase Change Materials (Chapter 4).

Building regulations and codes aim to provide guidance and standardise certain aspects of building construction so targets such as low energy use can be quantified. The CEH houses are complying with existing building regulations and being assessed against different house standards such as CfSH and Passivhaus. All new homes should be assessed against CfSH and be provided with a rating which will be given to the new owner. Passivhaus is not a mandatory rating but can and should be used as a marketing tool as a house built to those standards is likely to be very energy efficient and of a high quality.

The Passivhaus standard is a successful standard but was born to respond to the requirements of relatively cold central Europe and so has been adapted for warmer European climates through the Passive-on project. Requirements such as air-permeability limits could be relaxed to account for quality of labour and lifestyle differences.

The government is currently reviewing the CfSH and redefining Zero Carbon. A new consultation document proposes that the future CfSH should include a maximum annual energy use per square meter to be met which would be higher than the ones proposed by the Passihaus standards. This way the government would not force the use of heat recovery systems as the Passivhaus does (Lane, 2009).

The CfSH does not directly account for passive design measures which can potentially make a highly energy efficient building as it relies on the result of the SAP assessment only. Currently, SAP does not account for some passive design features such as the use of thermal mass. Just in the new revision of building regulations (still to be published) summer overheating and the potential benefits of thermal mass will be taken into account. However, achieving a unique rating code that can perfectly account for passive and active design features is a close to impracticable task. Reliance on dynamic simulations is also not feasible as their use is limited to few specialised professionals.

Nevertheless dynamic thermal simulation is a powerful tool if used with awareness and can provide accurate insights into building performance and the influence of aspects such as thermal mass (Chapters 5, 6 and 7). Alternative means to implement thermal mass in MMC buildings, such as the ones proposed in this work should also be integrated in Building Regulations and contribute towards better rating levels.

MMC houses can help the UK to achieve its zero carbon targets and so the government should consider financial incentives to MMC houses to cover insurance and mortgage issues and improve social acceptance. It is important to find an approach to make zero carbon MMC houses more financially attractive to developers and homebuyers as this is the easiest way to change the market to work towards a zero carbon society. The Environmental Audit Committee goes as far as suggesting that “the government should consider introducing higher penalties for developers who fail to meet energy efficiency standards” (Environmental Audit Committee, 2008: p. 3).

It is not surprising that, with more than 30% of all UK primary energy demand being used in dwellings and 60% of it being used for space conditioning alone (DTI, 2005: p. 1- 25; Association for the Conservation of Energy, 2007: p. 1-4), house design has become the focus of attention. There is a lot of controversy over optimal pathways to more energy efficient homes and whether if MMC is the answer. On the top of that discussion are the agencies and regulatory institutions setting targets and enforcing standards. However, one should keep in mind that there is a big difference between target and reality and that gap is still to be addressed.

There is no easy answer to the debate but there is a natural path to be followed which will inform us of the right track: experience.

2 CONCEPTS OF HEAT STORAGE IN BUILDINGS

This chapter starts by giving a background study on heat transfer in buildings to facilitate the understanding of the terms and of the properties that influence thermal storage. It also maps thermophysical properties of common building materials which are explored further in consecutive chapters. Subsequently it describes traditional means of envisaging and exploiting thermal mass in building design, particularly in dwellings.

2 CONCEPTS OF HEAT STORAGE IN BUILDINGS

> *"The lightweight home (in a warming UK climate) was found to need air conditioning by the year 2021. This compared to 2061 for the medium-heavy and heavyweight homes."*
> Bill Dunster Architects for Arup R&D, 2005 on the report Housing and Climate Change: Heavyweight vs. Lightweight Construction (Dunster, 2005)

Since ancient times man has learned to use thermal mass to improve their thermal environment, either by living in caves, burying their food and water to keep it fresh or building stone and brick chimneys to absorb heat from a fire and later reradiate it to the space. Nonetheless, currently there is significant debate on the value of thermal mass in the design and construction of dwellings. This is a relatively new discussion due to the recent promotion of Modern Methods of Construction (MMC) as described in Chapter 1, which generally comprises less high thermal mass materials than the traditional construction.

Bill Dunster Architects and Arup R&D (2005) presented research work that illustrated the importance of mitigating climate change effects by designing homes with thermally massive passive features in order to offset the expected temperature increases. The work also stated that thermally lightweight homes would result in substantially higher room temperatures and levels of discomfort. It states that masonry houses that take advantage of their inherent thermal mass can save a considerable amount of energy over their lifetime compared to a lightweight timber frame house.

A highly insulated building with no thermal storage can overheat even in winter months when the exterior temperature may fall below $0^{o}C$ (Athienitis and Santamouris, 2002). The risk of overheating in super-insulated houses occurs not just in the warmest season but also in other seasons, specially because shading devices are generally only designed for summer. As long as there is solar penetration into the building there is a risk of excessive heat. In a report done by FaberMaunsell it has been demonstrated that in a lightweight well insulated house, external temperatures of $29^{o}C$ may result in internal temperatures of at least $39^{o}C$ and even north facing rooms may overheat (Orme and Palmer, 2003: p. 3). The work provides a detailed study on the influence of insulation on the overheating of houses.

In attempting to mitigate overheating in housing it is important to consider the basic principles that contribute to it. This chapter presents some concepts of energy transfer in a building as well as the influence of the mass on it. It covers the flow of energy through the building's envelope and the storage of energy in the mass for later utilization.

2.1 CONCEPTS OF HEAT TRANSFER IN BUILDINGS

By slowly storing and releasing relatively large quantities of heat per unit volume, thermal mass that is well implemented in a building can help to regulate the indoor temperature. Generally speaking, thermal mass refers to any material that has the capacity to absorb, store and release heat. Consequently, one can characterise the thermal mass of a material by referring to its thermal conductivity, specific heat capacity and density and by understanding heat transfer mechanisms acting on it.

2.1.1 Heat Transfer Mechanisms

Heat transfer is the movement of energy due to a temperature difference. It can occur by radiation, convection or conduction. Differently from conduction and convection where the energy travels through matter, in radiation the energy travels in electromagnetic waves after being emitted by a body. The rate of emitted radiant energy is dependent on the substance, its microscopic structure, temperature and relation to the surroundings. The net energy transfer rate depends on spatial and temperature relationships of the surface and its surrounding environment (ASHRAE, 2005).

From this concept it is easy to understand why the central actor regarding passive design is the sun. The sun's radiated energy arrives on Earth in the primary form of heat and light, travelling through space as shortwave radiation. Because it travels in parallel rays, the perpendicular position identifies the maximum density of radiation reaching a body. Any deviation from perpendicular reduces this density and the amount of energy intercepted.

When the emitted energy hits a surface it is reflected, transmitted or absorbed. All surfaces both reflect and absorb radiation but do so in different ways. The energy absorbed by surfaces is radiated back as longwave radiation. For any transparent layer, part of the incident radiation (I) is transmitted, another portion is reflected and the remaining is absorbed. For example, glass can transmit nearly all the shortwave solar radiation received but absorbs most of the longwave radiation and retransmits that as heat energy. This is the cause of the ‘greenhouse’ effect: heat is trapped within transparent structures.

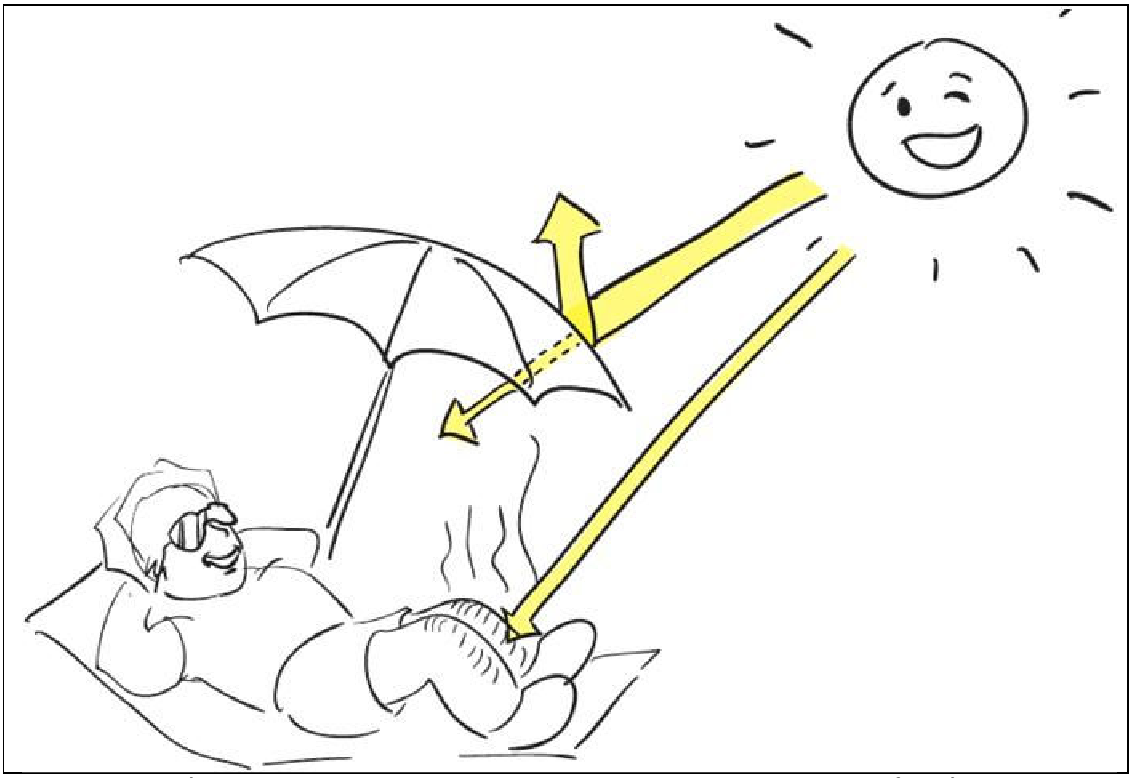


Figure 2-1: Reflection, transmission and absorption (cartoon made exclusively by Weikai Gong for the author)

A short description of these concepts and their relationship, governed by the First Law of Thermodynamics (an example of which is given in Equation 2.1), called the Law of Conservation of Energy, can be found below (Athienitis and Santamouris, 2002 ; ASHRAE, 2005). In order to understand how each material responds to radiation we use the following properties:

- Emissivity (ε): a measure of a material's ability to radiate absorbed energy. It is a ratio of the energy radiated by the material to energy radiated by a black body (ε=1) at the same temperature. Generally, the blacker the material the closer the emissivity is to ε=1 and the more reflective the material the lower its emissivity.
- Absorptivity (α): the capacity of a material to absorb incident radiant energy. It is dependent on the temperature of the body and the wavelength of the incident radiation. Absorptance is the ratio of the radiant flux absorbed by an object to that incident upon it.
- Reflectivity (ρ): the capacity of a surface to reflect incident radiant. The wavelengths of radiation that are reflected are determined by the colour, texture and clarity of the surface material and the reflection occurs at an angle equal to the angle of incidence. Reflectance is the ratio of the radiant flux reflected by an object to that incident upon it.
- Transmissivity (τ): the fraction of incident radiant energy being transmitted through a transparent object. It is dependent on the temperature of the body and the wavelength of the incident radiation. Transmissivity is the transmittance of a material for a unit thickness

sample and transmittance is the ratio of the total radiant energy transmitted to that incident upon it.

Equation 2.1: First Law of Thermodynamics

$$\alpha + \rho + \tau = 1$$

Where:
α= absorptivity
ρ= reflectivity
τ=transmissivity

ASHRAE Handbook (2005) and J. A. Clarke in Energy Simulation in Building Design (2001) have a comprehensive list of construction materials and its emissivities and absorptivities.

The portion of radiant energy, for example solar radiation, that is absorbed is transformed to another form of energy, for example heat energy. This heat energy is transported between parts of the material by transfer of kinetic energy between particles or groups of particles at atomic level. The stimulated molecules impact the adjacent molecules with their vibration dissipating and spreading the energy and so the absorbed radiation is redistributed through the material due to the natural phenomenon of maintenance of balance. This thermal transfer process occurs in the direction of the lower temperature and is called conduction.

In gases, conduction occurs by elastic collision of molecules while in liquids it is believed to be caused by longitudinal oscillations of the structure's network. In metals, thermal conduction occurs like electrical conduction, through the motion of free electrons. In opaque solid materials such as wall's, floor's and roof's components, conduction is the main mechanism of heat transfer (ASHRAE, 2005).

Convection is the heat transfer due to the actual motion of a fluid itself. In order to transfer the heat from a solid material to a fluid (liquid or air) it is necessary to make it move across a radiant surface to agitate the molecules. When the heated molecules move away from the source they are replaced by new unheated molecules. Convection can be forced by a machine (fan or pump) or be natural as the expansion of the space between air molecules caused by temperature differences makes them less dense than the surrounding air and so lighter to rise. The upward force that causes them to rise is called buoyancy and can be used to drive 'stack' ventilation in buildings. The greater the temperature difference and the height the air has to travel, the greater the buoyancy and the stack effect.

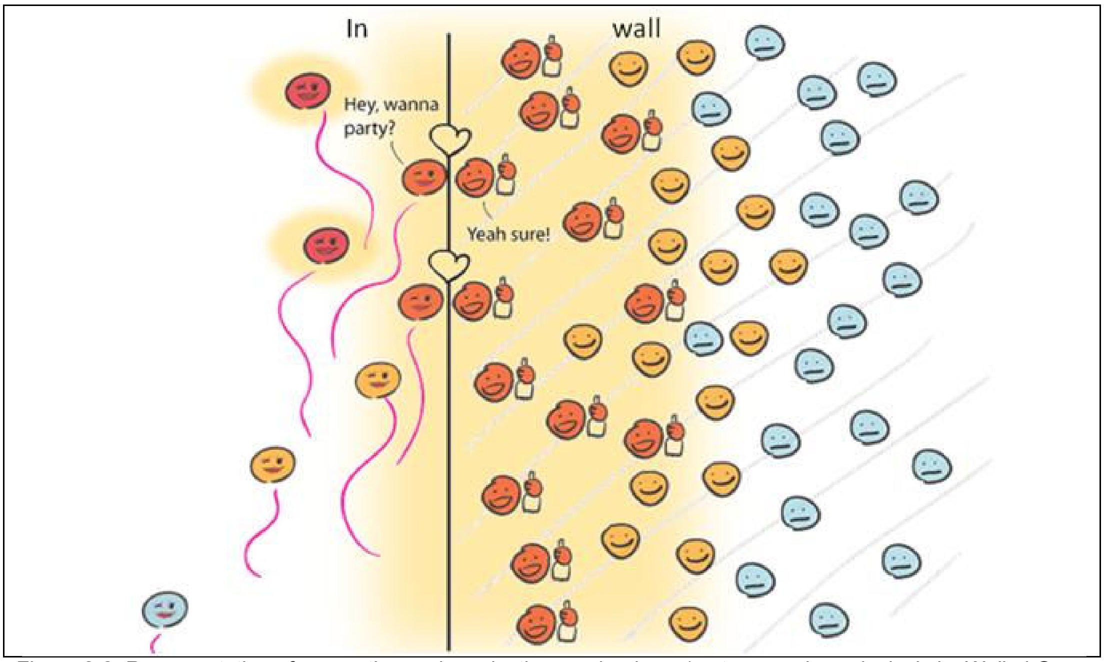


Figure 2-2: Representation of convection and conduction mechanisms (cartoon made exclusively by Weikai Gong for the author)

2.1.2 Thermophysical Properties of Materials

The rate at which energy is conducted depends on the material and it depends on the density, capacity of receiving and capacity of passing it on. Consequently the three most important properties of a material in thermal analysis are:

- Density (ρ): the mass of a material that fills a unit volume (kg/m^3)
- Specific heat (c): the quantity of energy needed to produce a temperature change in a mass of material (J/kg^oC)
- Thermal conductivity (k): the ability of a material to conduct heat at a unit thickness of material with both surfaces at a unit temperature difference (W/m^oC)

These properties are time-dependent due to material temperature and/or moisture fluctuations. Thermophysical properties might also be direction and/or position dependent if the material is non-homogeneous or anisotropic. Calculations might ignore such dependencies and assume these properties are constant.

Many authors have published comprehensive lists of building materials and their thermophysical properties. A good list can be found in Energy Simulation in Building Design (Clarke, 2001: p. 325-338) where the author assessed data reliability and divided the materials into categories. Some material properties that are relevant to this work can be found in Table 2-1 which have been collected from the above reference and also from the

CIBSE Guide A (CIBSE, 2006: p. 3-34 to 3-41). It is important to note that properties vary for different samples, test procedures and accuracy.

Table 2-1: Thermophysical properties of common construction materials (Clarke, 2001)

Material	**Conductivity (W/m°C)**	**Density (kg/m^3)**	**Specific Heat (J/kg°C)**
Block - Masonry medium weight	0.6	1350	840
Brick - Aerated	0.3	1000	840
Brick - Inner leaf	0.62	1700	840
Brick - Outer leaf	0.96	2000	650
Brick - Reinforced	1.1	1920	840
Cement (regular)	0.72	1860	840
Cement fibreboard	0.082	350	1300
Cement screed	1.4	2100	650
Ceramic tiles	1.20	2000	850
Concrete - Heavyweight	1.3	2000	840
Concrete - Lightweight	0.2	620	840
Concrete - Medium weight	0.32	1060	840
Earth (common)[28]	1.28	1460	880
Expanded polystyrene (EPS)	0.035	23	1470
Gypsum Plasterboard	0.16	800	840
Hardwood	0.05	90	2810
PVC (regular)	0.16	1380	1000
Sand	1.74	2240	840
Softwood	0.17	550	1880
Steel	45	7800	480
Water (liquid at 20°C)	0.58	1000	4200

The property that determines how easily heat flows through a building's envelope is conductivity. Thermal conductivity typically varies with temperature and, in anisotropic materials, with direction, but the variation can be small over a significant range of temperatures.

The reciprocal to conductivity, is thermal resistivity which is how much a material resists conducting heat as shown in Equation 2.2 below:

Equation 2.2: Thermal resistivity $$r = \frac{1}{k}$$

Where:
r= resistivity (m °C/W)
k= conductivity (W/m °C)

[28] This value is just for reference. The values measure on site will be discussed further on this work in Chapter 4.

Consequently, good conductors have poor resistivity and vice versa. Both properties are referring to the following parameters: 1 second time period through a $1m^2$ sample of the material that is 1m thick when there is a 1ºC temperature difference between the two surfaces.

Conductivity and resistivity take no account of any effect that varying the thickness of a layer of the material may have. Although a thin and a thick layer of the same material will have the same conductivity, they will conduct different amounts of heat because of the distance the heat has to travel.

Materials used for insulation usually have very low specific heat capacities and much lower thermal conductivities than materials with high thermal mass (e.g. expanded polystyrene in Table 2-1). Consequently they do not store heat and are able to reduce unwanted heat transfer. As air is not a good conductor of heat the most common way to thermally insulate something is by trapping air. If air is trapped in countless tiny fibres in a way that inhibits convection, air becomes a great insulator. So a good insulating material is not just a substance with poor conductivity but also a material that does not support convection and blocks radiation. A wool sweater is a good example of a good thermal insulator that traps air effectively. In addition, its low conductivity fibres are randomly distributed which means that even if it receives heat radiation, any conduction that happens is not in a straight line.

In order to understand how these properties influence thermal storage it is necessary to break the process into stages. In a simplified explanation it can be said that in thermal mass the heat transfer process occurs in 4 steps:

1. Heat is radiated from a body (e.g. the sun) to the surface of the material where it is absorbed;
2. Heat is conducted from the warmer surface to the cooler interior of the material;
3. When the surface becomes warmer than its surroundings it radiates heat back to the space becoming cooler again;
4. Heat from the warmer interior is conducted back to the surface.

Consequently, in order to be effective as thermal mass, a material must have a high heat capacity, moderate conductance and density and a high emissivity and absorptivity. For instance, wood does not provide good thermal mass because it is not very conductive (as shown in Table 2-1), rejecting the heat prematurely by radiation as the surface's temperature rises. Steel also does not make good thermal storage as its low emissivity indicates that the majority of the incident radiation is reflected rather than absorbed and its high conductivity (refer to Table 2-1), indicates that any stored heat is quickly conducted to the surface and radiated to the environment.

Materials such as concrete, water and masonry products have high absorptivity and so can absorb more solar radiation than what is reflected. In addition, they have a high density and moderate conductance (Table 2-1) which makes them very effective when acting as thermal mass. Earth can also be successfully used as thermal mass when used in construction (i.e. rammed earth or adobe), in underground buildings or other applications such as Earth-Air Heat Exchangers (EAHE), which were explored further in Chapter 3.

It is also important to notice that materials that might be considered similar (e.g. various types of brick) may have very different properties as shown in Table 2-1. Consequently, one must consider all properties carefully. Also, as thermal storage capacity is not dependent just on these properties (as it is explained further in this chapter), other aspects should be taken into account. For example, ceramic tiles could be considered a high mass material but if they have very reflective surface they will absorb less radiant energy. Furthermore, a surface's finishes such as paint, might also change the material's capacity to absorb heat and so influence its effectiveness as thermal mass.

As high thermal mass is dependent on a combination of factors, it is not simple to quantify. In Figure 2-3, Figure 2-4, Figure 2-5 and Figure 2-6 a mapping of common building materials (shown previously in Table 2-1) can be seen and the above considerations can easily be visualised. Metals, including steel, have been excluded as their very high conductivity would make the scale of the graph difficult to read. It can be noticed that the materials that would effectively work for thermal storage are grouped in each graph, giving an insight of which type of material could be called 'high thermal mass'. Good insulators are also grouped in the same region, with conductivity very close to zero and low densities.

The material in yellow (the Micronal phase change material) was added to the graph for reference as it is dealt with in Chapter 4. As it can be seen, if only the properties discussed here are taken into account then this type of material would not be seen as a substitute for conventional thermal mass as it is out of the 'thermal mass region' in the graph. However, it stores latent heat in addition to sensible heat. These concepts are explained in Chapter 4.

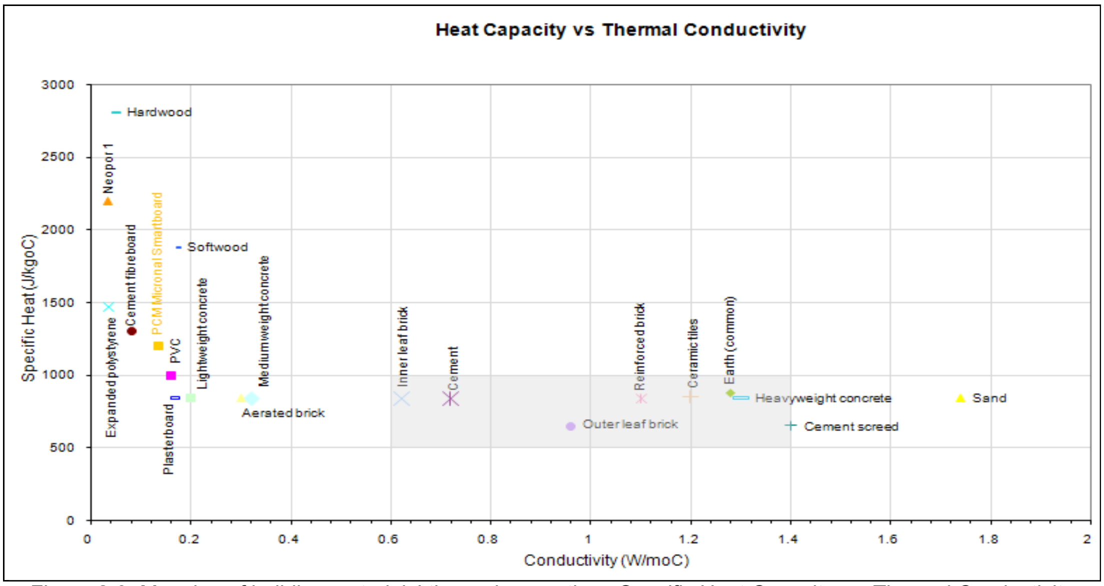


Figure 2-3: Mapping of building materials' thermal properties - Specific Heat Capacity vs. Thermal Conductivity

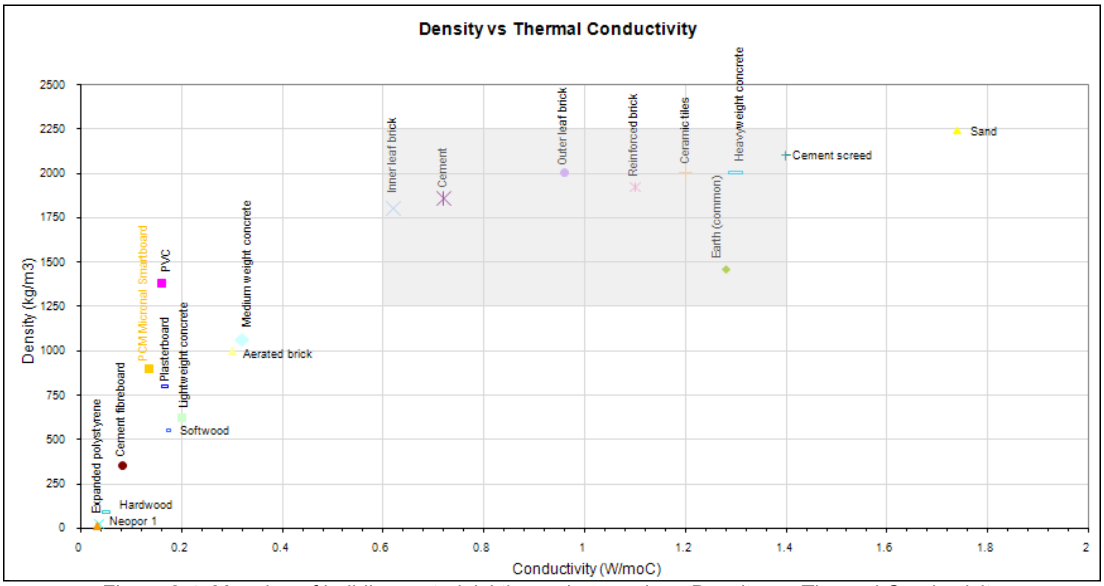


Figure 2-4: Mapping of building materials' thermal properties - Density vs. Thermal Conductivity

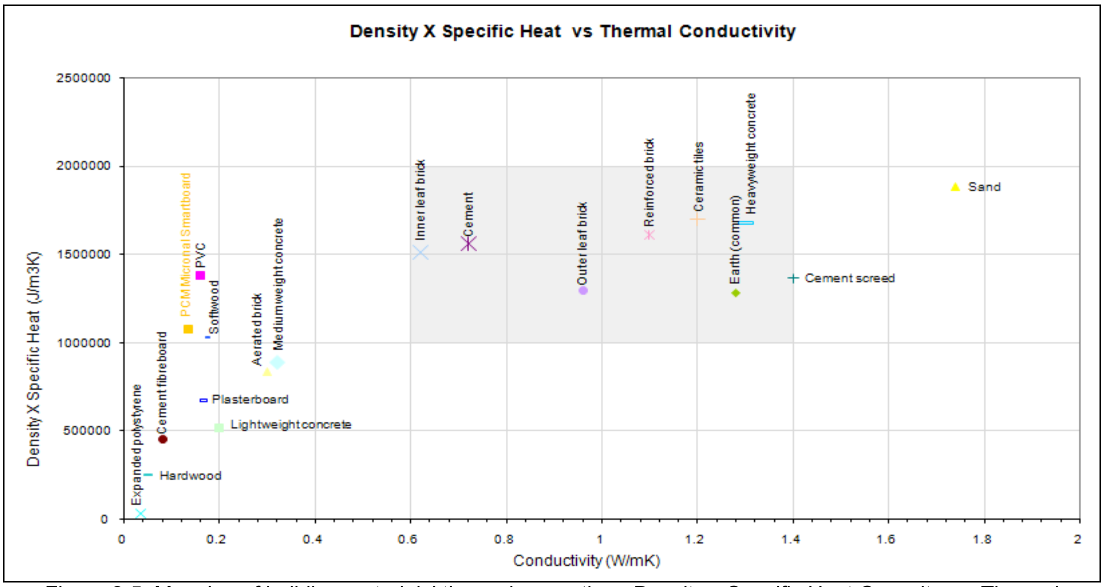


Figure 2-5: Mapping of building materials' thermal properties - Density x Specific Heat Capacity vs. Thermal Conductivity

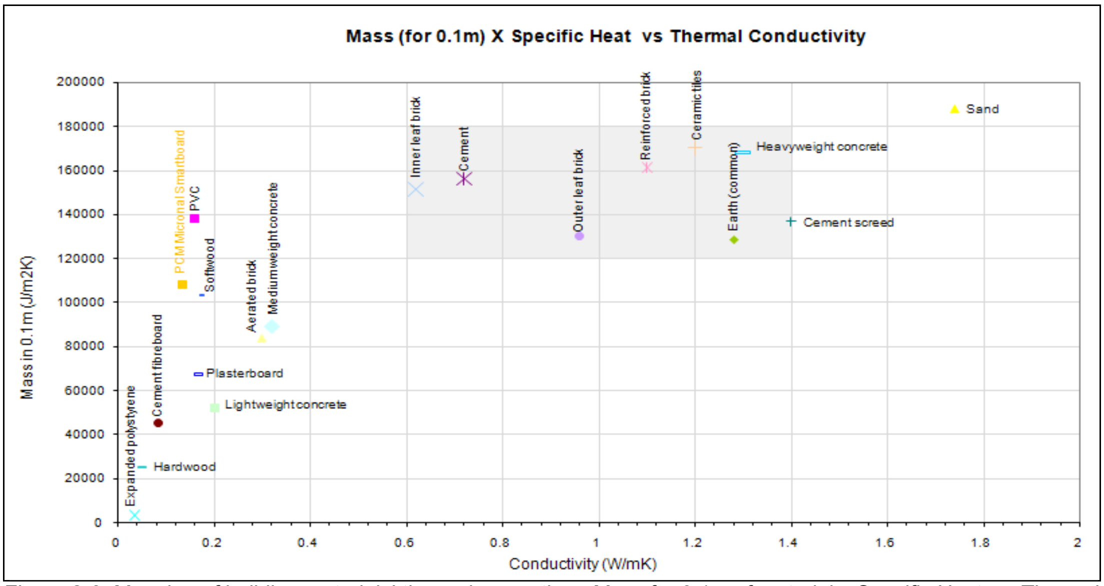


Figure 2-6: Mapping of building materials' thermal properties - Mass for 0.1m of material x Specific Heat vs. Thermal Conductivity

The application of these graphs is to allow a designer to quickly identify a potential material with high thermal mass by comparing information commonly available. However, these graphs represent just materials. Their effectiveness as thermal mass in a building also depends on how they are applied in the construction, how they are finished, their surface exposure and thickness. Chapter 5 will simulate heat transfer in buildings and the thermal mass of complete construction elements.

2.2 QUANTIFYING HEAT TRANSFER IN BUILDINGS

> *"As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality."*
> Albert Einstein, 1921

This section reveals how heat transfer calculations take into account the thickness of materials. It also explains heat transfer calculation in buildings defining the differences between steady-state and dynamic heat transfer calculations. It will be demonstrated that the later is more accurate for simulating thermal mass so a software that employs that approach is used in subsequent chapters.

2.2.1 Steady-state Heat Transfer

The law that governs heat conduction is known as Fourier's law and states that the rate of heat flow through a homogenous material is proportional to the area of the section at right angles to the direction of heat flow and to the temperature difference along the path of heat flow (ASHRAE, 2005: p. 3-1). Fourier's law can be written as:

Equation 2.3: Fourier's law of heat conduction

$$q = -k \frac{\Delta T}{\Delta x}$$

Where:
q = heat flux (W/m²)
k = conductivity (W/m°C)
ΔT/Δx = temperature gradient (ºC/m)

The negative sign is necessary to ensure that the equation is representative of true physical behaviour as heat flow is always from the higher to the lower temperature.

In steady-state heat conduction through a building's envelope the temperature on both sides of the wall remain unchanged over a long period of time, allowing the heat flux to approach a constant value. A representative image of the steady-state temperature profile in a wall of thickness *L* can be seen in Figure 2-7. The heat flows from the higher temperature, T_1, to the lower temperature, T_2, through the distance *L*.

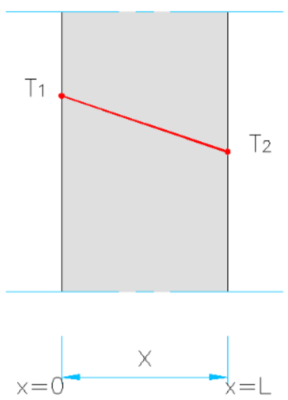


Figure 2-7: Steady-state temperature profile in a wall

By applying Fourier's law we can obtain:

Equation 2.4: Fourier's law applied to the wall's example

$$q = -k \frac{T_1 - T_2}{L}$$

Where:
q = heat flux (W/m²)
k = conductivity (W/m °C)
T_1 = initial temperature (°C)
T_2 = final temperature (°C)
L = thickness (m)

Therefore, to predict the thermal behaviour of a building, it is necessary to take into account the thickness *L* of the wall. Resistance is the relation between the material resistivity and its thickness as it can be seen in Equation 2.5 below (Childs, Courville et al., 1983 ; BSi, 2003):

Equation 2.5: Thermal resistance or R-value

$$R = r \times L$$

Where:
R= resistance (m^2 °C/W)
r= resistivity (m °C/W)
L= thickness (m)

Accordingly, the thicker the layer of material is, the greater its resistance to heat flow. Resistance is referred to as the R-value and it is convenient for multi layered walls since and overall R-value can be calculated by summing the values of each layer. The properties are referring to a $1m^2$ sample of the material that is 1m thick when there is a 1ºC temperature difference between the two surfaces.

Substituting Equation 2.2 in Equation 2.5, one can determine the Conductance of a material, better known as a U-Value or Thermal Transmittance (BSi, 2003 ; CIBSE, 2006). The U-Value of the building envelope is the major factor in the determination of the steady-state heat losses and gains.

Equation 2.6: Thermal conductance, transmittance or U-Value

$$U = \frac{k}{L} = \frac{1}{R}$$

Where:
U= conductance (W/m² °C)
R= resistance (m² °C/W)
k= conductivity (W/m °C)
L= thickness (m)

Consequently, by applying these to Fourier's law one obtains:

Equation 2.7: Conductance and Resistance in Fourier's law

$$q = U\Delta T \text{ or } q = \frac{\Delta T}{R}$$

Where:
q = heat flux (W/m²)
U = conductance or U-Value (W/m² °C)
R = resistance or R-value (m² °C/W)
ΔT = temperature difference (°C)

In addition, for a multi-layered wall the equation can be written as (Clarke, 2001: p. 8; BSi, 2003):

Equation 2.8: Heat flux through a multi-layered wall in steady-state

$$q = \frac{\Delta T}{R_1 + R_2 + \ldots + R_n}$$

Where:
q = heat flux (W/m²)
ΔT = temperature difference (°C)
R = resistance or R-value (m² °C/W)

One can use either resistance or conductance, to describe a material's thermal behaviour. In steady-state, two walls with the same U-Value or R-value will conduct the same amount of heat even though the thicknesses and materials may differ.

Traditionally designers have relied on these steady-state equations to assess heat loss through building envelopes. This approach would neither consider the dynamic behaviour of the materials nor is it completely precise as even thought they might have the same U-Value, in reality different construction arrangements will perform differently (Clarke, 2001).

2.2.2 Transient Heat Transfer

Figure 2-8 below illustrates a transient heat flow in the section of a homogeneous wall which is initially at a uniform temperature (a). If the external temperature is suddenly raised and the internal is kept at the same initial temperature (b), the temperature profile will develop as (c) and (d) until a new steady-state condition has been established (e). It can be noticed that it takes time for the heat to travel through the wall and that at any given time before (e) is achieved the heat flux will be different at different locations in the wall (Childs, Courville et al., 1983).

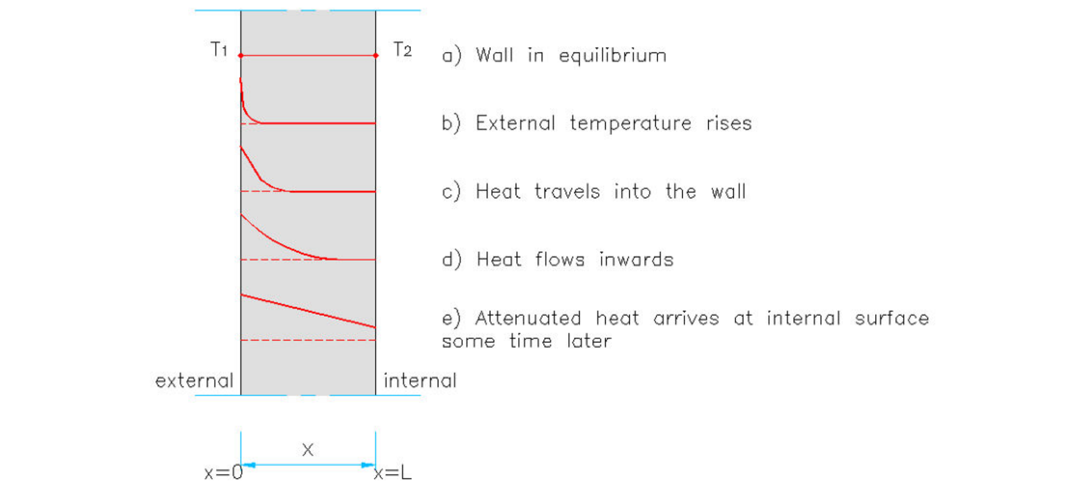


Figure 2-8: Development of a transient temperature profile in a wall following a temperature change

Figure 2-9 illustrates the actual heat flux on both sides of the wall compared to the heat flux predicted by a steady-state calculation (Childs, Courville et al., 1983).

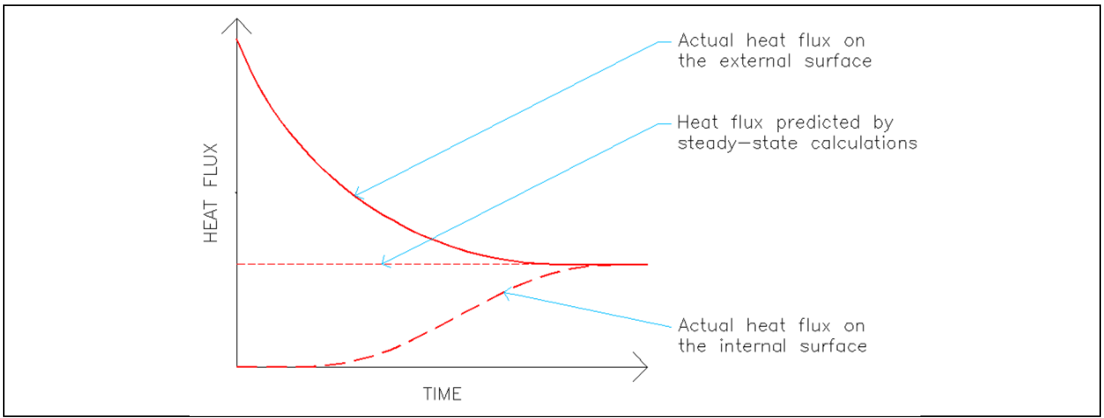


Figure 2-9: Development of a transient temperature profile in a wall

Thus, although the final heat fluxes at each surface can be determined by the steady-state calculations, if this was used to predict the heat flow through the wall it would result in considerable errors.

The final steady-state condition cannot be reached until a certain quantity of energy has been conducted through the wall. In order to find the amount of energy necessary to cause the change in temperature, the fundamental Heat Flow Equation (Equation 2.9) can be applied (ASHRAE, 2005).

Equation 2.9: Quantity of energy to cause a temperature change

$$Q = mc\Delta T$$

Equation 2.10: Mass of the material

$$m = \rho V$$

Equation 2.11: Volume of the material

$$V = AL$$

Where:
Q = quantity of energy input/output (kW)
m= mass of material (kg)
c= specific heat capacity of material (kJ/kg^{o}C)
ΔT= temperature difference (^{o}C)
ρ= density of material (kg/m^{3})
V= volume of material (m^{3})
A= area of material (m²)
L= thickness of material (m)

Using the previous example, if the average temperature of the external wall was T_1 and of the internal wall was T_2 before the transient started then, when steady-state conditions were reached, the average temperature of the wall was $(T_1+T_2)/2$. By replacing this in Equation 2.9 and rearranging it in order to give the energy per unit of surface area, Equation 2.12 can be written (Childs, Courville et al., 1983):

Equation 2.12: Quantity of energy to cause a temperature change

$$\frac{Q}{A} = \rho c L \frac{T_1 - T_2}{2}$$

Where:
Q = quantity of energy input/output (kW)
A= area of material (m²)
c= specific heat capacity of material (kJ/kg^{o}C)
ρ= density of material (kg/m^{3})
L= thickness of material (m)
T_1 = initial temperature (^{o}C)
T_2 = final temperature (^{o}C)

The product of ρ and c is known as the Volumetric Heat Capacity (VHC) of a material. If the temperature is a condition imposed to the wall then the product ρcL is a measure of the wall's ability to store energy per unit surface area. Relating the wall's ability to store energy to the wall's ability to conduct heat (the U-Value, Equation 2.6) the quantity known as Thermal Diffusivity (D) can be obtained (Childs, Courville et al., 1983) using:

Equation 2.13: Ability to store energy divided by ability to conduct heat

$$\frac{\rho c L}{\frac{k}{L}} = \frac{\rho c L^2}{k} = \frac{L^2}{D}$$

Equation 2.14: Thermal diffusivity

$$D = \frac{k}{\rho c}$$

Equation 2.15: Thermal effusivity

$$\varepsilon = \sqrt{k \rho c}$$

Where:
c= specific heat capacity of material (kJ/kg^{o}C)
ρ= density of material (kg/m^3)
L= thickness of material (m)
k= conductivity (W/m ^{o}C)
D= thermal diffusivity (m²/s)
ε= thermal effusivity (j/m² ºC)

Thus the thermal diffusivity is an indication of the speed at which the temperature profile moves through the core of a wall and, consequently, it is a useful value when characterising thermal mass. Materials with high diffusivity transmit boundary heat flux fluctuations faster than materials with low values (Clarke, 2001) and so the material will quickly respond to any changes in temperature (Kalogirou, Florides et al., 2002). Similarly, the greater the quantity L^2/D, the longer the time required to reach steady-state conditions.

The Thermal Effusivity (*ε*, Equation 2.15) of a material is often referred to as Thermal Inertia. It is the square root of the product of conductivity, density and heat capacity and so is a measure of the material's capacity to exchange thermal energy with its surroundings. It characterises the transient thermal behaviour during the contact of two materials. High effusivity means that a material will more readily absorb a heat flux on a surface (Kalogirou, Florides et al., 2002). In summary, diffusivity characterises the transfer of heat through a material's core and effusivity through a material's surface.

The effusivity of the skin and the object it touches determines the interfacial surface temperatures of the boundary. If the effusivity of a material is high (i.e. ceramic or metals), the interfacial temperature is lower than if the effusivity is low (i.e. wood or carpet). Hence the difference we feel when touching different materials. In addition, it is this property that explains the phenomenon of firewalking which is no more than a balance between how much heat energy the body absorbs or releases in a certain amount of time. The body with greater thermal effusivity will prevail in maintaining the temperature for a certain period of time: the skin in this case. Coal is a poor conductor but its conductivity will 'catch up' if the person stands on it for too long so it is all about the time spent on the burning coal.

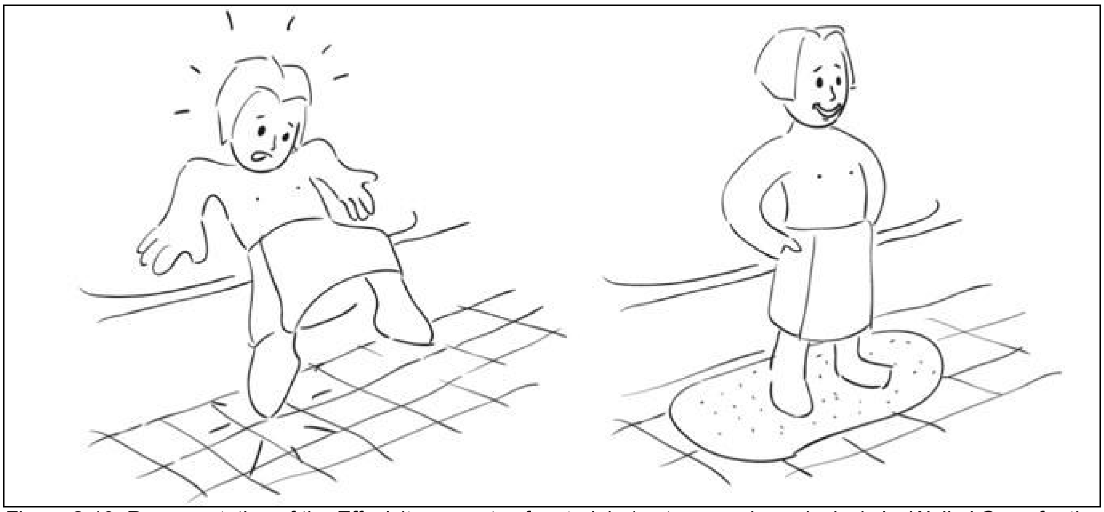


Figure 2-10: Representation of the Effusivity property of materials (cartoon made exclusively by Weikai Gong for the author)

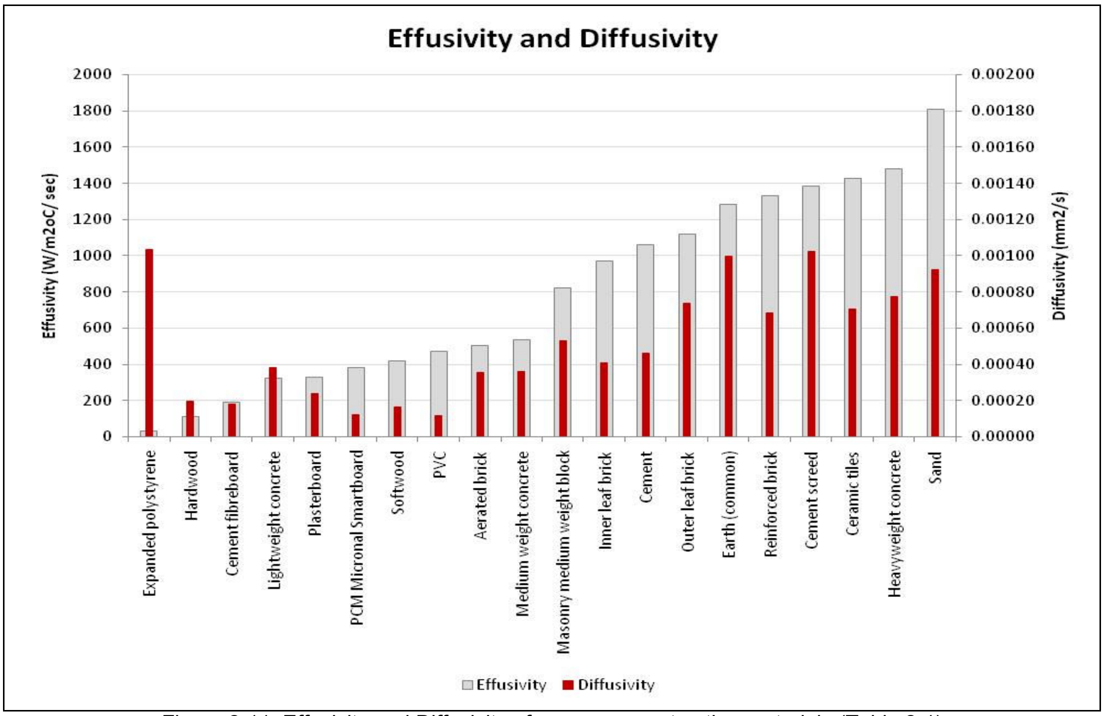


Figure 2-11: Effusivity and Diffusivity of common construction materials (Table 2-1)

Although thermal diffusivity and effusivity help to characterise a material's capacity to act as thermal mass, they do not do so completely. There are two other concepts that help characterise the influence of thermal mass: Time Lag and Decrement Factor.

Considering a situation when both sides of the wall are initially at the same temperature and the external side experiences a rapid increase of its temperature, the actual heat flux would lag behind the heat flux predicted by the steady-state equation. This time difference is referred to as Time Lag which is, for a single layered homogenous wall, less than or equal to $L^2/6D$. When the transient begins there is no lag but as it progresses it approaches $L^2/6D$ exponentially consequently taking an infinite amount of time to attain it (Childs, Courville et al., 1983).

Since there is a need to determine a time when, for practical purposes, the lag is not changing anymore, the concept of Time Constant was introduced. This is the time that a transient heat flux takes to reach 36.8% of its value and so, after 3 time constants (95%), a transient is fundamentally complete despite the fact that theoretically it continues for an infinite amount of time. The time constant for a single layered homogenous wall is $L^2/\pi^2 D$ (Childs, Courville et al., 1983) which is approximately $0.3L^2/D$.

Now considering that, after some time, the external wall's temperature went back to its original value. When this decrease in temperature happens the same lag can be observed but this time the heat flux predicted by the steady-state equation is greater than the actual heat flux. This situation is illustrated in Figure 2-12 below.

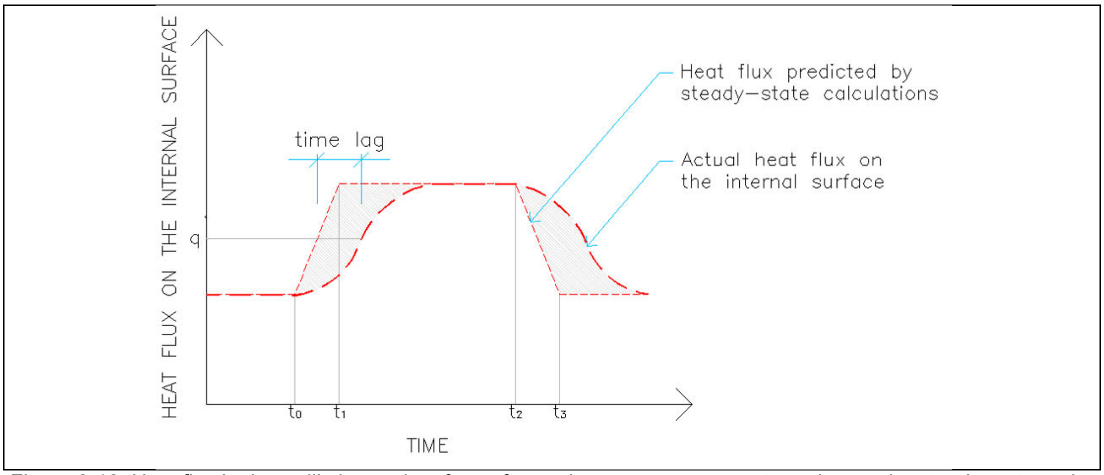


Figure 2-12: Heat flux in the wall's internal surface after an increase on temperature, time under steady-state and a decrease on temperature

The shaded areas represent the difference on the actual total amount of energy conducted through the wall and the amount predicted by the steady-state equations. It is important to notice that the two shaded areas are equal and that the total amount of energy that flowed through the wall from time t_0 until steady-state conditions are re-established is the same as the steady-state equation prediction. Thus steady-state calculations are able to predict the total energy flow even though it cannot predict the instantaneous heat flux at any time during the transient.

Given that the steady-state calculation just uses the wall's R-value and not the energy storage capacity of the wall (referred to as thermal mass) it can be concluded that the thermal mass does not affect the total energy flow through the wall in this situation. It does, however, affect the time that the energy takes to reach the internal surface.

If the time between t_1 and t_2 is completely eliminated and so there is no time to reach steady-state conditions between the changes in temperature, then differences on the actual peak flow and the one predicted by steady-state can be noticed. The peak will not just be diminished but also be presented at a later time, differences caused by the wall's thermal mass. Once again the actual total heat flow is the same as the predicted heat flow as it can be seen in Figure 2-13.

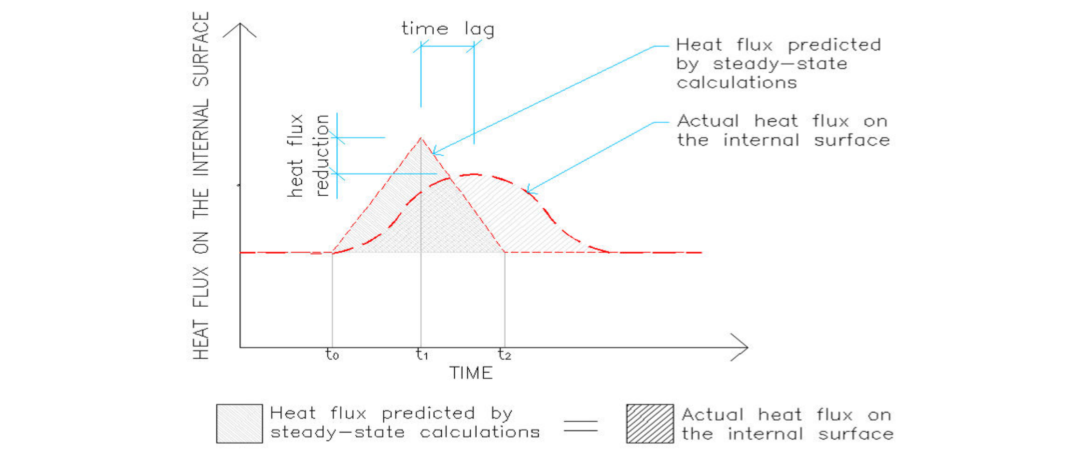


Figure 2-13: Heat flux in the wall's internal surface after an increase on temperature followed by a rapid decrease

The reduction in heat flux is named Decrement Factor. For a single layered homogenous wall the time lag and the decrement factor will increase when the quantity L^2/D increases (Childs, Courville et al., 1983).

2.2.3 Dynamic Heat Transfer

In fact, if time lag occurs then steady-state conditions are hardly, if ever, observed in a building. Consequently the only way to properly predict the influence of thermal mass is by dynamic calculations.

Even though steady-state conditions effectively never occur in a building subjected to the weather, weather conditions can be nearly periodic, with similar temperatures for many days. A simplified representation of this situation can be seen in Figure 2-14 below.

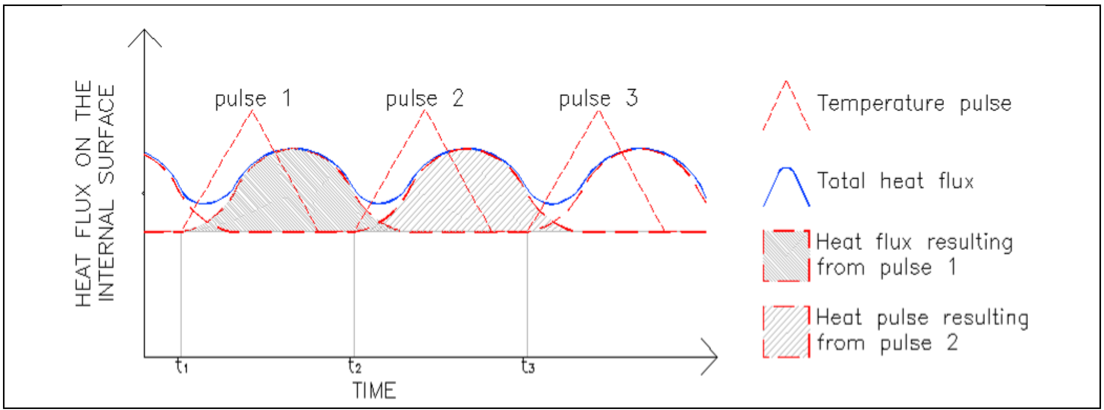


Figure 2-14: Heat flux in the wall's internal surface after a series of temperature pulses

As it can be seen in the figure above, the cycle starting at t_2 is still under influence of the previous cycle caused by pulse 1 in addition to pulse 2. In the case of this simplified example, because the pulses are equal, the total heat flux for this cycle can be seen in the interval t_2 to t_3. Therefore, for this case, the total heat flux for a cycle can be predicted by steady-state calculations. These calculations, however, cannot predict the instantaneous heat flux at any point during the cycle as explained previously.

By using the principle of superposition, a solution for the problem can be attained by summing individual temperature pulses of different heights combined to recreate the cycle. This approach, named the Response Factor Method, created by Brisken and Reque in 1956 (Davies, 2004), is used by many building analysis softwares. Basically, it approximates the outdoor temperature pulses into triangular temperature pulses and the total heat flux is determined as a sum of the response to all pulses.

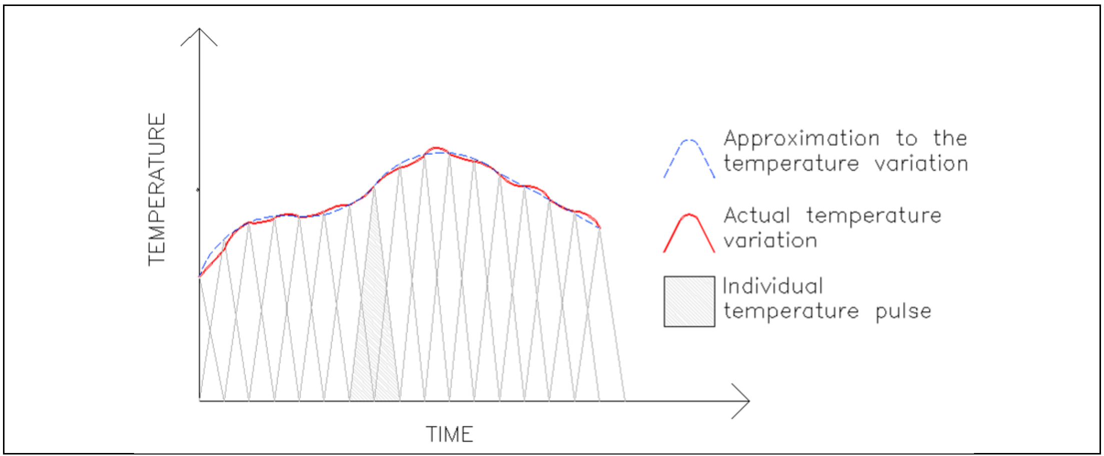


Figure 2-15: A cycle of temperature change broken into individual temperature pulses using the Response Factor Method

The response factor method can be divided in two branches, the Time-domain and the Frequency-domain response function methods, both derived from the case of transient heat transfer and intra-zone energy flows. These methods have been used as means to determinate the thermal behaviour of buildings since the 1970s (Davies, 2004). The time-domain method calculates hourly internal conditions from hourly weather data inputs. The frequency-domain method assumes that the weather data can be represented by a series of periodic cycles and produces cyclical responses of the system. Detailed explanations of these methods were published by Clarke (2001).

There are several methods available for assessing the dynamic performance of a building. One of the simplest, based on a variation of the frequency-domain method, is the Admittance Method created by the UK Chartered Institute of Building Services Engineers (CIBSE). The CIBSE admittance method is a cyclic model in which the assumption is that weather is represented as a harmonic with a period of 24 hours. It uses the material’s admittance (explained next) as well as time lag and decrement factors, to define their dynamic response.

This cyclic model can be used to make a rapid assessment of peak summertime temperatures, space cooling loads and preheat requirement and is very useful in the design stage of a project. However, according to CIBSE, because of the simplicity of the model, its application can be limited specially at predicting summertime overheating as the true benefit of mass cannot be assessed (CIBSE, 2006).

Thermal Admittance (measured in W/m^2K) is a factor that represents the quantity of heat that passes through a unit area of a material (BSi, 2007: p. 3). Admittance is equal to the walls U-Value in steady state but differs when the time dependency is taken into account. It is likely to be high for constructions that have high thermal mass materials in their inner layers and low if they have insulating materials so it can also be an indication of the construction's thermal mass. In multi-layered structures, admittance is mainly determined by the properties of the material in the layers adjacent to the internal surface. Therefore, admittance is effectively a dynamic U-Value concerned only with the part of the construction that influences the internal space.

The Concrete Centre appoints admittance as a simple measure of thermal mass (The Concrete Centre, 2006) but also suggests caution in its use to assess overall building performance as it can underestimate the actual peak cooling capacity of a high thermal mass structure by up to 50% in comparison to more sophisticated thermal modelling techniques that use real weather data (Saulles, 2009).

Detailed calculation procedures for admittance can be found at CIBSE Guide A (2006: p. 3-31 to 3-32) and the British Standards 13786:2007 (BSi, 2007). The CIBSE Guide A provides a comprehensive list of values of thermal transmittance, thermal admittance, decrement factor and surface factor for a range of materials which allow a quick understanding of these thermal properties for typical constructions and also its use in building thermal simulations. According to it, the traditional brick and block construction has an admittance of around $3W/m^2K$ whilst a timber frame wall has an admittance of $0.75W/m^2K$ (Table 2-2).

In the subsequent chapters, this work uses Tas to calculate the thermal performance of houses. Tas is a software tool designed by EDSL that uses a dynamic approach through a method derived from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) response factor technique where "conductive heat flows at the surfaces of walls and other building elements are functions of the temperature histories at those surfaces" (EDSL, 2009: p. 3-5). Tas theory manual gives more details of the calculation procedures and validation (EDSL, 2009). Although Tas was chosen for its accuracy in thermal calculations it is understood by the author that no mathematical estimate can truthfully predict real conditions, which are not just influenced by the changing climate but also by people's actions.

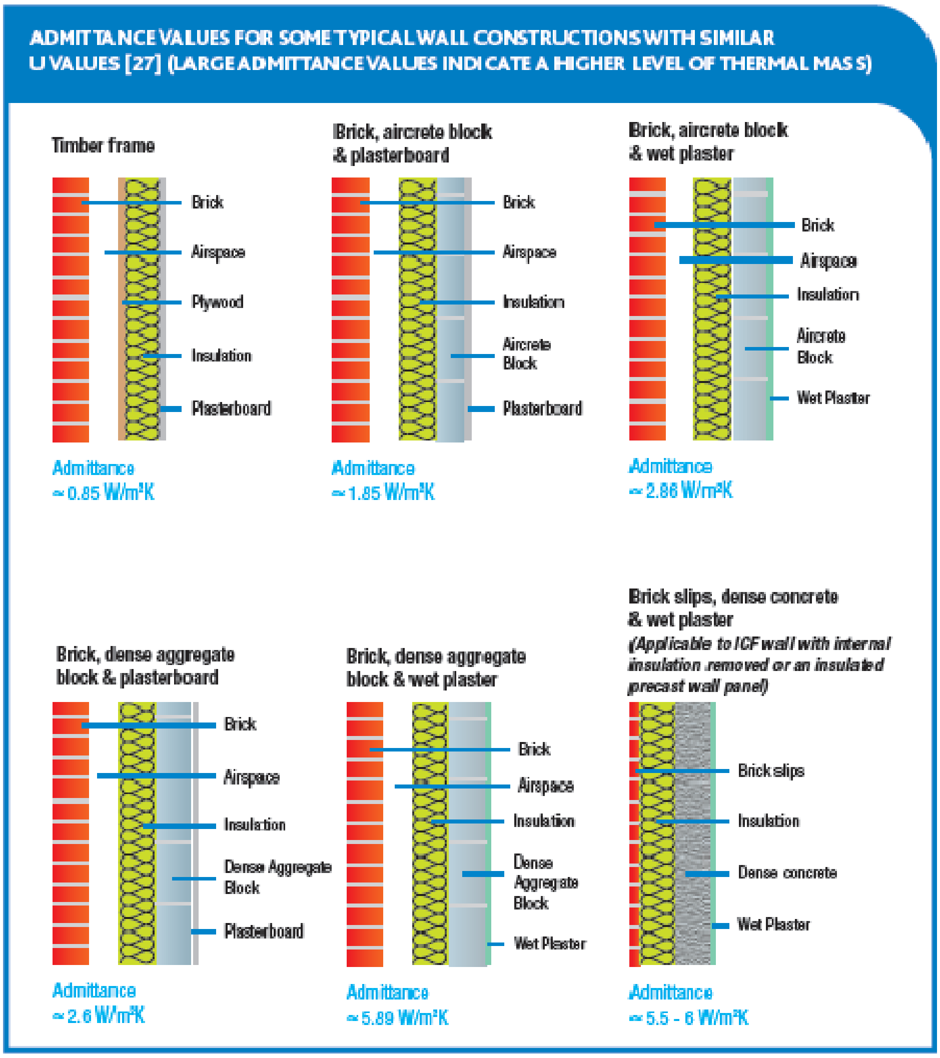


Figure 2-16: Examples of the admittance of certain wall types as calculated by the Concrete Centre (The Concrete Centre, 2006: p. 12)

Table 2-2: Admittance, conductance and decrement factor of some common wall constructions (CIBSE, 2006: p. 3-46 to 3-55)

Construction	**Admittance (W/m^2K)**	**Conductance (W/m^2K)**	**Decrement Factor**
Dense concrete wall (19mm render, 50mm mineral wool insulation between battens, 200nn dense concrete block, 13mm dense plaster)	5.32	0.70	0.16
Solid brick wall with insulation (19mm render, 50mm EPS insulation, 220mm solid brick, 13mm dense plaster)	4.23	0.54	0.12
Brick and block cavity wall (105mm brick, 50mm EPS insulation, 100mm lightweight aggregate concrete block, 13mm dense plaster)	2.98	0.52	0.42
Precast concrete panel wall (80mm dense concrete, 50mm EPS insulation, 100mm dense concrete, 12.5mm plasterboard)	2.61	0.56	0.17
Timber frame wall (105mm brick, 50mm airspace, 19mm plywood sheathing, 95mm studding, 95mm mineral wool insulation between studs, 12.5 plasterboard)	0.75	0.39	0.58

2.3 STORAGE AND RECOVERY OF HEAT IN MASS

> *"When compared to lightweight dwellings, the thermal mass in masonry and concrete construction can provide significant year-round operational savings if designed appropriately. For example, research has shown that a typical two-bed semidetached house in south east England that fully utilises its thermal mass is likely to save around 14 to 33 tonnes of CO_2 over the 21st century."*
>
> The Concrete Centre in the report 'Thermal mass for housing' (2006)

Based on the previous discussion it is clear that many factors influence the thermal behaviour of a building and that the properties of the materials have a crucial influence on the expected results. It is also evident that accurately predicting that behaviour is not a simple matter. A designer should understand the weight each design decision would have in the building's performance so software calculations can be informative. The next section illustrates and clarifies how heat gets stored in thermal mass and how this can influence the expected result in a building's performance.

2.3.1 Influence of Thermal Mass in Heat Transfer

In order to explain the process of storing and releasing heat, a hypothetical homogenous wall of a high mass material subjected to the weather is considered. If the external diurnal temperature variation is approximated to a sine wave and the temperature resultant in the internal wall is plotted using either steady-state or dynamic calculations, one can expect a graph similar to Figure 2-17 (Childs, Courville et al., 1983).

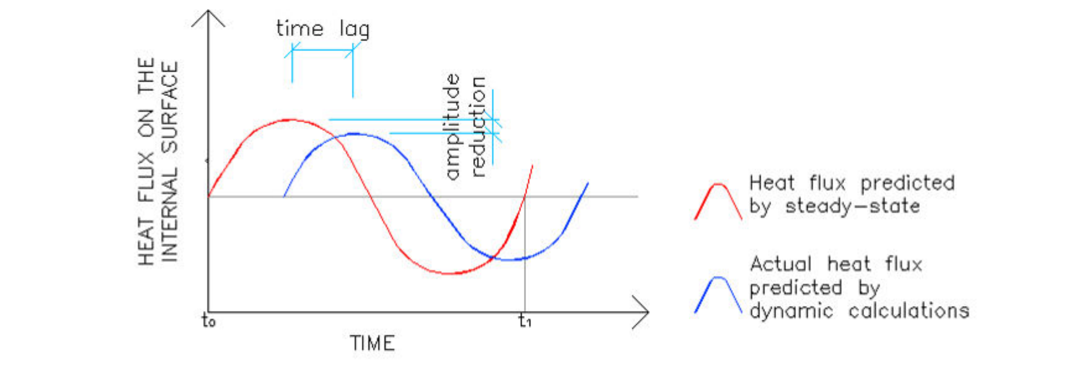


Figure 2-17: Difference between heat flux calculated by steady-state and dynamics

The steady-state results will vary sinusoidally and in phase with the outside temperature variation. The actual flux, although also varying in a sine wave, will lag behind and be out of phase with the outdoor temperature variation and steady-state heat flux. The average and the total heat flux will not be influenced by the mass but the time delay when the heat arrives to the internal surface will be influenced by the mass.

Based on this and on the previous discussion, two important aspects of thermal mass can be noted. Firstly, there is a reduction in the variation of the heat flux through the wall. Secondly, the mass has the ability to delay the time of occurrence of the maximum and minimum heat flux through the wall. These abilities can have a large influence in a building's comfort and energy usage. This will be demonstrated explicitly in Chapter 5.

Childs, Courville and Bales (1983) have developed an analytical solution to determine the heat flux ratio and presented a parameter (Equation 2.16) in which the peak heat flux and time lag are dependent upon.

Equation 2.16: Parameter of heat flux amplitude ratio

$$\sqrt{\frac{L^2}{\left(\frac{D}{P}\right)}}$$

Where:
L= thickness of material (m)
D= thermal diffusivity (m^2/s)
P= time period for one cycle (s)

Using Equation 2.6 and Equation 2.14 one can obtain:

Equation 2.17: Parameter showing the dependency between some wall properties and the heat flux amplitude ratio as proposed by Childs, Courville and Bales (1983)

$$\sqrt{\frac{R\rho cL}{P}} \text{ or } \sqrt{\frac{\rho cL}{UP}}$$

Where:
R= resistance ($m^2\,{}^oC/W$)
U= conductance ($W/m^2\,{}^oC$)
ρ= density of material (kg/m^3)
c= Specific heat capacity of material (kJ/kg^oC)
L= thickness of material (m)
P= time period for one cycle (s)

As explained previously, that the product *ρcL* is a measure of the wall's ability to store energy per unit surface area, *U* is an indication of the wall's ability to conduct heat and *R* is an indication of the material's ability to resist heat conduction.

The total heat flux at the internal surface can be divided in two components: a constant heat flux which is dependant only on the U-Value and therefore calculated by steady-state and a fluctuating heat flux directly influenced by the thermal mass. The total heat flow over a cycle is influenced by the U-Value but not by the thermal mass. The peak heat flux and the time lag are influenced by both.

From the relationship in Equation 2.17 some points can be noted. It can be seen that decreasing the U-Value or increasing the storage capacity (*ρcL*) will have a similar effect on the amplitude ratio defined by Equation 2.17. However, as stated above, reducing the U-Value will reduce the maximum heat flux whilst increasing the storage capacity will not cause such change. Therefore the U-Value has a greater influence on the maximum heat flow than thermal mass.

After the heat energy is absorbed by the surface, conduction becomes the central mechanism of heat transfer. Figure 2-18 shows the development of the temperature profile following a rise of the temperature on an uninsulated surface of a wall made of a high thermal mass material. The external surface of the wall is insulated.

As shown previously, the amount of heat stored is proportional to the *ρcL* product and the speed at which the profile moves through the wall is governed by the thermal diffusivity (*D)*: the higher its value the faster the development of the profile. Considering Equation 2.14, it can be said that the lower the *ρc* product, the higher the diffusivity. However, the lower the *ρc* product, the smaller the capacity to store heat of the material. A better indication of the speed of the heat's penetration in the wall is the product *kρc* which is named Thermal Penetration (in J/m² ºC). It is also common in literature the mentioning of the parameters thermal penetration time and thermal penetration depth which refer to product *kρc* and its time and penetration.

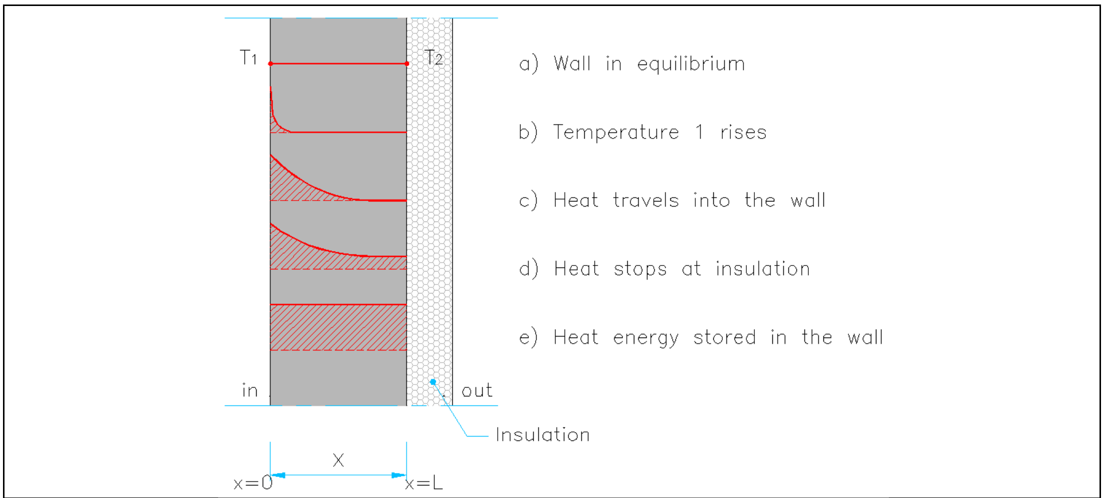


Figure 2-18: Development of temperature profile in thermal mass when T1 rises

Under steady state conditions, the quantity of energy which can be stored in a wall can be calculated by Equation 2.9. However, under usual conditions the wall would not experience such stable conditions.

Figure 2-19 shows the temperature profile developed in the mass after a rise of the internal surface's temperature followed by a decrease back to its original level. It can be seen that the heat seems to travel through the wall in a wave, decreasing its amplitude as it goes.

From this it is easy to understand the importance of the thermal penetration mentioned before as the material with the higher value will typically be able to store more heat.

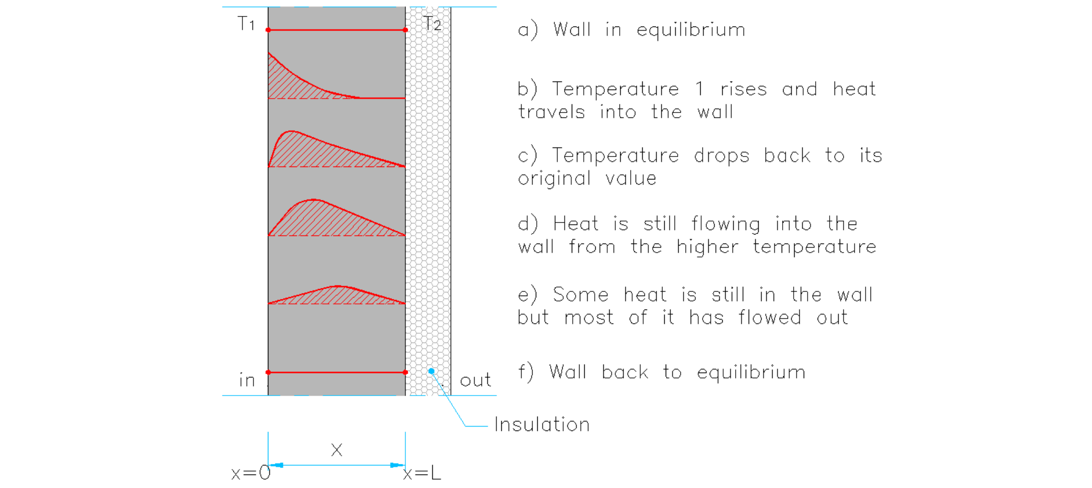


Figure 2-19: Development of temperature profile in thermal mass when T1 rises and drops back to its original state

It is clear that, to maximize the benefits of a building's thermal mass, it should be exposed to radiant or convective heat until it achieves its storage limit and then this heat should be recovered by the building's interior (if this is desirable) or discharged to the outside. Consequently, the ideal climate to apply this strategy in a totally passive way would be one with large diurnal temperature fluctuations (Kalogirou, Florides et al., 2002). If the nights are much colder than the days, night time ventilation can be used to discharge the stored heat.

Figure 2-20 represents time lag and decrement factor in the development of the temperature profile in a wall. In this example heat enters a wall at 1pm with a value Q_0 and reaches value Q_1 at 5pm so the time lag is of 4 hours and the decrement factor is Q_0 minus Q_1.

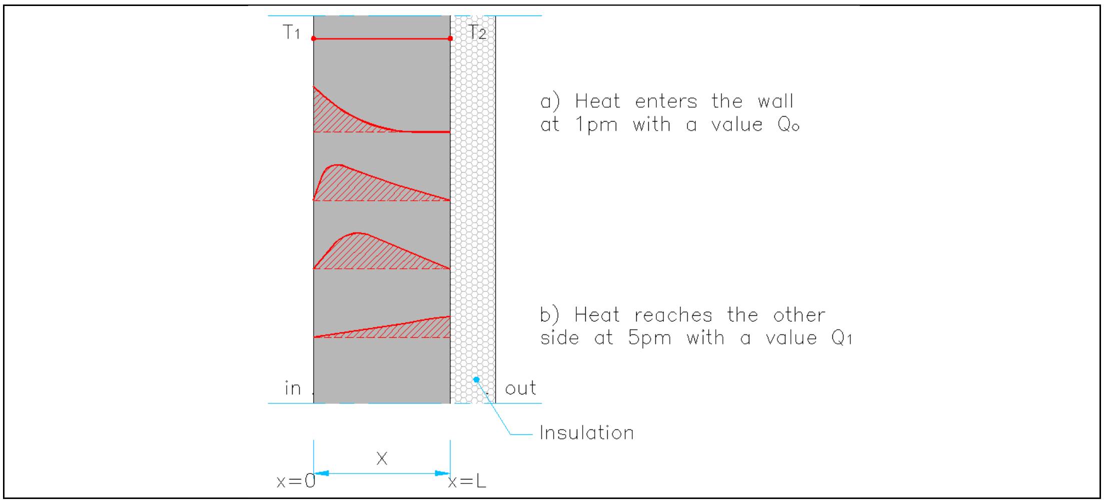


Figure 2-20: Representation of time lag and decrement factor in the development of temperature profile in thermal mass when T1 rises and drops back to its original state

Time is an important issue to be considered by the designer as if the time lag is too long it might be difficult to make use of the thermal mass in a daily basis. For example, if the time lag is longer than 12 hours, heat might be still travelling inwards when there is more heat available in the space and so the thermal mass might saturate with heat. Too much thermal mass thickness might also be unfavourable in winter as the space would take longer to warm up due to the dumping of heat in the mass (the thermal mass would act as a heat sink).

Only a small excess of heat gain over loss will cause overheating and for example, only 10W of “residual” heat gain (excess of heat gain over losses) will cause the air temperature of a $17m^2$ room to rise by 17^oC in 10 hours (Orme and Palmer, 2003: p. 4). That shows the importance of considering whole building energy balance carefully. Chapter 5 explores the benefit of using thermal mass in winter and summer using a simple building as an example. The subsequent sections in this chapter briefly study other parameters that have an influence on the full building energy balance.

2.3.2 Frequent Ways of Exploiting Thermal Mass

As seen, if applied internally in well-insulated buildings, thermal mass can contribute to the storage of energy during the day and release at night (provided that there is significant temperature difference) reducing and shifting the peak temperatures in the space. In mild climates, where uninsulated buildings are common, thermal mass in the walls may help delay and smooth out the incoming heat flow by solar radiation. In simple terms, thermal mass can be beneficial if there is enough external temperature swing to allow for removal of stored heat.

When heat enters a building it can be stored in its thermal mass but as heat transfer occurs in the direction of the lower temperature, the energy can only be transferred to the mass by convection when the temperature of its surrounding air is higher than the temperature of the mass’ surface. Convective heat transfer happens again when the mass’ temperature is higher than the air and so the air can recover the stored energy. The use of this strategy is called convectively coupled thermal mass.

Convectively coupled thermal mass evidently relies on internal air temperature swings. The charging of heat will occur when the air temperature is hot enough for a long enough period of time. The opposite will need to happen to allow discharge of heat. A greater swing in temperature affects both human comfort and energy use.

It is also possible to use radiatively coupled thermal mass. This occurs when there is a surface at a higher temperature at the proximities of the mass, or for example a window allowing solar radiation to shine through and reach the high mass wall. Once the high mass wall's surface is warm, conduction happens to the interior of the mass. The heat can be recovered by the space by radiation if there is a colder high absorptivity surface near the mass or if convectively air is allowed to move close to the warmer surface.

The best way to place thermal mass is maximizing the surface area and not the thicknesses; this enhances the heat transfer between the space and the mass. In addition, insulation might be provided on the external surface of the wall to keep the stored heat in the building. Studies in USA show walls where the insulation material was concentrated on the interior of the building performed much worse (KOSNY, et al. 2002). In the case of voids or cavities then heat radiation might happen between the wall's layers and so might be lost. If there is no wall insulation to stop conduction to the exterior then heat might also be lost.

It was previously mentioned that the 'CIBSE Guide A' provides a comprehensive list of values of thermal transmittance, thermal admittance, and decrement factor for a range of constructions, which allow a quick understanding of these thermal properties for typical constructions and also its use in thermal simulation. However, some demystification should be made regarding the most common British construction method for housing, brick-cavity-block. This is sometimes considered a heavyweight construction but this is not realistic firstly because it usually has lightweight floor structures, secondly because the brick is usually behind insulation leaving just the block to act as thermal mass. In addition, different types of block have different performances. An aircrete lightweight concrete block provides smaller benefits as far as thermal mass is concerned. This will be demonstrated in Chapter 5. Despite this there is still guidance pointing to this construction type as being massive as it can be seen below.

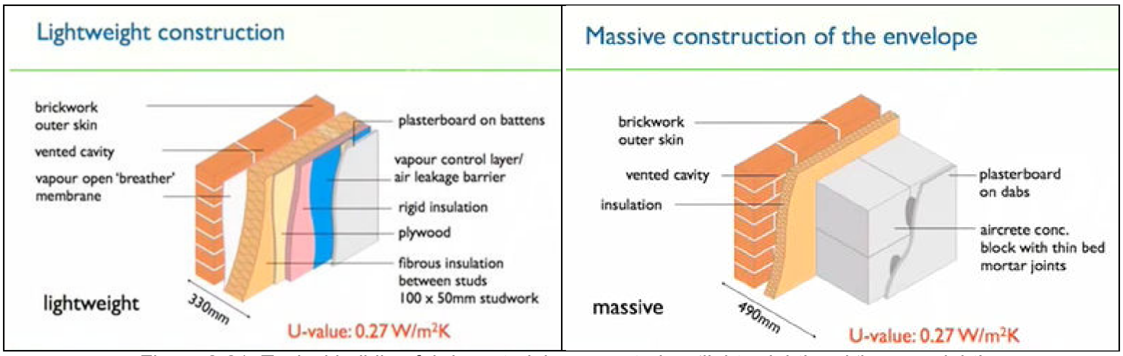


Figure 2-21: Typical building fabric materials suggested as 'lightweight' and 'heavyweight'

There are two basic ways of employing materials to act as thermal mass:

- Direct thermal storage materials: placed directly in incident solar radiation as radiatively coupled thermal mass.
- Diffuse thermal storage materials: placed all over the building relying on both, radiative and convective heat transfer.

The most common materials used for thermal storage are concrete, concrete block, brick, stone, and earth. Dark coloured materials have the added advantage of absorbing more solar radiation. Relying on floors for thermal storage might be complicated as they tend to be covered with carpets and/or furniture. Problems are also encountered when an external layer of insulation is required as that can have a tendency to be more expensive and is less accepted aesthetically.

Less common but more efficient is the use of water as thermal mass (in this case the main mechanism of heat transfer inside the material is convection which has the added benefit of distributing the heat energy better) e.g. concentrated in a water wall or as a feature in the space (i.e. a pond or aquarium) or distributed inside containers built in the walls and floors.

Having provided the inherent thermal mass in the building's envelope and internally, care should be taken not to decouple it by adding surface finishings that might hinder the heat transfer between the space and the mass. This might be in the form of painting, wallpaper, plasterboard, certain types of tiles, etc. The most common forms of this problem are suspended ceilings, which are usually added to hide a concrete slab for example and dry-lining with an air gap (Orme and Palmer, 2003: p. 16). If attention is not given to the thermal mass finishing its benefits might be completely blocked and a massive wall might behave as a lightweight construction.

2.3.3 Sunspaces

Both case studies used in this thesis make use of sunspaces (or conservatories) as a main strategy for space conditioning, so it is worth looking briefly into this concept. The main function of south facing sunspaces designed to collect solar energy in the UK is to reduce the need for auxiliary energy for space conditioning. Energy saving from a sunspace may come from 3 aspects: the buffer effect, the supply of pre-heated ventilation air and the supply of sun-heated air to the house when solar radiation is available. Sunspaces are very popular in British houses because of their attractiveness and are often badly utilised as far as thermal performance is concerned.

Sunspaces should be designed to collect solar energy when required and to act as a buffer zone protecting the interior from outside temperature swings. Consequently, sunspaces may often be outside comfort conditions in order to support comfort conditions inside the main living areas. It can be part of the ventilation strategy pre-heating air that can then be delivered to the building. It may also provide additional usable space which is likely to be pleasant for its direct visual connection to the outside. However, this desirability and usability may also cause a negative effect as some people use active heating or cooling devices to keep their sunspaces utilizable throughout the year. When this happens, rather than contributing passively to reducing energy use in the home, the sunspace would contribute actively to raise the house's energy use.

Sunspaces employ a combination of direct gain and indirect gain system features and are usually coupled to thermal mass. Solar radiation entering the space during the day is retained in the thermal mass and in the air of the room. This heat can be released back into the house at night by means of conduction through a shared mass wall resembling an indirect gain system, or by vents that permit the air between the sunspace and living space to be exchanged by natural convection. In this last case, the common wall might be insulated. Another option is the use of heat exchangers to extract the excess heat of the sunspace and use it elsewhere in the building.

Apart from the right positioning of thermal mass, the design of sunspaces should take into account orientation, angle of glazing, shading, dimensions and flexible openings. Excess solar radiation can easily overheat the sunspace and the interiors not just in summer times but also in sunny days of spring or autumn. Ventilation and shading can help to reduce overheating and should be carefully designed. These topics will be expanded on later in this work.

A simple sunspace coupled to a high thermal mass wall is illustrated in Figure 2-22. Another possibility is to add a Trombe wall (Figure 2-23) to the system which encompasses vents for better use of the air heated in the conservatory.

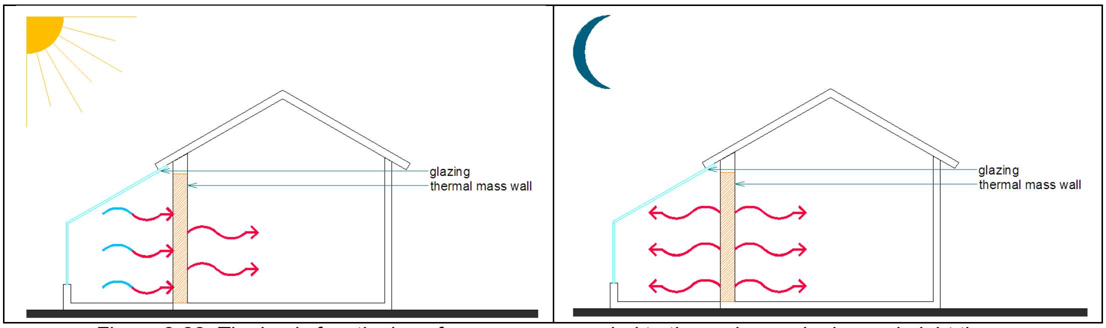


Figure 2-22: The basic functioning of a sunspace coupled to thermal mass in day and night times

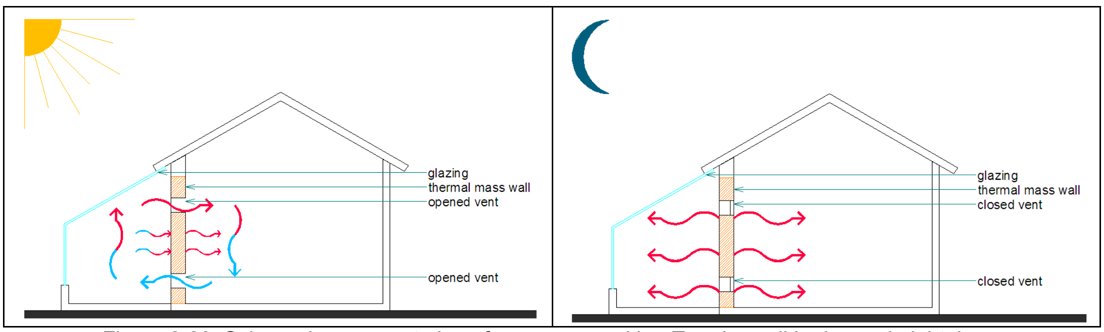


Figure 2-23: Schematic representation of a sunspace with a Trombe wall in day and night times

2.4 OTHER INFLUENTIAL FACTORS

Factors such as ventilation, fenestration and thermal bridging may alter, inhibit or enhance heat transfer in building materials. Although those are not the focus of this work, it is necessary to briefly define the terms and quantities as they are utilised in subsequent chapters. Considering them is imperative when studying a building's thermal performance.

2.4.1 Fenestration

Fenestration is defined as the design and disposition of windows and other exterior openings of a building. As studied before, conduction through opaque elements of a building is reduced the more insulation is used. With tighter building regulations (as mentioned in Chapter 1), conductive heat transfer through these components is often reduced to a point where little conduction occurs and so transparent components became of much greater importance. Fenestration is thus one of the key players in a building envelope.

Windows are particularly essential to the design and performance of a building when the goal of energy efficiency is pursued. This is for various reasons: the allowance of solar radiation in the space, the view and connection to the outside, daylight and ventilation. The design of fenestration is therefore a daily challenge for practicing architects trying to balance all these issues. For example, achieving very high levels of daylight usually means large windows which may be associated with excessive heat gain and loss, and a higher building cost. On the other hand, very small windows may mean that little use is made of daylight as a source of energy and may also add to occupant dissatisfaction. The scope of this work does not include an investigation on the topic 'daylight performance vs. thermal performance'. It will, however, take into account that effective thermal strategies might impact on visual strategies and therefore should be considered by designers.

Fenestration products such as windows have different energy performances depending on climate, season, area and orientation. A transparent element means energy transmission through radiation and conduction which will have a high impact on the need for heating and/or cooling energy. Designers should observe the characteristics of such products, especially transmittance and conductance (U-Value), before specifying it. The U-Value of windows is made up of three components: the glazing, the frame and the interaction between both (CIBSE, 2006: p. 3-20 to 3-22). There are diverse types of windows and glass. CIBSE Guide A gives details on how to calculate window properties and also give examples of typical fenestration elements.

Regarding the effective use of thermal mass in buildings, the choice of fenestration specification will have a huge impact on the expected performance. Not only thermal characteristics and dimensions should be carefully considered but also opening sizes for ventilation. Ventilation may determine if the heat stored in the mass is successfully discharged. This is the subject of the next section.

2.4.2 Ventilation

Ventilation can be described as intentional or unintentional air circulation. It is the introduction of outside air into the building in amounts necessary to provide healthy and comfortable conditions for the occupants by diluting pollutants and revitalizing and refreshing the air. When applied to homes and offices, ventilation can also mean the provision of an environment that stimulates the worker to higher productivity (CIBSE, 2006: p. 4-2 to 4-3).

Pollutants can be from unavoidable sources such as carbon dioxide resultant from an occupant's metabolism and from avoidable sources which may include excessive organic emissions from furnishing and equipment and pollutant releases from inadequately enclosed appliances. The minimum required ventilation rate for air quality varies from 6l/s/person (low indoor air quality) to 15l/s/person and above (high indoor air quality). Usually a value of 8l/s/person is adopted for building design (CIBSE, 2006: p. 4-2).

In order to clean the air, firstly one should consider controlling or eliminating the source of pollution. This is because ventilation is usually an effective measure to deal with unavoidable pollutants but source control is the most efficient method to minimise the effect of the avoidable pollutants. Secondly, natural or induced ventilation should be considered. Thirdly, if the other measures are not successful, filtration devices could be used but those tend to be expensive and generally not feasible (CIBSE, 2006: p. 4-2 to 4-3).

Good ventilation design is also essential to help the distribution of heat and/or cooling to achieve thermal comfort and this will have a considerable influence on energy efficiency. Approximately 30% of the energy delivered to buildings can be dissipated in the departing ventilation (Orme, 1998). Natural ventilation can provide cooling but there is a limit to its effectiveness so care should be taken to control sources of internal gains and solar gains. Temperature in buildings in the UK regularly exceed external temperatures by more than 3^{o}C and keeping it cool in summer might be possible by a combination of ventilation and thermal mass (CIBSE, 2006: p. 4-3).

The velocity of the airflow is also important. The comfort zone depends on the temperature and is a very subjective notion (as discussed in Chapter 5), but generally inside a building between 0.5m/s to 1.5m/s is considered comfortable, which means light air or light breeze that can be felt on face (Szokolay, 2008: p. 17). More than 3.0m/s may be disturbing and even air velocities greater than 1.5m/s might cause undesirable effects such as draughts and the blowing of papers. Under overheated conditions air velocities up to 2.0m/s may be welcomed (Szokolay, 2008: p. 18). Ground areas where wind speeds exceed 5m/s are likely to be uncomfortable, speeds greater then 10m/s are very unpleasant and over 20m/s can be dangerous. Rennie and Parand (1998: p. 31) state that with a desirable indoor air velocity of 0.8m/s would give approximately 3°C of cooling perception which is a very significant achievement and certainly a point in favour of the use of natural ventilation strategy, especially in summer once it can promote important enhancement of the cooling sensation even if the external air temperature is above comfort levels.

Ventilation can occur by natural or by mechanical means. To produce air flow and consequently ventilation, three elements are needed: air, a hole, and a driving force. The amount of air moved out of the building will be equal to the amount of air moved in and the high pressure air flows toward lower pressure air. Ventilation strategies operate by displacing or mixing. Displacement ventilation works when outdoor air is delivered close to the floor and rises through the room due to heat from occupants taking any stale air with it, which is exhausted at a high level. Air displacement due to temperature and pressure differences is called the 'stack effect' and usually has a non-uniform spatial concentration of pollutants. Mixing is stimulated by natural turbulence, which can make the pollutant concentration uniform. It can also be used for heating and cooling. The supply air is used to dilute (not displace) the concentration of any contaminants by mixing with the room.

The principle of heating, ventilation and air-conditioning (HVAC) systems is to provide and maintain environmental conditions within the conditioned space. The type of system selected is determined by the designers and the building owner's financial and functional goals and should attempt to provide the best environment for employee comfort, productivity, and good indoor air quality with energy efficiency and cost-savings. The selection of the type of HVAC system is a critical decision to be made by the designer and the building owner.

In low buildings with small rooms it is easy to achieve acceptable levels of ventilation and to control both wind and stack effect with controllable windows. But in high buildings the external and internal temperatures tend to be too different and this condition makes the top of the building too hot and the bottom unacceptably cold. As the results of natural ventilation are uncertain, unpredictable and difficult to control, and although it may be satisfactory in many cases, fans are frequently part of good ventilation systems.

A good ventilation strategy is a fundamental requirement in building design, as it is one of the main factors responsible for guaranteeing health and comfort of the occupants. The effective use of high thermal mass elements is also directly related to ventilation and both strategies should be considered together. The temperature of the air, its velocity, its flow direction, its quantity and frequency of displacement will all cause an impact on how energy is stored in, and discharged from, each building element. These are going to be investigated further in this work when the case study houses are accessed (Chapters 6 and 7) and when the hybrid system is presented in Chapter 8.

2.4.1 Air-tightness

Air-tightness prevents uncontrolled energy loss, reduces moisture flow to the roof space and provides protection from transient outdoor pollution. However, if infiltration in a building is completely eliminated it might become prone to under ventilation, which may bring serious health risks.

Heat losses occur mainly by conduction through the building envelope or by convection through infiltration. Cracks and openings in these external walls produce infiltration and undesirable ventilation, decreasing the efficiency of the systems.

UK dwelling construction is slowly moving from very leaky to moderately airtight buildings but there is still room for a lot of improvement in this area. This change has an impact on the importance of well-thought ventilation strategies.

In the paper "Passivhaus in the UK: Is it desirable? Is it achievable?" (Schiano-Phan, Rodrigues et al., 2008) the author of this thesis discuss the desirability of very airtight houses in the UK where the standard proposed by the German Passivhaus institute (<0.6ACH at 50Pa as described in Chapter 1) for air-tightness is amazingly difficult to achieve at present. Even though the author gave special on-site attention to the avoidance of infiltration during the construction of the BASF house (Chapter 7) the result of the infiltration test was 5ACH at 50Pa which is about 0.27ACH at atmospheric pressure. This is much higher than the Passivhaus standard but in line with UK low energy examples (Stephen, 2000). The Passivhaus standard requests a mechanical ventilation system but the mentioned work was based on the hypothesis that there is no need for such system in the mild UK climate as described in the paper. Consequently the BASF house relies on passive ventilation only.

2.4.2 Thermal Bridging

Thermal bridge is a term used to describe the loss or gain of heat through junctions between building materials. In a building where none or little insulation is used, thermal bridging is almost a redundant term as the heat losses or gains will be dominated by the conduction through the plain areas of the envelope (CIBSE, 2006).

For this reason, in the past little or no attention was given to thermal bridging and it usually was not taken in to account in calculations. However, this is one more aspect of building design and construction gaining importance in recent years with the advent of tighter building regulations. In well insulated buildings the proportional effect of thermal bridging can be very significant and will affect the overall performance of the building.

The main problem occurs when the bridging material (for example, a steel beam) is at or near the surface of the envelope and so is able to conduct heat from one side of the element to another. Good design and attention to details should reduce or completely avoid this problem and its effects should not exceed 10-15% of the total transmission heat loss (S M Doran and Gorgolewski, 2002 ; CIBSE, 2006 ; Way and Kendrick, 2008). Any conductive materials should be wrapped by the insulation so it has no direct contact with the outside air.

2.5 CONCLUSIONS

The use of thermal mass for fresher and more comfortable environments is an ancient tactic. However, the application of thermal mass in highly insulated buildings is a relatively new discussion, especially in the UK where it has been headlined due to the current promotion of lightweight construction techniques for house building. Studies have proven its significance in achieving thermal comfort and especially in mitigating summer overheating which is an increasing problem. The correct application of thermal mass may represent considerable energy savings.

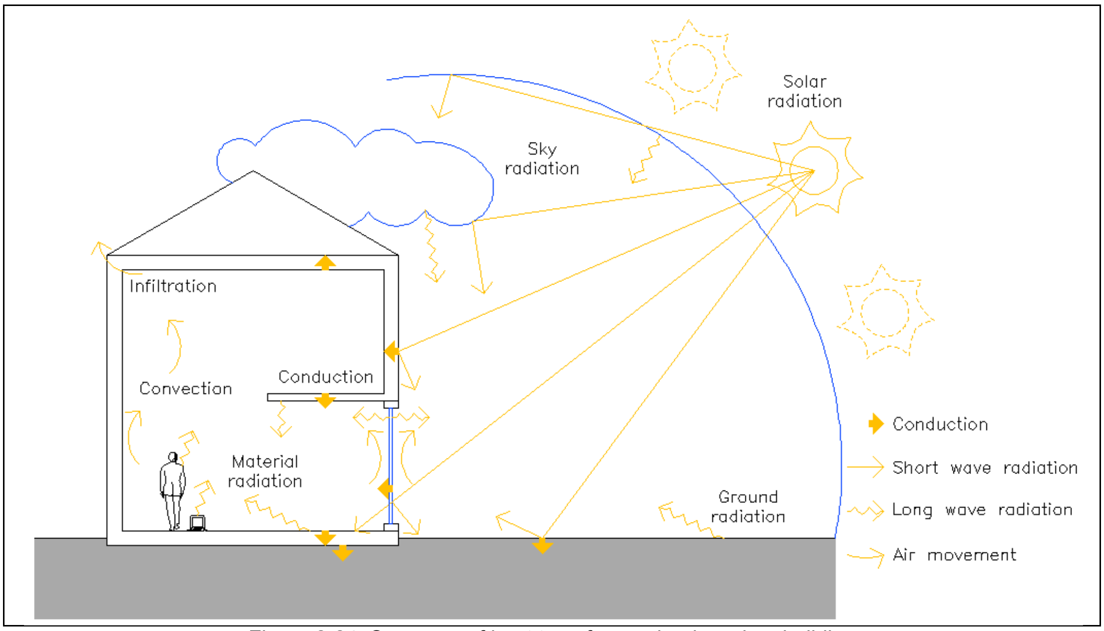


Figure 2-24: Summary of heat transfer mechanisms in a building

In the passive design of buildings, the central actor is the sun which continuously radiates useful energy. In order to understand how much of this energy can be reflected, transmitted or absorbed by a material one has to look into the material's reflectivity, transmissivity, absorptivity and emissivity. Once that energy is absorbed by matter it is transformed into, for example, heat energy which then travels by conduction. The other two means of heat transfer are radiation and convection which is due to the motion of fluids such as the air. A summary of those concepts applied to buildings can be seen in Figure 2-24.

The rate at which energy is conducted and stored in matter depends on the material's conductivity, density and specific heat. Any material can store heat but in order to be effective as thermal mass a material must have a high heat capacity, moderate conductance and density and a high emissivity. Thermal mass can be described as a material's capacity of absorbing, storing and releasing heat. By absorbing part of the excess heat of a space it can contribute to a reduction in the variation of the heat flux through a wall and a shift on the time of occurrence of the maximum and minimum heat flux. Consequently, it can mean lower indoor temperature swings and a shift in the timing of the peak temperature, which might also contribute to the saving of energy for a HVAC system. The time delay due to the thermal mass is known as a time lag. Thicker materials with high resistivity will take longer to conduct the heat flux. The reduction in cyclical temperature on the inside surface compared to the outside surface is known as the decrement factor. The interplay of all the factors involved in the process is so complex that it is best analysed by using dynamic simulation softwares.

A good storage mass should absorb heat when available and release when needed. Other factors should also be considered such as volume of mass and surface finishing. Figure 2-3, Figure 2-4, Figure 2-5 and Figure 2-6 are an easy way to identify materials with potential to be used for thermal storage. Materials used for insulation have usually very low heat capacity and much lower thermal conductivity than materials with high thermal mass. Consequently they do not store much heat and are able to reduce unwanted heat transfer.

Nevertheless, in order to determine if a material will or will not be effective as thermal mass in a building one has to carefully look into its application. Care should be taken not to decouple the mass form the space and to encourage heat transfer between the indoor air and the mass. As much as possible the high thermal mass material should be in direct contact with the higher temperature air in the room. Therefore, certain construction methods, despite being heavyweight, might not be effective for thermal storage (i.e. brick and block walls with insulation between the two leafs or a concrete slab with a suspended ceiling). It is also important that the material is exposed to temperature variations in order to charge and discharge the heat from the mass.

An ideal installation of thermal mass, in a hot summer day would mean that, when the outdoor's temperatures are at their peak, the interior temperature remains cold because the heat is still penetrating in the mass. When the mass is saturated with heat and the colder night falls, the colder interior air would then extract the stored heat from the walls helping to stabilise the temperature. Night-time ventilation can be applied to remove the heat to the outside, provided that the temperatures are low enough. In winter, the building can still benefit from the mass as it can be used effectively to collect and store solar gains or heat provided by mechanical systems which could then operate in off-peak hours.

It is evident that the effectiveness of thermal mass as a strategy increases with the increase of the internal temperature swings as heat transfer is increased by the temperature difference. If the mass is not allowed to discharge its heat then the cycle cannot be repeated. Consequently, thermal mass may not be effective in a climate with little daily temperature variation. Convectively coupled thermal mass relies on internal air temperature swings whilst radiatively coupled thermal mass relies on receiving direct radiation from the sun or another surfaces.

From these considerations it can be said that the influence of thermal mass in a building varies mainly with the climate, the way the mass is coupled to the space, the position and extension of the mass in relation to the building's interior and the insulating layer. Ventilation may also have a great influence on the mass' effectiveness. The quantity of thermal mass available should be enough so it does not reach its storage limit before it is time for heat discharge (either to the building interior or to the outside). As usually the desired heat charge/discharge cycle would happen on a daily basis, time is a crucial matter.

Due to the mass reliance on temperature swings, the ideal climate to apply this strategy in a totally passive way would be one with large diurnal temperature fluctuations. So there is question left to be answered, is thermal mass good for the UK? Chapter 5 attempts to respond to this query.

3 A REVIEW ON EARTH TO AIR HEAT EXCHANGERS

This Chapter presents Earth to Air Heat Exchangers (EAHEs) as unconventional means of exploiting thermal mass to store heat. It reviews properties and design considerations after mapping out existing systems. It also discusses the suitability of predictive models for designers. Potential problems of such systems are examined along with possible solutions. It is believed to be the first time a complete review on EAHEs has been done. This reflection, together with the next chapter, leads to the proposition of the hybrid system further on in this work.

3 A REVIEW ON EARTH TO AIR HEAT EXCHANGERS

> *"Even with the lack of formal research on earth cooling, many systems have been built and in practice earth cooling tubes seldom live up to the hopes and expectations of enthusiasts."*
> (Abrams, 1986)

> *"In the 1970's and early 1980's, earth cooling tubes received a great deal of attention from architects, builders, and homeowners as an alternative or aid to conventional air conditioning. While the concept of routing air through underground tubes or chambers to achieve a cooling effect seems like a good idea, in practice it is not very effective, both technically and economically. Perhaps a few hundred systems were constructed, but information on the practical application of the concept is limited. There are few functioning installations, and limited quantitative performance data exists."*
> (Energy Efficiency and Renewable Energy (EERE) website, U.S. Department of Energy, 2009) [29]

The basic idea behind Earth to Air Heat Exchangers (EAHEs) is to make use of the mass of earth to dissipate heat by circulating air through buried pipes. When travelling in the pipes, warm air becomes cooler by giving up some of its heat to the surrounding soil. In cold days the system could work inversely by warming the air up to the soil's temperature before delivering it. The pipes need to be buried deep enough to avoid being influenced by ambient temperature swings and be long enough to allow enough exchange of heat. Since these systems can work with little energy, the use of the ground to dissipate excess heat of buildings has gained an increasing interest in recent years as a reflection of climate change concerns. Nonetheless, their acceptance is still controversial.

The Energy Efficiency and Renewable Energy (EERE) centre of the U.S. Department of Energy is one of the most complete sources of information in the field of green design. The first lesson regarding EAHEs drawn from the quotes above is actually not explicit: the difficulties with the terminology. A large numbers of technical terms have been used to describe the method studied in this chapter. Below there is a compilation of these names:

- Earth to Air Heat Exchanger (EAHE or EAHX)
- Air to Earth Heat Exchanger (ATEHE)
- Air-to-soil heat exchangers
- Subsoil heat exchangers
- Earth-air tunnel systems (EAT)
- Ground tunnels or ground tubes
- Ground coupled heat exchangers
- Earth cooling tubes or simply earth tubes
- Buried pipes
- Underground air pipes

[29] http://apps1.eere.energy.gov/consumer/your_home/space_heating_cooling/ index.cfm/ mytopic=12460 [Accessed on the 02nd of April 2009]

- Earth channels
- Hypocausts (meaning in Latin “heat from below”, named after the ancient Roman central heating systems)
- Labyrinths (commonly used for a network of interconnecting passages, usually within the building’s foundations)

As a result, some difficulties one might face when searching for a similar system are a lack of results in a bibliographic search or the need to learn all the related terminologies. All these terms refer to the same kind of system and most articles use just one of these names in ‘key words’. This work proposes the term Earth to Air Heat Exchanger (EAHE) to define this kind of system, selected for describing the system more accurately. The term labyrinth will sometimes be used for systems made within the foundations of a building.

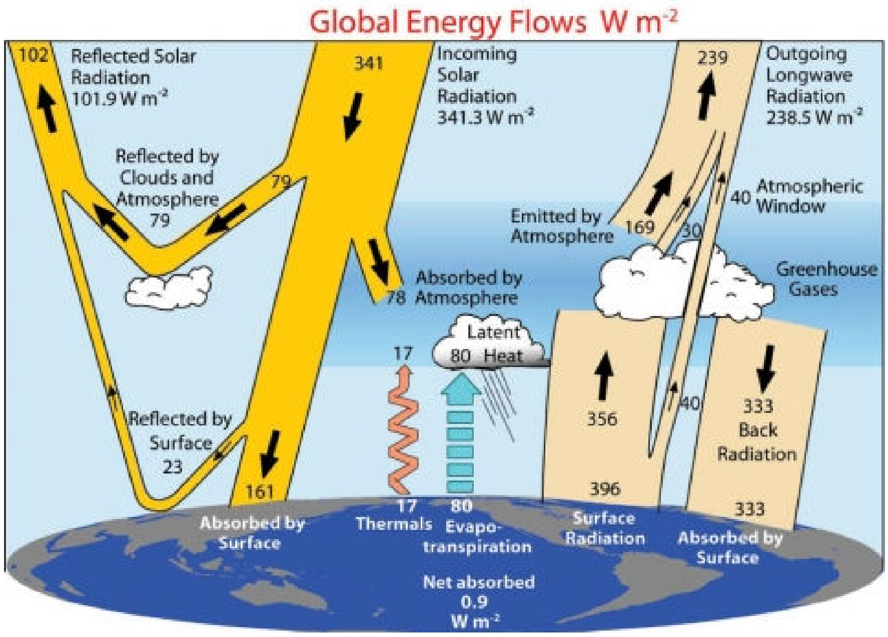
As the EERE quote above suggests there has been a change from a positive to a negative view in the last 20 years. The reason for such pessimistic words is a lack of long term assessed systems, a situation that seems to have not changed much over the years. Although the idea seems excellent given that potentially it would not consume much resource to improve the thermal comfort of a building, there is not enough technical information available and the concept still needs research.

This chapter will show that some installations have been reported to work effectively. However, few of the published works report real building applications and most are in other aspects of EAHEs, i.e. system modelling. In addition, long term monitoring of EAHEs installations is very rare. This emphasizes the distance between academic investigation and real life situations as it is discussed in different parts of this work. This study tries to partly fill that gap with the investigation of two real life applications in Chapters 6 and 7.

3.1 FUNDAMENTS OF EAHES

EAHEs make use of earth as a thermal sink to regulate air temperature. This section explains what makes that possible and how one might evaluate the potential energy savings of such systems.

3.1.1 Earth as a Thermal Sink



Kiehl, Trenberth and Fasullo update on the 1997 widely used diagram 'Estimate of the Earth's annual and global mean energy balance', publication to be released in summer 2009[30]

On a global scale, land and oceans act as heat storage to regulate our planet's atmosphere. They provide large amounts of thermal mass that absorb solar energy and release it back to the atmosphere when the latter is cooler than the land and oceans. We experience this effect when we swim in the sea in autumn and it feels much warmer than in the beginning of the summer season even if the ambient air temperature is lower. The heat we feel has been stored in the sea for months. There is a delicate balance, governed by the first law of thermodynamics (Equation 2.1), between reflection, absorption and heat release on our planet's surface. The disturbance of this balance, illustrated in Kiehl, Treberth and Fasulo's diagram above, is what causes changes in climate.

As shown in Chapter 2, heat takes time to travel in and out of a material. The same happens with soil so a time-lag occurs between the temperature fluctuations at the surface and in the

[30] http://chriscolose.wordpress.com/2008/12/10/an-update-to-kiehl-and-trenberth-1997/ [Accessed on the 2nd of April 2009]

ground. The large thermal capacity of soil keeps the ground temperature considerably lower than the ambient air temperature during summer and higher during winter. The range of seasonal variation of the soil temperatures decreases with increased depth, moisture content and soil thermal conductivity. Therefore, below a certain depth the earth temperature remains nearly constant throughout the year. It is this characteristic that converts the ground into a natural heat sink that can be used for cooling or heating. Typically, the temperature of the earth at deep depths (usually deeper than 6m) remains practically constant, about 2 to 3^{o}C degrees higher than the mean annual air temperature (Rye, 2005). However, it has been shown that at shallow depths there is a considerable fluctuation of the temperature on a daily and especially on an annual basis. This is due to many parameters such as the availability of solar radiation, soil composition and air temperature (Mihalakakou, 2002). In this paper Mihalakakou presents ways to accurately estimate soil temperature to be used in applications such as EAHEs.

As an example of the temperature fluctuations in shallow earth, measurements were taken by the author on the Creative Energy Homes site in August of 2005 when the air temperatures were close to its warmest and the soil was likely to have stored heat from previous summer months. Thermocouples were placed every meter inside a 4m long copper tube of 10mm diameter buried in the ground and the values were collected at various times for a week. Ambient temperatures peaked at 24^{o}C and the temperatures of the soil were found to be, in average, 15.5, 14.2, 13.9 and 12.5^{o}C at depths of 1, 2, 3 and 4 metres respectively. It was found that the soil contained approximately 11% gravels, 80% sand and 9% silt and clay of its weight. For a density of 1.5Mg/m^3 and a water content of 7%, the thermal conductivity was determined as approximately 1.1808 W/mK (Mori, Allinson et al., 2008: p. 5-6). These temperatures were found to be in line with previous work on site (Doherty, Al-Huthaili et al., 2004: p. 2631) and a technical report on the typical temperature profile in the soil in the UK (Rye, 2005). Supportive graphs of Rye's report are reproduced below in Figure 3.1 and Figure 3.2.

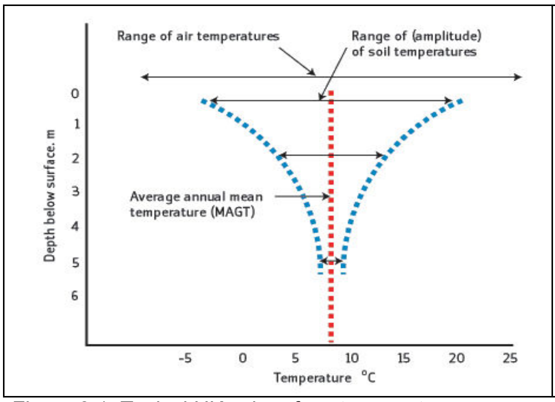


Figure 3.1: Typical UK subsurface temperature range as calculated by Rye (2005)

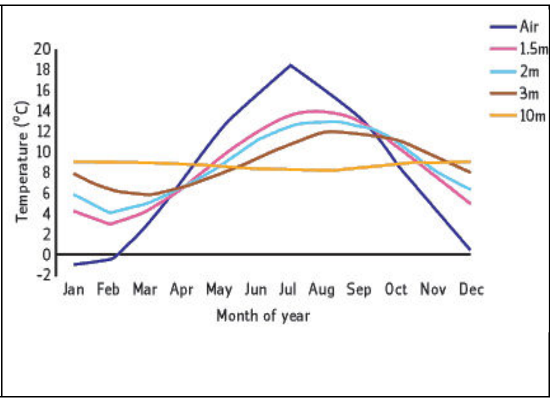


Figure 3.2: Temperature variations with depth in the UK as calculated by Rye (2005)

3.1.1 Using Earth for Thermal Storage in Buildings

As discussed in Chapter 2, a building exchanges heat with the environment by conduction, convection and radiation. Most conventional buildings use convection as their main mechanism since the biggest part of them is in contact with the air, then radiation and finally conduction since the part in contact with the ground is usually smaller. The idea of extending the use of earth in buildings is to increase the conductive heat exchange. It can happen directly by integrating the building within the earth or indirectly by forcing air to get in contact with the earth before delivering it to the building using for example underground pipes and labyrinths. Building construction using earth, i.e. rammed earth walls, are not included in this work.

1. Direct Earth Cooling

Direct earth cooling can happen by fully integrating the building within the earth, i.e. underground buildings, or partially integrating the building envelope. The basement walls of a building can also be used as an earth-to-air heat exchanger. The improvement of the building's thermal performance achieved by this technique is not just due to the thermal inertia of the earth but also because the earth around the building envelope makes it more air-tight (this avoids infiltration and leads to lower heating and cooling loads). Some other advantages of this technique include less visual impact, lower environmental impacts, better acoustics, lower maintenance costs, security, fire protection and protection against natural catastrophes.

There are, however, some limitations for the use of this technique. Problems like condensation and biological growth can occur that can diminish indoor air quality (Elifrits and Gillies, 1983). Care should also be taken when designing EAHEs to avoid excessive heat loss during winter. The accessibility to daylight should be considered, as should structural and economical limitations.

2. Indirect Earth Cooling and Heating (EAHEs)

Indirect systems cool or heat the air before it enters the building by passing it through underground channels. The channels could be part of a building's foundations (for which the term labyrinth is appropriate) or a separate pipe system. These tubes are buried several feet deep where the temperature is approximately constant to avoid the warmer daytime surface temperatures. In summer, warm outdoor air entering the tube gives up its heat to the cooler earth, and cools substantially before being delivered to the building. This technique can lower ambient air temperature by 10^{o}C, possibly even 15^{o}C, as will be shown in the next section. In winter, the inverse occurs as the soil is likely to be warmer than the outside air, which then can be pre-heated up to the earth's temperature before being further heated up by the building's main heating system. Because of pressure losses, commonly the system needs a fan to run although some can potentially run by natural means. A simplified example of the operation of an EAHE can be seen below in Figure 3.3 and Figure 3.4.

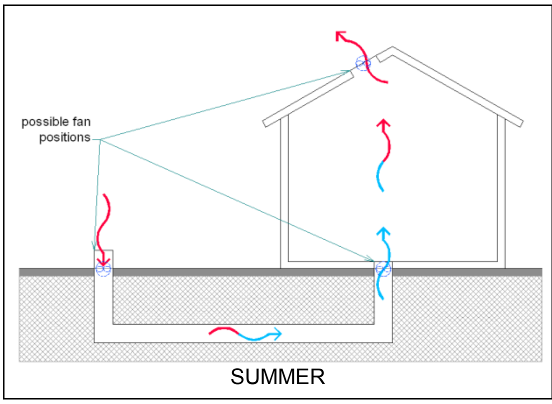


Figure 3.3: Earth-air heat exchanger in cooling mode

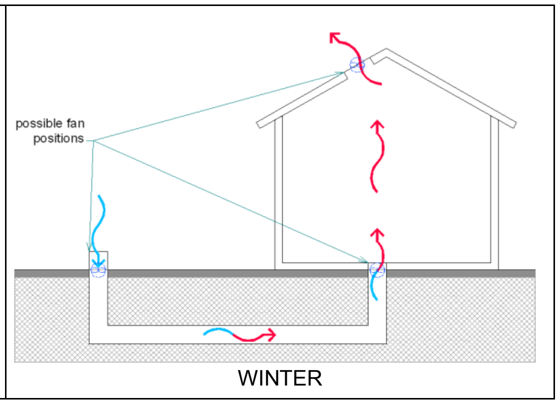


Figure 3.4: Earth-air heat exchanger in pre-heating mode

The idea of using earth channels to achieve thermal comfort is not only a human innovation: it can be seen in the termite mounds. The macrotermitine termites build some of the most spectacular animal-built structures on the planet. These structures are not the residence for the colony, they are actually organs of gas exchange, which serve the respiratory needs of the colony, located about a meter or two underground below the mound. The tunnels within the mound form a complex ventilation system for maintaining the atmosphere within the nest itself, where the worker termites and their fungus gardens reside. The mound itself is a wind capture device for capturing wind energy to power ventilation of the nest. They are adaptive structures, continually changed by the termites to maintain the appropriate nest atmosphere. Curiously, the upper part called the spire has a typical tilt which corresponds to the average zenith angle of the sun to make the most of the suns warmth (Turner, 2005).

Figure 3.5: Nature's EAHEs- the air channels inside the termite's mounds (Source: State University of New York College of Environmental Science and Forestry website, article by Scott Turner)[31]

[31] www.esf.edu/EFB/turner/termite/mound%20structure.htm [Accessed on the 2^{nd} of April 2009]

Man has also built and used conditioning systems using the ground for millennia and many interesting examples are found in ancient Egypt and ancient Rome. Buried pipes for cooling, named qanats, were often used in Islamic and Persian architecture, sometimes combined with water systems. However, the technique lay forgotten for decades until their relevance was rediscovered in the context of human-caused carbon emissions and the need for energy efficient building design.

3.1.2 Possible Energy Savings

As suggested above, the application of an EAHE to a building may result in significantly lower costs of cooling as well as a reduction in the CO_2 emissions due to the building's energy usage. Equation 2.9 can be applied to EAHEs to calculate the potential energy savings using air as the medium (Equation 2.9 below). Where there is condensation of water vapour, latent heat is also transferred to the air and may be taken into account. This equation will be used in Chapters 6 and 7 when two real EAHE installations are discussed.

Equation 3.1: Quantity of heat energy delivered by an EAHE

$$Q_{EAHE} = m_{air} c_{air} \Delta T + m \Delta h_{latent}$$

Where:
Q_{EAHE} = quantity of cooling or heating energy delivered (kW)
m_{air}= mass of air (kg)
C_{air}= specific heat capacity of air (1.012 kJ/kg^{o}C)
ΔT= temperature difference (^{o}C)
Δh_{latent} = specific latent enthalpy of water (kJ/kg)

Because the energy gain of an EAHE is dependent on the system's design, the period of operation, the inlet air temperature, the air flow and the soil temperature, Equation 2.9 will not allow direct comparison between different systems. Consequently one should relate the annual energy gain to the area of heat exchange to obtain a specific value in kWh/m^2. Nevertheless this value would still not provide a designer with a measure of system efficiency.

Although some EAHEs are driven by natural forces such as buoyancy, most of the time a powered fan is necessary and as a consequence the cooling or heating generated is not free. In refrigeration and air conditioning system, the coefficient of performance (COP) is defined as the benefit of the cycle (amount of heat removed) divided by the required energy input to operate the cycle (ASHRAE, 2005) as shown in Equation 3.2. If COP is applied to EAHEs then their comparison to traditional heating, ventilation and air conditioning (HVAC) systems is much clearer.

Equation 3.2: Coefficient of Performance of refrigeration or air conditioning systems

$$COP = \frac{EO}{EI}$$

Where:
COP = coefficient of performance
EO= system energy output as cooling or heating (kW)
EI= system energy input (kW)

It is important to remember that a direct comparison is not always possible. For example, most EAHEs would be programmed to operate on a time basis and so their fans would run constantly for the entire period of time they have been programmed. A HVAC unit would operate until it achieved its set point, at which point it would either switch off until required again or reduce its output to maintain its environment close to the set point. Therefore, assumptions need to be made regarding the kWh consumed by an HVAC unit to produce the same environmental conditions as those experienced by an EAHE.

A common HVAC unit have average year-around COPs of 2 to 3 meaning that for each kWh of electricity you use you get 2 to 3 times that many kWh in cooling or heating. Reported COPs of EAHEs range from 2 to around 5 (Sharan and Jashav, 2003: p. 7-9) to values as high as 12 (Goswami and Biseli, 1993: p. 3). The latter also combined an EAHE to a heat pump to improve the system's COP. Voss and Herkel (2007) reported COP as high as an astonishing 280 in Germany.

An alternative way to estimate the COP was proposed by De Paepe and Janssens (2003). A simplified method for designers to optimise EAHE configurations by reducing the pressure drop for a given thermal efficiency was proposed and so the pressure loss, not the electricity demand, was used to calculate the COPs.

Because the outlet air temperature of an EAHE is dependent on the system's design, the way the system is used, the inlet air temperature and the soil temperature, comparison between different systems is very difficult. Pfafferott (2003) proposed the use of a ratio of temperature variation, R_T, which is a fairer comparison as temperatures are related to their limits as shown in Equation 3.3. The smaller the result is the more cooling energy is delivered to the building.

Equation 3.3: Ratio of temperature ranges in inlet and outlet of an EAHE

$$R_T = \frac{T_{out,\max} - T_{out,\min}}{T_{in,\max} - T_{in,\min}}$$

Where:
R_T = ratio of temperature variation
$T_{out,max}$ and $T_{out,min}$= maximum and minimum temperature in the pipe's outlet (^oC)
$T_{in,max}$ and $T_{in,min}$= maximum and minimum temperature in the pipe's inlet (^oC)

The general efficiency of EAHEs can be defined as:

Equation 3.4: Overall efficiency of EAHEs

$$\varepsilon_{EAHE} = \frac{T_{out} - T_{in}}{T_{earth} - T_{in}}$$

Where:
ε_{EAHE} = overall EAHE efficiency
T_{out} = temperature in the pipe's outlet (^oC)
T_{in} = temperature in the pipe's inlet (^oC)
T_{earth} = undisturbed earth temperature (^oC)

Using this method, Gieseler and Bier (2002) found that the efficiency of small EAHE units for heating in residential applications is usually low, around 0.5 but it can be very high for cooling in summer.

When considering an EAHE's heating and cooling performance it is important to understand that there is a difference. The heating performance requires as high a rise in air temperature as possible (as even this is likely to not be enough for winter comfort) so it should consider the temperature rise between outlet and inlet. It is limited by the amount of fresh air that is needed in the building. The cooling potential is related to the smothering of outdoor temperature to counterbalance peaks and so it is proportional to the difference between outlet and desired comfort temperature. The increase of air flow rate can improve the cooling performance but is limited by the system's length and air residence time to allow enough exchange of heat.

The energy gain from an EAHE is not always desirable in a building as it might cool down or warm up the ambient temperature too much or at unnecessary periods. A control strategy needs to be set up probably based on temperatures to ensure supply of energy when is actually needed and so maximise energy savings.

3.2 EAHE APPLICATIONS

Although versions of this technique have been applied over centuries, principally in warmer climates, just over the last decade there has been a renewed interest in EAHEs in Europe. This section summarises the articles that were found on installed EAHEs whilst modelling and simulation of EAHEs are dealt with in Chapter 3.3. The locations of the installed systems described or mentioned on the studied papers can be seen in Figure 3.6. This map, produced by the author and available online, contains locations and the names of main author that cited each system.

Figure 3.6: The red dots mark the location of installed system found in published articles. Map produced using Google Maps and made available online[32].

There seems to be a concentration of EAHEs in Europe, either for economical reasons or just because European countries are more prone to publish material on the performance of buildings. In India, EAHEs are more likely to be used coupled to greenhouses. In Western and Northern Europe EAHEs for cooling applications are becoming increasingly common but few studies exist on their long-term performance.

In spite of the general belief that there is no need for cooling in Britain, air conditioning use is rising by 8% annually in the UK despite the fact that 89% of occupants prefer buildings without conventional air conditioning (Littlefair, 2005: p. 11). However, EAHEs are still rare in the UK and after careful search no published articles have been found on applications of EAHE in Britain. The only installed system in the UK mentioned in an article was a concrete EAHE coupled to a greenhouse in Iver (Santamouris, Mihalakakou et al., 1996) but not much information is available. No systems in the UK coupled to houses were found in published papers. In Chapters 6 and 7 two systems coupled to houses are analysed.

[32] Produced by the author and made available for public view under the name 'EAHEs around the world' at http://maps.google.co.uk/maps/ms?msa=0&msid=114961414432978732 577.00044e729620cac3b9c64&hl=en&ie=UTF8&z=2 [Last accessed on 09th of April 2009]

3.2.1 EAHEs in Commercial and Mixed-use Buildings

Since the renewed interest on the use of EAHEs, many systems were built mainly for the cooling of commercial buildings (Pfafferott, 2007), especially in Germany. For example, Pfafferott (2003) compares the thermal performance of three EAHEs coupled to office buildings in Germany: the DB Netz AG, the Fraunhofer ISE and the Lamparter Office. The three EAHEs were designed to match the building requirements and so the offices make use of no other cooling system. The article compares each performance with a frequency distribution that takes temperature limits for heat and cooling into consideration. Voss and Herkel (2007) report on the results of a government's programme to monitor energy use of commercial buildings in Germany. Six offices, one educational and one production building are reported to make use of EAHEs with COPs between 20 and 280. Although the COPs found are higher than conventional cooling systems, the large range shows a need for quality control in the design and commissioning of these systems.

Lain and Hensen (2005) mention that EAHEs for houses are currently popular in the Czech Republic but they do not give any examples. The work also says that the Slunakov Ecological Centre is the only large building employing the technique in the country.

In the evaluation of an office building in Belgium, Breesch and Bossaer et al. (2005) combined measurements and simulation studies to estimate the relative importance of the cooling techniques used in the design. They concluded that, although both techniques work well, night time ventilation was shown to be more effective than EAHEs in improving comfort conditions.

EAHE and displacement ventilation were combined in the Cité des Arts du Cirque building in Montreal (Athienitis, Roy et al., 2005) to provide large quantities of fresh air near the audience. The EAHE is made of two 60m long 1m diameter galvanised steel ducts which can work separately to satisfy smaller or larger requirements. The system uses fans in summer but work by buoyancy alone in winter and is able to satisfy up to 100% of cooling needs and around one-third of heating needs. The design of the system was aided by Computer Fluid Dynamics (CFD) simulations, which were confirmed by measurements. Zhang and Haghighat (2005) also used CFD to simulate a similar hybrid ventilation system in a building in Grong, Norway.

In Mathura, near Delhi in India, a hospital was equipped with an EAHE made of a main tunnel and several subsidiary tunnels all made waterproof by a layer of 0.4mm polythene (Sodha, Sharma et al., 1985). The tunnel was also used for services such as water, electricity and gas and had easy access. The cross-sectional area of the tunnel varies from 3.66x4.57m to 0.91x0.91m and it runs for 1000m with skylights at regular intervals. The outlets are in various parts of the hospital and are equipped with fans. Measurements were taken in summer and winter in an 80m section of the tunnel and it was found that, even with ambient temperatures peaking at 43^{o}C, this section of the EAHE alone was able to deliver air between 23 and 28^{o}C with a desirable high humidity in summer. In winter, air was delivered between 12 and 20^{o}C when ambient air varied between 4 and 21^{o}C. The authors concluded that the EAHE is effective in summer but not in winter and that the fact that water services are placed inside the tunnel might have affected the results regarding humidity as leaks were observed.

The Schwerzenbacherhof office building in Zurich (Zimmermann and Andersson, 1998: p. 15.1 to 15.8; Hollmuller and Lachal, 1999) has an EAHE coupled with night cooling, which was proven sufficient to keep thermal comfort during the cooling period without any other active system being used. The EAHE was constructed from a High Density Polyethylene (HDPE) array of 43 pipes of 230mm diameter, 23m length and with a distance of 116mm between each. The pipes were located at a depth of 6m below ground level where the temperature was shown to remain at an almost constant at 12^{o}C. The air inlet was situated in the courtyard of the building and was covered by a metal screen to prevent insects and debris from entering the system. The annual energy consumption of the fan used was 23 MJ/m^{2} of conditioned space. The cooling performance of the system was measured on the fourth floor of the building during a hot period in 1992 and at no point during this period was the room temperature above the comfort zone. At peak outside temperatures of 32^{o}C the maximum cooling rate provided was 54 kW and the EAHE supplied the rooms with air at 23^{o}C. The array of horizontal piping and the soft ground kept excavation costs to a minimum, making the installation of an EAHE an economically viable project and the authors believe this kind of system to be attractive for cooling and preheating ventilation air for many buildings in mild climatic regions.

Hollmuller and Lachal (1999 ; 2001) monitored the Caroubier building in Geneva, equipped with an EAHE made of 49 pipes with an axial distance of 300mm. The 125mm pipes are of 50m length and buried at a 0.5m depth below an underground parking. The EAHE is coupled to a heat exchanger on exhaust air. It was found that the shallow depth and the surface finishing above the pipes did have a large influence on the outlet air temperature. Nonetheless, in summer the EAHE was capable of keeping the indoor temperature below 26^{o}C and very stable. Monitoring over a 20 days winter period showed the heat exchanger as a better pre-heating technique than this particular EAHE.

Hollmuller and Lachal's (1999 ; 2001) general conclusions from the analyses of these two buildings are that the cost and the quantity of fresh air needed in winter can limit the benefits of EAHEs as pre-heating systems. They are, however, very effective and financially competitive as a substitute for a conventional HVAC system during summer. If the EAHE is installed for cooling it will have a free added benefit for pre-heating. Water can built-up in the pipes which can reduce winter performance but can enhance summer cooling. The authors overcame that problem in another building by using water in the pipes as a heat carrier coupled to an air to water heat exchanger.

An EAHE was installed and monitored in Dublin airport (Mihalakakou, Lewis et al., 1996a ; Mihalakakou, Lewis et al., 1996b). The system was modelled in a numerical transient model with the aim of investigating its heating potential in Ireland. The authors concluded the system is suitable for pre-heating and that the ground cover has a large influence on its performance but nothing was said about its cooling performance.

A system that presents similarities to EAHEs was designed and installed in the RMC Headquarters by Edward Cullinan Architects. A mechanical ventilation system that operates at night brings in cool air to be stored under the floor slab which then acts as the supply ducting throughout the office (Thomas, 2005). Unfortunately no further information was found on this system and its performance.

3.2.2 Constructed Experimental EAHEs

In the arid climate of Kutch, India, a 50m long single pass EAHE, made of mild steel pipe of 100mm of diameter, was buried 3m deep below surface and its performance was monitored over a one year period. The average soil temperature was found to be 27^{o}C at that depth and a 15cm thick layer of sand was used around the pipes. A 400W fan was incorporated, designed to provide airflow rate of 5.6m^3/min (mean air velocity in the pipe 11m/s). When in cooling mode, the ambient temperature was reduced by 13.6^{o}C. Most of the cooling occurred in the first half (25m) of the tube, a result that is expected to happen because as the difference between the air temperature and that of the soil reduces, the heat transfer rates are reduced. When the system was in heating mode, it could raise the ambient temperature by 14.7^{o}C (Sharan and Jashav, 2003).

Henkel and Chen et al. (2004) designed and installed an EAHE at the University of Nebraska to explore its cooling potential for residential applications. The 450mm diameter corrugated steel pipe is 57m long and was buried in a 3m deep trench where a sand bed was placed at the bottom to hinder moisture build-up beneath the tube. This installation differs from all the others studied because the pipe was perforated over the entire length to allow moisture to trickle out. A 560W fan was used to drive the air flow throughout the experiment and it was found that the outside wind conditions had a significant influence on the air velocity. The fan was placed at the outlet to cause positive pressure in the room and so minimise air infiltration losses. The system had an average COP of 4 and even with thermal saturation of the soil the cooling performance did not drop essentially. Humidity levels and air quality were not measured so one cannot tell if the strategy of perforating the pipes worked effectively.

Argiriou and Lykoudis et al. (2004) installed an EAHE in Athens coupled to a photovoltaic system to make the most of the fact that the cooling loads are almost in phase with the available solar irradiance. The system's COP was found to be, on average, around 12 and the arrangement was proven to be an efficient and reliable hybrid technology.

3.2.3 EAHEs in Houses

As the application of EAHEs in houses is one of the focuses of this work, it can be found in more detail below. It should be remembered, however, that there are no current published examples in the UK. Table 3.1, at the end of this section, summarises the systems described below.

Coolhouse is a project funded by the Energy Research Directorate of the European Commission to investigate innovative ventilation and cooling strategies for Southern Europe to facilitate the reduction in the use of domestic air conditioning. Part of the project, the Alma Verde Village and Spa is located in the Algarve, southwest Portugal, aims to provide high quality and comfortable houses with low energy usage. They combine insulation with high mass adobe walls, EAHEs and a conventional heating system. The ambient temperatures in this region fluctuate from around 3 to 38^{o}C and the soil's temperature at a depth of 2m was expected to be around 14^{o}C. Two PVC pipes 25m long and 16cm in diameter were buried at a depth of 2m. The pipes have a fall of 1:60 and are made of PVC, which, due to its low conductivity, exchanges heat at a very low rate avoiding heat saturation of the soil. PVC was selected because of low cost, durability, water tightness and the possibility of being periodically jet washed. A single 170W variable speed air-handling unit is used to pull air at a velocity of 4m/s through the tubes. In this project the outlets inside the houses are elegantly integrated as discrete slots around the perimeter of the floor slab (Figure 3.7), sized to suit the thermal loads of the space with air velocity below 1m/s (Fjaerem, 2004 ; Kennett, 2005).

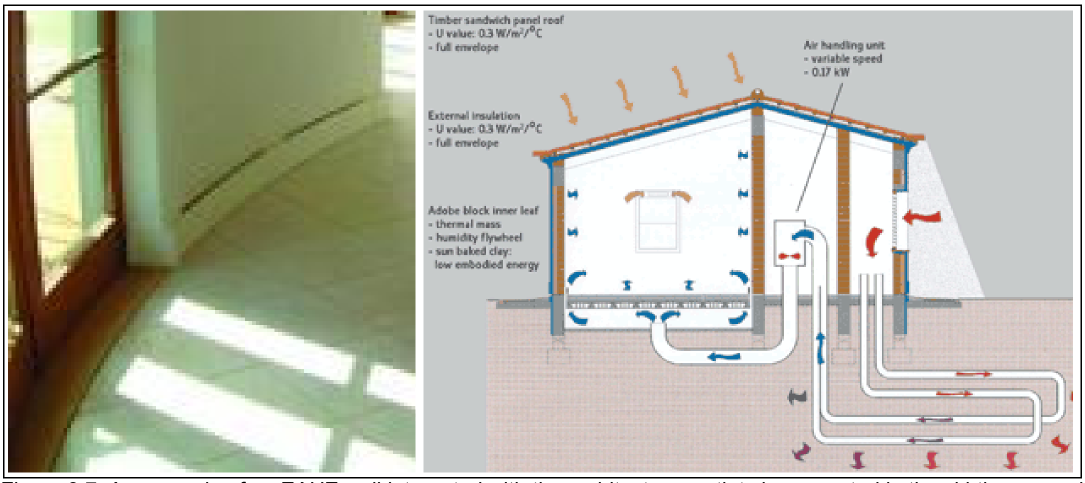


Figure 3.7: An example of an EAHE well integrated with the architecture- outlets incorporated in the skirting around the perimeter of the floor slab at the Alma Verde Village and Spa (Kennett, 2005: p. 43)

Coolhouse is one of very few real life projects that have gone through long-term monitoring. Three houses were examined and the performance of the EAHEs of two were compared (one of which was unoccupied). The first conclusion drawn is that the different treatment (various types of vegetation) applied to the top soil did not make a difference on the results. During summer, the system runs continuously during the night working as night time ventilation cooling the structure of the house. In the unoccupied house the temperature dropped as much as 12^{o}C and had a relatively constant indoor temperature of 25^{o}C even when the outdoor temperature was 38^{o}C. The occupied house had similar results although always around 2^{o}C higher as a result of the occupants and their activities. A comparison showed that the Coolhouse system saved over 33,400kWh of energy and more than €3,300 during the monitoring period, which would mean a payback period of 9 years less than a conventional cooling system (Fjaerem, 2004). Another interesting point made by the report is that a comparison of the monthly average temperature delivered by the EAHE with the average ambient temperature of every month is not an effective way to show the system's efficiency as the results tend to be similar and one would not appreciate the reduction on the peak temperatures on a daily basis. The authors also interviewed house occupiers who expressed satisfaction with the system and the fact that internal temperatures are not completely disassociated from outside conditions as it is the case with conventional air-conditioning.

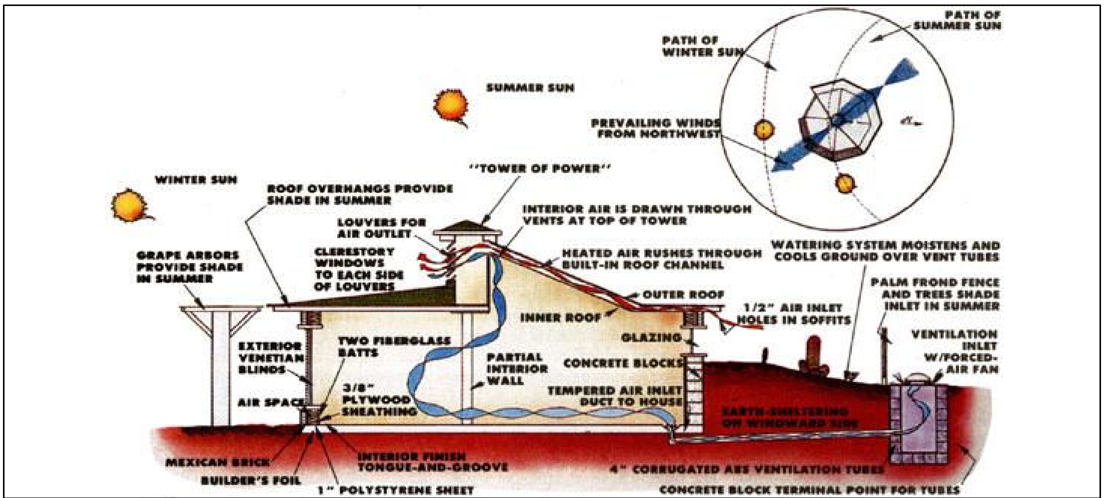


Figure 3.8: Jim Harmon's passive solar house in the Californian desert (Source: Mother Earth News website)[33]

A house designed by Jim Harmon for the harsh desert climate of Imperial Valley in Southern California makes use of earth to temper the air temperature by being half sunk in the ground and by using an EAHE for cooling and heating throughout the year. The EAHE is composed of 4 100mm corrugated plastic pipes which are 30m long and buried at a depth of 1m. By

[33] http://www.motherearthnews.com/multimedia/image-gallery.aspx?id=70376&seq=3 [Accessed on 10th of April 1009]

combining high insulation, double layers, solar shading, a wind tower and the EAHE, Harmon achieved thermal comfort throughout the year passively (Figure 3.8). An interesting aspect of this design is that, due to the pressure difference caused by the stack effect in the tower, its use of prevailing wind and exhausting of warm air at the highest point and due to the fact that the only source of fresh air is the EAHE, there is no need for a fan nearly the whole year. A watering system is used to keep the soil moistened and help to cool it down, making up for the shallow depth of the EAHE (Mother Earth News Editors, 1986).

Sawhney and Buddhi et al. (1997) have done a parametric study of an EAHE installation in a double storey building called Solar Passive Guest House designed for cities like New Delhi and Indore (India), climate of cold winters (down to 3^{o}C) and very hot summers (up to 45^{o}C). The closed loop system has 8 suction ducts (one in each bedroom), 2 heat exchanger pipes with a fan in the middle and 8 delivery ducts. The 85m long tubes are made of concrete with a diameter of 500mm and buried at a depth of 2.5m parallel to each other with a spacing of 1m. The local annual average earth temperature is very close to the annual average air temperature, ranging from 26^{o}C to 28^{o}C. The air exits are provided with a metal wire mesh to prevent insects from entering the pipes. The system has an inspection chamber for the purpose of periodic maintenance and to pump out any water that has leaked into the tubes. It also has 2 electric fans of 2200W capacity to force the air into the pipes. Temperature, relative humidity and air velocity were measured at different locations and it was found that the system effectively aids air temperature and humidity constancy inside the rooms. On a sunny summer day the indoor temperature was kept almost constant at 27^{o}C while the outside varied from 22 to 44^{o}C. The humidity was also more constant although usually higher than the outside.

The lack of studies on EAHEs in European countries led Trombe and Pettit et al. (1991) to develop an experiment on two identical houses, one with an EAHE and the other without in the south of France where summers are very hot and dry. The system is composed of an open loop 200mm PVC pipe buried at a depth of 2.5m and 42m long, partially under the house and partially under the garden. The peak temperature drop in relation to ambient temperature was 12^{o}C. They also observed a variation of the humidity levels of the outlet air but these did not reach levels that might become uncomfortable. The experiments used various fan speeds and concluded that good management and optimisation of fan use are essential to the success of the system.

Monama (Roaf, Fuentes et al., 2003: p. 304) is a house built for a family in Hyderabad, India, a city with unreliable main power supply where there are power cuts almost every day. Consequently, the design's goal was to diminish the reliance on the national grid and consequently cause a lower environmental impact although sustainable design and use of renewable energies were limited by site and budget. A system including an open loop buried pipes (length of 26m, diameter of 25cm and depth of 2m) and evaporative cooling was installed. A fan was used to draw in outdoor air and the air velocity through the pipe was 2m/s. An interesting system with adjustable tubes at the outlet permit user placement as shown in Figure 3.3. Simulations indicated that the system could achieve indoor temperature fluctuations between 27.5 and 29^{o}C when the outdoor temperature can reach peaks of over 40^{o}C.

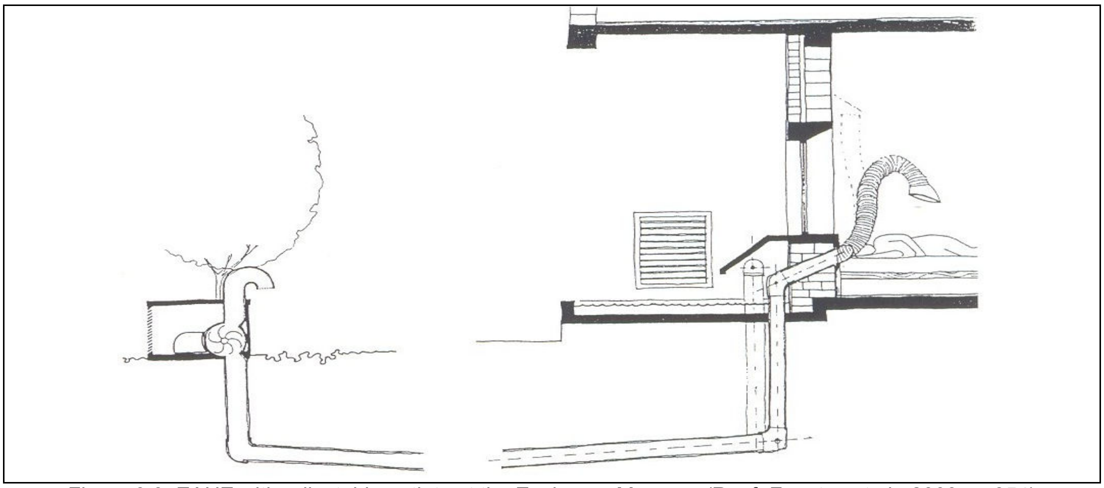


Figure 3.9: EAHE with adjustable outlets at the Ecohouse Monama (Roaf, Fuentes et al., 2003: p. 354)

In Formerie, north-west of France, a two dwelling building was constructed complying with PassivHaus standards (as seen in Chapter 1). The building has not yet been monitored but Thiers and Peuportier (2008) simulated it and compared it to a standard building. The ventilation system combines an EAHE with a heat recovery system, which is just used for further heating of the air in winter. The EAHE is made of a 30m long polyvinyl chloride pipe with a diameter of 200mm and buried at a depth of 1.6m depth. The simulations have shown substantial reduction of summer discomfort with the EAHE contributing to a reduction overheating degree days by 60% at an air exchange rate of 1.5ach.

In Destelbergen a wooden house with two exterior façades was built in a dense urban area as the first example of cost efficient passive housing in Belgium. During the first year of occupation the building was monitored and compared with computer simulation (Meulenaer, Veken et al., 2005). The house has an EAHE coupled to the house's main water heating system which further heats the air in winter. The pipe is 40m long, has an internal diameter of 110mm and is buried at a depth of 1.5m. During the whole year the use of the EAHE worked to dampen the daily fluctuations in ambient air temperature and in the hottest month recorded (August) the EAHE was required to cool the building 50% of the time. In that year, the outlet temperature of the EAHE varied between 10^{o}C and 19^{o}C only, fluctuating much less than the ambient air temperature.

These examples show that EAHEs are capable of reducing daily air temperature fluctuations in houses in a comparable manner to thermal mass in the building envelope and may be an efficient alternative to traditional high thermal mass walls.

Table 3.1: Summary of EAHEs installed in houses (note: NS stands for not specified)

EAHEs in Houses											
Name	**Location**	**Soil**	**System**	**Length**	**Diameter**	**Depth**	**Material**	**Slope**	**Fan/ Air velocity**	**Others**	**Max temp drop**
Alma Verde Village and Spa (Fjaerem, 2004)	Algarve, Portugal	14°C	2 pipes, closed loop	25m each	160mm each	2m	PVC	1:60 (2%)	170W, 4m/s	Protective insect mesh	12°C
Harmon's house (Mother Earth News Editors, 1986)	Imperial Valley desert, USA	Sandy, 23-27°C, watering system	4 pipes, open loop	30m + (not clearly specified)	100mm each	1m	Corrugated plastic	NS	Fan NS, buoyancy	Combined with wind tower	NS
Solar Passive Guest House (Sawhney, Buddhi et al., 1997)	Indore, India	26-28°C	2 pipes, closed loop	85m each	500mm each	2.5m	Concrete	NS, pump removes water	2200W, 6.3m/s	Protective metal mesh	17°C
French timber house (Trombe, Pettit et al., 1991)	South of France	NS	1 pipe, closed loop	42m	200mm	2.5m	PVC	NS	Fan NS, 0.43 to 0.63m/s	Pipe partially under the house	12°C
Monama house (Roaf, Fuentes et al., 2003)	Hyderabad India	NS	1 pipe, open loop	26m	125mm	2m	NS	NS	Fan NS, 2m/s	Adjustable outlet	11°C
French house (Thiers and Peuportier, 2006)	Formerie, north-west France	NS	1 pipe, open loop	30m	200mm	1.6m	polyvinyl chloride	NS	NS	Combined with HRV	NS
Belgian Passive Urban House (Meulenaer, Veken et al., 2005)	Destelbergen, Belgium	NS	1 pipe, open loop	40m	110mm	1.5m	NS	NS	NS	Combined with heating system	NS

3.2.4 Proposed Systems

One interesting example of an EAHE was not actually built but is worth mentioning especially because of the similarity to the innovative system proposed in Chapter 8 and because it is applied to a house.

The SEA (Solar heating, Earth cooling and Air circulation) House is an experimental project that aims to provide thermal comfort by reducing the temperature difference between southern and northern rooms. The strategy includes insulation, EAHE, a solar collection storage wall on the south side and a mass heat storage wall on the north side. An outstanding characteristic of this project is that the air does not circulate directly in the space; it goes through a layer between walls and insulation driven by buoyancy. This strategy allows the system to work independently of openings, which would usually decrease the efficiency of the passive cooling and heating (Zhang, Ishihara et al., 1994). A section and a plan of the house can be seen in Figure 3.10 below.

The proposed EAHE is made of ten polyethylene tubes with 20cm of diameter, 20m lengths each at a depth of 2m. The house was simulated to be in Tokyo (Zhang, Ishihara et al., 1997), where the soil temperature was assumed to be equal to the monthly mean ambient temperature. In summer, using an air flow rate of 100m^3/h, the EAHE achieved a reduction of external air temperature by almost 10^{o}C, from 35.2^{o}C to 25.8^{o}C. The air from the EAHE is used to cool the walls increasing in temperature up to 27.4^{o}C and then exhausted through the attic. The temperatures in the southern and northern room, which also make use of ventilation are fairly stable at 27.5^{o}C and 25.4^{o}C respectively. In winter the results have shown that without ventilation thermal comfort is not achieved and temperatures can reach 30^{o}C. Condensation does not occur because the house is always at a warmer temperature than the circulating air (Zhang, Ishihara et al., 1994).

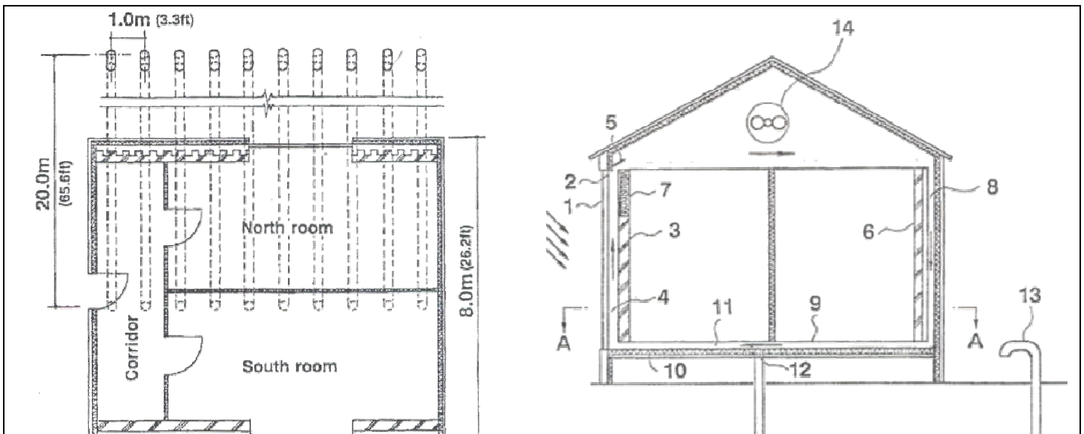


Figure 3.10: Plan and section of the SEA house by Zhang and Ishihara et al (1994)

3.2.5 Conclusions

There are currently no published examples of EAHEs in British houses. There is a great variety of systems that differ in most aspects, but all those reviewed were able to significantly contribute to space conditioning and users' comfort.

Most of the systems described in section 3.2 were analysed by means of computer modelling. Occasionally the analysis occurred before the construction of the system but mostly the systems are used to validate models. Generally these models are not used to inform the design process as they are not accessible and/or user friendly. The next section describes the most important literature found in this field.

3.3 EAHES PERFORMANCE PREDICTION MODELS

Several papers have been published on modelling EAHE's performance. These are either one-dimensional heat transfer problems or three-dimensional complex models. Most of these methods are of high complexity and so unsuitable for use by designers. Architects, who are often interested in installing an EAHE, give up due to lack of knowledge or design criteria. The complex models tend to not find their way from academia to practice (De Paepe and Janssens, 2003) and so do not support the installation of new systems. This phenomenon was the subject of a previous study by the author (Rodrigues, 2005).

3.3.1 Steady-State One-dimensional Models

Analytical steady-state models describe the disturbance of the ground by the pipe but do not allow for many variables such as starting up and shutting down of the system, thermal saturation of soil, air humidity, water build-up and latent heat gain. They have the advantage of providing quick results and are suitable for an estimation of annual outputs.

Because of the complexity of the available models, De Paepe and Janssens (2003) proposed a simplified method for designers to optimise EAHE configurations by reducing the pressure drop for a given thermal efficiency. They studied the influence of different design parameters on the non-dimensional group called number of transfer units (NTU) and the change of the EAHE effectiveness as a function of it. They introduced 'specific pressure drop' as a measure of the pressure drop needed to realise a given thermal performance used it to derive a design method. Finally they proposed a design graph to help to find configurations for an EAHE based on the assumption that an effectiveness of 80% is considered to be optimum for an EAHE. A one-dimensional transient model was proposed in Italy (Cucumo, Cucumo et al., 2008) and has shown good agreement with De Paepe and Janssens' model and experimental data from the literature.

Sodha et al. (1985) proposed a simple theoretical model to validate experimental results of an EAHE installed in a hospital complex as mentioned in section 3.2.1. In order to make the mathematical model simple, it was assumed that the tunnel was uniform and circular, the surface temperature of the surrounding medium changed uniformly, materials and soil were homogeneous, and that initially the temperature distribution of the surrounding earth was uniform. Latent heat from vapour was taken into account. The model was validated against measurements taken in summer and winter on an 80m section of the EAHE.

A numerical model of a two pipe EAHE was proposed by Bojic and Trifunovic et al. (1997) by dividing the pipes into elementary volumes calculated by steady-state equations, which were then applied to a time-marching method. One pipe was made of 140mm PVC and the other of 150mm steel, both 50m long and buried at 1.5m. The authors proposed to plug the existing gap in the literature on how the season, soil conductivity, pipe material and pipe distance influence the heat exchange of the EAHE (Bojic, Papadakis et al., 1999). General conclusions are that the EAHE covers only a portion of the building's needs for cooling or heating and that its energy usage is lower in summer than winter.

Extensive modelling and validation of EAHEs coupled to greenhouses in India were undertaken (Ghosal, Tiwari et al., 2004 ; Ghosal, Tiwari et al., 2005 ; Ghosal and Tiwari, 2006 ; Tiwari, Akhtar et al., 2006). The models showed fair agreement with experimental results and the technique was found suitable for such applications in India.

3.3.2 Dynamic and Three-dimensional Models

Usually numerical models have three interacting variables: thermal conduction of the ground, heat transfer from the ground via pipe wall into air, and thermodynamic changes, such as humidity and temperature of air. They use non-steady multidimensional thermal conduction calculations based on the Fourier differential equation explained in Chapter 2 and divide the ground into a three dimensional grid. They are generally more accurate than steady-state models and can take into account different materials and operations.

Mihalakakou and Santomouris et al. (1994a ; 1994b) developed a complete transient numerical model of coupled heat and moisture transfer for a single pipe EAHE and validated it with collected data. An extensive sensitivity analysis was undertaken to examine the impact of the main design parameters on the cooling performance of the system. The effeciency and cooling potential were presented in graphs to support the design of EAHEs. The graphs are easy to understand but are restricted to the values and weather data (Athens) used as input in the simulations. The model was developed further and parametrical predictions were successfully compared with numerical predictions (Mihalakakou, Santamouris et al., 1995). The model was later used to describe the thermal influence of key variables in Dublin where an EAHE was shown to be suitable for heating of air (Mihalakakou, Lewis et al., 1996a). The same model was used again many times in subsequent publications (Mihalakakou, Santamouris et al., 1995 ; Santamouris, Mihalakakou et al., 1995 ; Santamouris, Mihalakakou et al., 1996). Notably it was extensively used to model EAHEs in greenhouses and once it was used integrated to a building model (Jacovides and Mihalakakou, 1995 ; Santamouris, Mihalakakou et al., 1995).

Kaushik and Kumar (1994) proposed a theoretical model of a building with a hybrid ventilation system that included an EAHE. This model allowed the analysis of the sensitivity of the building's indoor temperature to the variation of different EAHE parameters. Hanby, Loveday and Al-Ajmi (2005) carried out a parametric optimization of an EAHE for Kuwait by coupling a validated numerical model to a constrained optimization method, which was shown more effective than just a parametric study. Later the method was coupled to a building (Al-Ajmi, Loveday et al., 2006) and the simulation showed that the EAHE had the potential to reduce the cooling energy demand by 30% over the summer season.

Hollmuller and Lachal (2001 ; 2003 ; 2005) analysed other models proposed by previous authors and concluded that just one took latent heat gain in the pipes into account but not in a flexible manner. Consequently, the authors proposed a finite difference numerical model accounting for sensible and latent heat gain in EAHE pipes. Their model simultaneously takes into account both phenomena as well as frictional losses, water infiltration and flow along the pipes. There is flexibility regarding inputs such as the control of air flow, geometry and inhomogeneous soil. The model was adapted for use in TRNSYS (Transient Systems Simulation Program[34]), a flexible simulation program designed to simulate the transient performance of thermal energy systems by breaking complex problems down into a series of smaller components (Hollmuller and Lachal, 1998). The use of TRNSYS requires extremely detailed information on the building and system to be simulated as the software makes few assumptions and requires extensive knowledge of thermal dynamics and computer programming.

A transient model based on numerical heat transfer and CFD was developed and validated against experimental data in Southern China (Wu, Wang et al., 2007). The model has shown high reliability and the authors tested a range of systems of varying length, depth and pipe diameters. The paper concluded that up to 74kW of cooling can be obtained from an EAHE in that region.

Lee and Strand (2008) developed a new module for the software EnergyPlus for the simulation of EAHEs. EnergyPlus models heating, cooling, lighting, ventilating, and other energy flows as well as water systems in buildings. It is a stand-alone simulation program without a user-friendly graphical interface which reads input and writes output as text files[35]. They used a novel approach which included a detailed algorithm, able to calculate the soil temperature around the pipes from weather data files, encoded within the software. The 'CalcSoilSurfTemp' program calculates the annual average, amplitude and phase constant of soil surface temperature. This can then be used by the user as input parameters into the earth tube model in EnergyPlus. The model was validated against theoretical and experimental data and used to investigate the influence of different parameters on a system's cooling performance and the heating and cooling potential of EAHEs in four USA

[34] More information at http://sel.me.wisc.edu/trnsys/ [Accessed on the 13th of April 2009]

[35] More information at http://apps1.eere.energy.gov/buildings/energyplus/ [Accessed on the 16th of April 2009

locations. Like TRNSYS, the use of EnergyPlus requires detailed information of the building and systems in a code format and so is not user-friendly.

Other even more complex models have been proposed. An approach using dynamic deterministic and intelligent techniques was proposed by Mihalakakou (2003) to deal with the heating performance of EAHEs in Athens. It also proposes a Neural Network for estimating the thermal performance of the system. Neural Networks were also used in India (Kumar, Kaushik et al., 2006) and were found to have an accuracy of ±2.6% while a deterministic model showed a ±5.3% accuracy. The same authors proposed the use of finite difference and validated the model against experimental data (Kumar, Ramesh et al., 2003). Kumar and Sinha et al. (2008) also proposed a model based on a genetic algorithm which was proven more accurate than a deterministic model and in good agreement with experimental data.

All these complex models are hardly used in practice and their applicability is limited to people who are able to use calculation codes and can invest the time. They are, however, valuable because they show that EAHEs are a promising technology.

Tzaferis and Liparakis et al. (1992) evaluated eight models by studying their sensitivity to inlet air temperature, air velocity and pipe design and comparing them to experimental results. The sensitivity analysis has shown that the main parameters determining the outlet temperature are inlet and ground temperature and that there is a limit to the influence of pipe design (length and diameter) and air velocity to the resultant temperature. The authors concluded that the different approaches give commensurate results. This is mainly because they are different methods to use the same equations. Consequently, a simpler approach such as a steady state calculation may potentially give accurate enough results, especially at design stage. An up-to-date study of this matter is an interesting possibility for future work as the capacities of computer simulation have changed significantly in the last 15 years.

3.4 DESIGN AND CONSTRUCTION REQUIREMENTS

It is difficult to separate EAHE properties into categories as each is very intimately correlated to another. One should make a compromise between all of them to accomplish an effective system. In order to find such a subtle balance an effective tool, out of the complex models mentioned previously, would be ideal but most of them are incomplete and/or not suitable for designers in early stages of a project as discussed. The following list of parameters to be considered has been put together based on the works discussed above and personal experience.

3.4.1 Physical Properties

- Air intake: The arrangement can be an open loop system (using external air) or a closed loop system (using the air circulating through the building). There is controversy as to which one is better. Many authors state that closed loop systems are more efficient because they do not exchange air with the outside therefore not requiring dehumidification. However, these seem to have fallen out of favour probably because they do not provide the building with fresh air without filtration.
- Tube material: Many different materials have been used in the past and it has been proven that their choice has little influence on the thermal performance of EAHEs because the ground thermal resistance dominates so the material of the tubes is not so crucial. Consequently the selection of material should consider cost, availability, strength, non-corrosion, non-toxicity, resistance and durability. One should not forget that the pipes need to support the earth's weight and so need to be tough. Corrugated pipes, although of a stronger structural strength, should be rejected as the corrugation can potentially trap dust and water. Porous materials should also be avoided as water can percolate and cause air quality problems. PVC (polyvinyl chloride which is a common thermoplastic resin) or polypropylene tubes are cheap, easy to install and corrosion resistant and they can perform almost as well as metal tubes (even though, for example, copper has much better thermal transmittance). For larger diameters concrete might be cheaper but it is less suitable from a hygiene point of view. Nevertheless, sustainability issues on the sourcing, manufacturing or disposal of the pipes might also be considered although one has to compare these issues with the long-term benefits in reducing the use of air-conditioning systems and consequently CO_2 emissions to judge their sustainable value. The most common materials used include PVC and concrete.
- Tube diameter: Optimum tube diameter varies depending on choice of materials, cooling necessity, tube costs, tube length, and airflow velocity and volumes required. As observed from the examined articles, diameters vary from 100 to 1000mm and the most common are between 100 and 200mm. Smaller diameter tubes are more effective per unit

area than large tubes because they have more surface to exchange heat per unit volume but this can also increase the costs significantly. They also mean higher friction losses so might need a higher fan power to compensate for the pressure loss.

- Tube length: Optimum tube length varies depending on the local soil conditions, soil moisture, site factors, tube depth and, especially, amount of cooling or heating wanted. There is no known simple formula to determine the proper tube length in relation to the amount of cooling desired. The most common lengths for residential applications are around 25 to 40m and for other buildings lengths vary greatly. Some authors such as Givoni (1994) believe that tubes longer than 15m are unnecessary but one could not state that without considering all the other properties and the long-term use of the system. Due to condensation, longer tubes of smaller diameter can dehumidify better and provide more surface area per unit volume for heat exchange. When the available earth space is restricted, an array of pipe summing to the same length can be used. Florides and Kalogirou found that a typical loop is 35–60m long per kW of heating or cooling capacity (2007: p. 2447).

- Tube depth: The tubes should be buried as deeply as possible. However, there is cost-effectiveness to be considered and rarely is burying them in depths of more than 4m justifiable. Consequently, they should be buried as deeply as is cost-effective and practical and at least 1.5m should be adopted. As observed from examined case studies usually they are buried between 1.5 and 2.5m. Figure 3.1 and Figure 3.2. give some guidance on this for UK applications.

3.4.2 Thermal Properties

- Soil characteristics: Whilst the pipe's conductivity is not so important, soil properties are imperative. EAHEs are likely to be less efficient in hot, humid areas because the ground does not remain sufficiently cool at a reasonable depth during the summer months but this should not be a problem in the UK. The application of EAHEs is ideal in situations where the ground is not too warm, i.e. 12^{o}C or lower at chosen depth and where the ground is easy to excavate. If the soil composition presents too much gravel and rocks, a bed of sand could be made to accommodate the pipes and ensure that its surface is completely surrounded by earth enhancing heat exchange. Being close to ground water could be a desired feature of the site as the flowing water aids heat exchange and the removal of heat from the ground. However, special attention should be given in this case on the selection of material and properly sealing the pipes to avoid the ingress of water.

- Efficiency of the heat transfer: With long term usage of EAHE systems, thermal saturation of the earth surrounding the pipes must be addressed, by means of spacing the pipes, surface landscaping and watering. The earth temperature can be further lowered by shading the surface, mulching it with stone or wood chips or irrigating it to provide moisture for evaporation. Effective control can also address the issue of thermal saturation by allowing enough time between uses for the soil to get back to its original temperature (Mihalakakou, Santamouris et al., 1994). Longer pipe lengths might be considered if the system is likely to be used for long periods of time as the first section of the pipes in contact with the incoming air is likely to get saturated with heat first.

- Heat transfer mechanism: In EAHEs there is both, conductive and convective heat transfer. Because the pipe's material is in constant contact with the soil, which has much larger mass (and consequently much longer time lag as seen in Chapter 2) and small temperature fluctuation, the soil's thermal resistance will dominate. Nevertheless the pipe surface is the contact point between air and soil. As seen in Chapter 2, heat transfer from a surface to a fluid such as air can be difficult. As an EAHE's performance depends on this, it should be enhanced firstly by means of providing enough area for heat exchange and secondly by regulating the air flow to allow for enough residence time for air inside the pipes.

3.4.3 Air Quality

- Microbial growth: The main risk to air quality is the potential of microbial growth in the airway because they can be transported quickly throughout the building. If condensation or ground water leakage occur and water accumulates in the tubes, it might encourage the growth of bacteria. The dark and humid atmosphere inside the tube may also facilitate the growth of odour-producing fungi. Fungal growth is potentially the biggest problem and it is likely to occur. The optimum conditions for microbial development are temperatures above 21^{o}C and relative humidity above 70% but some moulds can grow at subzero temperatures and in relative humidity as low as 45% (Santamouris, Mihalakakou et al., 1995 ; Santamouris and Asimakopoulos, 1996). Filtration can provide defence against fungal spores and micro organisms entering the system and soakaways and pumps can remove water accumulated in the pipes. Access to the system to enable periodical inspections and cleaning are highly desirable.

- Air humidity: In the UK it is an industry standard that relative humidity levels within buildings should be between 40 and 70%. Lower levels than these are thought to cause health problems, mainly with respiratory tracts and eyes (CIBSE, 2006: p.1.4). Dehumidification or humidity control, which is an important part of cooling, is difficult to achieve with EAHEs so mechanical dehumidifiers may be necessary.

- Pollution from soil: It is not sensible to apply the technology to buildings that lie on rocky ground or in areas that are subject to ground pollution from Radon. Radon is a radioactive gas that leaks out of rock and soil and can decay giving off harmful radiation. EAHEs might also be unsuitable for use in buildings that require very precise control of temperature and humidity.

3.4.4 Construction Issues

- Condensation: There is the risk of condensation that could reduce air quality. Condensation is likely to happen mainly during peak summer and autumn in the UK but studies indicate that the risk will not be sustained for long periods and will be reduced by evaporation from the transfer of air through the pipe (Rye, 2005). The tubes should be sloped slightly and have adequate drainage to avoid microbial growth and insure that water build-up inside does not block the passage of air. Pumps could also be used, especially if large amounts of water are likely to get trapped in the pipes.
- Cleaning and maintenance: It is important to consider ways to clean and maintain the system although most of authors do not speak about this aspect. One possibility is to keep the tubes short enough and inclined towards a drain to allow for jet washing. Another is to keep a cord inside the pipes so a towel soaked with a disinfecting solution can be pulled through. In the EAHE described in Chapter 6 a metal basket with a mesh has been left on the entrance of the soakaways with a cord to allow it to be pulled up through the vertical tubes. This should allow for removal of any leaves or insects that might fall in the pipes.
- Inlets and Outlets: The inlets should be screened to prevent insects and small animals from entering the tubes and placed in a shaded spot away from foot traffic. They should be sheltered from rain and could also have an air filtration system to avoid micro organisms from entering the system. The outlets should be in a position that allows easy distribution of the air and protected from dust and foot traffic. A diffuser or lid to allow for system closure when necessary, possibly electronically controlled, is essential. In addition, the lid protects the outlet in the event of house cleaning. Fans could be placed either at the inlet or at the outlet and could also be electronically controlled.
- Fan: The position of the fan (at the inlet or outlet) does not make a big difference in the system's efficiency especially if the system is well sealed. It is important that the fan is appropriately housed and protected from weather and that access is allowed for maintenance purposes.
- Trenches: Health and safety are the main aspects to be taken into account when digging the trenches. The first considerations are type of soil, its water content and trench depth. These allow the risks of collapsing walls to be assessed. The solutions are either to enlarge the trenches making sloped walls, an approach that might mean more excavation and, consequently, greater time and higher costs or to completely assemble the pipes above ground and lower them in the ditch. Before lowering the pipes, it is important to make sure that the base of the trench is ready for them (i.e. no rocks that might perforate the pipes and correctly levelled allowing for the slope). Care should be taken during the backfill of the ditch to ensure that pipes do not collapse. As an example of trench construction, in Chapter 6 the installation of a one-pipe EAHE is described in detail and in Chapter 7 the installation of a commercial system is illustrated.

- Combination with other systems: EAHEs could be combined with natural or mechanical ventilation and/or with other cooling and heating systems. It is important that the designer considers how the delivered air is going to be distributed in the building and so aid the improvement of its internal conditions. Generally, outlets are placed at lower levels, i.e. on the floor, and close to the room's perimeter. If the conditioned air is to be used in other parts of the building then the internal layout should reflect that and allow air circulation horizontally and vertically. Air could also be delivered to the main heating system to allow further heating before entering the room, i.e. in trenches with heat exchangers (example in Chapter 7).

3.4.5 Economics

Although the fans required to pull air through the pipes use considerably less electricity than would be consumed by a conventional air conditioning unit, the economics of EAHEs are usually controversial and sometimes their use is reported as a downside of these systems. This is mainly due to high capital costs and the need to correctly optimise the system to get full advantage of their use.

- Construction costs: The system can be very expensive primarily because of the excavation works. This could be addressed by combining the system with the foundations of the building or extending the digging to accommodate the pipes around the perimeter of the foundation hole. Nonetheless, this might not be enough area and so extra digging should always be considered.
- Material costs: The length and the diameter of the pipes depend on the cooling load of the designed building and the available budget. In terms of material selection, concerns with costs usually surmount concerns with thermal conductivity. When space is restricted an array of pipes can be used and might be more cost-effective but smaller diameter tubes can significantly increase costs. Plastic pipes are usually cheaper but care should be taken to avoid collapse of the pipes. Stronger pipes, such as galvanised steel, might add about 25 to 30% to material costs (Goswami and Biseli, 1993: p.3-4).
- Running costs: The cost of the project, materials, construction, labour and electric power rates to run a fan and maybe a dehumidifier should be addressed carefully and compared against the energy savings in a life cost analysis. Lower air-flow rates are beneficial as they allow for residence time helping to achieve better heat exchange and also meaning cheaper running costs as less power is required for the fan. However this depends on a compromise between other considerations such as pipe length and diameter. If possible the fan should be powered using a renewable source of energy and PVs (photovoltaic cells) are a good option as the availability of solar energy coincides with peak cooling needs (Argiriou, Lykoudis et al., 2004).

- Cooling: In cooling applications it might enable the designer to completely eliminate other forms of air conditioning and so become economically viable (especially in the long run). EAHEs are usually very expensive to build but very cheap to run which is opposite to a normal air conditioning application. As mentioned before, Fjaerem has shown that the Coolhouse system installed in Portugal saved over 33,400kWh of energy and more than €3,300 during the monitoring period which would mean a payback period of under 9 years when compared with conventional cooling system (Fjaerem, 2004: p. 24).

Table 3.2: Comparison of the Coolhouse EAHE against a conventional air-conditiong system (Kennett, 2005)

System	Conventional HVAC	Coolhouse system
Cooling capacity (kW)	2.5	2.5
Electrical load (W)	700	170
Net COP	3.5	14.7
CO_2 emissions for 1000 hours/year (kg carbon/year)	79.1	19.21

- Heating: For heating applications alone EAHEs are usually not feasible because they will not warm the air up to a comfortable temperature therefore requiring additional heating. However, if a system is being installed for cooling purposes then it should also be used in winter to pre-heat the air and aid the main heating system. Gieseler et al (2002) simulated different ventilation systems for low energy houses in Europe and found that, although cost efficiency of heat recovery units is dependent on the climate, these have generally a much better cost efficiency than EAHEs for heating. The efficiency was calculated with an equation similar to Equation 3.4. They reported an investment cost of €40/m (around £36/m at the time this work was completed).

Hollmuller and Lachal's (2001) reported costs of an EAHE installed in a residential and commercial building in Switzerland of 15F/m^3 (£9/m^3) for excavation, 15.3F/m (£9.1/m) for material and laying of pipes and almost ten times higher cost, 135F/m^3 (£90.7/m^3), for refilling (for which concrete was used). They found that air pre-heating with the EAHE was more expensive than any other fuel in every case but cooling was competitive against traditional HVAC systems.

Generally the final system layout will largely depend on available budget. The high capital cost associated with EAHEs is an issue as investors are generally not prepared to invest money for which they will see no return as the end users are the ones who will save in energy bills. However, the more low energy design becomes fashionable, the more systems are likely to be built as they could support the vending of the property.

3.4.6 Commercial Systems in the UK

There is just one system found to be available commercially, although there are some companies that are becoming specialised in designing and installing EAHEs in diverse configurations.

Rehau, a polymer specialist, developed the first commercially available EAHE made of special pipes, named Awadukt, which have their conductivity enhanced and an anti-microbial silver inner layer. Because of that and their inlet columns with coarse or fine filters, the company claims that it is possible not just to save money and energy, but also to improve the air quality in buildings significantly. The pipes have also high longitudinal rigidity, various fittings, and condensation collection and disposal through pumps. Rehau developed the Awadukt thermo pipe's free software to aid the specification of their systems. The Rehau product and software were used in the BASF house described in Chapter 7. More information, software and guidelines on how to install their product can be found on the product's website[36].

Rehau has formed a strategic alliance with ICAX™ Limited, which provides Interseasonal Heat Transfer™ (IHT) for the collection and storage of solar energy for buildings in a wide range of construction projects. There are two types of products derived from this alliance, the Asphalt Solar Collector, which makes use of the great thermal capacity of roads to regulate air temperature and the Thermal Bank, which is a bank of earth used to store heat energy collected in the summer for use in winter to heat buildings. Both products use similar concepts to EAHEs. More information can be found on ICAX's website[37].

Fulcrum Consulting [38] is an international firm of consulting engineers that has been specialising in the design and implementation of EAHEs. One example is a new building for the University of Cambridge's Gonville & Caius College, which provides residences, recreation spaces and conference facilities. The EAHE is made of 800mm corrugated steel ducts, which are installed underneath the underground car park and encased in concrete. The project also has heat exchangers and supplementary heating by electric radiators (Holdsworth, 2004). Unfortunately, no data on the performance of the system was found. Fulcrum has also used ICAX systems a few times.

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[36] www.rehau.co.uk/building.solutions/civil.engineering/ground.heat...geothermal.energy/ awadukt.thermo [Accessed on 25th of April 2009]

[37] www.icax.co.uk/ [Accessed on the 25th of April 2009]

[38] www.fulcrumfirst.com [Accessed on the 25th of April 2009]

Atelier Ten[39] (environmental design consultants and building services engineers) has been implementing EAHEs as labyrinth concrete tunnels in several projects in Europe and Australia. Their first application was on the Planet Earth Galleries for the Earth Centre in Doncaster, UK. No published results were found on their systems. They claim to be also developing a study on the use of EAHEs in big-box retails.

[39] www.atelierten.com [Accessed on 25th of April 2009]

3.5 CONCLUSIONS: BENEFITS, DRAWBACKS AND BARRIERS

EAHEs consist of a pipe or an array of pipes buried horizontally in the ground and through which the outside air is drawn to be conditioned by means of heat exchange with the soil. The ground temperature is dependent on the depth, meteorological influence, thermal and hydraulic ground parameters, and nature of surface and land use.

EAHEs should be treated as a ventilation and air-conditioning system both for costing and control of air quality. Most EAHEs cannot work only by free convection and so there is a need for mechanical ventilation and they are not energy-free. An optimised control for the fan is essential to make the most of the system's capacity but control of temperature is not possible as it derives from the system's parameters. There might also be a need for humidity control.

The systems can be very expensive and budget can limit the performance. The cost of project, materials, construction, labour, and electric power rates to run the fan and humidifier should be addressed carefully. The overall price of an EAHE is one of the most significant drawbacks of this strategy. They are generally expensive to build but cheap to run, which makes them an unappealing solution for investors. Hopefully this will change as low energy design is becoming increasingly attractive for buyers. Usually they compete economically with conventional cooling systems but must be supported by another heating system.

Due to the simplicity of the system and the fact that air is the heat transfer medium, the system is not likely to cause ecological stress, although care should be taken with the digging of the trenches and closure or removal of the pipes. Material selection might consider sustainable issues but these should be compared with the long term benefits of EAHEs.

There is a risk of condensation and/or water ingress in the pipes and consequently potential for microbial growth. Good construction, air filtering and well-designed drainage could eliminate these problems. Maintenance and cleaning should also be considered. The general public might have concerns over the air quality of EAHEs, however, not many people are seen cleaning the ducts of their conventional HVAC systems!

Inlets should be placed in a suitable and sheltered location and have protection against insects and small animals. Outlets should be placed according to the building's ventilation strategy design and should allow for optional complete closure. Discomfort due to high air velocity might occur especially in the heating period. This implies that EAHEs should be an integral part of the building's design and so specified primarily by the architect. This may also mean that the system can be integrated into the earth excavation associated with foundations to reduce cost.

EAHEs may provide up to 100% of a building's cooling need if properly planned. However, to make that possible, firstly a building should be designed under the principles of passive solar design to have only minor cooling loads. If needed, an EAHE can be combined with a second cooling system. During the heating season, the outside air is heated to the ground's temperature and can then be used for frost protection and/or as the air intake of the main heating system saving on energy use. There is a general consensus that EAHEs are not worth considering for heating alone. However, pre-heating of air can be considered a 'free' service if pipes have been installed for cooling. Presence of water in the pipes might lower winter pre-heating capacity but increase the cooling potential of the system.

System performance is generally not well documented and long term data are unavailable. In addition, papers usually do not cover the energy required to run the systems, long-term thermal saturation of the soil, air quality issues or optimisation of controls. No publications on EAHE coupled to British houses were found and very few systems coupled to other British buildings are mentioned and none of their performance data has been published. Chapters 6 and 7 demonstrate the application of two EAHEs to UK houses.

There are many accurate models for predicting the performance of EAHEs, however, these are hardly used in practice as their applicability is restricted by time and skill availability. Although they are useful for showing that EAHEs are a promising technology, they rarely leave the academic environment. Generally EAHEs are just one more component in a building's design and, above all, constrained by physical space and by financial limitations. In practice a designer's main concern is with the size of pipes, number of pipes, their location and whether adding an extra meter is economically reasonable. There is a need for simplified rules of thumb to guide designers in the first stages of a project. The inaccessibility of these models is another major barrier to a wider use of EAHEs.

When specifying an EAHE it is important to keep in mind the quantity of fresh air that the building requires. Cooling capacity of the system might be improved by higher air flow rates but this is not always desirable. During the heating period an EAHE's performance is limited by the minimum quantity of fresh air required only for air quality. That is one of the reasons why these systems are usually better suited for commercial buildings, which have generally higher cooling loads than houses. Forthcoming chapters include a study of other techniques such as phase change materials (PCM) and/or night ventilation and whether they could deal with all summer overheating issues making EAHEs less desirable.

In general, as long as the issue of air quality is addressed, EAHEs coupled to buildings are considered beneficial for the achievement of indoor comfort with a lower energy use for heating and cooling. Furthermore, they are a readily available on-site energy source which does not significantly rely on grid energy supply and can effectively be combined with other systems.

4 USING PHASE CHANGE MATERIALS IN BUILDINGS

This chapter presents the second of the unconventional means of storing and using heat in buildings studied in this work, Phase Change Materials (PCM). It gives an overview of it, covering its main properties and characteristics. The chapter also describes various systems employing PCMs and how those can be beneficial to achieve thermal delight in architecture. This study enabled the study of the houses in the next chapters and the innovative system proposed in this work.

4 USING PHASE CHANGE MATERIALS IN BUILDINGS

Following the previously mentioned rise in temperature caused by climate change and the significant changes that the building sector has been undergoing, shifting towards what potentially could be a larger use of Modern Methods of Construction (MMC) for housing construction, potential overheating issues will be of greater concern.

The energy required to cool down the air temperature by 1^{o}C is generally much higher than the energy required to warm up the same air. Air conditioning use is rising by 8% annually in the UK, despite the fact that 89% of occupants prefer buildings without conventional air conditioning (Littlefair, 2005: p. 11). The traditional HVCA systems based on air as a heat carrier are not just being sidelined for their high energy demand but also because they do not offer satisfying comfort. This is mainly due to draughts and to the lack of relationship between the external climate and the internal space.

Evidently a shift towards the use of systems that integrate radiant comfort should occur. A trend in the market can be observed and water pipes are broadly being used, implanted in floors or ceilings. In general, such systems are not just less energy demanding but also assure more comfort as they work by radiation instead of convection, thus being better accepted by users. Another option is the use of thermal mass which, coupled with natural ventilation, can reduce the peak internal temperature by nearly 5^{o}C (CIBSE, 2005: p. 6).

As described before in Chapter 1, MMC buildings tend to be highly insulated and almost air-tight. Consequently the heat flow through the envelope is practically eliminated and the walls are almost adiabatic. This construction method allows for high performance levels with a reduced use of material so the thermal storage capacity is relatively smaller than traditional construction. However, there is still a need for the use of thermal mass to avoid overheating problems and to improve winter internal conditions. With the most important advantages of MMC being the reduced use of materials, the possibility of reuse and recycling of components and the lightness of the structure, the integration of thermal mass, which is obtained usually through heavy elements, can be problematical as those would defeat the benefits of MMC.

The basic idea behind using Phase Change Materials (PCM) in the building's envelope is to integrate thermal mass in dry assembled light structures without adding unnecessary weight to the construction. PCMs are materials, such as salts or paraffin, that undergo a phase change process by reordering its microstructure resulting in the storage or release of latent heat. The melting temperature can be adjusted as necessity. If PCM is made to store heat at a useful temperature it will maintain that temperature level until the whole phase change process has taken place so reducing ambient overheating or cooling. Therefore, a sort of programmable inertia can be achieved by regulating the melting temperature and the quantity of PCM in the building. This process and its influence in regulating a space's temperature are explained in detail in this chapter. This chapter also includes a description of available PCMs and a brief summary of relevant published systems.

4.1 FUNDAMENTALS OF PHASE CHANGE MATERIALS

Sensible and latent heat (cartoon made exclusively by Weikai Gong for the author)

The use of thermal mass is regarded by some as essential to manage internal temperature peaks and its cycles. A building with thermal storage could diminish and shift most of the cooling and heating loads, changing it from peak to off-peak periods allowing for energy savings.

Heat that results in a temperature change is called sensible heat implying a heat that can be sensed. If an object's temperature rises as heat is added or falls as heat is removed then the heat that causes the changes is called sensible. Objects have a heat capacity whilst materials have a specific heat capacity, which is the amount of heat required to change a unit of mass of a substance by one unit of temperature (Bird and Ross, 2002: p. 212, 213). Generally the term thermal mass is used for any material that is capable of storing heat. The materials commonly used in constructions as thermal mass have the capacity of storing sensible heat. Several materials can be used for sensible heat storage in buildings i.e. concrete, adobe, stone and bricks.

Latent heat is the amount of energy in the form of heat released or absorbed by a substance during a change of state. All pure substances are able to change their state for example from solid to liquid or from liquid to gas. In order for the change to happen, energy must be either supplied or taken away to break the molecular attractions between the constituent particles of a substance allowing it to change its state. This energy, usually in the form of heat, must be supplied or removed externally and does not cause a change in the substance's temperature and so is called latent heat meaning a 'hidden' heat (Bird and Ross, 2002: p. 214, 215). Latent heat provides much higher storage capacity at a smaller temperature difference and this can be demonstrated using water as an example.

When we put ice in our drinks we are not just making use of sensible heat exchange, we are making use of water as a PCM. As the ice melts it absorbs heat from its environment; as it solidifies in the freezer compartment, it releases heat into it. To change its phase water uses heat energy to break or form its hydrogen bonds.

Figure 4.1 below shows a simplified diagram of the molecular structure of the water in its different phases. As ice, water has an 'organised' structure, which gives it its geometric look we see in snowflakes. Every slightly negatively charged molecule of oxygen is able to connect to two positive molecules of hydrogen. Once some of these hydrogen bonds are broken by heat energy, the ice melts and liquid water is able to adapt to any shape by simply breaking and reconnecting the bonds in a less organised manner (White, Harrison et al., 1992: p. 125-126). If more heat energy is put into the system, more bonds are broken and the molecules can move freely, forming water vapour. During the fusion, evaporation, condensation or solidification process, the temperature of the water is kept constant while a heat is being absorbed or released (Bird and Ross, 2002: p. 215).

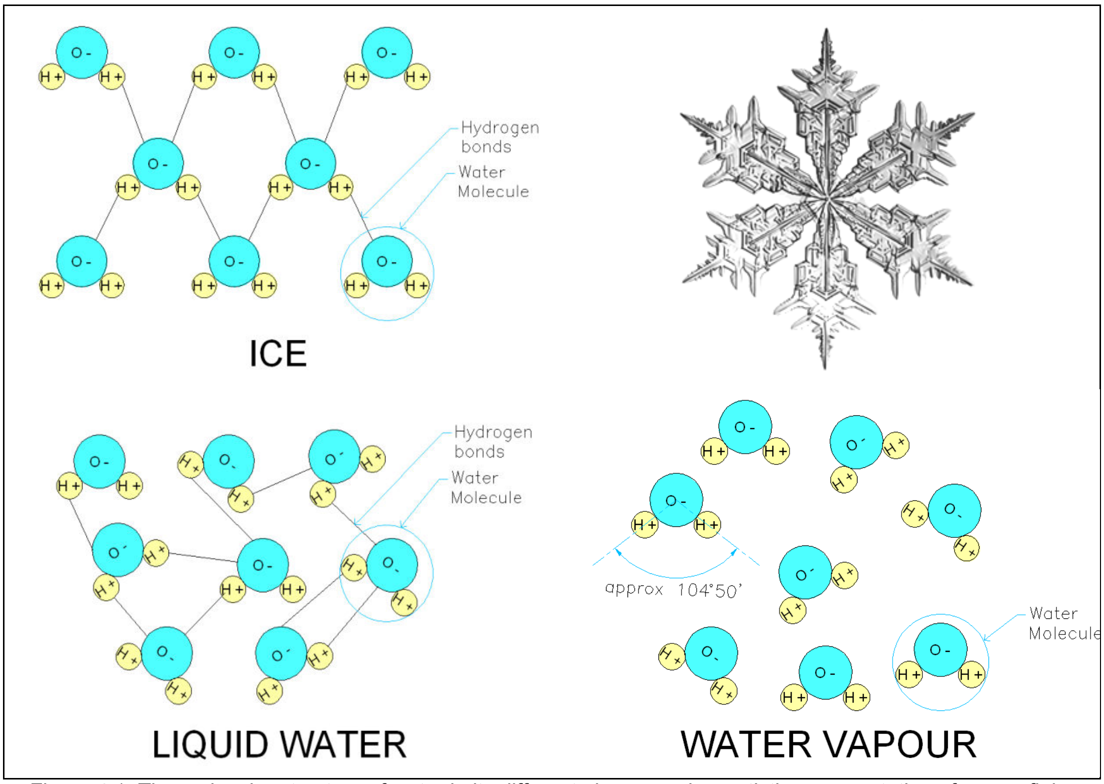


Figure 4.1: The molecular structure of water in its different phases and an artistic representation of a snowflake

The amount of heat is needed to cause the change is defined by the specific latent heat capacity. It was mentioned in Chapter 2 that specific heat capacity is the quantity of energy needed to produce a temperature change in a mass of material and its units are J/kgºC. Specific latent heat is the quantity of heat energy required to change the state of a unit mass of a substance, in J/kg (Bird and Ross, 2002: p. 215). A summary of the thermophysical properties of water can be seen in Table 4.1 below.

Table 4.1: Thermophysical properties of water (Bird and Ross, 2002: p. 213-217)

Specific heat capacity water at 25°C (approximated)	4.2 kJ/kg °C
Specific heat capacity ice at -10°C (approximated)	2.1 kJ/kg °C
Specific heat capacity water vapour at 100°C (approximated)	2.0 kJ/kg °C
Latent heat of fusion (approximated)	335 kJ/kg
Latent heat of evaporation (approximated)	2260 kJ/kg

The specific heat capacity of water is much smaller than its latent heat. For example, water at its normal boiling point of 100 ºC has a specific latent heat of vaporization of 2260kJ/kg but its specific heat capacity as a liquid and as vapour are only 4.2 and 2.0kJ/kgºC respectively. This means that to convert 1kg of water at 100ºC to 1kg of vapour at 100ºC, 2260kJ of heat is necessary which will be absorbed by the water. However, to heat up 1kg of liquid water by 100°C only 420kJ is needed. This is graphically represented in Figure 4.2 below.

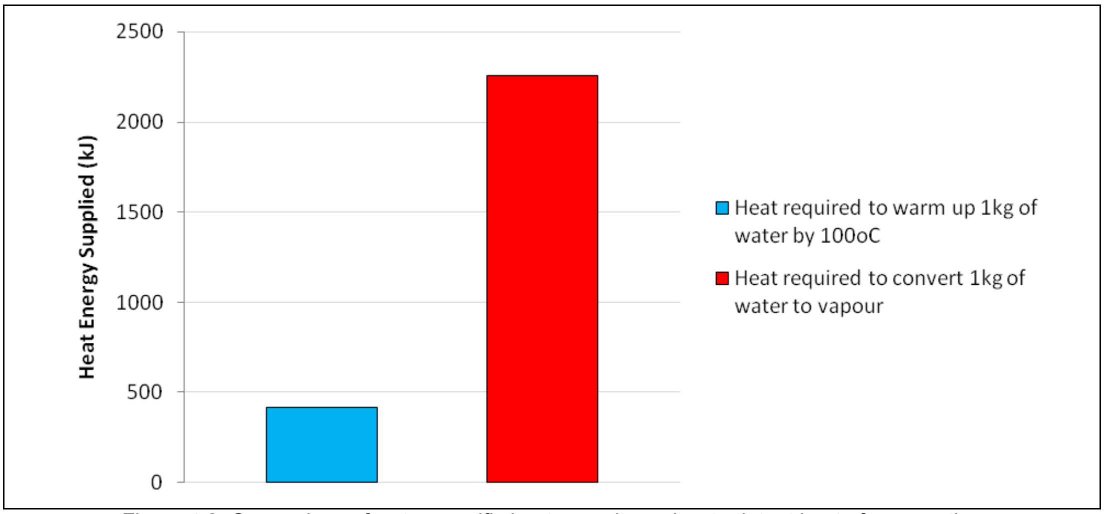


Figure 4.2: Comparison of water specific heat capacity and water latent heat of evaporation

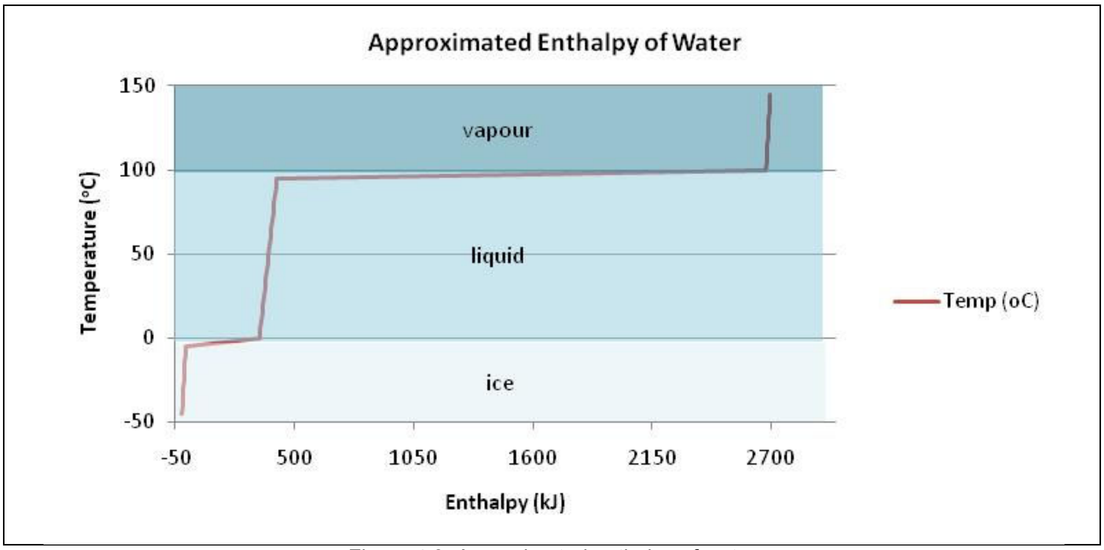


Figure 4.3: Approximated enthalpy of water

In Figure 4.3 it can be seen that during the change of phase, water absorbs and releases large amounts of heat almost without any change in temperature. As a solid, liquid or gas, water still absorbs and releases sensible heat but in much smaller amounts. That is why latent heat is potentially a much more efficient means to store heat.

Traditional building materials use sensible heat for energy storage. The sensible heat capacity of a material can be calculated using Equation 2.9 as demonstrated previously. In phase change materials, the sensible heat is augmented by the latent heat as defined by the following equation:

Equation 4.1: Quantity of energy summing sensible and latent heat

$$Q = mc\Delta T + m\Delta h_{fusion/evaporation}$$

Where:
Q = quantity of energy input/output (kW)
m= mass of material (kg)
c= specific heat capacity of material (kJ/kg^{o}C)
ΔT= temperature difference (^{o}C)
$\Delta h_{fusion/evaporation}$= specific latent enthalpy (kJ/kg)

A main issue with using latent heat in any application is how to increase its heat transfer with the surroundings. For example, our bodies use the evaporation of water to cool us down and we do so through our most extensive organ, the skin. The process of sweating happens through the exposure of water on our large skin surface allowing the departing molecules of vapour to take heat with them. By blowing additional air across your skin the effect of sweating can be enhanced preventing any build-up of humid air near its surface. The same concept using water can be used in building applications in systems that employ evaporative cooling. Unfortunately, due to various reasons to do with some of its properties (particularly its phase change temperature), water cannot be used as a PCM in building envelopes.

The application of PCMs to provide means of thermal storage has been practiced for many years for example, by using ice as a thermal storage for retaining items at a constant low temperature. Even in ancient times ice houses were built incorporating large blocks of ice cut from frozen rivers in the winter season and protected with sawdust insulation to for use in the spring periods. The food industry has also been using PCM based products for many years to maintain products at a controlled low temperature during transportation and storage. Frozen low temperature melting salts have also been used within plastic containers by the pharmaceutical and the hospital industries to keep chemicals and medicines at a controlled temperature. However, to be implemented in buildings, PCMs have to have ideal characteristics which are described in the next section.

4.2 PROPERTIES, CLASSIFICATIONS AND CONTAINMENT

As illustrated in the previous sections, PCMs are ordinary pure substances we may see and touch everyday such as water, fats or salts. In order to classify the different types and evaluate the possibilities of their use, one has to look into their properties in detail. Some of these properties make several PCMs unsuitable for any known application and in particular for building systems with the purpose of improving human comfort, which is in itself very limited. A few problems can be overcome by means of containing the PCM in an appropriate envelope thus shielding it from the environment. This section describes these issues in detail.

4.2.1 Desirable PCM Properties for Building Applications

It was demonstrated above in Equation 4.1 that, in order to characterize a phase change material, one has to identify its specific latent heat of fusion and its specific latent heat of vaporization in addition to defining the temperature range over which the change of phase happens. These are probably the first and most obvious desirable properties of a PCM for any application: it should match your requirements in terms of quantity of heat and desirable temperature. (Farid, Khudhair et al., 2004)

Consequently not all PCMs can be used for thermal storage in construction. Many researchers have investigated the use of PCMs in buildings. In their reviews of thermal storage in buildings, authors (Farid, Khudhair et al., 2004 ; Khudhair and Farid, 2004: p. 1150; Tyagi and Buddhi, 2007: p. 1151-1152; Sharma, Tyagi et al., 2009: p. 322) recommend that the following properties are considered:

1. Thermal properties

- Suitable phase-transition temperature of the PCM to match the operating temperature of the system and/or building.
- High latent heat of transition per unit volume to reduce the required physical size.
- High thermal conductivity of all phases to assist the charging and discharging of heat.

2. Physical properties

- Favourable phase equilibrium for a constant storage capacity of the material with each freezing/melting or vaporisation/ liquidification cycle
- High density to allow for smaller containers.

- Small volume change on phase transformation to avoid containment problems. Most of PCMs undergo variations of more than 10% in volume during fusion (Farid, Khudhair et al., 2004).
- Low vapour pressure at operating temperature to reduce the containment problem.

3. Kinetic properties

- High nucleation rate to avoid super cooling of the liquid phase that might happen if the melting point is well above the solidification point.
- Sufficient crystallization rate when freezing so that the system can meet demand of heat recovery from the storage system.

4. Chemical properties

- Completely reversible freezing and melting cycle, no degradation by loss of water or chemical decomposition.
- Capacity of uncountable number of freezing and melting cycles for a long lifespan.
- No corrosion effect on construction materials for easy assembly and use.
- Non- toxic, non-flammable and no non-explosive for safety.
- Long-term chemical stability and no segregation (i.e. grouping around the envelope edges) for stable performance throughout the phase change cycles so no thermodynamic properties are affected during its lifespan.

5. Economics

- Abundance and large scale availability.
- Cost effectiveness.

In addition to the above characteristics, this work proposes that the following should also be considered:

- Ecologically harmless, it should cause no adverse effects on plants, animals or micro-organisms during sourcing, manufacturing or disposal.
- Recyclability.
- Easy handling and ability to accept finishing.
- Low maintenance if any and easiness to clean if exposed.
- Compatible aesthetic properties such as crystallinity or opacity might be desirable.

It is outside the scope of this thesis to study these characteristics so it is suggested that a new study could be developed as part of further work.

4.2.2 Classification of PCMs

There are large numbers of PCMs with fusion and solidification at a wide range of temperatures, making them attractive in a number of different applications. They are generally divided into organic, inorganic and eutectic (Tyagi and Buddhi, 2007: p. 1151-1152; Pasupathy, Velraj et al., 2008: p. 43-44; Sharma, Tyagi et al., 2009: p.323) as summarised below:

1. Organic compounds: paraffin and fatty acids

    - Chemically stable, non-corrosive, high latent heat and low vapour pressure.
    - Flammable, high changes in volume and low conductivity.

2. Inorganic compounds: salt hydrates and metallics

    - Higher latent heat per unit volume, high thermal conductivity, lower in cost and non-flammable.
    - Corrosive to most metals, supercooling and decomposition can affect their phase change properties thus use of nucleating and thickening agents to minimize these problems is recommended (Etheridge, Murphy et al., 2006).

3. Eutectics: two or more components

    - The components melt and solidify congruently to enhance a certain PCM property and/or minimise another.
    - Can be organic-organic, organic-inorganic and inorganic-inorganic.

Comprehensive lists of most possible PCMs in all categories can be found in Farid et al. (2004: p. 1600-1604; 2007: p. 1151-1152; 2009: p. 323-327) Tyagi et al. (2007: p. 1151-1152) and Sharma et al. (2009: p. 323-327). These sources also include extensive lists of references of published applications and PCM suppliers. A list of possible candidates for application in buildings can also be found at Khudhair et al. (2004: p. 265).

The three principal PCMs investigated for use in building envelopes, usually in the form of phase change wallboards, are fatty acids, paraffins and salt hydrates because of their suitable phase-transition temperature (Figure 4.4). Fatty acids come from meat by-products and vegetables. They are cheap, renewable, non-corrosive and readily available. Different types of fatty acids have different melting points. Fatty acids can be incorporated into wallboards by immersion or encapsulation (discussed in the next session) and have similar heat and stability characteristics to paraffins. Paraffins are waxes that are widely available, inexpensive, and that have different phase-transition temperatures according to their carbon-chain length (Sharma, Tyagi et al., 2009: p. 323). Generally only ultra-pure paraffins melt and freeze sharply at a given temperature. Generally, like other PCMs, they present a region of temperatures where the change of phase takes place. Like fatty acids, paraffins can be incorporated into wallboards by direct immersion or by encapsulation and adding it to the board's mixture during the manufacturing process. Potential problems with all organic PCMs relate to the fact that they will continue to burn in normal atmospheric conditions after igniting and so present fire hazards.

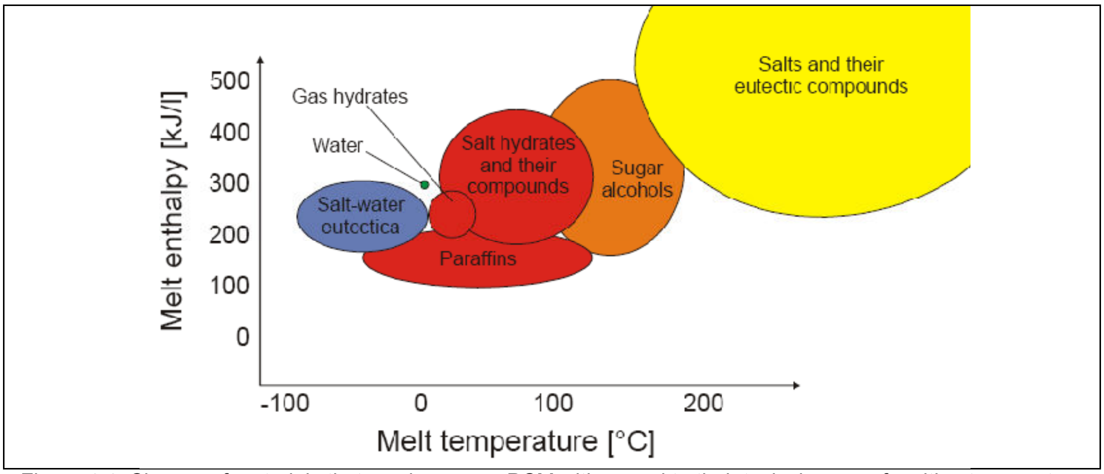


Figure 4.4: Classes of materials that can be use as PCM with regard to their typical range of melting temperature and melting enthalpy (Mehling, 2001)

Salt hydrates are crystalline solids made of inorganic salts and water. The solid-liquid transformation is actually a dehydration-hydration of the salt, which is similar to the thermodynamic process of solidifying-melting. This might cause incongruent melting and settling of salts at the bottom of the container. They might also present supercooling of the liquid before crystallization begins. Salt hydrates are nevertheless the most important group of PCMs because of their high latent heat of fusion per unit volume, high thermal conductivity and small volume changes (Sharma, Tyagi et al., 2009: p. 325). Many PCM applications commonly use salt hydrates but they tend to absorb moisture, which decreases their effectiveness. In order to improve their performance, salt hydrates might require costly and impractical encapsulation.

Unfortunately low cost materials tend to require the largest storage volume per unit of heat stored. Smaller storage PCMs are generally more expensive and require encapsulation due to corrosion, toxicity or changes in the volume during the phase change.

4.2.3 Containment of PCMs

Some of the problems described above can be overcome by means of containing the PCM in a suitable way. Therefore encapsulation and composite materials are a key issue in PCM technology. Various techniques have been developed to allow simple and effective solutions for the integration of PCMs into a building fabric. The main techniques are direct immersion, macroencapsulation and microencapsulation, which are explained below.

Direct immersion is the simplest and cheapest way of making PCM elements for buildings, such as wallboards. However, to produce mass scale PCM immersed wallboards, manufactures would have to implement major changes in factories. The time of immersion varies depending on the amount of desired PCM and the immersed element becomes water-resistant. In this process, leakage could be one of the main problems as the material in the liquid phase could flow away from the location where it is applied. Another problem is fire hazard as many PCMs are flammable. This could be overcome by fire-retardant treatments (Khudhair and Farid, 2004 p. 273).

Rozanna et al. (2005) tried to immerse a gypsum board for 1 hour in a fatty acid PCM. They found that the board absorbed enough PCM to acquire similar thermal properties to those of the PCM and the physical characteristics of the board remained unchanged. They concluded that further study with a suitable insulator to avoid damaging of the PCM should be carried out. Khudhair and Farid (2004 p. 269-270) describe different ways of impregnating concrete with PCMs and give extensive references regarding this subject.

Encapsulated PCM is easier to employ as it should not adversely affect the function of the construction material. In macroencapsulation, the most common form of encapsulation, containments used are usually larger than 1 cm in diameter. Macroencapsulation holds the liquid preventing it from escaping, facilitating handling and reducing external volume changes. Furthermore, it promotes a barrier to protect the PCM from being contaminated by the environment improving the material’s compatibility with the surroundings. However, not all macroencapsulated PCMs presented good results, especially due to poor conductivity and solidification of the PCM around the edges preventing effective heat transfer (Farid, Khudhair et al., 2004 p. 1605-1606; Khudhair and Farid, 2004 p. 271-273; Pasupathy, Velraj et al., 2008 p. 47)

This effect does not affect microencapsulated PCM as the dimensions are very small: usually containers smaller than 1 mm in diameter. It is quite a recent form of PCM encapsulation and serves the same purpose as macroencapsulation. Additionally it improves the heat transfer to the surroundings through its large surface to volume ratio, improves cycling stability since phase separation is restricted to microscopic distances and prevents damage to the parent material as the capsules are microscopic (Farid, Khudhair et al., 2004 p. 1605-1606; Khudhair and Farid, 2004 p. 271-273; Pasupathy, Velraj et al., 2008 p. 47).

Through the research C-TIDE (Changeable Thermal Inertia Dry Enclosures), Imperadori, Masera et al. (2006) developed a PCM blanket prototyping a specific packaging system based on 8 x 4 cm aluminium pouches. The blanket was sandwiched between plasterboard and the results of the work were deemed satisfactory. The installation of the prototype blanket can be seen in Figure 4.5 below. Other examples of macro and micro encapsulated PCM can be seen in Figure 4.6 below.

Typically the PCM is mixed with other substances in order to improve one or more of the PCM properties by, for example, facilitating the handling, improving the cycling stability or improving the heat transfer, through the addition of materials with large thermal conductivity. Encapsulation and mixing with other substances allow the PCM to be incorporated simply and economically into conventional construction materials as described in the next chapter.

Figure 4.5: Example of macroencapsulated PCM being installed in a building (Imperadori, Masera et al., 2006: p. 4)

Figure 4.6: Examples of PCM in its different forms provided by the company Phase Change Material Products Limited (Source: PCM Products Website)[40]

[40] www.pcmproducts.net/PlusICEvariations.pdf [Accessed on the 23rd of February 2009]

4.3 PCMS IN THE BUILDING ENVELOPE

PCMs have been widely used in latent heat thermal storage systems for heat pumps, solar water-heating systems, solar cookers, greenhouses and spacecraft thermal control applications, but the use of PCMs in building envelopes was rare until the past decade although actively considered since the 1980s (Sharma, Tyagi et al., 2009: p. 333).

Latent heat storage through phase change materials is a concept that is potentially interesting for lightweight building construction. Unlike sensible heat storage, latent heat storage provides much higher storage density, with a smaller temperature difference between storing and releasing heat consequently being much more efficient in terms of volume and weight. The sensible heat capacity of the building envelope can be summed to or substituted by the latent heat capacity as shown in Equation 4.1.

As cited in section 4.2.2, the three principal PCMs investigated for use in building envelopes are salt hydrates, fatty acids and paraffins. The most common format is PCM wallboards as they are usually the easiest to install in new as well as retrofit constructions and can simply replace the existing wallboards. Nevertheless, incorporating this additional heat storage capacity into the building fabric has been explored in various configurations by many researchers as will be described below.

The way the PCM is applied in the project is critical for its performance. Availability of PCM should match the demand with respect to time and to power. For example, the designer needs to carefully consider how much excess heat that the PCM needs to absorb, when the peak heat happens and if the time of discharge is short enough to be effective before the next cycle happens.

PCMs can only store energy and cannot remove it from a space, which might become an issue especially in highly insulated envelopes. The heat is released back to the room when the air temperature falls below the phase change temperature and the surfaces containing PCM are kept at a high temperature for a long period of time. It has been reported by many authors before that latent thermal storage only performs well if the storage is cyclically being discharged. If the discharge cannot be done by natural means (i.e. natural drop in temperature or night time ventilation) then mechanical cooling sources may be used (Bruno, 2005: p. 27; Etheridge, Murphy et al., 2006: p. 28).

Night time ventilation with thermal storage is already a recognized technique. Most of the existing systems use a heavy weight structure for thermal storage but some using PCM can be found in literature. The majority of the existing systems using PCM rely on the night cooling to solidify the PCM that was charged with heat on a daily cycle.

As mentioned, besides passive applications, PCM could be coupled with a mechanical cooling device to induce the heat discharge. If that discharge can be continuously controlled then the heat can be released to the outside rather than back into the conditioned space. Based on this, an innovative system is proposed in Chapter 8 of this thesis.

Most PCMs have poor thermal conductivity. The PCM behaves as a solid most of the time so conduction is nearly the only heat transfer mechanism. Consequently, the main problem is achieving sufficient heat transfer between fluid (i.e. air) and PCM (Turnpenny, Etheridge et al., 2000 ; Bruno, 2005: p. 27-28). This can be partially compensated by the provision of large surface areas of the heat storage material and by adopting means to improve the thermal transfer (for example by adding a material with large thermal conductivity to the mixture). There are some examples where PCM was attached directly to heat exchangers or heat pipes (Turnpenny, Etheridge et al., 2000 ; Turnpenny, Etheridge et al., 2001).

A major advantage of PCMs in the envelope is that, since storage occurs inside the space where the load occurs, there are no losses or costs due to transport of energy. That, in addition to the shift in peak time, can have significant impact on the utility supply and may contribute not just to energy savings but also to grid reliability and the development of dynamic and smart energy grids (modernized electricity networks promoted by the government).

Essentially there are three different ways to use PCMs for heating and cooling of buildings (Mehling, Hiebler et al., 2002: p. 1; Zhang, Zhou et al., 2007: p. 2202, 2203): passively, coupled with active heating or coupled with active cooling. It can be incorporated in walls, floors and roofs making use of their large surface areas or in separated heat/cold stores (Figure 4.7). Only references that used PCM incorporated in building structural elements (rather than in separated stores) were studied for this work. Those were divided as described in the following section.

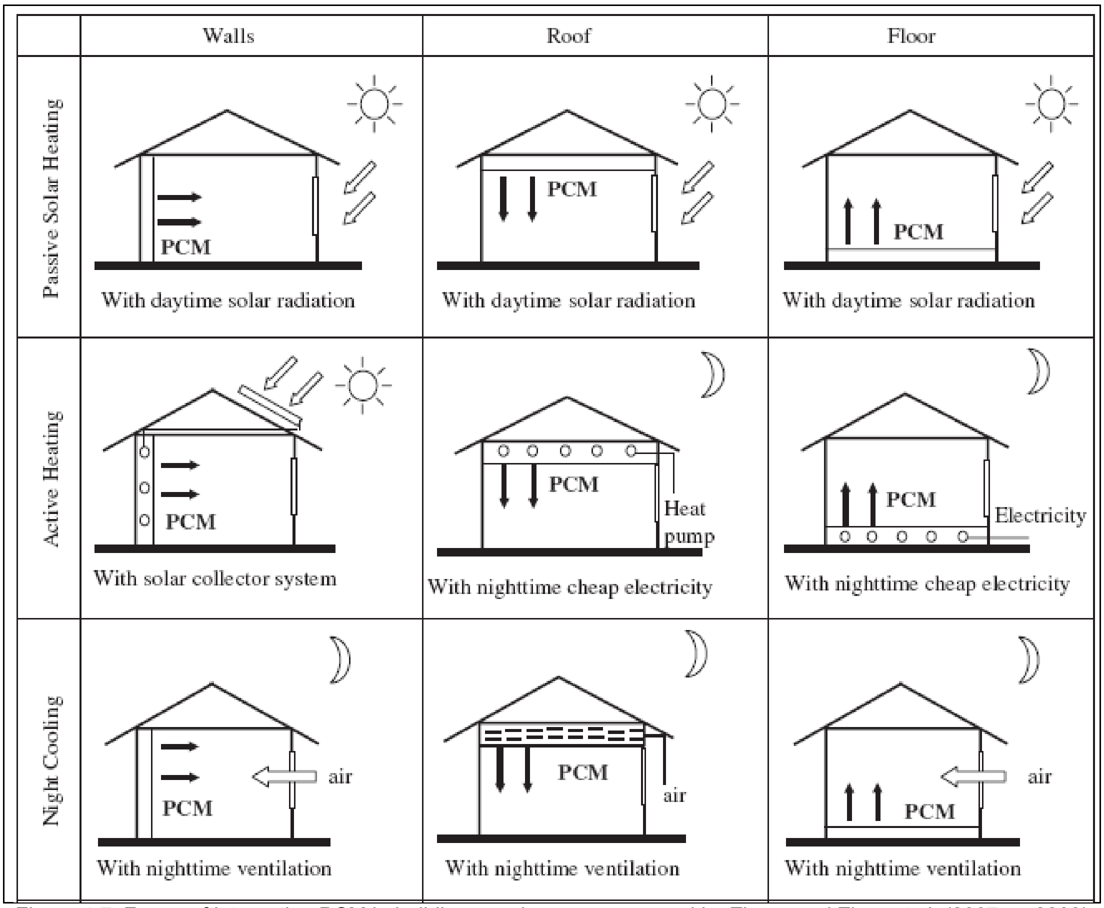


Figure 4.7: Forms of integrating PCM in building envelopes as proposed by Zhang and Zhou et al. (2007: p. 2203)

4.3.1 PCM in Different Parts of the Building Envelope

Although many research projects have studied the incorporation of PCM in building structure, especially to improve the comfort of lightweight buildings, most of them turned out to have drawbacks due to macroencapsulation or direct immersion. Microencasulated PCM is still a relatively new product; it should become increasingly accessible and make PCM products accessible for a wider audience. Some commercial products are detailed in the next chapter. As the largest exposed surfaces in a building are its walls, floors and roof, they are the preferred positions for PCM integration.

Carter (1981) used a computer model to compare two PCMs with different phase change temperatures (21 and 27^{o}C) incorporated in different parts of the structure of a passive solar building in the cold and mild climate of Canada. The work investigated how long the solar energy collected could meet the building's demands and how much PCM would be needed. It concluded that, as PCM will operate best if kept at its phase change temperature for maximum period of time, solar radiation should be channelled to act directly on the heat storage medium and also that high phase change temperatures might lead to overheating while low phase change temperatures may require impractically large surfaces. The work also highlights that in places with mild winters and low availability of solar radiation (such as the UK) materials with PCMs that have their change of phase just slightly above the desired room temperature work best.

Castellón and Nogués et al. (year unknown) investigated the inclusion of microencapsulated PCM, melting point of 26ºC, in concrete and tested by building 2 equal cubicles. The first one was made using PCM concrete in 2 walls and the roof and the other using regular concrete. The experiment showed that the maximum temperature in the wall with PCM appeared about 2 hours later than in the one without PCM and its temperature was usually 2 to 3^{o}C lower.

As shown in Figure 4.5, as part of the C-TIDE project, Imperadori and Masera et al. (2006) tested a prototype of a 'PCM blanket' made of aluminium pouches containing PCM which could be installed either on the floor or walls. The tests were concerned with the ease of installation of the product in an internal wall, its effectiveness and the implications of sandwiching it within regular plasterboards. The results were satisfactory as peak temperatures and energy consumption were reduced. The same PCM blanket was combined with an underfloor water piping system and installed in a test box by Principi and Di Perna et al. (2005). The water was used to discharge the PCM of heat, which activated the solidifying process and could potentially be used to charge it with heat in winter. The system was found to be an effective solution to reduce overheating in summer.

As part of the same project, three experimental boxes were built in Ancona, Italy, with and without salt hydrates (melting temperature of 32^{o}C) on their south facing wall. The salt was packed in aluminium pouches that were then sandwiched between 2 aluminium sheets forming a sort of a tile. The biggest difference between this experiment and the others is that this time the PCM was placed outside the wall, between the insulation and the external finishing, acting as a shield to solar radiation. The first box was without PCM, second with PCM and third with PCM and a ventilated air gap before the finishing. The main objective here was to determine the heat flux on the PCM wall which was found to be up to 50% lower proving the potential of the PCM to reduce energy consumption. Another finding was that the air gap was not essential as it did not considerably improve the results (Principi, Di Perna et al., 2005).

4.3.2 PCM Wallboards

Shilei, Neng and Guohui (Shilei, Neng et al., 2006 ; 2007) proposed an experiment in China to evaluate the benefits of wallboards immersed for 6 to 10 minutes in fatty acids. The PCM became 26% of the total weight of the board and had a phase change temperature around 18^{o}C and a latent heat capacity around 37 to 19J/g. The PCM boards were installed in a test room and tested over 6 days. They were successful in flattening the indoor temperature fluctuation even in winter and helped to reduce the need for electric power.

Neeper (2000) has drawn important conclusions from an extensive examination of the diurnal temperature variation of a room temperature with PCM wallboards that did not receive direct solar radiation. His first finding is that the maximum diurnal energy storage occurs at a value of the PCM transition temperature that is close to the average room temperature in most conditions. He has also found that diurnal energy storage decreases if the PCM does not have a sharp transition temperature and that even if the wallboard has a greater latent capacity, the diurnal storage achieved in practice may be limited to the range 300 to 400 kJ/m^2. He suggested that wallboards with $400kJ/m^2$ latent capacity can be comparable to exposed masonry in all internal surfaces.

Plasterboards with integrated microencapsulated paraffin (phase change temperature range of 25 to 28^oC) were studied by Voelker and Kornadt et al. (2008) by means of experimentation in 2 test rooms, one having conventional plasterboard. These were built of lightweight materials and had a large glazed facade ratio in Weimar, Germany. Reduction of peak temperature of 4K was observed and it was proven that the PCM loses its heat storage capacity after a few hot days if they cannot be discharged by additional ventilation.

Feustel and Stetiu (1997) have largely investigated the potential of double PCM wallboards in California which were proven effective in reducing the room's air temperature. However, they concluded that cooling the PCM by convection in the room's space only is very inefficient as the amount of air movement close to the walls is relatively small. The work suggests that, especially in periods of fairly warm nights, it would be beneficial to force the air supply along the wall's surfaces and that new ways of doing this should be investigated. In another work (Stetiu and Feustel, 1998) they coupled PCM wallboards with mechanical night ventilation which successfully provided the prospect of air-conditioning system downsizing. Nonetheless they found that in climates where outside temperature remains above 18^oC at night "the use of PCM wallboard should be coupled with discharge mechanisms other than mechanical night ventilation with outside air". These conclusions strongly support the system to be proposed in Chapter 8 of this work.

4.3.3 PCM in Ceilings

Ceilings are one of the best positions to incorporate PCM in a building for three reasons. Firstly the ceiling is likely to be the most exposed surface in the space as the walls and floors are usually sheltered by furnishings and other fittings. Secondly, as the warm air rises, the ceiling is more exposed to higher temperatures that might aid heat transfer. Thirdly, air ducts and other services are usually located above the ceiling leaving space to retrofit systems.

A passive double layered PCM ceiling was studied theoretically and experimentally by Pasupathy and Velraj et al. (2008). The panels are made of steel filled with a salt hydrate and installed on the top of a concrete slab and below the roof. The system was firstly analysed using mathematical modelling and then tested using test rooms in Chennai, India. It is found to be successful in reducing temperature swings even though it did not work throughout the year as in summer the room temperatures were above the phase change temperature for most of the time.

Koschenz and Lehmann (2004) proposed a ceiling panel made of microencapsulated paraffin mixed with gypsum and water pipes in a metal tray that is suitable for retrofit as well as new construction. The focus was on maximising heat storage while minimising the panel's thickness. A numerical model was used to determine the required properties of the system, a prototype was built and tested and a pilot application was envisaged. The results showed that a 5cm-thick panel was able to maintain a comfortable room temperature. The potential fire hazard was a problem left unsolved in this work. Figure 4.8 shows schematic drawings of the system.

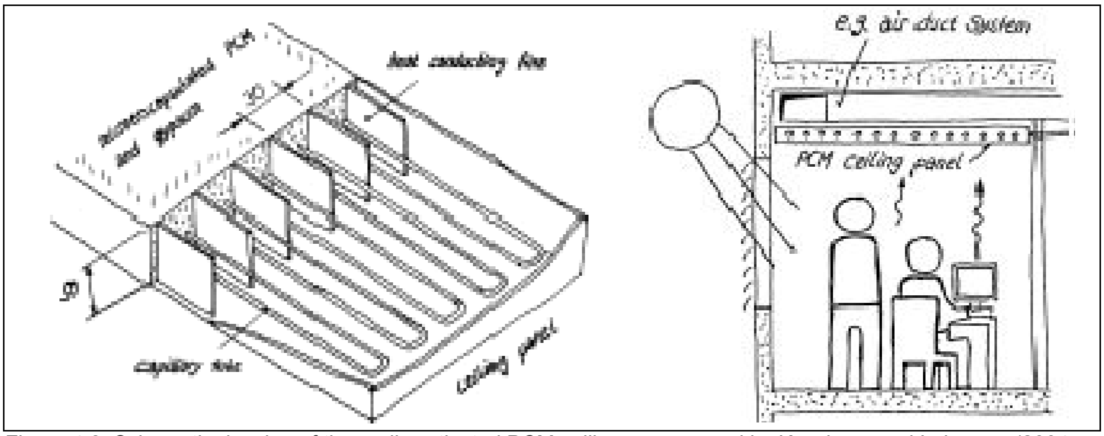


Figure 4.8: Schematic drawing of thermally activated PCM ceiling as proposed by Koschenz and Lehmann (2004: p. 568, 569)

Turnpenny and Etheridge (2000 ; 2001) proposed an innovative system using PCM (melting around 24.5±27.8°C and freezing at approximately 23.8°C) and heat pipes to reduce the need for air-conditioning. The system was installed in a ceiling void, had the aid of a fan to improve heat exchange and can be retrofitted in existing buildings. In the first paper they proposed a model that, despite over predicting heat transfer rate, predicted temperature accurately and established the viability of the system. In the second paper they demonstrate that an installed prototype was able to prevent overheating in the UK offering cost savings and reduction of CO_2 emissions. Yanbing and Yi et. al. (2003) also proposed a fan assisted PCM (phase change temperatures around 22-25°C) ceiling system which is discharged by night time ventilation. The experiments, in agreement with the mathematical modelling, showed that the system could significantly improve the comfort level of the indoor environment.

In order to overcome overheating issues in the Stevenage Borough Council Offices in Stevenage, UK, the consultancy company Faber Maunsell has suggested, through the REVIVAL project that they install PCM salt hydrate contained in flat pouches in the existing ceiling voids (a system later named Cooldeck). Exposing the building's existing thermal mass was not an option for various reasons and the strategy was combined with others such as shading devices. In summer nights, a window fan pulls outside cool air and a ceiling fan causes turbulence aiding the heat transfer between the space and the PCM, which changes phase at 20-24^{o}C. In the day the process is reversed. Monitoring indicates that a reduction in the region of 5^{o}C in internal temperatures has been achieved relative to ambient temperatures (Barnard, year unknown). Detailed monitoring of the installations is being undertaken as part of the European REVIVAL project. Although there are hints that the system is commercially available, no indications of that were found by the time this work was finished.

4.3.4 PCM in Floors and in Underfloor Heating

Sponsored by an agency from the United States Government, Hittle (2002) made prototypes of floor tiles with different PCMs replacing the quartz powder usually used in the tile's recipe. This first evaluation of the tiles in a passive application was very promising and concluded that encapsulated wax was the best PCM for this purpose achieving an annual heating saving of 24%. Zhang and Xu et al. (2006) have also experimented with a passive application of paraffin in shape-stabilised floor plates. The comparison between this and another room without PCM showed an obvious reduction of the temperature swing in the former.

Schümann Sasol's energy storage technology division, Rubitherm, has developed an innovative PCM underfloor heating (Figure 4.9) which allows high heat storage capacity in a thin layer (Field, year unknown; Tyagi and Buddhi, 2007). Their first application in 25 German houses was so effective that the concept is now widely spread.

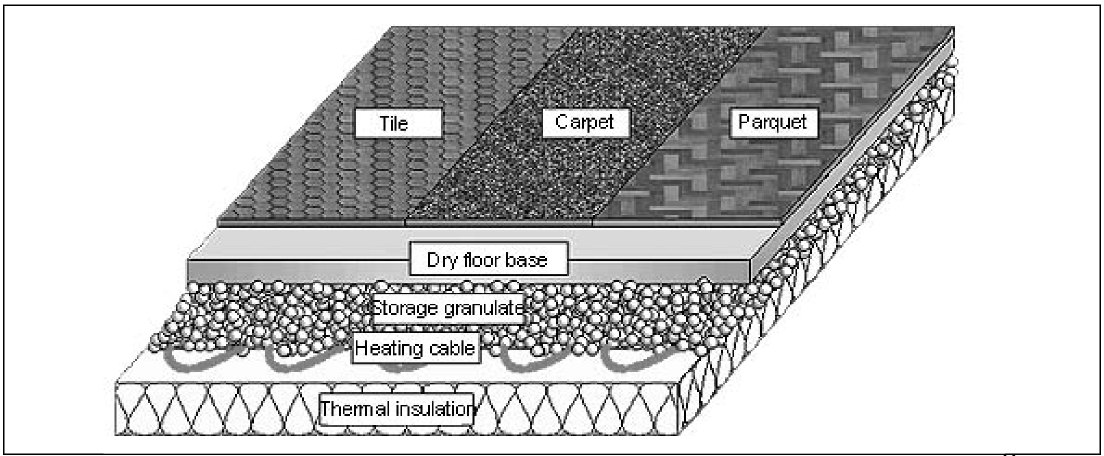


Figure 4.9: The underfloor heating with PCM system developed by Rubitherm[41]

4.3.5 PCM in Windows and Shutters

In liquid state, the PCM are nonscattering, clear and transparent homogeneous fluids but in solid state, air bubbles and boundaries cause a less homogeneous appearance. In general, the transmittance in the visual spectrum is good and do not present changes in colour of the transmitted light. These characteristics are very important to consider in PCM systems such as windows and shutters. A double glazed panel with PCM is proposed by Weinläder and Beck et al. (2005) which, compared with a regular double glazing unit, showed about 30% less heat losses and 50% less heat gains in south oriented facades, potentially improving comfort in winter and summer. They investigated different PCMs encapsulated in transparent plastic containers that were placed behind a conventional window leaving an air gap of 10mm. Because the visual impact of the PCM in the window might not be easily accepted, the authors proposed that the system could use a screen-print of a container with scattering properties. Leakage of PCM was a problem not solved in this work.

Ismail and Henriquez (2001) proposed a double glazed window with a PCM moving curtain. The PCM in liquid phase was stored in a tank and pumped to the gap between the glass sheets whenever the temperature reached a pre-set value. The contact with the colder surface of the glass caused the PCM to freeze creating a solid layer that effectively reduced by up to 50% of the solar radiation transmitted through the window and consequently the heat gains in the room. They also concluded that in this case a coloured PCM, especially green, was more effective than transparent.

[41] From http://www.rubitherm.com/english/pages/03a_underfloor_heating.htm [Accessed on the 8th of March 2009]

4.3.6 Other PCM Systems

PCM tromble walls are much lighter in weight and require less space for the same amount of heat storage than their traditional counterpart. They are, therefore, more convenient not just for lightweight buildings but also for retrofit ones (Ghoneim, Klein et al., 1991). Bourdeau (1980) tested two walls and concluded that an 8.1cm PCM tromble wall had a slightly better performance than a 40cm thick masonry tromble wall.

The potential of combining solar heated hot water with PCM to condition spaces was investigated by Ip and Gates (2000). The work proposes and simulates a system that uses the solar heated hot water to melt the PCM in the room's envelope which in turn gives up the heat to the space. The system achieved significant energy savings.

The systems described in this chapter have not been found to be available commercially and very few evolved from experimental stage to a real application. This is a clear example of the known distance between research (usually developed in an academic environment) and actual implementation of ideas. This is a gap the Creative Energy Homes project, described in Chapter 1, is attempting to bridge. The next chapter describes two products that made it out of the labs to the shelves; one of which is being used in the houses in Chapters 6 and 7.

4.4 COMMERCIAL PCM WALLBOARDS AVAILABLE IN THE UK

Although PCMs have been largely used in building cooling and heating systems, there are few PCM construction products available in the world market and their use in the UK has not been fully evaluated yet. This might be primarily because their main use is to improve the comfort inside buildings with little or no thermal mass (such as lightweight buildings), a quite new approach for the UK construction industry.

Despite the fact that PCM solutions and powders from diverse companies have been used to immerse or fill different construction components they are not commercially available and thus are not suitable for architectural design specification. When it comes to prefabricated PCM elements for the building envelope, just two types of readymade PCM wallboards were found to be available at the time when this work was written.

4.4.1 The DuPont™ Energain® Board

The DuPont™ Energain® board is a compound of a paraffin wax core (60%), a copolymer (ethylene based polymer 40%) to retain the paraffin and 130μm aluminium sheets laminating both sides enabling easy handling without posing any threat to health and safety. According to DuPont’s website, Energain® panels behave approximately like a 15cm thick brick layer and will be effective during the entire lifetime of a building[42]. Any cuts or punctures should be covered with an aluminium tape which is also provided by the company. The encapsulation process is confidential information. The product’s properties can be seen in Table 4.2 below.

DuPont supported the development of the software CoDyBa version CDB_dDDN_V2 in order to help engineers and specifiers to calculate how much of Energain is needed and where. The software calculates the thermal behaviour of a building with and without Energain and also outputs energy savings and CO_2 emission reductions. A designer could contact the DuPont Energain sales and technical teams to be advised on the matter or use the software directly. However, there is a cost associated with buying the software and it is not user-friendly.

[42] http://energain.co.uk [Accessed on the 8rd of March 2009]

Table 4.2: The DuPont Energain PCM wallboard (Source: DuPont Energain Website[43] and direct contact with the company)

DuPont™ Energain® Characteristics	
Paraffin wax core, copolymer and an aluminium cover	
Operating temperature	18 - 22 °C
Thickness	5.26mm
Width	1000mm
Length	1198mm
Weight	4.5kg/m^2
Density	0.81g/cm^3 or 810 kg/m^3
Latent heat storage capacity (from 15 to 35°C)	85 kJ/kg or 340 kJ/m²
Specific heat storage capacity (from 15 to 35°C)	95 kJ/kg°C or 385 kJ/m²
Maximum heat storage (from 15 to 35°C)	180 kJ/kg or 730kJ/m^2
Thermal conductivity liquid phase	0.18 W/m°C
Thermal conductivity solid phase	0.17 W/m°C
Quantity of PCM per m²	2.43 kg
Recommended use per 100Wh (from 14 to 30°C)	0.47 m²

4.4.1 The BASF Knauf Micronal PCM Smartboard®

BASF developed Micronal, a PCM that, according to the company, has been giving good results in terms of internal comfort improvement in some European countries (Schmidt, 2007). No independent assessment work was found but this product was used in the houses and experiments described in the next chapters of this work. The PCM is a paraffin wax microencapsulated in polymer capsules whose thickness is so thin that it allows the paraffin to respond to temperature changes without leakage. Figure 4.10 is an illustration of the board's microcapsules.

The product is available at 3 melting point temperatures, 21°C, 23°C and 26°C, in either solution, powder or already incorporated in some construction materials. It can also be used as a PCM machine-applied plaster to substitute regular plaster or be bought incorporated in aerated concrete blocks or radiant ceiling panels[44]. The main application explored here is Micronal DS 5000 X incorporated in Knauf lightweight plasterboards named Knauf PCM SmartBoard®. The first application of the product in the UK was in the two houses studied in this work.

BASF claims that the Knauf PCM Smartboard is thermally equivalent to 14cm of concrete or 36.5cm of brick (Figure 4.11). Table 4.3 above shows the properties of one of the Micronal

[43] http://energain.co.uk [Accessed on the 8th of March 2009]

[44] http://www.micronal.de/portal/basf/ien/dt.jsp?setCursor=1_290798 [Accessed on the 8th of March 2009]

products, the Micronal Knauf PCM SmartBoard 23, used for all the tests carried on in this work.

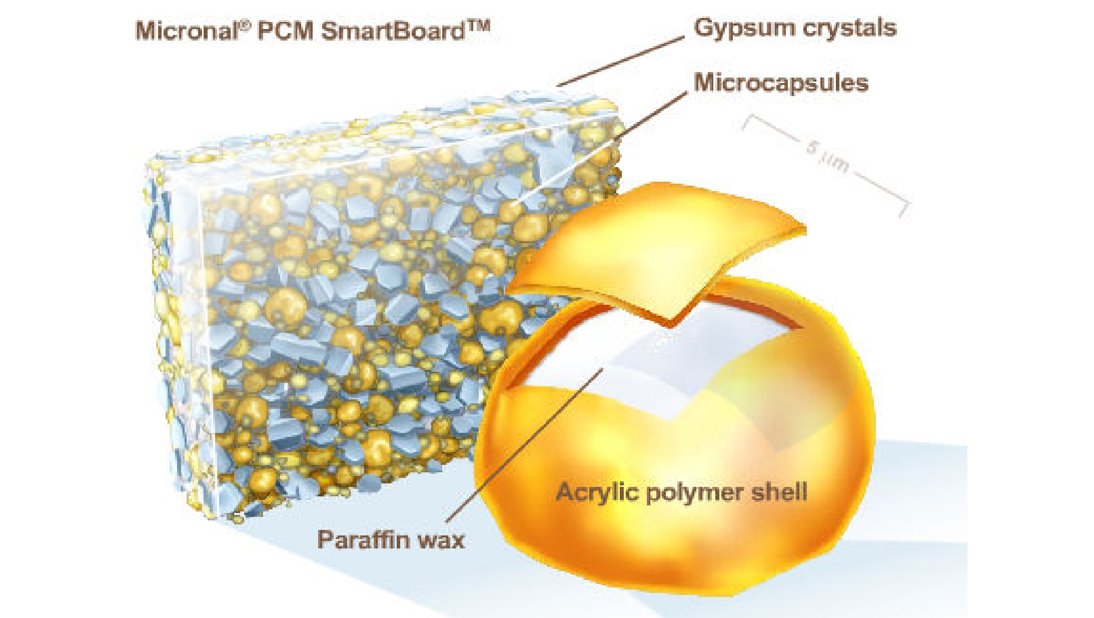


Figure 4.10: BASF's Micronal microencapsulated PCM mixed in a gypsum board (Source: BASF Micronal Website)[45]

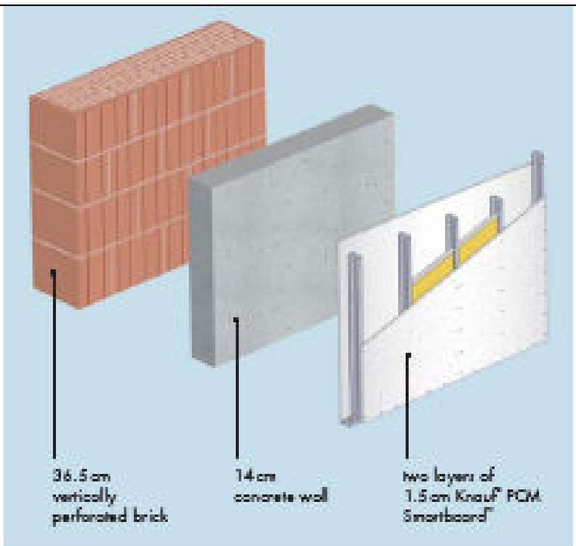


Figure 4.11: The Knauf PCM Smartboard using BASF Micronal and its equivalents in heavy weight building materials for thermal storage (Source: BASF Micronal Website)[46]

Figure 4.12 shows a graph illustrating the enthalpy of the Micronal Knauf PCM SmartBoard 23, prepared using data given by BASF. The graph permits an appreciation of the board's functioning and its relative sharpness at the phase change temperature range. As it may be seen, 23°C is the temperature where the change of phase process finishes, having started around 18-19°C.

[45] www.micronal.de [Accessed on 23rd of February 2009]
[46] www.micronal.de [Accessed on 23rd of February 2009]

Table 4.3: The Micronal Knauf PCM SmartBoard (Source: BASF Micronal Website[47] and direct contact with the company)

Micronal Knauf PCM SmartBoard® 23 Characteristics	
Glassfiber nonwoven-covered gypsum wallboard with embodied Micronal DS 5000 X PCM	
Operating temperature	19 - 23 °C
Thickness	15mm
Width	1250mm
Length	2000mm
Weight	11.5kg/m^2
Density	900 kg/m^3
Latent heat storage capacity	110 kJ/kg or 330 kJ/m²
Specific heat storage capacity	1.2 kJ/kg°C
Maximum heat storage	110 kJ/kg
Thermal conductivity liquid phase	0.18 W/m°C
Thermal conductivity solid phase	0.18 W/m°C
Quantity of PCM per m²	3 kg
Recommended use per 100Wh	1 m²

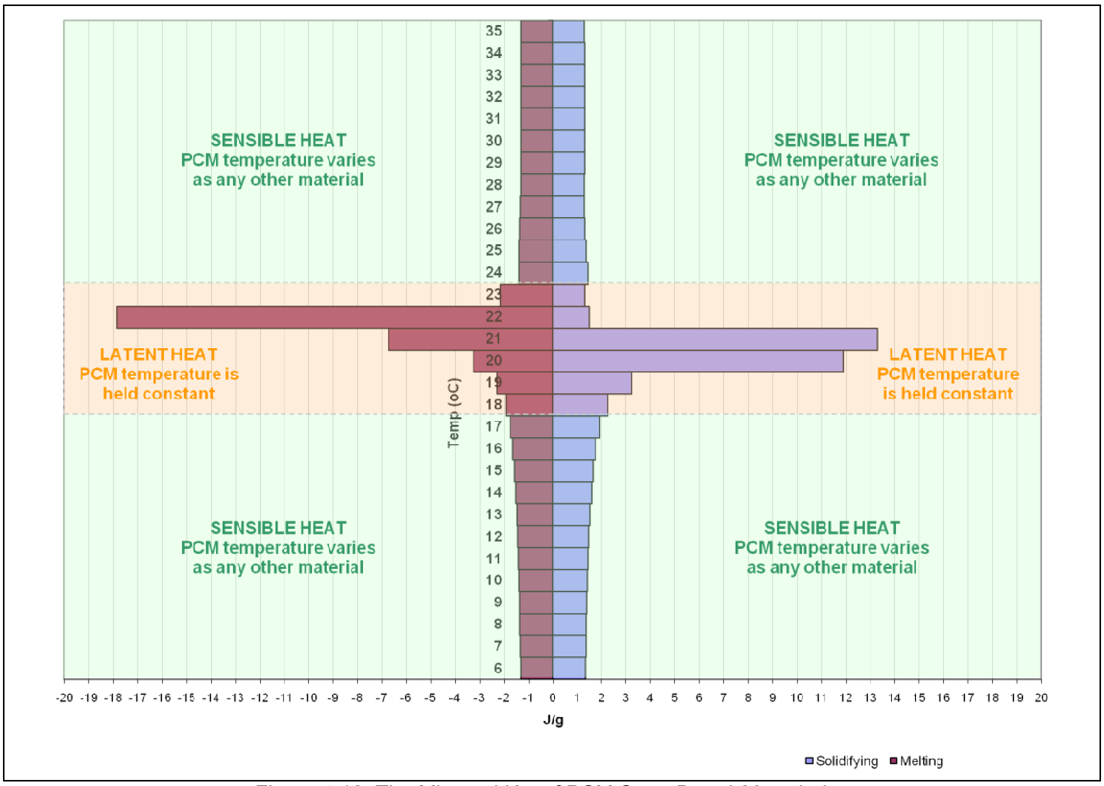


Figure 4.12: The Micronal Knauf PCM SmartBoard 23 enthalpy

At one of BASF's office buildings in Ludwigshafen (Germany), which would present temperatures above 28°C even in late autumn, 6kg of PCM per m² (heat capacity of 660

[47] www.micronal.de/portal/streamer?fid=290930 [Accessed on 8th of March 2009]

kJ/m²) was installed. During a monitoring period of 6 days the temperature in the office did not exceed 26°C while the reference room climbed above 28°C (Schmidt, 2007: p. 8).

According to BASF, “since the wall surfaces [with Micronal 23°C] remain close to 23°C, even higher air temperatures indoors still feel comfortable. Infrared radiation from cooler bodies has a positive effect on the way heat is perceived by people in the room” (Schmidt, 2007: p. 15).

BASF also invested on the development of a software tool to support the integration of their product in building design. PCM Express was created by Valentin EnergieSoftware in a partnership between BASF and the Fraunhof Institute for Solar Energy (ISE) in Freiburg as part of the research project ‘*Development of a user-friendly planning and simulation program in the combined project 'Active PCM storage systems for Building PCM Active*’[48]. When this work started, the program was in its early stages and not available for the public. A prototype was tested by the author until its final release. The software is easy to use but does not interact with common building simulation software.

[48] More information including cost can be found at:
http://www.valentin.de/index_en_page=pcm_express [Accessed on 8th of March 2009]

4.5 CONCLUSIONS: BENEFITS, DRAWBACKS AND BARRIERS

Well implemented relatively small amounts of PCM can have the effect comparable to large amounts of conventional thermal mass with the added advantage of being easy to retrofit during a refurbishment. For its small phase change temperature range, it also has the major advantage over traditional heavy weight materials of not 'wasting' heat through the wall warm-up period (mentioned previously in Chapter 2).

Published works of actual building applications are rare despite the extensive experimentation in laboratories. Unfortunately that just highlights the customary distance between academic works and real applications. In addition, long term monitoring of PCM usage is unexisting. This work has tried to start filling that gap with the investigation of two real life applications in Chapters 6 and 7. Nevertheless, all the studied work benefited from the use of PCMs. The most important conclusions that could be drawn were:

- PCM seems to be able to effectively shift the time of the peak temperature and diminish space temperature swings. This will be tested further on in this work.
- PCM could be installed in any exposed internal surface of the space. However, it may be more effective and easy to install in ceilings.
- Direct solar radiation could be used to improve the quantity of energy stored even though it is not essential.
- In internal passive applications of PCM in climates with mild winters and low availability of solar radiation, the chosen PCM should have a transition temperature just slightly above the comfort zone.
- PCMs used outside the insulated envelope can act to reduce heat flux through the wall.
- The maximum diurnal storage achieved in practice by PCM wallboards may be limited to the range 300 to 400 kJ/m^2 despite the latent capacity of the PCM as learnt from the examples given in this chapter.
- Cooling the PCM only by natural air movement in the room is very inefficient so a means of forcing air flow along the wall's surface is desirable.
- PCMs are more effective if combined with a discharge method i.e. night time ventilation or water pipes. Night time ventilation is not enough to discharge the PCM if the temperature at night is relatively high.
- PCMs can successfully be implemented in other passive applications frequently used in bioclimatic architecture design such as tromble walls, and fenestration or shading elements as shown in the studied literature. It can also be effectively combined with active systems such as solar collectors to condition the air of a room.

Considering all these advantages, one might enquire why PCMs are not yet extensively used in architecture. One of the main obstacles for a wider use of PCMs in buildings, in the author's opinion, is the difficulty to model it in established computer packages. There is limited availability of tools that are able to simulate it and they are not incorporated in software generally used by building designers. This means not just extra money but also extra skill and extra time, expensive commodities in architectural practices. TAS, a widely used software for building modelling, described and used for simulations from Chapter 5 onwards, does not simulate PCM. EDSL, the developers of TAS, informed (in March 2009) that they intend to develop an added PCM feature to the program but that still should take some time and was not to be released in the next version.

The vulnerability to fire, a problem faced by us when specifying the first application of the Micronal SmartBoard in the UK, is another major issue. Paraffin is flammable and remains so even when encapsulated and, as it is, the Micronal SmartBoard was fire-rated the same class as timber by BRE. In order to be able to install the Micronal SmartBoard in the houses studied in Chapters 6 and 7, standard plasterboards had to be installed on top of the PCM boards to act as a fire-retardant buffer. DuPont claims that their Energain drylining is enough of a fire-retardant.

An additional and imperative obstacle for a broader utilization of PCMs is the extra price of adding it to a building. As it is almost a monofunctional element (especially if another layer of regular plasterboard is needed on top) the cost can only be justified on the long-run savings on energy. Conversely, a heavyweight wall would also be serving as enclosure and/or have a structural function. By the time this work was printed, the author was told by BASF that a Micronal Knauf PCM SmartBoard 23 was priced around 10 times as much as regular plasterboard. Being an active component of a building, a PCM board should not be directly compared to standard plasterboard but if the benefits of using it cannot clearly be seen (as simulations are not always available) then it could be very hard to persuade the client to pay the extra cost. DuPont mention a payback period of around 10 years but did not mention the cost of the product. Nevertheless, these products have just been tested over long periods in laboratories so their installed life span has not yet been fully assessed.

Practical issues might also add to the implementation difficulties. As explained previously, most of PCMs have low conductivity and so need extensive surface areas to effectively exchange heat with a space. Such a surface area might not always be available and/or the installation of the boards might compromise other aspects of design such as acoustics. It also might require additional mechanical means of cooling. Many authors stressed the need for additional cooling as relying on natural convection alone is very inefficient. Consequently, effective use of PCMs in buildings relies heavily on a complete understanding of its concept, good design and consideration of charge and discharge mechanisms. The system proposed in Chapter 8 may overcome these issues.

Finally, concerns with sustainability can also be an impediment to a widespread use of these boards as some of these products are based on petrochemicals and/or use large amounts of energy to be produced. They also might not be recyclable and/or toxic. However, one has to look into the long-term benefits in reducing the use of air-conditioning systems and consequently CO_2 emissions to fully appreciate its sustainable value.

Overall the use of PCMs in building applications can be very beneficial for the comfort of the occupants and also aid a reduction in heating and cooling loads. Additionally, there is also a decrease in thermal losses due to less transport of energy and an important shift in the peak time of energy need. This way, energy demand time might be better matched with supply time, and contribute significantly to a more efficient and reliable grid energy supply and the development of dynamic and smart grids which are the future of electricity networks.

5 THERMAL SIMULATION OF HEAT STORAGE

This chapter contains original research examining the thermal storage capacity of common wall construction methods using building materials identified in Chapter 2. The build up of the wall is up-to-date with the highest standards with regards to energy efficiency. These simulations allow an evaluation of not just their thermal capacity but also of how it influences a building's thermal performance. The chapter defines and justifies each assumed parameter starting by the climate data and its future scenarios when overheating becomes a greater issue. Its conclusion of wherever thermal mass is enough to mitigate overheating in the UK today and in the future leads to an exploration of other means of exploiting it without compromising the designer's choice of building materials.

5 THERMAL SIMULATION OF HEAT STORAGE

> *"There is no need for cooling in the UK except if a building is badly designed. Most of buildings in the UK are badly designed."*
> Max Fordham, founder of the Max Fordham Consulting Engineers in a seminar at the Department of the Built Environment University of Nottingham, 2009

> *"But how much thermal mass is enough thermal mass? Or is that not an easy question to be answered?"*
> Michael Stacey, architecture and professor at the Department of the Built Environment University of Nottingham, 2008

Whilst the obvious merits of employing the passive design approach are widely accepted in the UK, there is a lack of understanding of the performance and appropriate use of high thermal mass materials.

In this chapter the occurrence of overheating in highly insulated buildings in the UK and the influence of the thermal mass of the walls in regard to this issue has been investigated. Eight different wall construction types were selected offering various degrees of heat storage capacity. It seemed unreasonable to categorise each type with regards to its 'weight' (i.e. lightweight or heavyweight construction). Rather they have been characterised by their admittance, decrement factor and time constant which are constantly referred to in the literature as ways to identify thermal mass (as discussed in Chapter 2).

This extensive parametric study could only be achieved by using advanced dynamic simulation techniques to develop an understanding of the critical parameters. This chapter presents the results of a simulation of a simple building using Tas modelling software. This special-purpose simple model allows full appreciation of the effect of thermal mass in a direct gain room without the complexity of a real project. These simulations form the basis for the work done in Chapter 6 and Chapter 7.

The advantages of producing a simpler model include fewer inputs allowing efficient application of the principle of superposition and the study of the importance of each input. The influence of each construction type and weather conditions and its relative effects in the interior's temperature swings were easy to explore because the building had few exposed surfaces and a number of isothermal surfaces.

The aim is to firstly find out if thermal mass is essential in the UK when U-Values are reduced to a point when almost no conductance happens through the fabric. Low U-Values already mean large wall thicknesses and so the addition of a layer just for its heat storage capacity might be undesirable.

Secondly, this chapter investigates if occupancy has an influence on the effectiveness of thermal mass. With full time occupants there is no large temperature fluctuation but with part time occupancy people may have to wait for the house to warm up, which might use even more energy than keeping the house warm continuously. If mechanical heating is being used, is it worth having thermal mass or would some of that heat/coolth be lost in the mass storage?

Finally this chapter studies the importance of thermal mass as temperatures get warmer. It does so by using the UK Climate Change Impact Programme (UKCIP) climate change scenarios, which are explained in section 5.1.3.

5.1 THE SIMULATION BASIS

As seen in Chapter 2, building simulation softwares consist of mathematical models calculated with the aid of a computer to determine the interplay of thermal processes within a building. They can take different approaches such as steady state (the model's parameters are considered constant and do not vary with time) and dynamic models (parameters vary with time and the calculation represents the behaviour of the building over a chosen period of time).

Thermal simulation of buildings by computer modelling is complex but becoming increasingly necessary in modern building design, especially when the targets discussed in Chapter 1 are to be met. Not long ago the project design was done by the architect who would then send it to the engineers to size and fit the mechanical systems. Thermal comfort requirements would be reduced to a set air temperature neglecting any other aspects.

However, due to the pressure to produce highly efficient buildings of the current global scenario, architects are starting to consider the dynamic thermal response of buildings and bringing engineers and environmental consultants to the early stages of the design ensuring their knowledge and skills are fully applied. Many architectural practices are developing simulation skills in-house but this is not a rule as thermal simulation is time-consuming and requires deep understanding of the principles involved. Without that understanding, building simulation may become a risky exercise when results are unquestioned even if inaccurate.

5.1.1 The Simulation Software

The thermal modelling programs available to the author were Ecotect, IES and Tas by EDSL. Because the author had some experience with Ecotect, the first analysis was undertaken using this software. However, it did not reach the required standards mainly because the software uses steady calculations as its fundamental approach.

A recent report prepared for Kingspan Century by Bobby Gilbert and Associates Ltd (an experienced consultancy company on building design and assessment) reviewed simulation, assessment and design software. The capabilities of the software packages, usability, level of integration and other characteristics were tested and the conclusion was that the ideal software package will be different for each user according to individual preferences to some degree and depends on the type of work being carried out. However, based on their assessment, Bobby Gilbert and Associates recommend the use of Tas for thermal simulation for having the best workflow methodology of all packages, for having full flexibility to model complex systems and to be as accurate as any of the other competitors (Gilbert, 2006).

Tas simulates the thermal performance of buildings using as fundamental approach dynamic calculations based on the response factor method. The main functions of the software are for the assessment of the environmental performance of the building, natural ventilation analysis, prediction of energy consumption, energy conservation options and others. The program output is a series of hourly shots of the thermal state of the building throughout a typical year based on weather data selected by the user. It allows the testing of the influence of many thermal processes that may occur in the building and presents a comprehensive picture of the way it is likely to perform. Tas has 20 years of commercial use in the UK and around the world with a good reputation for its accuracy (EDSL, 2009).

The software Tas Building Designer is divided in 2 parts, the Tas 3D Modeller and the Tas Building Simulator. The building's geometry is modelled in the first and then exported to the simulator, which simulates the thermal performance of the building by assessing (EDSL, 2009):

- Conduction in the building's fabric using a method derived from the ASHRAE response technique;
- Convection at the buildings surfaces using a combination of empirical and theoretical relationships taking into account temperature difference, surface orientation and wind speed;
- Long-wave radiation using the Stephan-Boltzmann law using the surface's emissivities from the materials database;
- Solar radiation (direct and diffuse) absorbed, reflected and transmitted using the solar data in the weather file;
- Internal conditions including gains from lighting, equipment and occupants as well as infiltration rates and plant operation;
- Gains considering radiant (on the surfaces) and convective (into the zone's air) portions;
- Infiltration, ventilation and air movement between zones and respective thermal transfers, taking into account air flows rising from wind and stack pressures;
- Solar radiation through transparent components considering absorption, reflection and transmission;
- Heating and cooling plants with radiant and convective portions;

Equations combine all these variables and are then solved to determine the sensible heat balance for each zone, considering internal gains and the energy balance at the external surfaces. The latent heat balance is solved by taking into account latent gains, moisture transfer by air movement and the operation of humidification and dehumidification plant.

When a simulation program runs the building's response calculations, it is assumed that initially (usually in day 1) all the zones are in a steady state condition. Consequently, depending on how thermally massive the building is, an iteration of several days is needed before valid values are computed. As a result, the predicted values may differ substantially from the actual values in the initial period of the simulation. Mithraratne and Vale (2004) found that the initial part of simulation's results (as much as two months) deviate from the actual values due to unaccounted thermal accumulation, depending on the massiveness of the building. The work investigated modified building simulation software that enabled simulations using the same annual weather data repeatedly. Tas assumes a steady state condition corresponding to an inside air temperature of 18°C in all zones and an outside air temperature obtained from the first hour of the weather data used. It does, however, allow for preconditioning days to account for that issue. A minimum of five days preconditioning is recommended by Tas for all buildings but as this work is dealing with thermal mass, a longer preconditioning period of 60 days was assumed.

In order to properly use any thermal simulation software, a good understanding of the principles explained in Chapter 2 is needed so the results can be appreciated and useful. One may assume that the software is accurately calculating the building's response. However, the results are largely dependent on the data input by the user so the assumptions have to be carefully selected.

5.1.2 The Nottingham Climate

All the work done in this report considered the climate of the city of Nottingham, latitude 53^{o}N, longitude 1.25°W and altitude 117m, in the East Midlands of England where the University of Nottingham is located. Due to its latitude, the sun in Nottingham is usually found at:

- Highest position: 21st of June, 60.4^{o}
- Lowest position: 21st of December, 13.5^{o}
- Autumn Equinox: 23rd of September, 37.2^{o}
- Spring Equinox: 23rd of March, 37.5^{o}

The chosen weather data has a large influence on the results of simulations and consequently on the capital cost of the building's service systems and running costs (CIBSE, 2006). It is the designer's responsibility to choose the right data from an available range for the same location, usually covering a colder and a warmer sets of data. For this work, the Design Summer Year Weather Data (DSY) for Nottingham was chosen, which is made of hourly collected data on the year 2002. This is the recommended data for the design of buildings focused on summer performance and overheating assessment, and considering a year with a hot, but not extreme summer. Extensive detailing of how these data were produced can be found in CIBSE Guide J: Weather, solar and illuminance data (CIBSE, 2002).

In Excel (Microsoft Office package) a simple program was created by the author to facilitate the visualisation and analysis of any hourly weather data. It instantaneously graphs dry and wet bulb temperatures, wind direction and speed, specific and relative humidity and global and diffuse solar radiation for each month and for the whole year. The fore mentioned weather data for Nottingham was inserted in this and relevant results are presented below.

As it can be seen in Figure 5-1, Nottingham has a temperate climate, with prevailing low temperatures throughout the year and an annual average dry bulb temperature around 10°C. The highest and the lowest dry bulb temperatures recorded in that year were 29.1°C (August) and -6.7°C (January) respectively as it can be seen in Figure 5-1. With an external maximum temperature above 25°C from June to September, there is risk of overheating in buildings in Nottingham especially if their designs make use of passive strategies to diminish winter heating loads and do not consider strategies to control cooling loads.

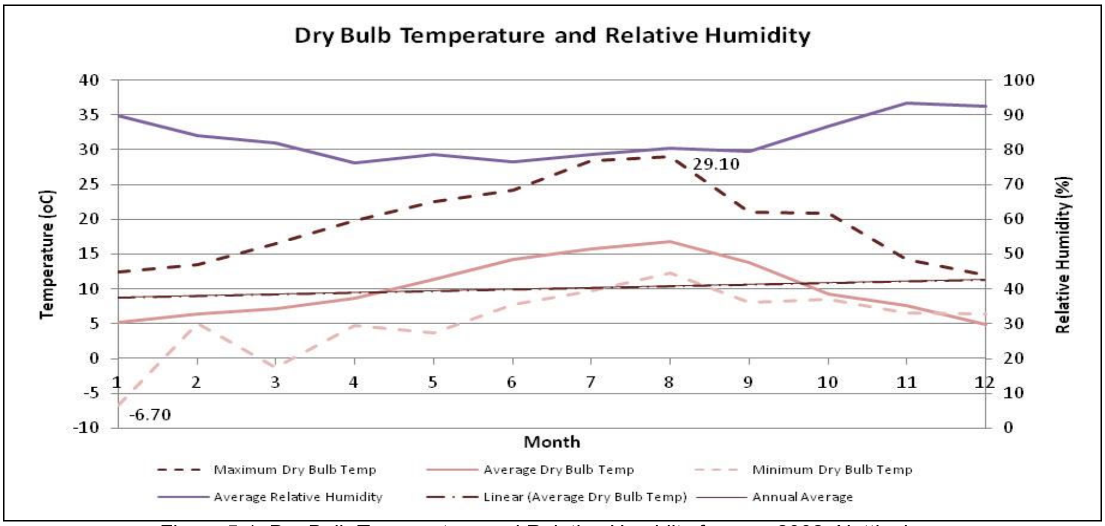


Figure 5-1: Dry Bulb Temperature and Relative Humidity for year 2002, Nottingham

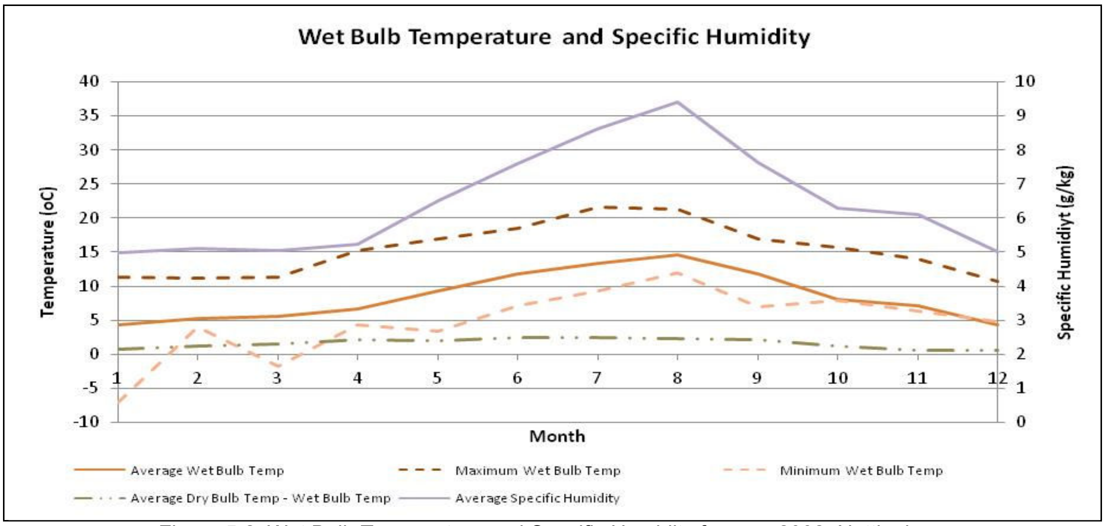


Figure 5-2: Wet Bulb Temperature and Specific Humidity for year 2002, Nottingham

The annual average dry bulb temperature is also an indication of the ground's temperature as seen in Chapter 3. Temperatures measured at University of Nottingham when ambient temperatures peaked at 24^{o}C were found to be, on average, 5.5 to 2.5^{o}C higher than the annual average at depths of 1 to 4 metres respectively.

Annually, the average wet bulb temperature varies from 4.3°C to 14.6°C and the average difference between dry bulb and wet bulb fluctuates between 0.52^{o}C and 2.43^{o}C (Figure 5-2). The comparison between the dry bulb and the wet bulb temperatures is an indication of the cooling effect on the thermal sensation due to the humidity levels. In Nottingham, the annual relative humidity levels show an average of 83.3%. The frequency of coincidence of wet and dry bulb temperatures is important for air conditioning and natural ventilation design particularly for warm climates and it can suggest the use of passive strategies such as evaporative cooling. As humidity levels in Nottingham are high throughout the year, increasing humidity would not help to reduce overheating sensation. Consequently, this work has concentrated mainly on reduction of temperature.

Figure 5-3 illustrates the temperature differences between day and night demonstrating that there is potential for night time ventilation in Nottingham. However, when considering natural day and night ventilation in Nottingham, one should remember that the city is known for high crime rates, especially for house burglary.

The sky condition is overcast most of the year and there is limited access to solar radiation especially in the cold months, which implies limited use of renewable energy technologies such as photovoltaics and solar collectors (Figure 5-4). Figure 5-5 shows that the prevailing wind comes from South-East and South-West. However, during the warmer months there is good availability of wind coming from North-East and North-West. The average wind speed is around 8 knots (just above 4m/s) but it can get as high as 30 knots (15.4m/s).

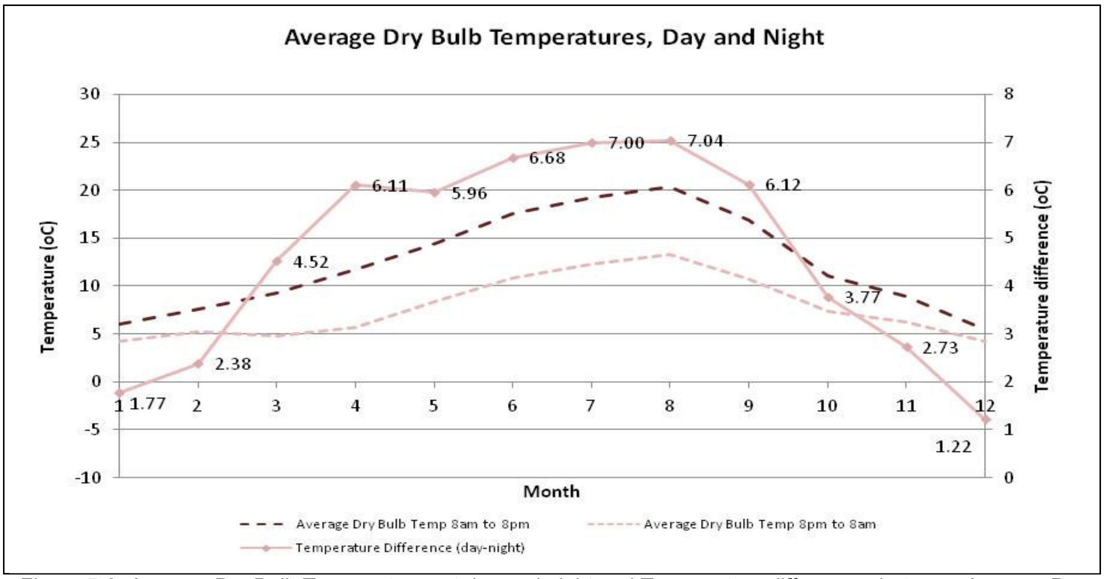


Figure 5-3: Average Dry Bulb Temperatures at day and night and Temperature differences between Average Dry Bulb Temperatures at day and night, Nottingham

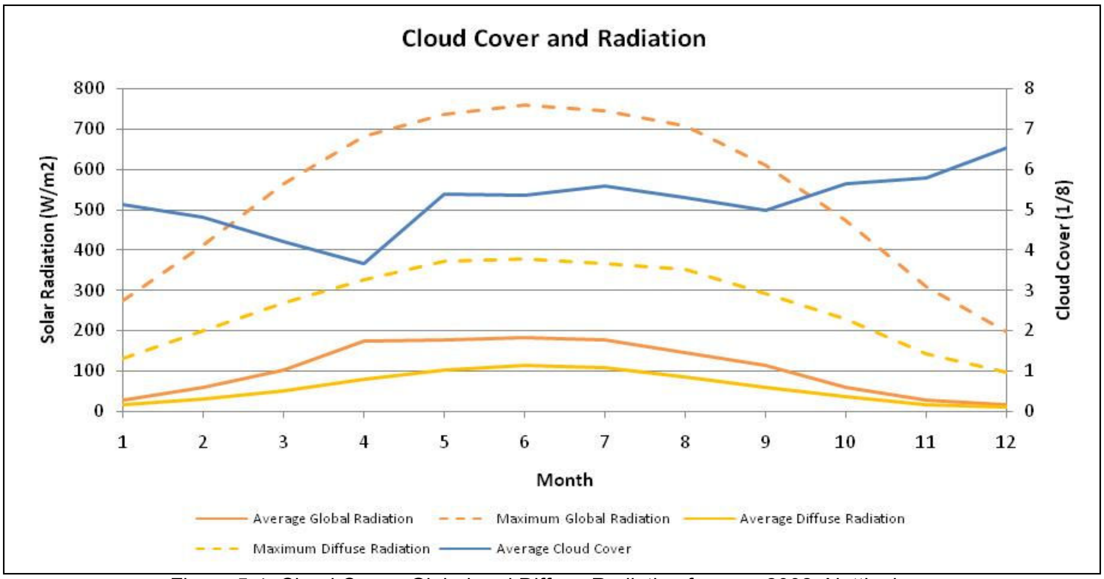


Figure 5-4: Cloud Cover, Global and Diffuse Radiation for year 2002, Nottingham

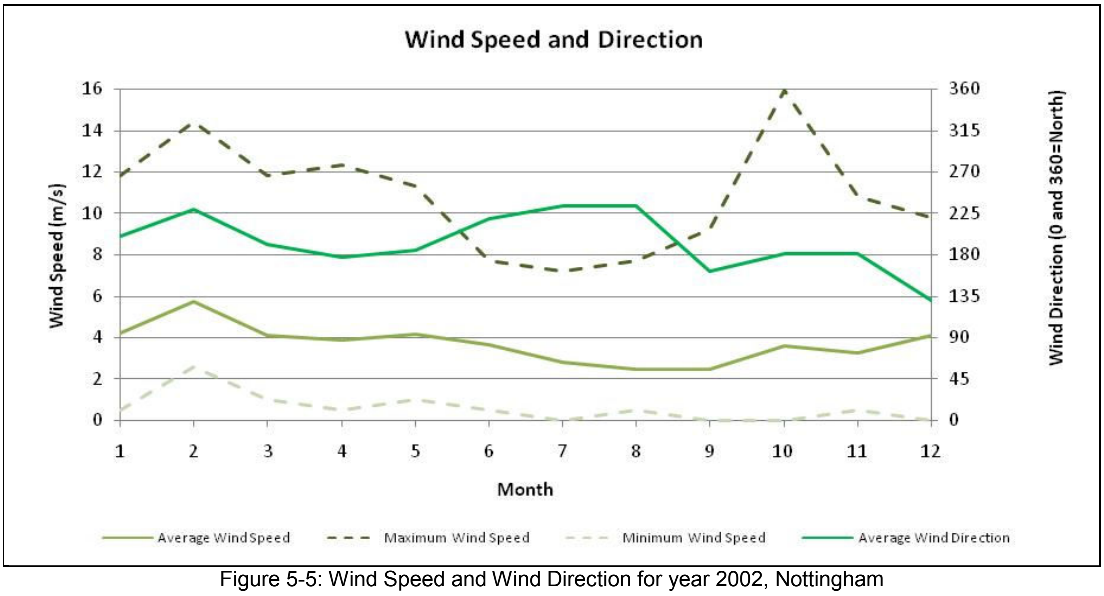


Figure 5-5: Wind Speed and Wind Direction for year 2002, Nottingham

5.1.3 The Weather and the Climate Change

The same weather data was investigated using the UKCIP scenarios for building environmental design. The programme provides information on how the UK's climate is likely to change until 2080 as a response to rising levels of greenhouse gases in the atmosphere. It is based on probabilistic projections at a national level for the years 2020s, 2050s and 2080s under the high, medium and low emission scenarios and at 10, 50 and 90% probability levels (Jenkins, Murphy et al., 2009).

The temperature of central England has increased by about 1ºC since the 1970s (Jenkins, Murphy et al., 2009: p. 5). If a scenario of medium carbon emissions under a 50% probability level is taken into account, by 2080 the mean summer temperature may rise up to 4.2^{o}C whilst the mean daily maximum temperature in summer can rise up to 5.4^{o}C (Figure 5-6). Changes in the warmest day of summer can be up to 4.8^{o}C (Figure 5-7) while the cloud cover is expected to decrease by 18%. If a higher level of emissions is taken, the mean daily maximum temperature may rise up to 9.5^{o}C and the warmest day up to 12.3^{o}C (Jenkins, Murphy et al., 2009: p. 6-7).

In the East Midlands, there is 50% probability level that the annual mean temperature will rise by 4^{o}C (Figure 5-6) if carbon emission levels are kept high.

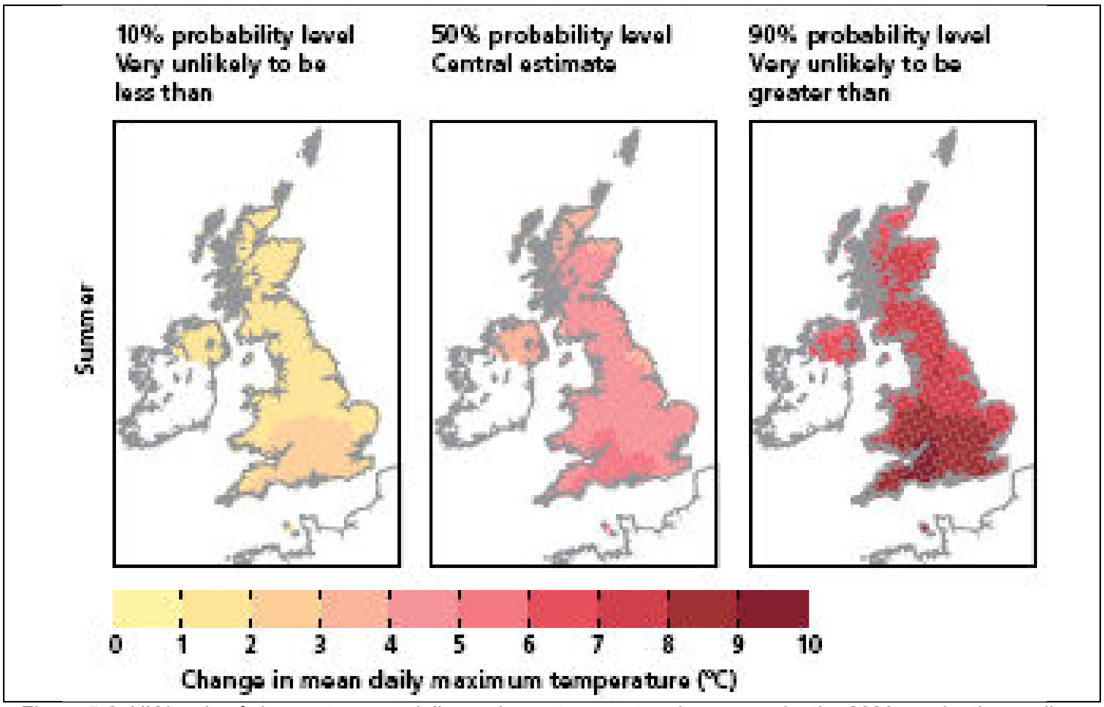


Figure 5-6: UK levels of change to mean daily maximum temperature in summer by the 2080s under the medium carbon emissions scenario (Jenkins, Murphy et al., 2009: p. 31)

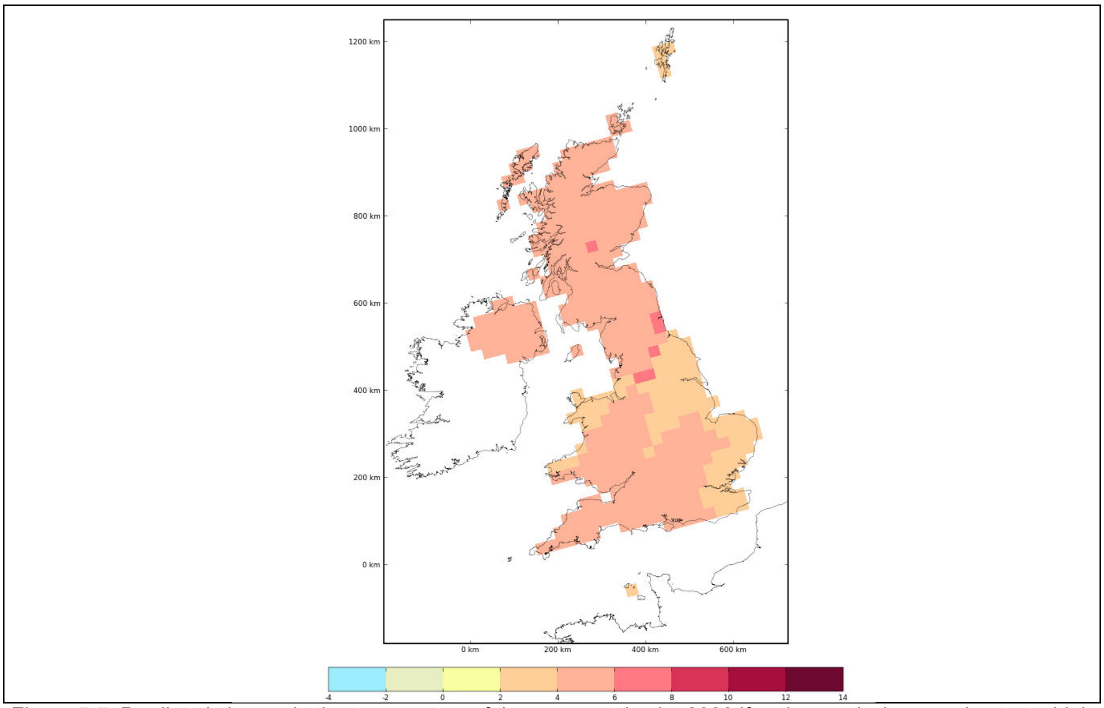


Figure 5-7: Predicted change in the temperature of the warmest day by 2080 if carbon emissions are kept at a high level (50% probability level). Source: UKCIP website[49]

The UKCIP programme has developed a weather generator that simulates future weather data. The CIBSE DSY for Nottingham was applied in the generator to create a series of future scenarios to be used in the thermal simulations. As the low emission scenarios represent a future where there is a commitment to a large reduction of greenhouse gas emissions on a global scale, which seems unrealistic, the worst case scenario (emissions continue to increase until the middle of the century) was selected.

As it may be seen in Figure 5-8, the average temperature in Nottingham is expected to rise by over 4^{o}C while relative humidity is expected to fall by about 5%. Figure 5-9 shows the predicted dry bulb temperature and relative humidity in August in Nottingham over the years. Temperatures go as high as 36^{o}C while relative humidity may fall below 30%. Night time temperatures also rise making the use of strategies such as night time ventilation more difficult.

These predictions are intimidating and clearly the risk of overheating in British houses will rise with the ambient temperatures. The simulations in this chapter will determine how thermal mass can help to improve the conditions in homes in the UK considering these future scenarios. Next section will define the thermal comfort range that is used throughout this work.

[49]Available at ukclimateprojections.defra.gov.uk/content/view/1298/545 [Accessed on 27th of July 2009]

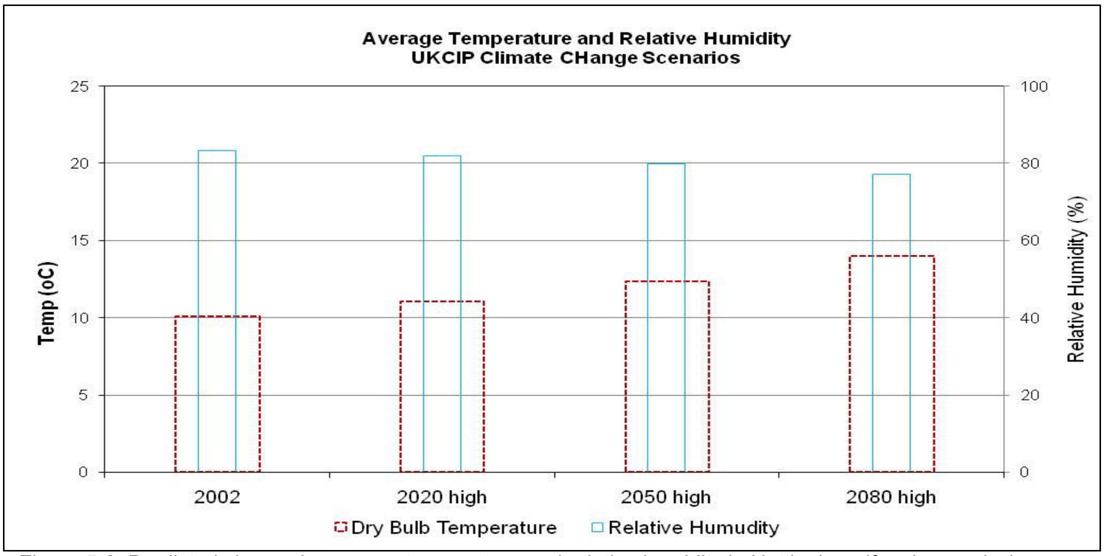


Figure 5-8: Predicted change in average temperature and relative humidity in Nottingham if carbon emissions are kept at a high level. Produced using the UKCIP weather generator

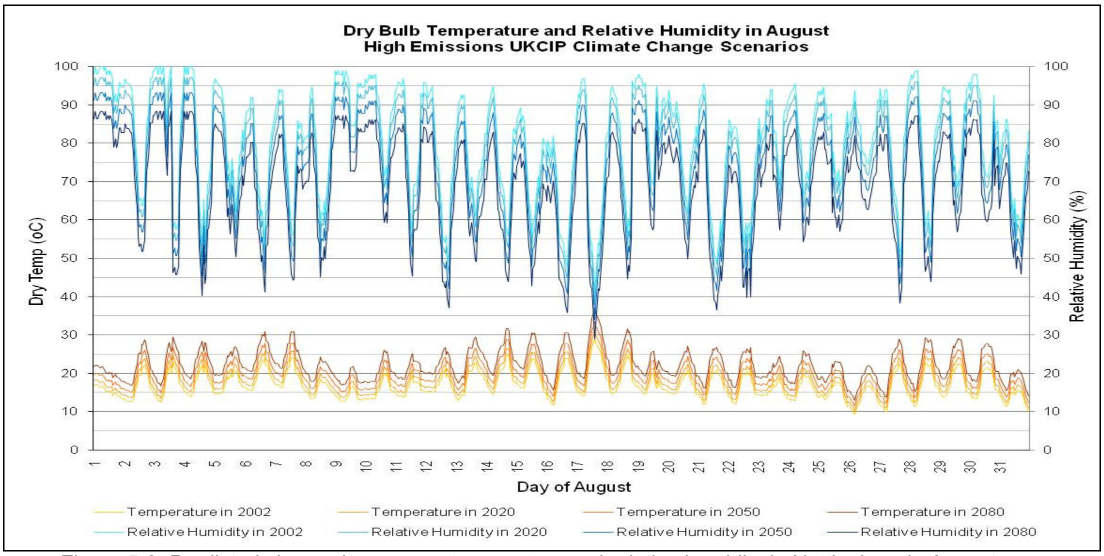


Figure 5-9: Predicted change in average temperature and relative humidity in Nottingham in August over approximately 80 years if carbon emissions are kept at a high level. Graph produced using the UKCIP weather generator.

5.1.4 Determination and Interpretation of Thermal Comfort

> *"The use of our extremely sophisticated environmental control systems is directed to this one end- to produce standard comfort zone conditions. A parallel might be drawn to the provision of our nutritional needs. (...) Our level of understanding makes it theoretically possible to provide for all our nutritional needs with a few pills and injections. However, (...), a few tubes of an astronaut's nutritious gloop are no substitute for a gourmet meal. They lack sensuality- taste, aroma, texture, temperature, and colour. The thermal environment also has the potential for such sensuality, cultural roles and symbolism that need not, indeed should not, be designed out of existence in the name of a thermally neutral world"*
>
> Lisa Heschong, (1999: p.16-17)

> *(About the equation to define thermal comfort) "When such a precise equation gives us results to a decimal number for something we can just understand to a much larger magnitude then something is fundamentally wrong."*
>
> Ray Cole at the PLEA conference 2009, 22nd of June in Quebec, Canada

Thermal sense is not traditionally considered in the list of our five senses, or at least, it is not distinguished from touch. It is, however, a different sense as we have dedicated nerve endings to tell us what is happening. As with all the other senses, there is pleasure related to the stimulation of it. Evidence of this is that a lot of us use our anxiously awaited holidays to run to extreme thermal conditions such as a hot beach or a snowy mountain.

The traditional five senses give us neutral pieces of information, which might or might not change our experience. This is the main difference between thermal sense and the other senses: the thermal information is never neutral; it is in fact reflecting what is being experienced by the body. Hence, our nerves are 'heat flux meters' as they cannot read a temperature but they can tell how quickly our bodies are gaining or losing heat. This subject has been touched from another point of view in Chapter 2 when the term effusivity is explained. When touching different surfaces at the same temperature, for example metal and wood, what we actually feel is the heat flux to the material rather than the surface's temperature.

Our metabolism is very adaptable and makes use of a series of strategies to adjust to a new condition until the thermal stimulus is no longer perceptible. Consequently, we are ready to perceive changes in the environment but not a steady state thermal condition (Heschong, 1999: p. 18-19). Unfortunately, for the purposes of building design, comfort has been defined as the absence of any form of thermal discomfort. This comfort condition will therefore require only minimal activation of any of the regulatory systems described above and cause negligible or no delight for the senses. It is like eating the same food over and over again.

Because of the metabolic strategies employed to adapt to a specific condition and other factors, such as temperature differences on various body parts and quantity of clothing, thermal comfort is highly subjective. The body's heat loss or gain is interdependently related to the following environmental and physiological factors (CIBSE, 2006: p. 1-3):

- Dry Bulb Temperature (DBT)
- Mean Radiant Temperature (MRT)
- Relative Humidity (RH)
- Air Movement (Vel): usually measured in meter per second
- Clothing Level (Clo): 1clo (1 clo=0.155m^2 ^{o}C/W) means shirt, trousers, jacket or sweater, socks and shoes which correspond to a temperature difference of around 5.5^{o}C
- Metabolic Rate (Met): 1met means approximately 58W/m^2

The rate of body energy (in the form of heat) production, known as metabolic rate, varies depending on activity, starting at a production rate of around 60W for an average person when sleeping. When doing office work a person generates around 100 to 140W (around

75W of sensible heat and 55W of latent heat), a person walking produces around 150W and doing physical activity such as exercising, around 250W (CIBSE, 2006: p. 6-2 to 6-6; Race, 2006: p. 5). In order to be comfortable we need to balance this heat production by an equal amount of heat loss from the body. If the loss exceeds generation we feel cold and if we cannot lose heat fast enough we feel hot. Heat is lost from the body in the same way as other materials: by evaporation, by radiation, by convection and by conduction (in smaller portions). This thermal balance can be expressed by Equation 5.1, according to Szokolay (2008: p. 16). Equilibrium is achieved when ΔS is zero, what would theoretically mean thermal comfort.

Equation 5.1: Body thermal balance

$$M \pm Rd \pm Cv \pm Cd - Ev = \Delta S$$

Where:
M= metabolic heat production (W)
Rd= net radiation exchange (W)
Cv= convection including respiration (W)
Cd= metabolic conduction (W)
Ev= evaporation including respiration (W)
ΔS= change in stored heat (W)

The human thermo-regulatory system has heat control mechanisms, such as sweating, to maintain a temperature of about 37^{o}C. This allows our bodies to sustain the appropriate temperature in a range of combinations of activity levels and environmental variables.

Many different models were developed for predicting the general thermal sensation and degree of discomfort or thermal dissatisfaction of people exposed to moderate thermal environments. The mathematical models take into account the relationship between one or more climatic factors and the resulting comfort sensation that would be experienced by someone. Because such a relationship is difficult to determine experimentally, most models are based on survey data of large numbers of people under different conditions. Their aim is to produce an index that, taking into account all the above mentioned factors, can provide a thermal comfort rating on which to base design decisions.

The Predicted Mean Vote (PMV) or Fanger model combines the influence of the factors listed above into one value on a thermal sensation scale that the majority would find acceptable (Table 5-1). It is the mean value of the votes of a large number of people exposed to the same environment (CIBSE, 2006: p. 1-7). As not everyone will be comfortable at the same temperature, the Predicted Percentage Dissatisfied (PPD) is also used to identify the percentage of people who would be dissatisfied. People would vote using Table 5-1 to determine the PMV. A PMV of ±0.5 relates to a PPD of 10% i.e. around 10% will be dissatisfied (Race, 2006: p. 39).

Table 5-1: Thermal sensation scale (CIBSE, 2006: p. 1-3)

Index value	Thermal sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

In addition to the immediate adaptation to the environmental conditions, the human body is also capable of adjusting itself on a long-terms basis (from a few days to up to six months of exposure). This adaptability, however, is not only related to the above mentioned factors, but also includes psychological aspects. Thermal comfort is defined in the British Standard as "that condition of mind which expresses satisfaction with the thermal environment" (BSi, 2007). In the UK's climate, conditions within buildings are unlikely to cause thermal stress. Thermal discomfort, conversely, can occur frequently and, although it will not present direct health issues, it can cause problems such as fatigue and irritability, reducing work productivity and attention, which might cause accidents (Race, 2006: p. 4).

While PMV is a deterministic method, the adaptive approach is a behavioural approach as it is based on the fact that people are prepared to adapt to their environment (i.e. by removing layers of clothes or turning a fan on) if they are given the opportunity. It does not predict comfort responses but rather the conditions under which people are likely to be comfortable. Experience has shown that a temperature that might feel too hot in April for example might be accepted in July as it is summer and higher temperatures are expected so this method relates the indoor temperature to the outdoor. Discomfort will occur when a change in temperature happens too fast or in an unexpected manner and/or is outside normally accepted limits (Race, 2006: p. 15, 16).

The following equation for free running buildings, is based on data from a range of buildings, climates and cultures as proposed by Humphreys and Nicol' model in 1998 (cited in ASHRAE, 2005: p. 8-18), can be used to calculate the likely comfort temperatures using monthly mean outdoor temperature:

Equation 5.2: Adaptive Comfort Temperature $$T_{comfort} = 18.9 + 0.255T_{external}$$

Where:
$T_{comfort}$= operative comfort temperature in free running buildings (^oC)
$T_{external}$= external monthly average temperature (^oC)

Currently, CIBSE recommends the operative temperature ranges in Table 5-2 for houses. They correspond to a PMV of ±0.25 but may be widened by 1^oC at each end if a PMV of

±0.5 (i.e. PPD of 10%) is acceptable. For practical purposes, the influence of humidity on warmth in moderate thermal environments may be ignored and is generally acceptable within the range of 40 to 70% (CIBSE, 2006: p. 1-4). In Table 5-2 the values between brackets are the higher limit accepted for short periods of time and the values with an underline are target temperatures.

Table 5-2: Recommended comfort temperature range for dwelling based on common environmental and physiological factors (CIBSE, 2006: p. 1-8)

Dwelling Zone	**Activity (met)**	**Clothing Winter/ Summer (clo)**	**Suggested Air Supply Rate (l/s/person or ach)**	**Winter Operative Temperature (°C)**	**Summer Operative Temperature (°C)**
Bathroom	1.2	0.25	15	20-22	23-25
Bedroom	0.9	2.5/1.2	0.4-1ach	17-19	<u>23</u>-25 (26)
Circulation	1.8	0.75/0.65	-	19-24	21-25
Kitchen	1.6	1.0/0.65	60	17-19	21-23
Living Room	1.1	1.0/0.65	0.4-1ach	22-23	23-<u>25</u> (28)
Toilet	1.4	1.0/0.65	>5ach	19-21	21-23

The values in Table 5-2 are for free-running buildings (buildings that are not consuming energy for either of heating or cooling for the time when the temperature was set) where people might accept higher values. CIBSE sets 25°C as an acceptable indoor temperature in summer and 28°C as maximum benchmark for peak temperature in living rooms and 26°C in bedrooms. For temperatures between 25ºC and 28ºC an increasing number of people may feel hot and uncomfortable and temperatures that stay at, or over, 28 ºC for long periods of the day will result in dissatisfaction for the majority of occupants. These values come from the Adaptive Approach to Comfort and should not be exceed for more than 1% of the annual occupied hours. CIBSE also recommends that the overheating criteria be assessed against the CIBSE DSY and adds that “it is also required that there be no local discomfort (either warm or cold) at any part of the human body due to, for example, asymmetric thermal radiation, draughts, warm or cold floors, or vertical air temperature differences” (CIBSE, 2006: p. 1-3).

By applying Equation 5.2 to the weather data described in section 5.1.2 and comparing those results with the CIBSE guidelines (average of the suggested range of temperatures), the following graph was obtained:

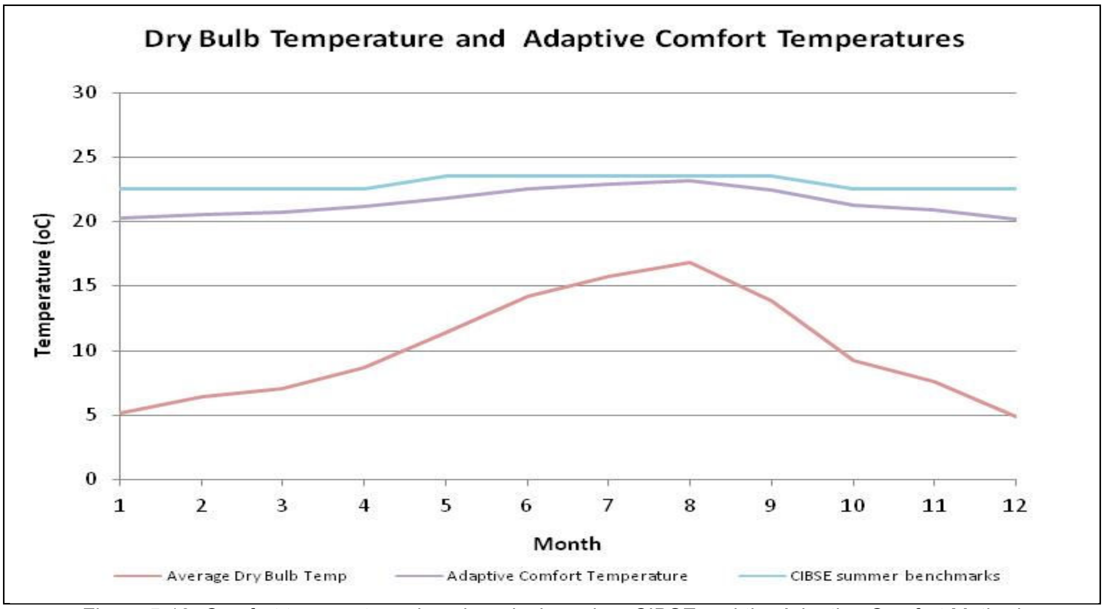


Figure 5-10: Comfort temperatures benchmarks based on CIBSE and the Adaptive Comfort Method

The approach of the Adaptive model extends the comfort zone range, providing a more realistic vision of comfort levels according to the local conditions diminishing the need for active systems hence also reducing energy use. Therefore, in building design, it is of special relevance the creation of adaptive opportunities to enable the users to control their environment.

Traditionally in the UK no attention has been given to overheating in housing and hence there is no clear definition of the problem. Szokolay says that “there is scope for considerable debate as to what would form a suitable definition of overheating in housing” (Szokolay, 2008). Both, high peak temperatures and long term moderate overheating may cause a house owner to buy an air-conditioning system. This work will look into peak temperatures and the periods of time they occur based on the standards investigated in this section and use the PMV method to describe the results. The research done through hundreds of simulations that follow will be assessed in terms of the comfort criteria described in this section.

5.2 THE CONSTRUCTION TYPES

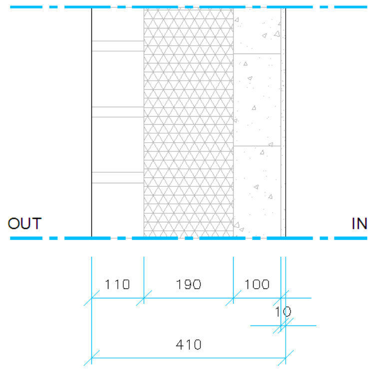
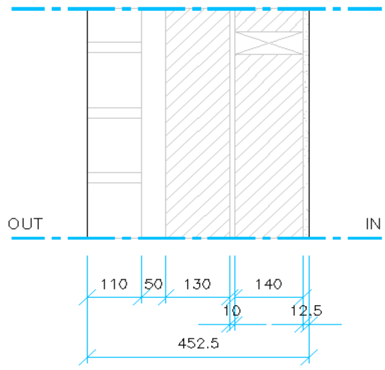
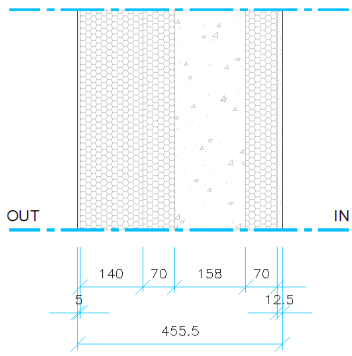
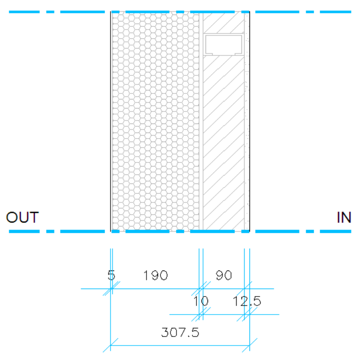
The focus of the simulations was an investigation of wall types so the floor and roof were kept the same, selected from common constructions (concrete floor with timber finishing and roof tiles on timber structure for the roof). The starting point to decide the build up of the walls assessed was to use the most common construction methods (traditional and modern) and achieve a U-Value of 0.12W/m^{2}K in order to comply with the higher UK standards (Code for Sustainable Homes level 6 as described in Chapter 1) and international standards (Passivhaus also described in Chapter 1). With that in mind eight different wall construction types were selected:

1. Brick and Block full fill cavity wall (BB)
2. Timber frame part fill cavity wall (TF)
3. Insulated concrete formwork wall (ICF)
4. Steel frame wall (SF)
5. Structural insulated panel wall (SIPs)
6. Cross laminated timber wall (CLT)
7. Solid Concrete Block wall (SB)
8. Precast concrete panel wall (PCP)

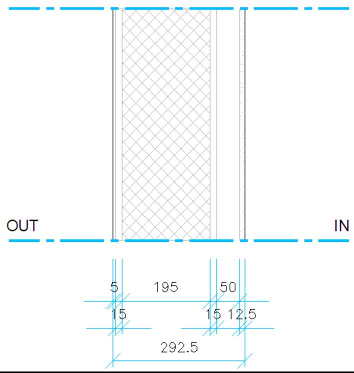
Each one is described in the next sections and relevant characterising values such as admittance, decrement factor and time constant can be seen in Table 5-3. The time constants were calculated with the aid of Tas and the decrement factor using Ecotect. Service voids or air gaps were considered where appropriate i.e. if the structure does not allow for space for services. The thicknesses are written with and without service voids or air gaps (first and second number respectively) to allow for better comparison as the size of those may vary greatly. The removal of these does not have a great influence on the U-Value of the final construction but may impact the time constant if placed on the inside of the main insulating layer. This is just the case for SIPs and CLT which are types of construction that most probably will have a service void on the inside of the wall.

The constructions that do not have brickwork externally received a 5mm external surface finishing with similar absorptance to the brick used in the other ones (i.e. 0.7). Internally all the walls have the same surface finishes, either of lightweight plaster or of plasterboard. The insulation of the walls was increased (when compared with a typical wall) to achieve a U-Value of 0.12 W/m^{2}K. The location of the extra insulation took into account practicality and best positioning to maintain the thermal mass characteristics if any. Some wall thicknesses might be currently unrealistic suggesting that suppliers might have to adapt to the new reality of highly insulated buildings. The same floor, roof, windows and shading were used for all cases. For thermal properties of each layer please refer to Appendix 5.A in the end of this chapter.

Table 5-3: The properties of each wall type

1. BRICK AND BLOCK WALL (BB)  OUT a. 110mm Brick Outer Leaf b. 190mm Phenolic Insulation c. 100mm Aerated Concrete Block d. 10mm Lightweight Plaster IN	**Decrement Factor** (0-1)	0.4
	Time Constant (hours)	2.82
	Admittance (W/m^2K)	2.49
	U-Value (W/m^2K)	0.12
	Thickness (mm)	410
2. TIMBER FRAME WALL (TF)  OUT a. 110mm Brick Outer Leaf b. 50mm Air Gap c. 130mm Rockwool d. 10mm Plywood e. 140mm Rockwool f. 12.5mm Plasterboard IN	**Decrement Factor** (0-1)	0.2
	Time Constant (hours)	4.67
	Admittance (W/m^2K)	1.01
	U-Value (W/m^2K)	0.12
	Thickness (mm)	402.5-452.5
3. INSULATED CONCRETE FORMWORK (ICF)  OUT a. 5mm Rendering b. 140mm Extruded Polystyrene (EPS) c. 70mm Extruded Polystyrene (EPS) d. 158mm Heavyweight concrete e. 70mm Extruded Polystyrene (EPS) f. 12.5mm Plasterboard IN	**Decrement Factor** (0-1)	0.03
	Time Constant (hours)	116.5
	Admittance (W/m^2K)	0.86
	U-Value (W/m^2K)	0.12
	Thickness (mm)	455.5
4. STEEL FRAME WALL (SF)  OUT a. 5mm Rendering b. 190mm Extruded Polystyrene (EPS) c. 10mm Plywood d. 90mm Rockwool e. 12.5mm Plasterboard IN	**Decrement Factor** (0-1)	0.36
	Time Constant (hours)	4.9
	Admittance (W/m^2K)	1.01
	U-Value (W/m^2K)	0.12
	Thickness (mm)	307.5

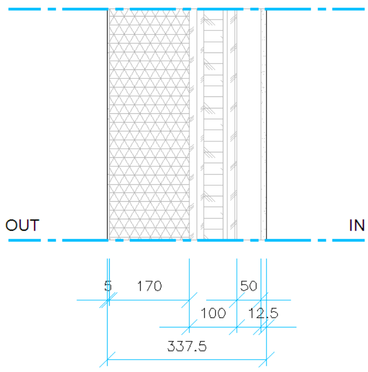
5. STRUCTURAL INSULATED WALL PANELS (SIPs)



OUT
a. 5mm Rendering
b. 15mm Softwood board
c. 195mm Extruded Polyurethane (PUR)
b. 15mm Softwood board
c. 50mm Air Gap
d. 12.5mm Plasterboard
IN

Decrement Factor (0-1)	0.81
Time Constant (hours)	2.4
Admittance (W/m^2K)	2.28
U-Value (W/m^2K)	0.12
Thickness (mm)	242.5-292.5

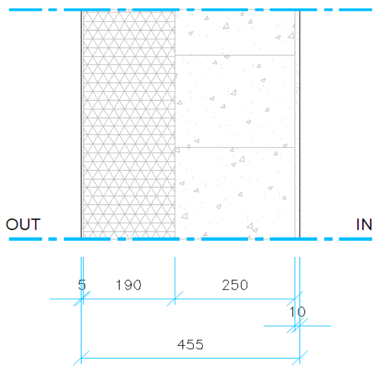
6. CROSS LAMINATED TIMBER WALL (CLT)



OUT
a. 5mm Rendering
b. 170mm Phenolic Insulation
c. 100mm Cross Laminated Timber
d. 50mm Air Gap
e. 12.5mm Plasterboard
IN

Decrement Factor (0-1)	0.31
Time Constant (hours)	10.0
Admittance (W/m^2K)	1.9
U-Value (W/m^2K)	0.12
Thickness (mm)	332.5-382.5

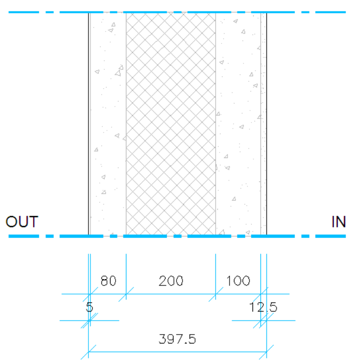
7. SOLID CONCRETE BLOCK WALL (SB)



OUT
a. 5mm Rendering
b. 190mm Phenolic Insulation
c. 250mm Aerated Concrete Block
d. 10mm Lightweight Plaster
IN

Decrement Factor (0-1)	0.27
Time Constant (hours)	7.3
Admittance (W/m^2K)	2.75
U-Value (W/m^2K)	0.12
Thickness (mm)	455

8. PRECAST CONCRETE WALL PANELS (PCP)



OUT
a. 5mm Rendering
b. 80mm Heavyweight Concrete Panel
c. 200mm Extruded Polyurethane (PUR)
d. 100mm Heavyweight Concrete Panel
e. 12.5mm Plasterboard
IN

Decrement Factor (0-1)	0.22
Time Constant (hours)	5.0
Admittance (W/m^2K)	4.28
U-Value (W/m^2K)	0.12
Thickness (mm)	397.5

5.2.1 Brick and Block Full Fill Cavity Wall (BB)

The most typical house construction in the UK has load bearing brick and block cavity walls. Aerated concrete blocks are generally used because they are lightweight and have good insulating properties (Dye and McEvoy, 2008: p. 51, 52). The cavity between the brick and block is left for better thermal insulation properties and weather resistance when compared to a solid brick or block wall. The two leaves of a cavity wall are tied together with wall ties, which can be butterfly type (for cavities between 50 and 75mm) or vertical twist type (cavity width between 75 and 300mm) (Chudley and Greeno, 2008: p. 320-322). This type of construction has a number of variations but the example in this study was selected for being the most common (Table 5-3). The thermal performance standards can be achieved in several ways but the most usual method would be to fill the cavity with an insulating material. Here the insulating layer had to be increased greatly if compared to an ordinary wall to achieve the required U-Value. In addition, phenolic insulation was used as opposed to regularly used rock wool for its better performance in smaller thickness. Generally this wall type is finished internally with a lightweight plaster and externally the brick would be left exposed (Chudley and Greeno, 2008: p. 450).

5.2.2 Timber Frame Part Fill Cavity Wall (TF)

Timber frame has a long history in Scandinavia and North America but it has just been in the UK since the 1960s. It is usually composed of factory-made structural timber panels with an internal lining of plasterboard and an outer sheathing of plywood with insulation between the framing (Chudley and Greeno, 2008: p. 386; Twist and Lancashire, 2008: p. 17-20). An outer layer of brickwork is the most common way of waterproofing the wall especially in the UK where the traditional brick appearance is more accepted although it might receive many different types of cladding (Table 5-3). The cavity is usually kept to prevent fire spread. Regarding thermal performance it depends on the type of insulation used, the most common being mineral wool.

5.2.3 Insulated Concrete Formwork Wall (ICF)

ICF wall elements combine two expanded polystyrene panels (EPS) held together by polypropylene webs, which are fixed during the EPS moulding process. Each element interlocks vertically and horizontally building the wall. The web supports reinforcing bars where required and once the wall is formed concrete is poured into the formwork (Logix, 2008: p. 1; ICF Tech Ltd, 2009: p. 4). ICF walls can be partially assembled off-site or totally assembled on-site and its insulation is permanently fixed as part of the structure. They can be load-bearing or not and are usually easy to assemble. At the Creative Energy Homes project, students under supervision built the basement walls of the Stoneguard House (Chapter 6). ICF was also used to build the ground floor of the BASF House (Chapter 7).

This type of construction is commonly seen without the extra insulating layer used here to achieve the required U-Value (Table 5-3). This layer has been applied externally to allow for the concrete to be as close as possible to the house's interior. However, as a result of the internal EPS layer, the thermal mass of the concrete is insulated so the time constant is very high.

5.2.4 Steel Frame Wall (SF)

Steel frame wall systems are similar to timber frame but using galvanized steel components, which are shaped and cut in a factory using automated machines controlled by computer. If the design is well-developed, the frames can leave the factory with all the holes for the services cut for a fast and dry site assembly. The system allows great design flexibility, various cladding options and very short on-site time[50].

The steel frame construction used in these simulations is similar to the Stoneguard House wall where the brickwork has been substituted by EPS with rendering. This configuration allows the wall to be practically made of insulation and the external layer of EPS helps to avoid thermal bridging which could be a problem due to the high conductivity of the steel (Table 5-3). Students under supervision also helped to build the steel frame walls of the Stoneguard House (Chapter 6). For both, ICF and steel frame construction, the students received very little training previous to the successful construction of the walls showing how easy the systems are to assemble regardless of the skill of the labour used.

5.2.5 Structural Insulated Panel Wall (SIPs)

SIPs are structural elements consisting of two high density face layers (usually oriented strand board, softwood or plywood) which are bonded on both sides of a low density, cellular core (usually closed cell polyurethane, phenolic foam or expanded polystyrene). According to BRE (Bregulla and Enjily, 2004: p. 1) they are light and strong, allowing flexibility in the design in addition to being thermally efficient and fast to erect. Thermal bridging and air infiltration are minimised by effective design and the application of sealants.

The insulation in SIPs panels may vary depending on the manufacturer and has structural importance as it holds the two sheets that form the panels together in addition to giving it thermal resistance. SIPs panels might receive different claddings varying from brick skins to rendering but here it has been finished with render only (Table 5-3) as one of the main benefits of the system is that it can receive finishes directly keeping the thickness much

[50] More information can be found at www.stoneguard.co.uk/protec [Last accessed on the 4th of August 2009]

smaller. Internally SIPs are typically finished with plasterboard and a service gap is usually necessary to avoid perforation of the panel (Hemsec Sips Ltd, 2006).

SIPs panels were used to build the first floor walls and the roof of the BASF House (Chapter 7) where it was finished with a metal cladding.

5.2.6 Cross Laminated Timber Wall (CLT)

CLT is commonly used in continental Europe but is relatively new in the UK (Trada, 2009). CLT is the most typical for of solid wood panels although not all wood panels are cross laminated. Each element is pre-cut in a factory to any shape and form allowing great design flexibility.

It differs from timber frame and massive timber for having a layer of cross laminated softwood boards glued together (from 50 to 500mm) which gives the panels their structural strength. The insulation comes separately from the main structure so it tends to be a thicker construction type. It might receive different insulating materials and claddings but here it has been considered with rendering on top of the phenolic insulating layer (Table 5-3). The services generally would not be installed within the structure so there is a requirement for a service void, although this is a not a rule as the wood might be left exposed internally. There is no on site cutting provided that the project has been properly detailed.

5.2.7 Solid Concrete Block Wall (SB)

Precast concrete blocks are used to build this common load-bearing wall type (Table 5-3). There are diverse types of blocks but the most frequent, used here, is lightweight aerated concrete block with a density of 475kg/m^3 (Chudley and Greeno, 2008: p. 319, 450).

This kind of wall is usually finished with lightweight plaster and should be insulated externally if the building is expected to benefit from the block's thermal mass. Insulation types may vary; here phenolic insulation was selected for its better performance in smaller thickness as used in the Tarmac Homes Code 6 house in the Creative Energy Homes project[51].

5.2.8 Precast Concrete Panel Wall (PCP)

Precast concrete panels do not have a widespread use in the UK for housing although it can be found in applications such as schools, hotels and hospitals (Chudley and Greeno, 2008: p. 383-385). Precast concrete cladding panels are more frequently seen (not the subject of

[51] More information can be found at www.creative-energy-homes.co.uk [Accessed on the 4th of August 2009]

this section). The system compromises of quality controlled factory produced reinforced concrete walls and other elements.

Precast concrete wall panels are a cost effective and fast load-bearing construction type. The thickness of the concrete may vary greatly as well as the type of sandwiched insulation. Here extruded polyurethane was used and its thickness was increased significantly if compared to a typical panel in order to achieve the required U-Value (Table 5-3). Internally the panels can be finished just with paint but it is usually dry lined with plasterboard.

5.2.9 Wall Properties Comparison

Admittance, described in Chapter 2 is the rate of heat flow between the internal surfaces of the structure and the space for each degree of temperature change so it can be considered a representation of the dynamic response of a building element when subject to sinusoidal variation in temperature. It takes into account the element's surface and each layer's thermal properties, but it is primarily determined by the layer closest to the internal space. Consequently, the admittance of an ICF wall will be closer to the value of the insulation alone while the PCP will have admittance closer to the value of the concrete.

Decrement factor, also described in Chapter 2, is the ratio between the heat flows from one surface of the structure to another due to variations in temperature. It is expected to be high for low thermal capacity structures and decrease with increased thermal capacity (CIBSE, 2006: p. 5-14). Time constant is the approximate time that takes for the construction to regain thermal equilibrium after a change in temperature. A low thermal capacity structure will have a shorter time constant while a high capacity construction will have a value that is much longer.

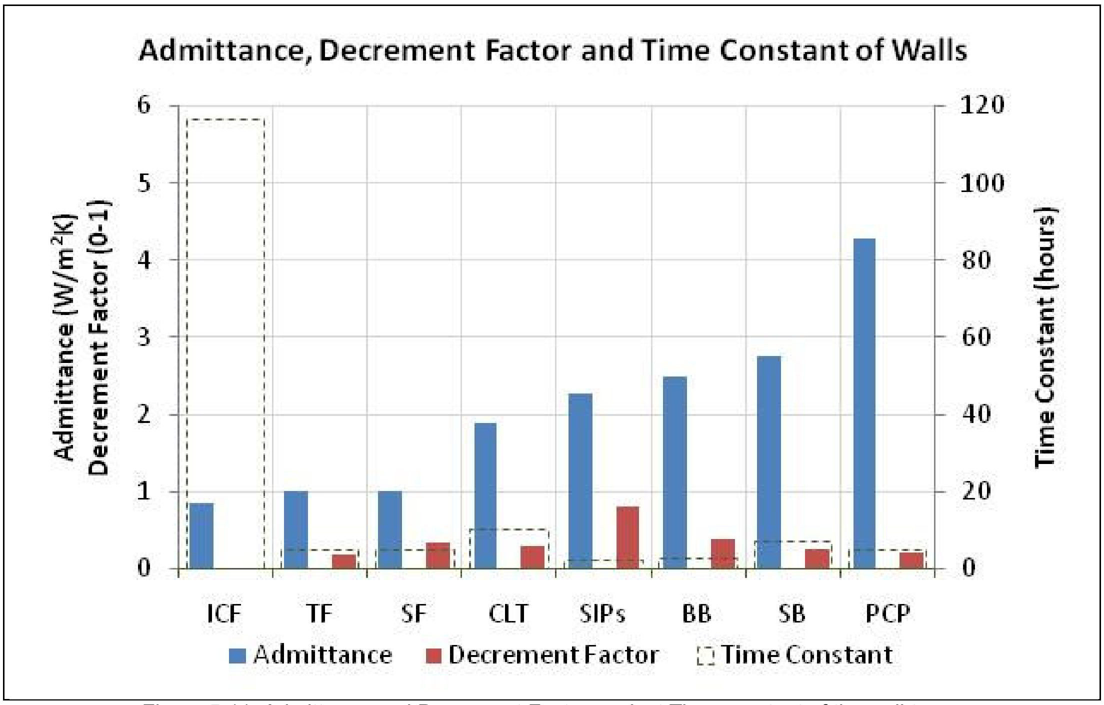


Figure 5-11: Admittance and Decrement Factor against Time constant of the wall types

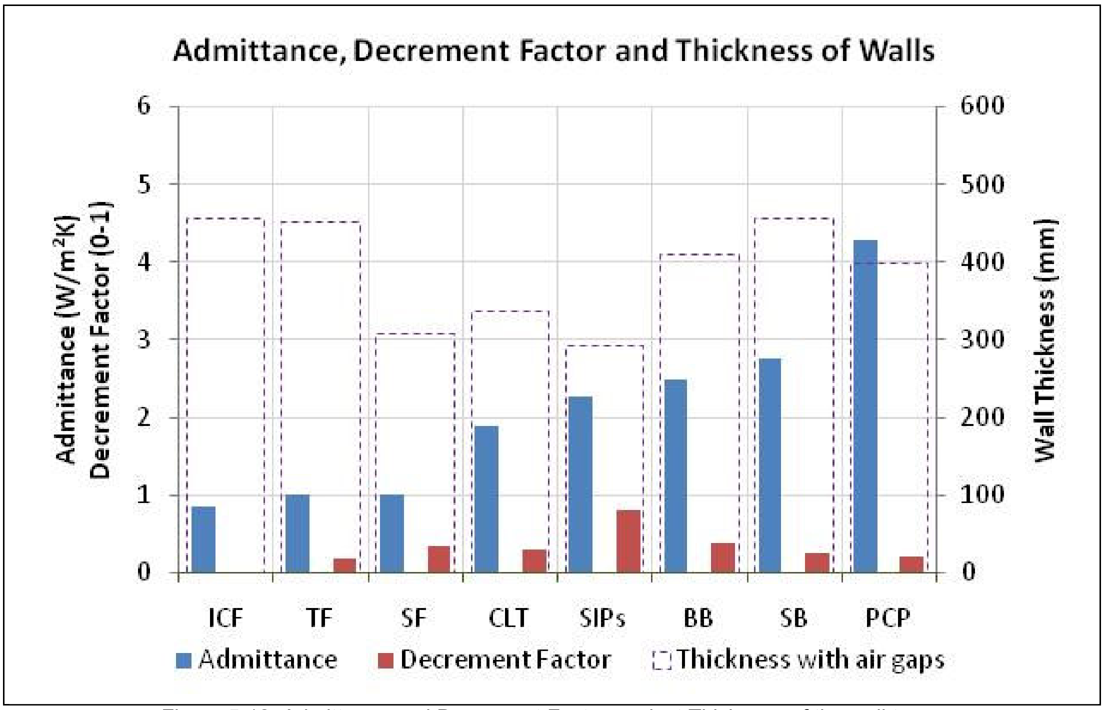


Figure 5-12: Admittance and Decrement Factor against Thickness of the wall types

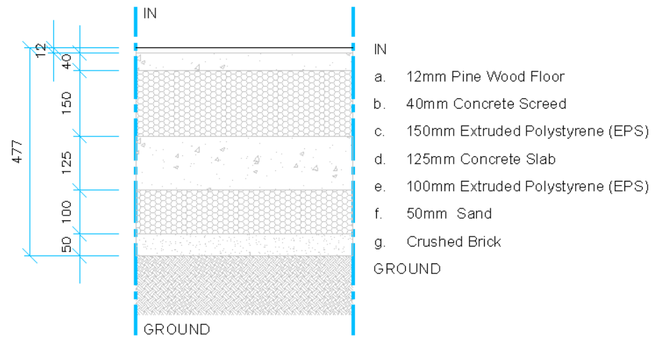
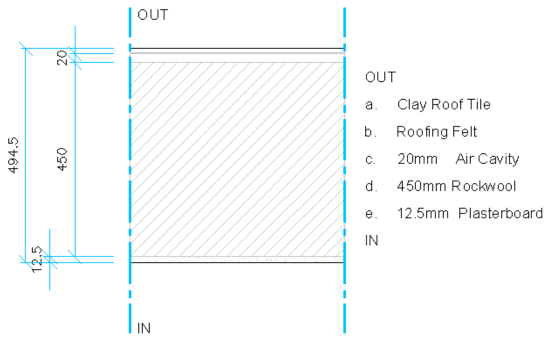
In Figure 5-11 and Figure 5-12 admittance, decrement factor, time constant and thickness of each wall was plotted and organised by admittance for easy comparison. As discussed in Chapter 2, the literature suggests admittance is probably the easiest way to evaluate a construction type with regards to thermal mass. A heavier construction (i.e. ICF) does not necessarily mean better admittance. ICF is a particular case due to the very low conductivity of the inner layer. As a consequence, its decrement factor is exceptionally low (close to zero) and its time constant almost 120 hours meaning that heat would have great difficulty in entering the wall and take a very long time to be delivered back to the space.

In these graphs it can be observed that decrement factor and time constant do not follow a pattern that relates in any way to admittance. In addition, construction types such as SIPs and CLT are in the middle of the chart even though they do not have any material that would traditionally characterise thermal mass. The performance of each wall type will be investigated dynamically in the next section in order to understand if these figures are really meaningful to characterise thermal storage capacity.

5.2.10 Ground Floor, Roof and Window

All the simulations used the same ground floor, roof and windows. The windows were assumed to be of a U-Value of 1.4 W/m^{2}K, double glazing with 12mm argon filling in a wooden frame. The ground floor and roof were assumed as shown in Table 5-4.

Table 5-4: The properties of the ground floor and roof

<table>
<tr><td rowspan="5">GROUND FLOOR

</td><td>Decrement Factor
(0-1)</td><td>0</td></tr>
<tr><td>Time Constant
(hours)</td><td>215.7</td></tr>
<tr><td>Admittance
(W/m^{2}K)</td><td>3.83</td></tr>
<tr><td>U-Value
(W/m^{2}K)</td><td>0.10</td></tr>
<tr><td>Thickness
(mm)</td><td>477</td></tr>
<tr><td rowspan="5">ROOF

</td><td>Decrement Factor
(0-1)</td><td>0.1</td></tr>
<tr><td>Time Constant
(hours)</td><td>31.9</td></tr>
<tr><td>Admittance
(W/m^{2}K)</td><td>1.58</td></tr>
<tr><td>U-Value
(W/m^{2}K)</td><td>0.10</td></tr>
<tr><td>Thickness
(mm)</td><td>494.5</td></tr>
</table>

5.3 THE BASE CASE MODEL

This section will look into the influence of the wall types on the performance of a simple model by looking into frequency of temperatures outside comfort zone.

The model is shown schematically in Figure 5-13. It is composed of one zone of $100m^2$ and $270m^3$ of volume. All the walls are external, made up of the same building material and of an area of $30m^2$. Each layer is assumed to be isotropic. The south wall contains a $10m^2$ (10% of the floor area) window with a 50mm frame. The model was fixed throughout the simulations as it was not the scope of this work to experiment with different dimensions and configurations. However, this could make an interesting topic for further work.

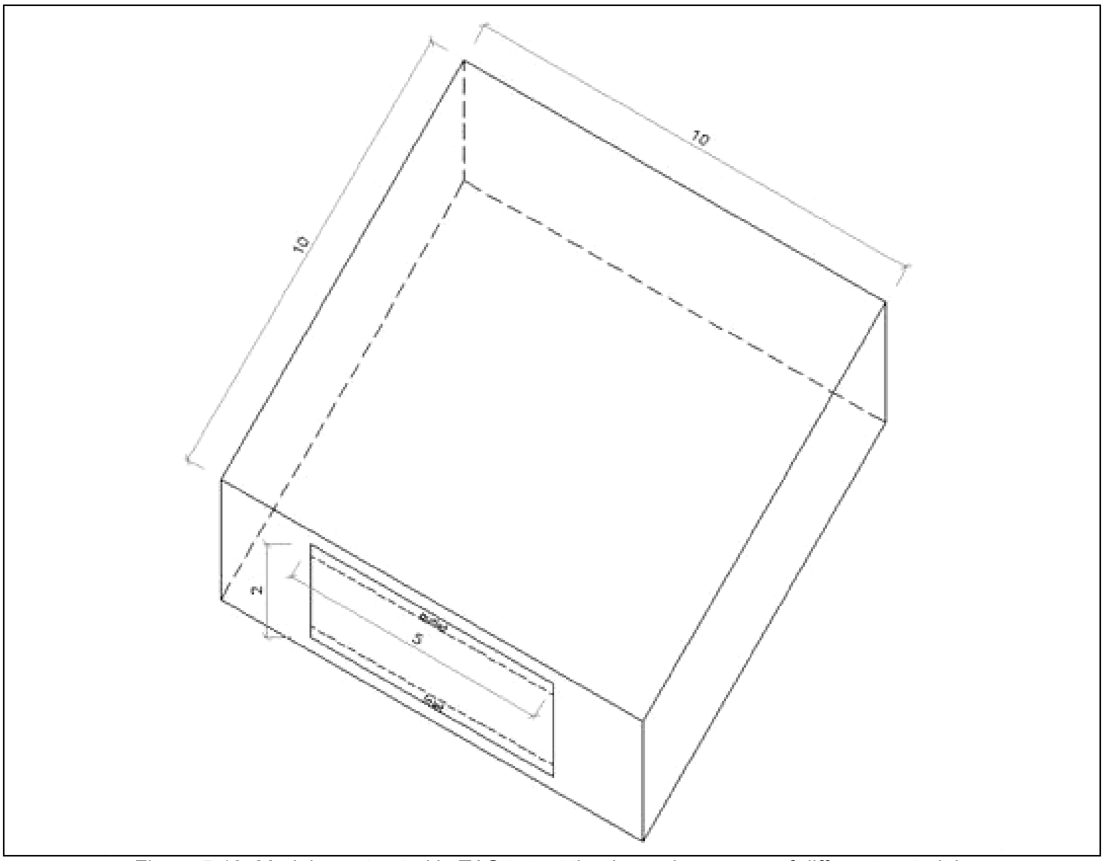


Figure 5-13: Model constructed in TAS to test the thermal response of different materials

The development of each case followed logical steps that involved the change of one parameter each time. A sensitivity analysis of these parameters is essential to explore the impact of each variable. The aim of sensitivity analysis is to explore the relative importance of fundamental design variables and the effect of various inputs and assumptions (Hamby, 1994 ; Athienitis and Santamouris, 2002). In summary, this type of analysis determines the sensitivity of the outputs to variations in the inputs, assisting on the build up of confidence in the model and recognition of its uncertainties to establish the quality of the assessment.

5.3.1 Scope and Method

The aim of this exercise is to determine the difference in the performance of the different building fabrics under the same conditions. The simplified model allows for a better understanding of the outcomes of the simulation.

The model and assumptions were kept the same for all the simulations in this section. The only change was the wall construction type whilst floor, roof and windows were kept the same.

Each simulation was named as shown in Table 5-5. As all inputs were the same the variation seen in the results are due exclusively to the different wall types. The Base Case simulations were then compared using peak temperatures, frequency of hours outside comfort zone and the PMV method.

Table 5-5: Base Case simulations

				Base Case Weather data 2002, infiltration 0.05ACH, no shading, no occupancy
				BC
Construction type	1.	Brick and Block full fill cavity wall	**BB**	BC BB
	2.	Timber frame part fill cavity wall	**TF**	BC TF
	3.	Insulated concrete formwork wall	**ICF**	BC ICF
	4.	Steel frame wall	**SF**	BC SF
	5.	Structural insulated panel wall	**SIPs**	BC SIPs
	6.	Cross laminated timber wall	**CLT**	BC CLT
	7.	Solid Concrete Block wall	**MT**	BC MT
	8.	Precast concrete panel wall	**PCP**	BC PCP

5.3.2 Assumptions

Many input parameters in dynamic simulation represent quantities that are difficult or impossible to be measured accurately so estimates and assumptions should be used. These have a large influence in the results so in this first simulation they were kept as simple as possible.

1. Weather: the weather data used was the CIBSE Design Summer Year Weather Data (DSY) for Nottingham based on the year 2002 described in section 5.1.2.

2. Calendar: it is assumed that summer (or no heating period) is from the 1st of May to the 30th of September and winter (heating period) is from the 1st of October to the 30th of April.
3. Internal Gains: no internal gains were assumed in this first simulation.
4. Ventilation and infiltration: as discussed in Chapter 2, ventilation and infiltration become even more imperative in highly insulated houses and can have a big impact in the building's performance.
   - Infiltration: in the first simulation, infiltration was assumed to be low at 0.05ACH in line with best practice in passive design.
   - Ventilation: no ventilation was assumed.
5. Comfort Temperature Range: as described in section 5.1.4, thermal comfort is extremely subjective and sometimes more acute temperatures are desirable. In this work the benchmarks suggested by CIBSE and described in Table 5-2 are used. The simulation results are illustrated by means of number of hours in a year when temperatures in the room go above $25^{o}C$ and above $28^{o}C$. In addition, the PMV method will be used to estimate the percentage of people who feel comfortable in each condition.
6. Heating: no heating was assumed.
7. Cooling; no cooling was assumed.

5.3.1 Results

The building has presented a degree of overheating with all the different fabric types. This is of course due to the lack of shading, ventilation or any passive strategies to mitigate the problem. However, it is worth remembering that the building also does not have internal gains which could lead to much worse overheating issues.

Figure 5-14 shows the temperature ranges for each of the different fabrics and for the external temperature. While for almost 93% of the time the external temperature is below $18^{o}C$, for all fabric types this percentage was around 45% showing that solar gains alone can deal with a large proportion of the heating demand of a building. Of course this would vary according to the size and orientation of the windows. At the same time as the fabric types performed in similar ways for temperatures below $18^{o}C$, they performed differently for warmer temperatures.

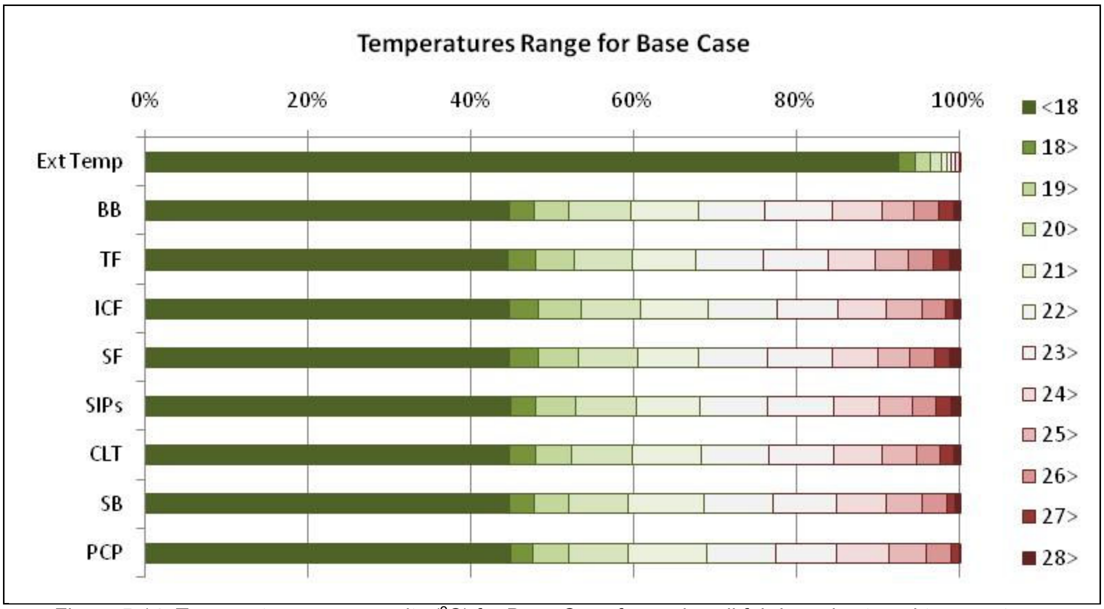


Figure 5-14: Temperature range results (°C) for Base Case for each wall fabric and external temperatures

Regarding overheating TF had the worst performance being above 25°C for over 10% of the time and even exceeding the maximum benchmark of 28°C for over 1% of the time (Figure 5-15). It was followed closely by SF which presented worse results for warmer temperatures. The best performance was of PCP which just reached 28°C for 0.07% of the time, practically negligible. The next top performers were SB and Insulated ICF both with very similar results. This is surprising considering that in SB the concrete is exposed to the space while in ICF the concrete is hidden behind an insulating layer. Another surprise is the fact that BB and CLT presented similar results being above 25°C around 9.4% of the time and above 28°C around 0.6%. It is worth remembering that they had very different admittance, decrement factor and time constant values.

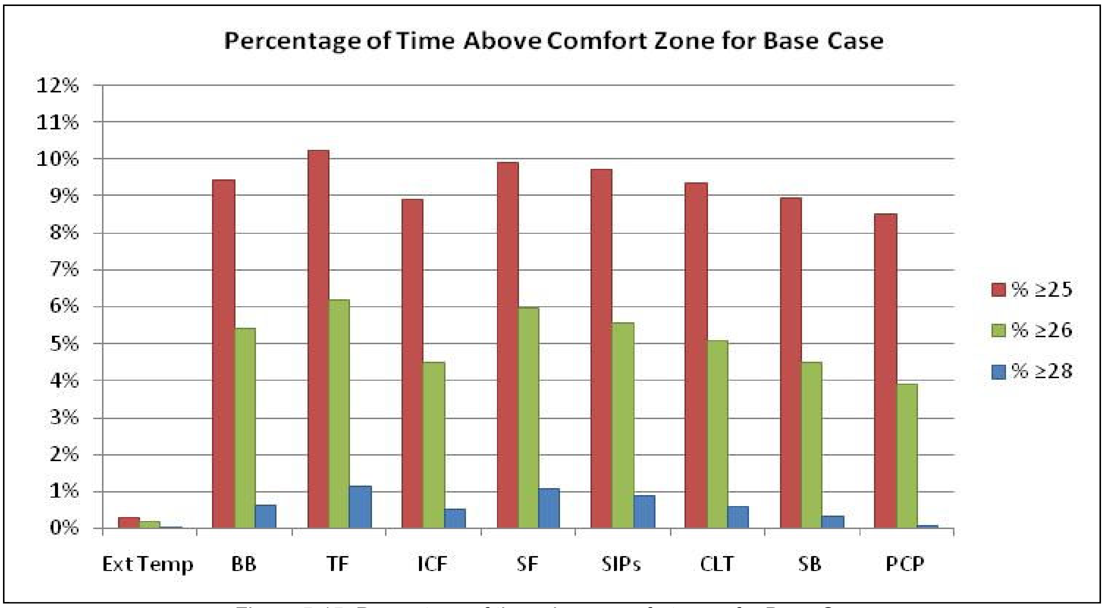


Figure 5-15: Percentage of time above comfort zone for Base Case

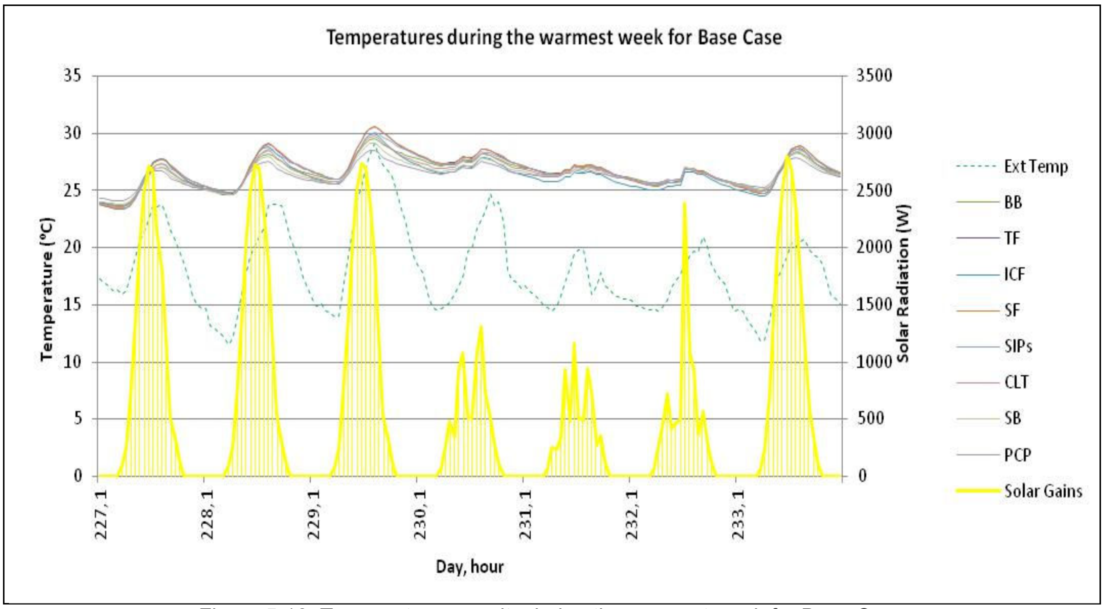


Figure 5-16: Temperatures results during the warmest week for Base Case

Figure 5-16 shows the warmest week when peak temperatures can be found. All the different fabrics were able to maintain fairly stable internal temperature (within 5^{o}C on a daily basis) despite the external temperature swings and the different availability of solar radiation.

Judging from the values for time constant, one would expect firstly a delay in the peak temperatures for some wall types (especially SB, CLT and PCP) and secondly a slower temperature drop for these wall types with a higher night time temperature and a more stable daily pattern. However, these expectations are not met when the results are analysed and the peak internal temperature happens at the same time as the peak external temperature.

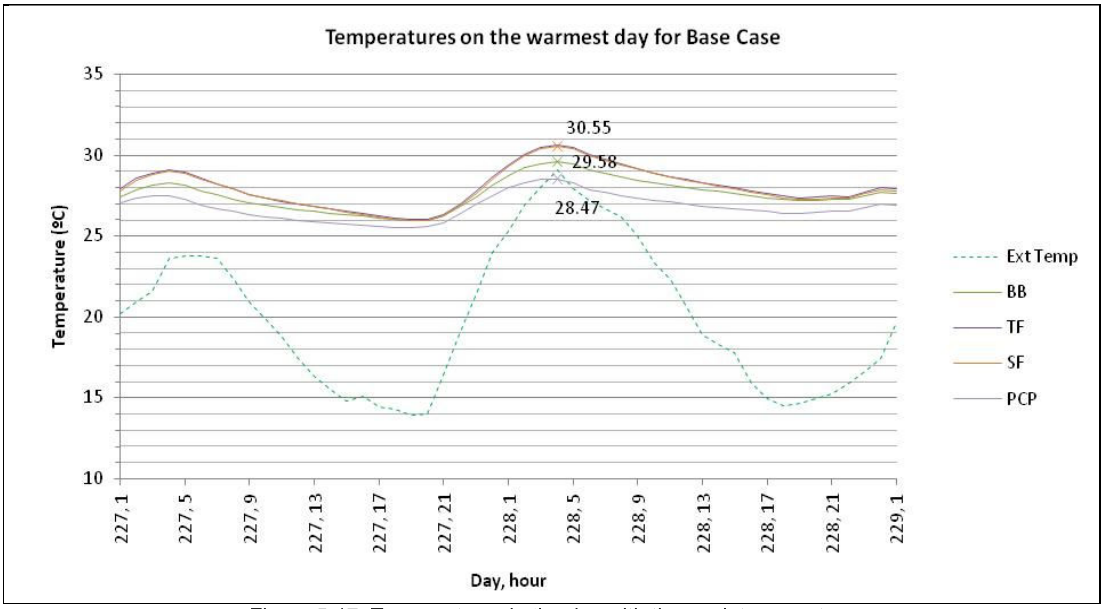


Figure 5-17: Temperatures in the day with the peak temperature

A closer look at the day with the peak temperature (Figure 5-17) reveals that the worst performers (TF and SF) had a close behavioural pattern reaching 30.5°C, which is about 2°C higher than the best performer (PCP). BB was the middle value, 1°C higher than PCP. Interestingly, at night when outside temperatures dropped, all the specification performed in a similar manner and the space does not seem to benefit greatly from the heat stored in the walls during the day. In fact, PCP drops about 0.5°C below the other cases. While these differences might seem small in the long run they mean a lot more energy would be consumed if a mechanical device was used for space conditioning.

In winter the coldest internal temperature (day 11) did not coincide with the coldest external temperature (day 2). Figure 5-18 shows that all the different fabrics are able to keep temperatures above 6°C despite external temperature reaching -6.7°C due to the low U-Value of the building's envelope and that the space is much more sensitive to solar gains than to external temperature swings. This shows that, with tighter building regulations regarding fabric, the role of good passive design becomes even more significant.

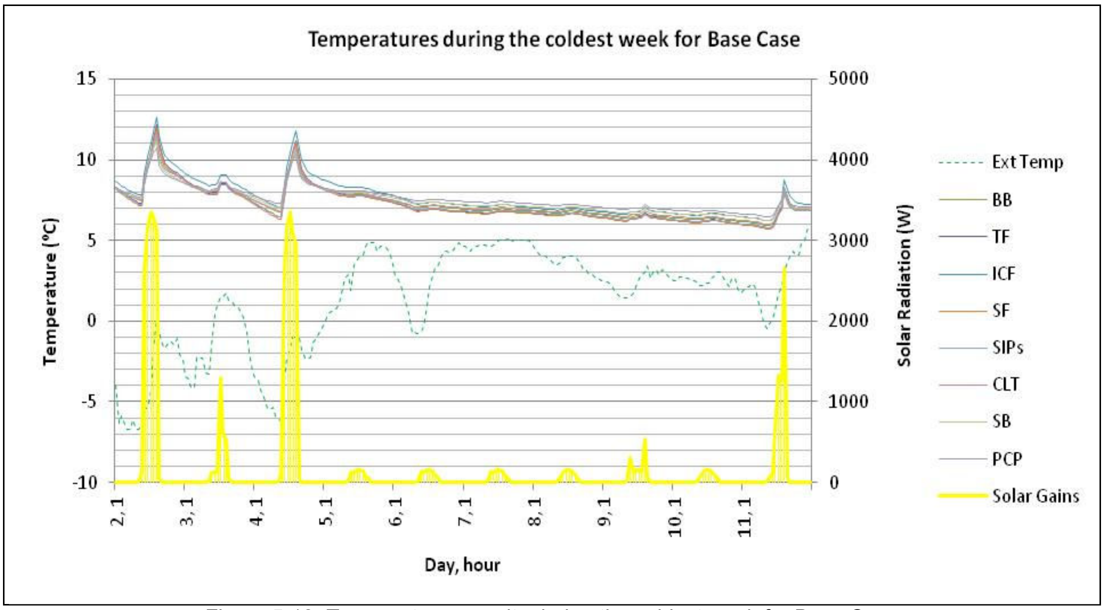


Figure 5-18: Temperatures results during the coldest week for Base Case

The day with the coldest external temperature (Figure 5-19) shows the thermal mass of the PCP wall is contributing for a 'flatter' pattern of temperature change with a slower response to gains and so a smaller minimum and maximum peak temperature (7.72 and 10.73°C respectively). In this time of the year, ICF seems to have the faster response to solar gains and warm up to a higher temperature (12.63°C) also keeping warmer for longer. Please note that in this graph the type and thickness of the lines representing ICF and PCP have been changed to facilitate viewing.

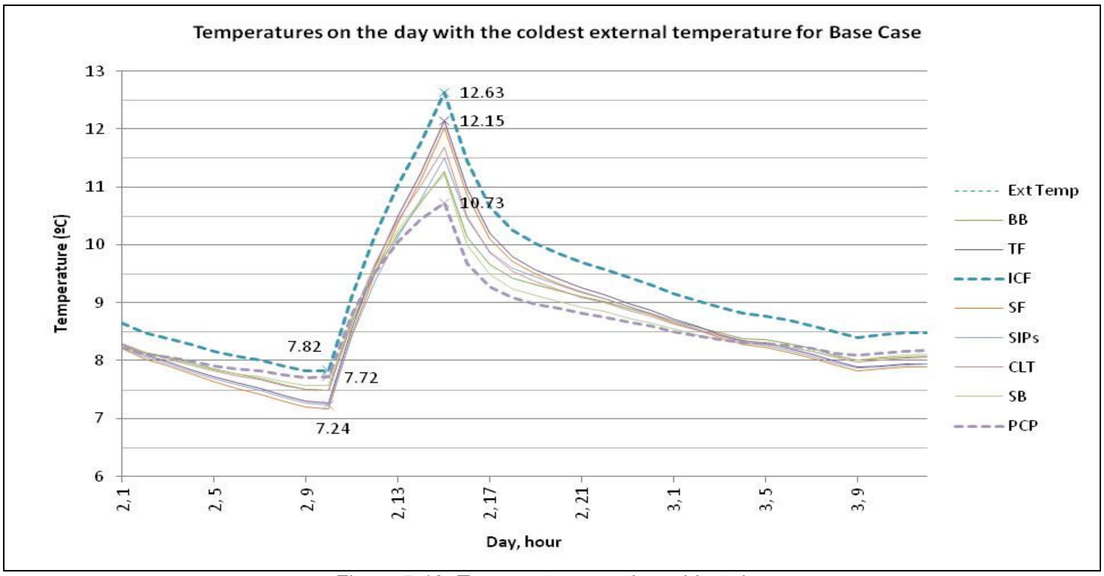


Figure 5-19: Temperatures on the coldest day

Overall, PCP presented the smaller peak internal temperature difference (22°C) while TF and SF swing around 3°C more. On average, over the year the difference between internal and external temperatures is very similar.

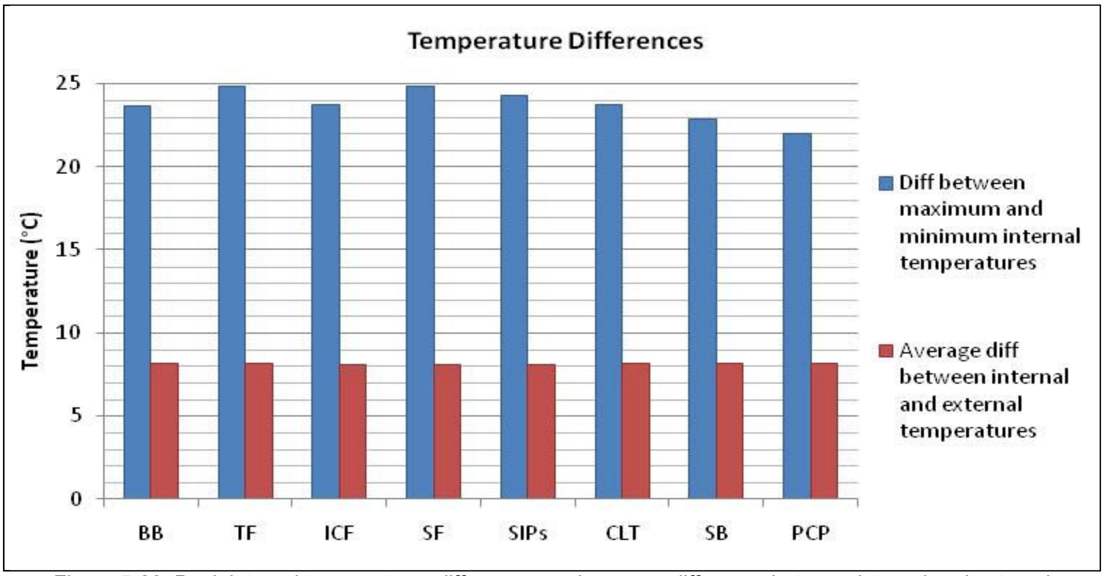


Figure 5-20: Peak internal temperatures differences and average difference between internal and external temperatures

If the Predicted Mean Vote (PMV) method is used to predict how people would feel in this space with each different fabric, the results reveal that most people would feel slightly cool, cool or cold for about 50% of the time. This was expected as the model does not consider any heating. The results also show that most people would feel neutral (PMV 0±0.5) for more than 40% of the time. Here PCP and SB presented the best results (45.2 and 44.3% respectively). When it comes to overheating, people would feel slightly warm, warm or hot for 1.6% of the time for PCP and for 3.6% of the time for TF. Using this parameter, SB and ICF performed well (2.4 and 2.1% respectively) while BB was not as good (3.2%). Figure 5-21 shows the frequency of hours the PMV lies within a given range.

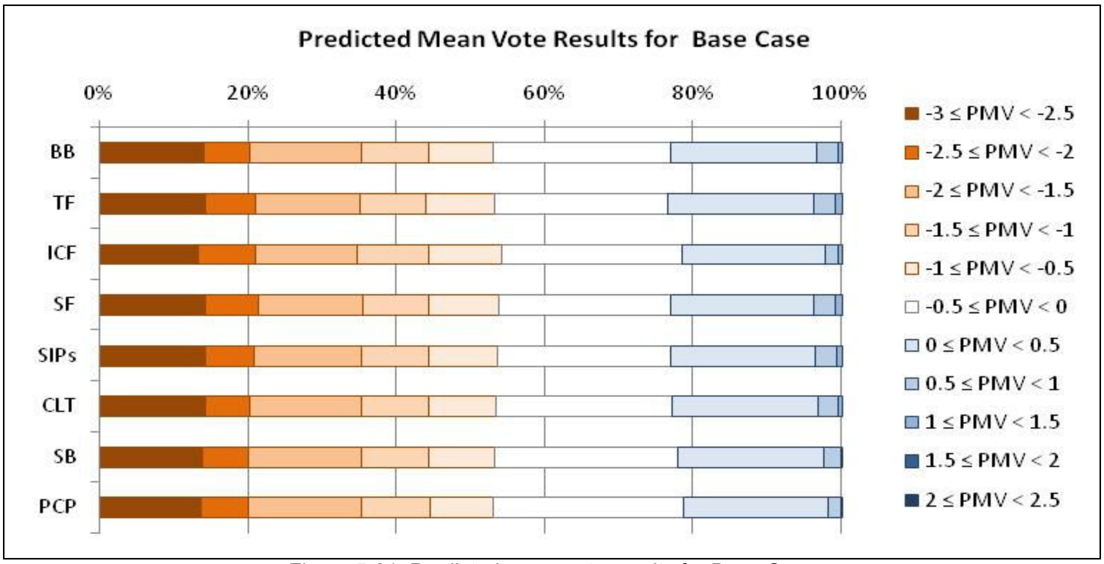


Figure 5-21: Predicted mean vote results for Base Case

Whilst these simulations gave an insight into the differences in the performances of the different fabrics, it does not consider basic passive design principles to mitigate overheating. Consequently, the next case uses the same model but with solar shading for the warmest times of the year as this is probably the simplest passive design strategy to be applied.

5.4 MODEL WITH SHADING, OCCUPANCY AND HEATING

At this stage shading was assumed as an essential part of the design so Case 0 was created. This is the same building as Base Case but with the addition of shading which blocks solar radiation in summer and allows it in winter as seen in Figure 5-22.

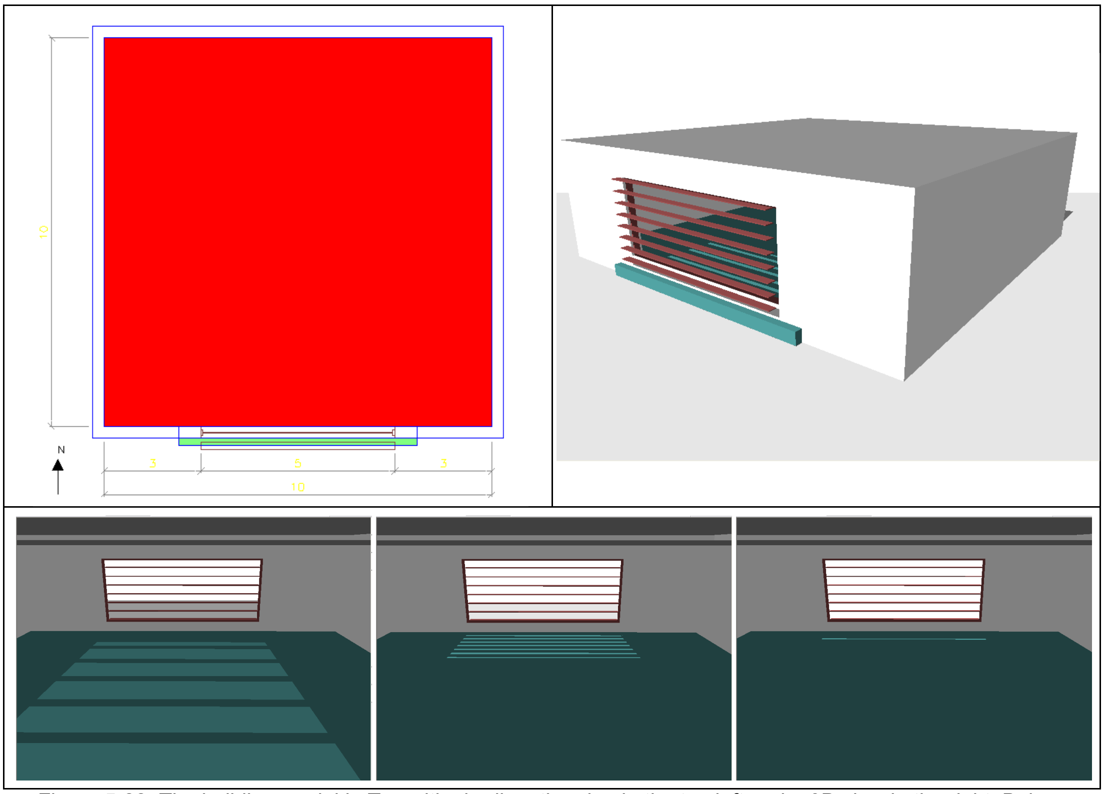


Figure 5-22: The building model in Tas with shading, the plan in the top left and a 3D view in the right. Below, internal views showing solar penetration in winter, autumn and spring, and summer respectively.

This section presents the results of four different cases, each created with one additional change made, building on the case that preceded it. It starts with Case 0 which is similar to Base Case but with the addition of shading, then introduces full time occupancy (Case 1), full time heating during the heating season (Case 2) and compares these to part time occupancy and heating (Case 3).

5.4.1 Scope and Method

The aim of these simulations was to determine firstly the influence of the fabric on the results if overheating mitigation strategies are in place (shading in Case 0) and secondly the difference occupancy makes to the results. It also looks into energy demand if heating is on full time (Case 2) and part time (Case 3).

Table 5-6 summarises Cases 0, 1, 2 and 3.

Table 5-6: Summary of Cases 0, 1, 2 and 3

			Case 0 Weather data 2002, shading, infiltration 0.05ACH	Case 1 As Case 0 + 2 full time occupants, infiltration 0.2ACH	Case 2 as Case 1 + winter constant heating	Case 3 as Case 2 but with intermittent occupancy and heating
			C0	**C1**	**C2**	**C3**
Construction type	1. Brick and Block full fill cavity wall	**BB**	C0 BB	C1 BB	C2 BB	C3 BB
	2. Timber frame part fill cavity wall	**TF**	C0 TF	C1 TF	C2 TF	C3 TF
	3. Insulated concrete formwork wall	**ICF**	C0 ICF	C1 ICF	C2 ICF	C3 ICF
	4. Steel frame wall	**SF**	C0 SF	C1 SF	C2 SF	C3 SF
	5. Structural insulated panel wall	**SIPs**	C0 SIPs	C1 SIPs	C2 SIPSs	C3 SIPs
	6. Cross laminated timber wall	**CLT**	C0 CLT	C1 CLT	C2 CLT	C3 CLT
	7. Solid Concrete Block wall	**MT**	C0 MT	C1 MT	C2 MT	C3 MT
	8. Precast concrete panel wall	**PCP**	C0 PCP	C1 PCP	C2 PCP	C3 PCP

The results were plotted for each case with each wall type and compared between wall types and cases. Just the most relevant graphs are shown here but more graphs are provided in Appendix 5.B.

5.4.2 Assumptions

The model was kept the same except for the addition of shading. Each case introduced a different parameter based on the following assumptions:

1. Weather: as Base Case
2. Calendar: as Base Case
3. Internal Gains: Internal heat gain represent the heat (sensible and latent) emitted by occupants, lighting, appliances or equipment inside a space, which might need to be removed by air-conditioning or ventilations. It may result in an increase in the temperature and humidity within the space. There are no good published data on internal gains in dwellings but it can be estimated as shown below (CIBSE, 2006: p. 6-2 to 6-6):
   - Occupants: when occupancy was introduced, two people were assumed to be sedentary in the space so occupancy sensible gains was 1.4W/m^2 and latent gain 0.8W/m^2. Case 1 and 2 have full time occupancy and in Case 3 occupants were

considered to be out during the whole day everyday and at home from 8pm to 8am (12h).

- Lighting: no lighting gains were assumed.
- Equipments gains: no equipment gains were assumed.
- Appliances: no appliance gains were assumed.

4. Ventilation and infiltration: infiltration was assumed to provide occupants with fresh air but no ventilation was added.
   - Infiltration: in the first simulation (Case 0), infiltration was assumed to be low at 0.05ACH at atmospheric pressure, in line with best practice in passive design and the same as Base Case. Once occupancy was introduced (from Case 1), infiltration was assumed to be sufficient to provide occupants with their need for fresh air (8l/s per person) which is approximately 0.2ACH at atmospheric pressure in this model. This is higher than the standards discussed in Chapter 1 but selected in order to simplify the assumptions as effectively infiltration is acting as background ventilation (i.e. trickle vents).
   - Ventilation: no ventilation was assumed.
5. Comfort Temperature Range: as Base Case
6. Heating: heating was assumed for Cases 2 and 3 during the heating period (1st of October to the 30th of April) when the house was occupied (i.e. full time in Case 2 and part time in Case 3). The thermostat was set to a lower limit of 19^{o}C and an upper limit of 21^{o}C and radiators were used as emitters.
7. Cooling; no cooling was assumed.

5.4.3 Results

It was found that the addition of shading and complete elimination of solar gains in summer diminished overheating for all wall types (Figure 5-23). Temperatures go above 25^{o}C for 1% or less of the time in the case of SB and PCP and between 1 and 2% in the case of BB, ICF and CLT. TF, SF and SIPs presented temperatures above 25^{o}C for more than 2% of the time. Consequently, PMV just goes to 'slightly warm scale and nobody would feel uncomfortably hot at any point in the simulated year (Figure 5-24).

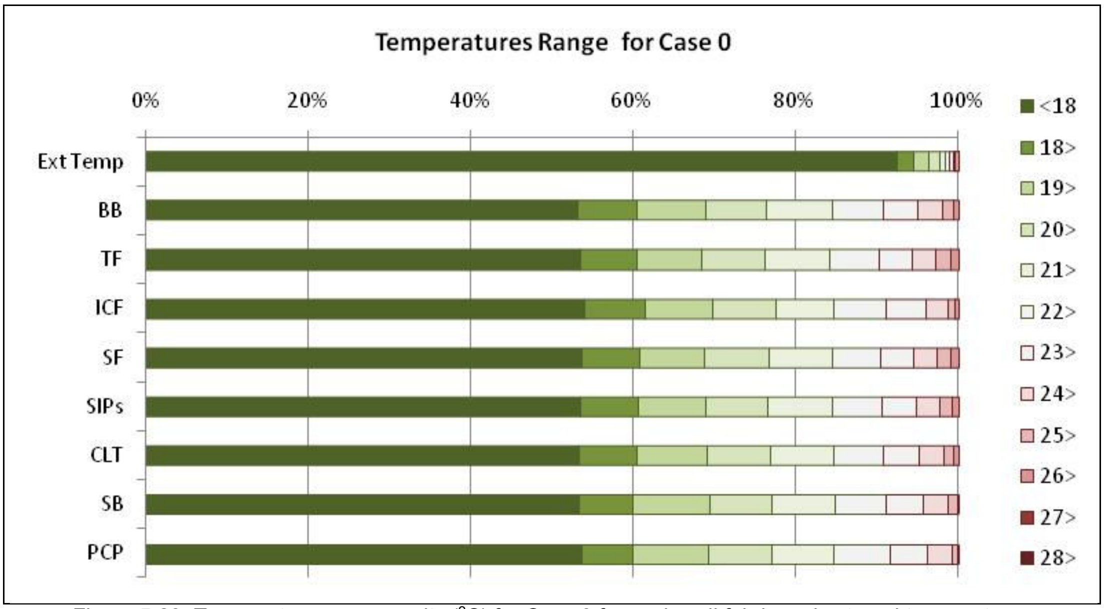


Figure 5-23: Temperature range results (^{o}C) for Case 0 for each wall fabric and external temperatures

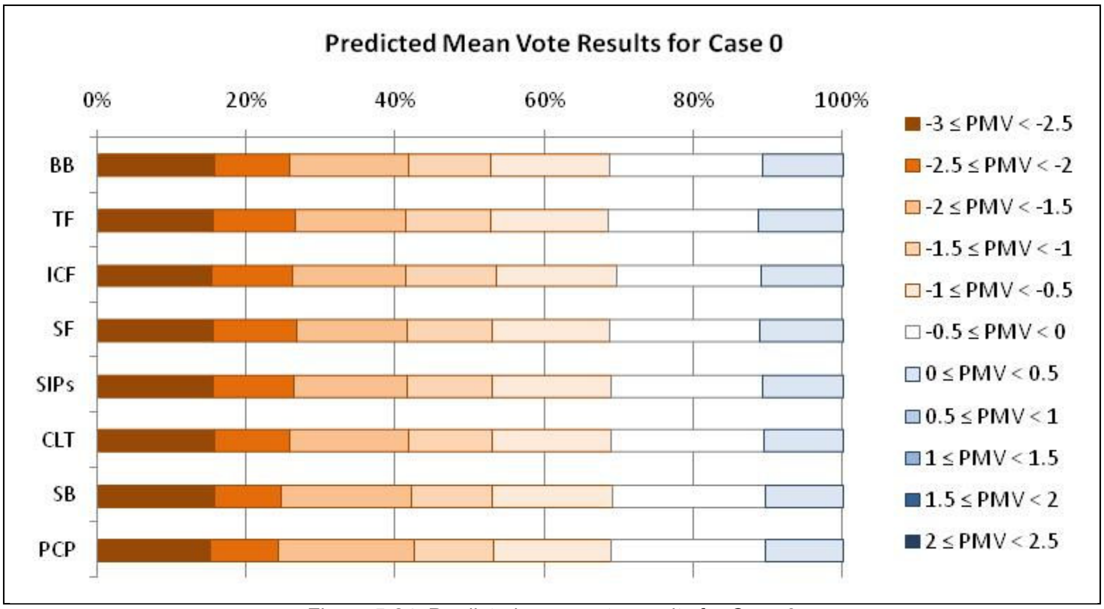


Figure 5-24: Predicted mean vote results for Case 0

Once occupancy is introduced, in Case 1, overheating is again observed. If the 'above 25^{o}C' criterion is used then all material types present overheating to a certain degree (Figure 5-25). However, if a higher temperature is acceptable then PCP, SB and ICF are the top performers reaching above 26^{o}C for less than or around 1% of the time followed by CLT and BB with less than 2%. TF, SF and SIPs were the worst cases reaching above 28^{o}C.

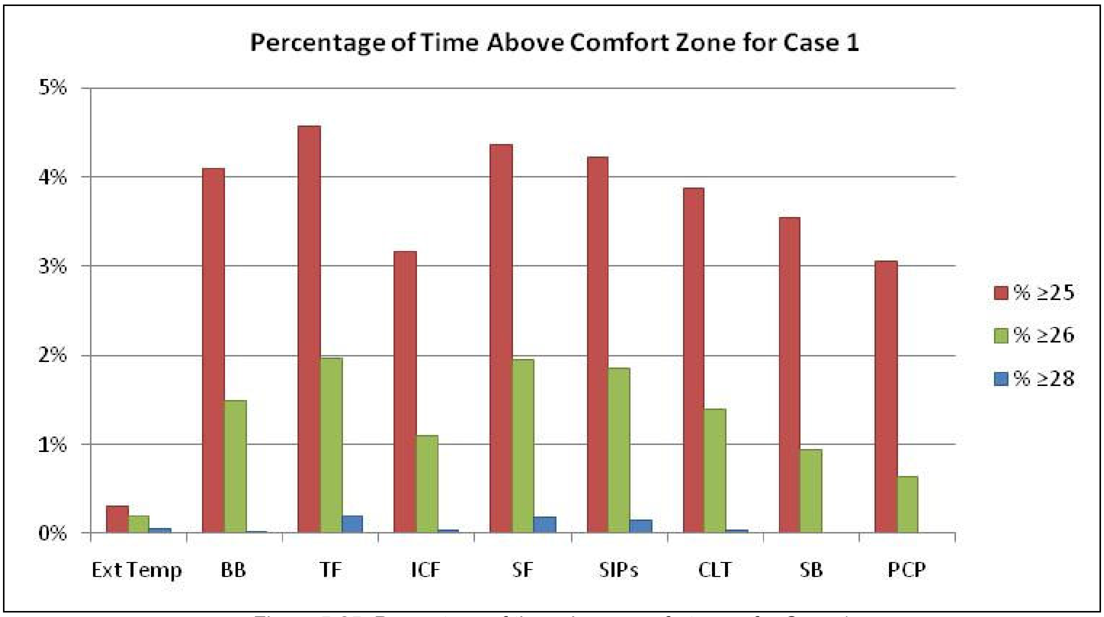


Figure 5-25: Percentage of time above comfort zone for Case 1

In terms of summer performance Case 2 is very similar to Case 1 as the only change was the addition of heating in winter. Consequently, most of people would feel comfortable for most of the time with the exception to the overheating presented in Figure 5-25 (more graphs of Case 2 and Case 3 can be seen in Appendix 5.B).

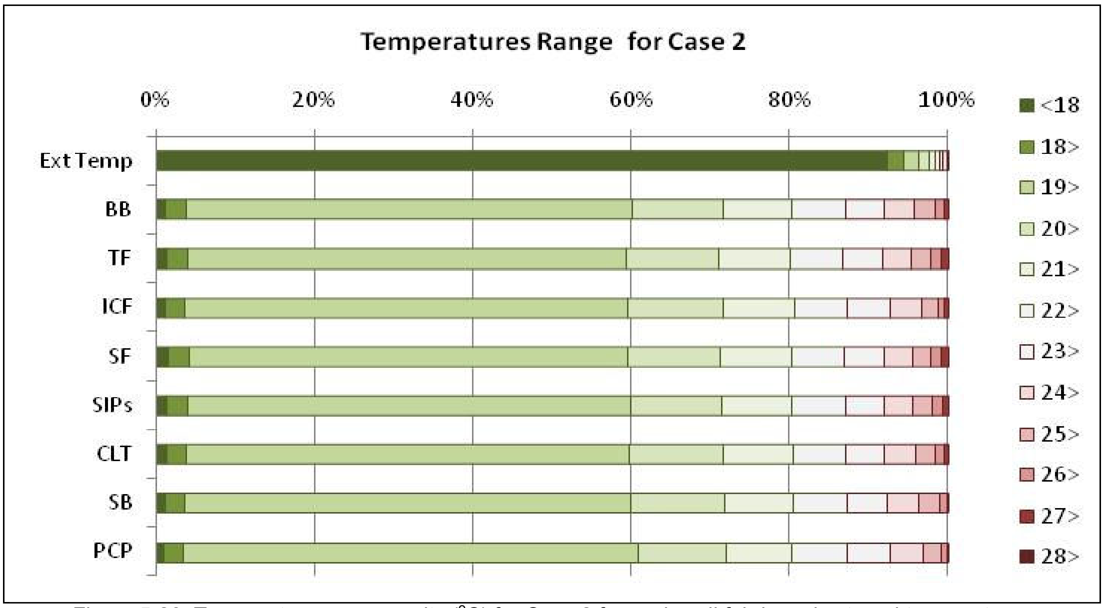


Figure 5-26: Temperature range results (^{o}C) for Case 2 for each wall fabric and external temperatures

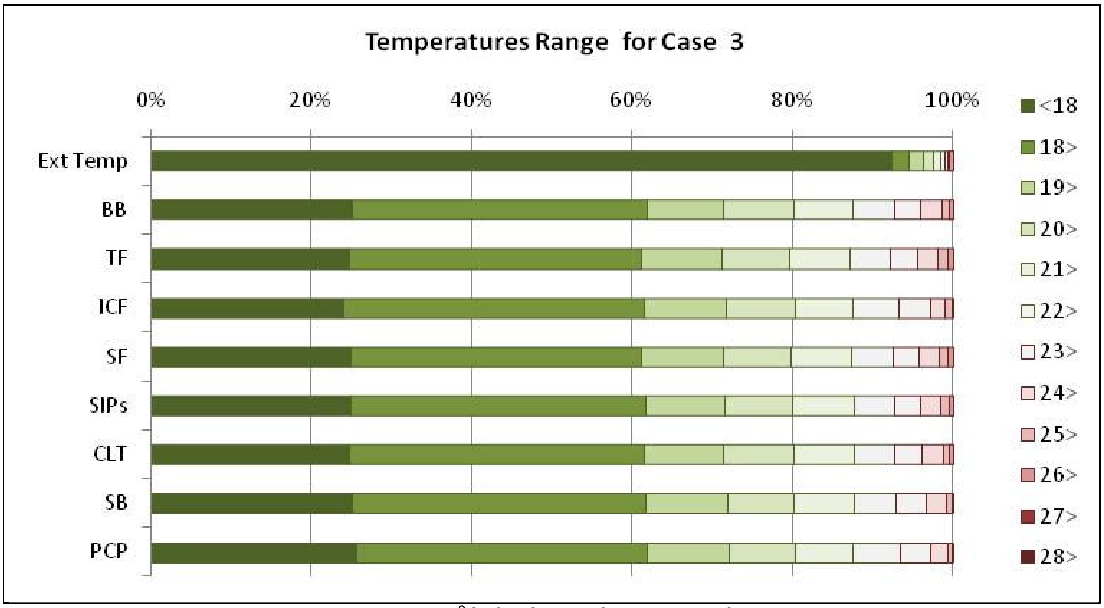


Figure 5-27: Temperature range results (°C) for Case 3 for each wall fabric and external temperatures

Case 3 has reduced overheating due to part time occupancy but the house is also kept at a lower temperature most of the day. As a consequence, despite the fact that the Case 3 house is just being heated up for half of the time (12h) while Case 2 house is permanently heated, the difference in heating demand is actually quite small suggesting that constant heating might not mean significantly higher energy bills in a highly insulated house (Figure 5-28). In the case of the higher mass wall types (PCP, SB) the difference is even smaller (less than 2kWh/m^2). PCP had the lowest heating demand of all wall types in Case 2 and 3, although in Case 3 the difference between wall types practically disappeared.

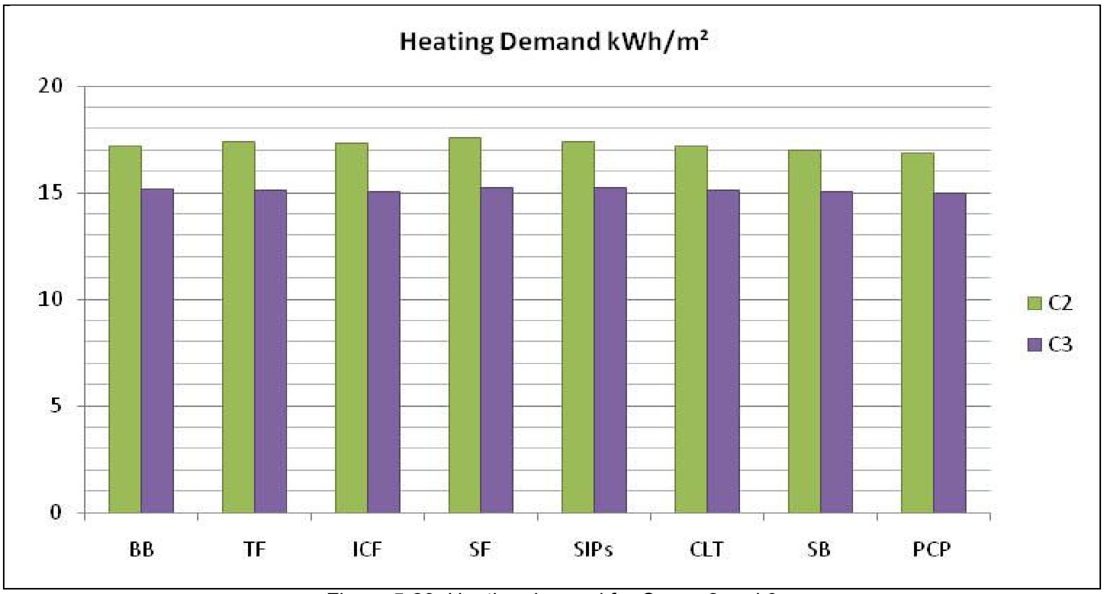


Figure 5-28: Heating demand for Cases 2 and 3

Figure 5-29 shows a comparison between each case for each wall type with regards to the percentage of temperature above 25°C. in Base Case, before shading was introduced, this was a major issue. In Case 0 the problem is almost mitigated with just TF, SF and SIPs presenting significant time above the limiting temperature and BB just above 1%. In Case 1 and Case 2 it became an issue once more especially for TF, SF, SIPs and to a smaller degree BB, all above 25°C for more than 4% of the time. Figure 5-30 concentrates on temperatures above 26°C and Figure 5-32 above 28°C. The higher mass wall types (PCP and SB) do not reach 28°C in Cases 1, 2 or 3. Nonetheless none of the results present significant overheating (i.e. likely to cause health issues) but some overheating that might lead to the use of air-conditioning devices.

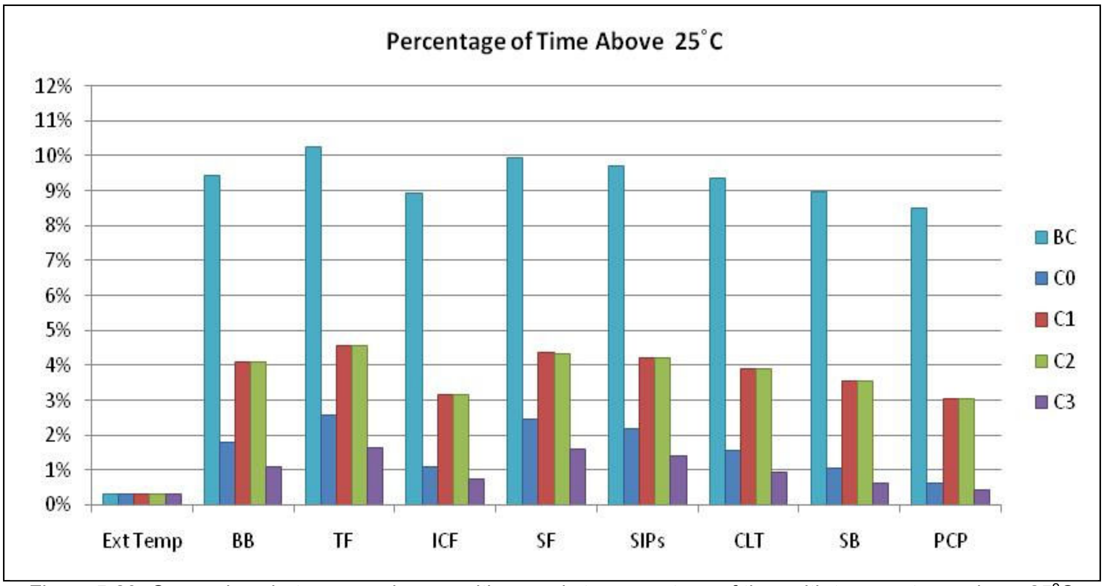


Figure 5-29: Comparison between each case with regards to percentage of time with temperatures above 25°C

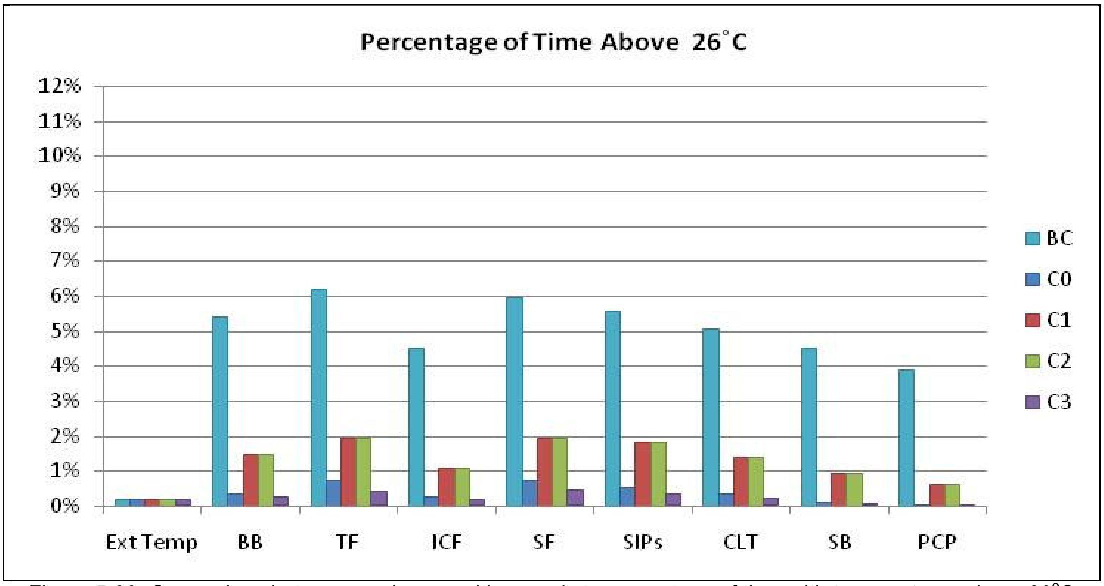


Figure 5-30: Comparison between each case with regards to percentage of time with temperatures above 26°C

It is interesting to note that ICF accumulates more hours in 25°C where it is similar to BB but when higher temperatures are considered it performs better than BB. On the other hand ICF performs almost equal to SB in Figure 5-29 and Figure 5-30 but worse in Figure 5-31.

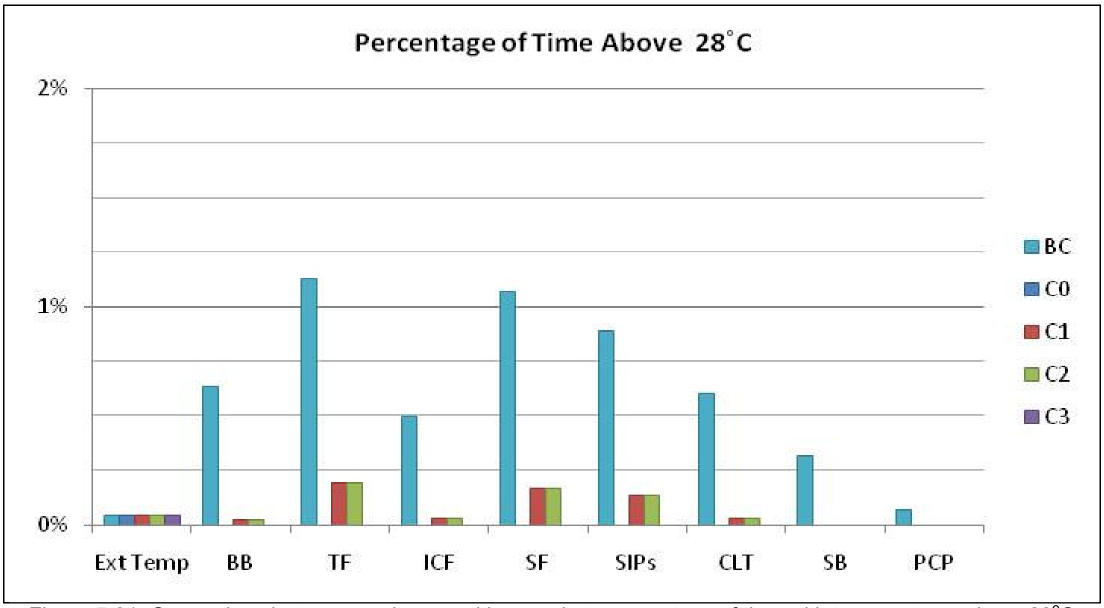


Figure 5-31: Comparison between each case with regards to percentage of time with temperatures above 28°C

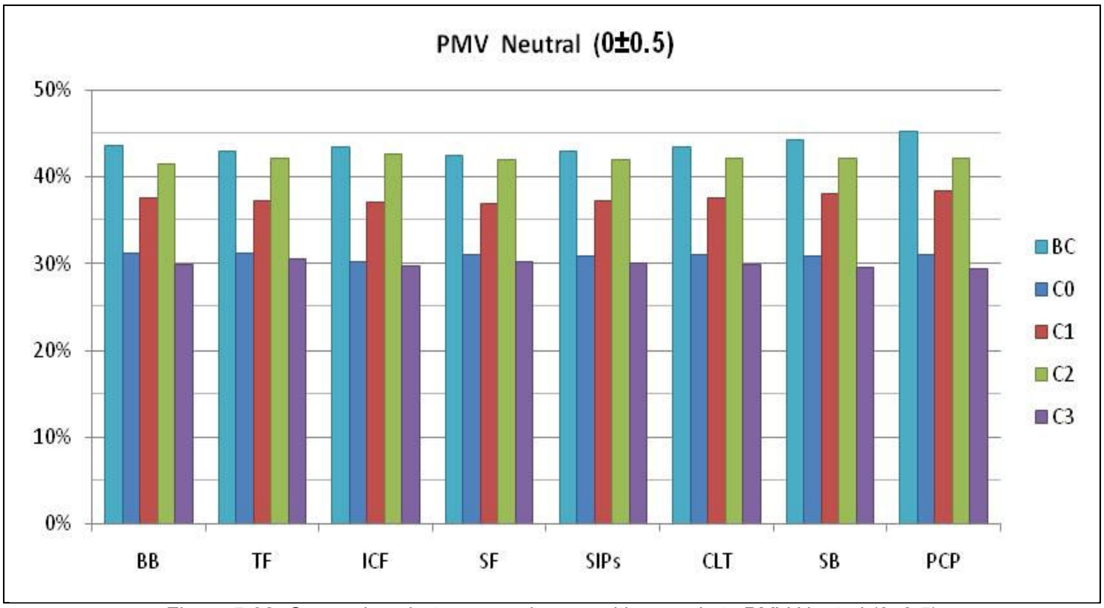


Figure 5-32: Comparison between each case with regards to PMV Neutral (0±0.5)

When the PMV method is applied to all the simulations, PCP scores highest in achieving PMV neutral (Figure 5-32) especially when there is no heating system (Base Case). It also has the lowest percentage of people finding it slightly warm (Figure 5-33) suggesting that higher thermal mass is connected to better comfort without active means of space conditioning.

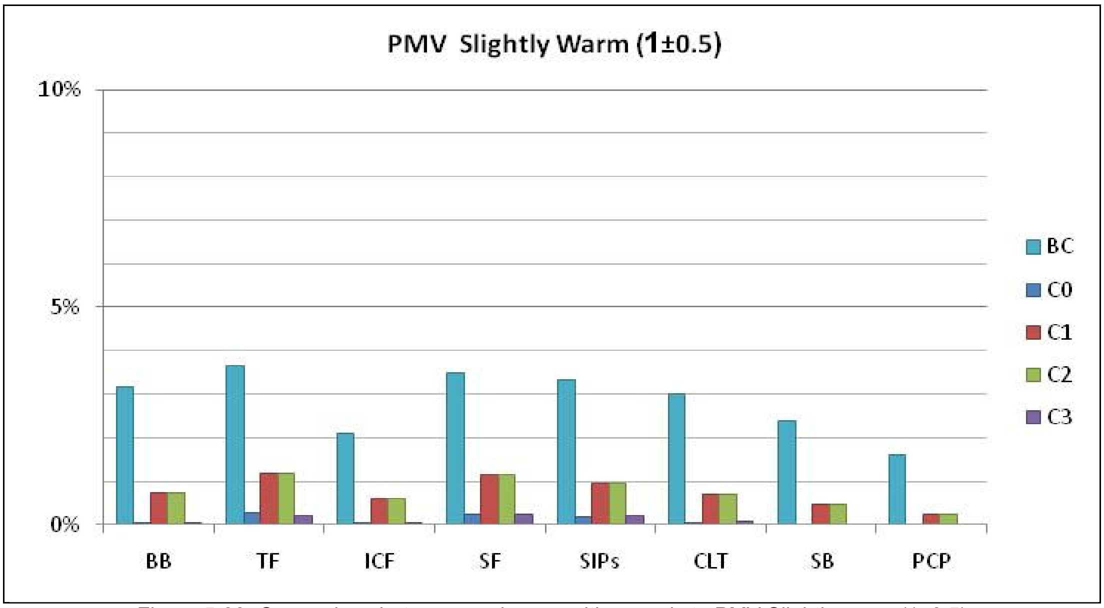


Figure 5-33: Comparison between each case with regards to PMV Slightly warm (1±0.5)

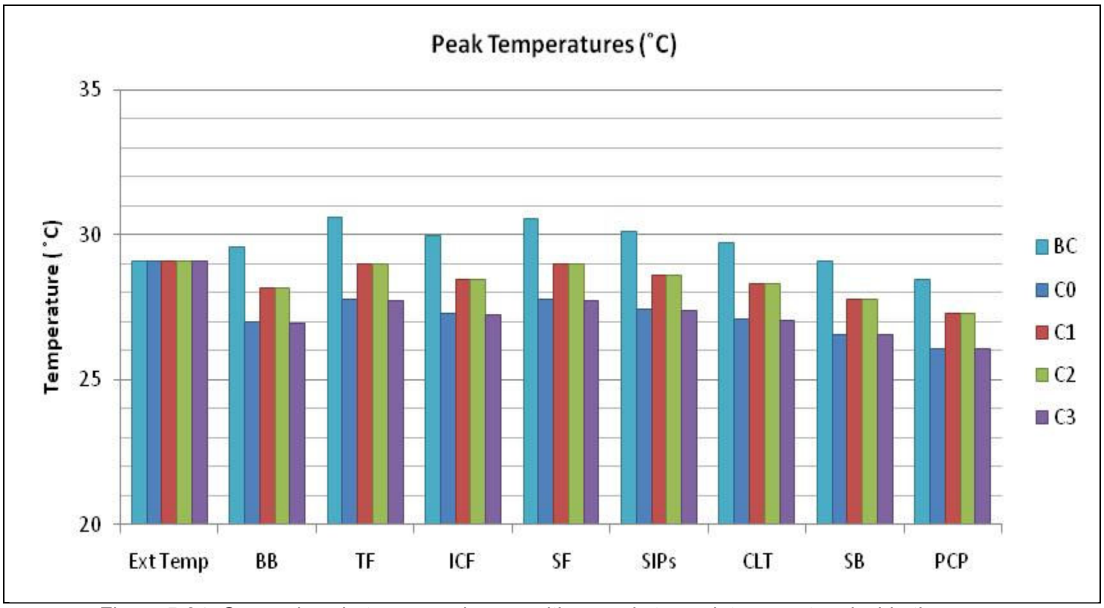


Figure 5-34: Comparison between each case with regards to peak temperature inside the space

Figure 5-34 allows a full appreciation of the most significant benefit of thermal mass, the reduction of peak temperatures. It must be remembered that the high mass building has not been optimised to work at its best and the temperature difference seen here is due to the wall's build-up alone. By combining different aspects of passive design including thermal mass one can achieve even better results. Nevertheless between the better performer and the worse there always seem to be at least a significant 2^{o}C difference in summer.

These observations suggest that the higher the temperature the better the high mass wall is going to perform. They also suggest that the high mass might be beneficial in winter too. The next section will look into overheating in future scenarios with the addition of ventilation.

5.5 MODEL USING FUTURE WEATHER SCENARIOS

This section uses the Case 3 model that presented no significant overheating in today's climate and low energy demand for heating (around 15kWh/m^2) and investigates its performance in the future weather scenarios discussed in section 5.1.3.

5.5.1 Scope and Method

The objective of this section is to investigate whether the house that presented no overheating in today's weather would present overheating in 2020, 2050 or 2080. The base model used was Case 3 and the model was kept the same for Cases 4, 5 and 6. Case 7 used Case 6 but with introduced ventilation. Once more, all the cases were tested with all the wall types. Table 5-7 summarises cases 4, 5, 6 and 7.

Table 5-7: Summary of Cases 4, 5, 6 and 7

			Case 4 As Case 3 but with weather data high-emissions 2020	**Case 5** As Case 4 but with weather data high-emissions 2050	**Case 6** As Case 5 but with weather data high-emissions 2080	**Case 7** As Case 6 but with ventilation
			C4	**C5**	**C6**	**C7**
Construction type	1. Brick and Block full fill cavity wall	**BB**	C4 BB	C5 BB	C6 BB	C7 BB
	2. Timber frame part fill cavity wall	**TF**	C4 TF	C5 TF	C6 TF	C7 TF
	3. Insulated concrete formwork wall	**ICF**	C4 ICF	C5 ICF	C6 ICF	C7 ICF
	4. Steel frame wall	**SF**	C4 SF	C5 SF	C6 SF	C7 SF
	5. Structural insulated panel wall	**SIPs**	C4 SIPs	C5 SIPs	C6 SIPs	C7 SIPs
	6. Cross laminated timber wall	**CLT**	C4 CLT	C5 CLT	C6 CLT	C7 CLT
	7. Solid Concrete Block wall	**MT**	C4 MT	C5 MT	C6 MT	C7 MT
	8. Precast concrete panel wall	**PCP**	C4 PCP	C5 PCP	C6 PCP	C7 PCP

5.5.2 Assumptions

1. Weather: the weather data used was the CIBSE Design Summer Year Weather Data (DSY) for Nottingham 'morphed' into weather data for 2020, 2050 and 2080, created using the UKCIP process described in section 5.1.3.
2. Calendar: as Base Case.
3. Internal Gains: as Case 3:
4. Ventilation and infiltration: starts the same as in Case 3 but Case 7 has added ventilation.

- Infiltration: 0.2ACH at atmospheric pressure.
- Ventilation: ventilation was introduced in Case 7 by means of windows opening in summer only (natural ventilation only). It was assumed that the windows would start to open when temperature in the house reached 22^{o}C and be fully opened at 28^{o}C just when occupancy was in the house. This is due to security issues and the fact that windows are rarely automated. If external temperatures exceed the internal temperature, the window will close.

5. Comfort Temperature Range: as Base Case.
6. Heating: as Case 3.
7. Cooling; no cooling was assumed.

5.5.3 Results

If 25^{o}C is considered as a limiting temperature, than all cases presented some degree of overheating regardless of the wall construction (Figure 5-35). In Case 4 PCP and ICF maintained 25^{o}C just above 5% of the time while BB, TF, SF and SIPs all exceeded 25^{o}C for more than 6% of the time. In Case 6, in 2080, 25^{o}C was the temperature for almost 30% of the time in all cases. It is clear that another means of cooling should be introduced, in this case ventilation in Case 7.

Even if 28^{o}C is considered as the limiting temperature there is overheating as all cases reach that temperature for more than 1% of the time (Figure 5-36 – please note the scale of this graph is different from the previous to facilitate viewing). When overheating is limited (i.e. Case 4 and 5) just the difference on the wall type is able to significantly reduce overheating. However, when temperatures go higher (Case 6), all wall types performed in a similar manner with 13% of the time above 28^{o}C showing the need to optimise the use of thermal mass by adding ventilation to remove the excess stored heat.

This is also clear when PMV is considered as there is significant difference in PMV ≥ 1 in Case 4 but that difference becomes smaller with the rise in temperature of Cases 5 and 6 (Figure 5-38). It is interesting to note in Figure 5-37 that between Case 4 and 5 there was no performance pattern, i.e. walls TF, SF and SIPs achieved more PMV neutral while BB and CLT kept at the same level and SB and PCP decreased. This might be due to winter performance as the last two always presented more time below 18^{o}C. More graphs can be seen in Appendix 5.C.

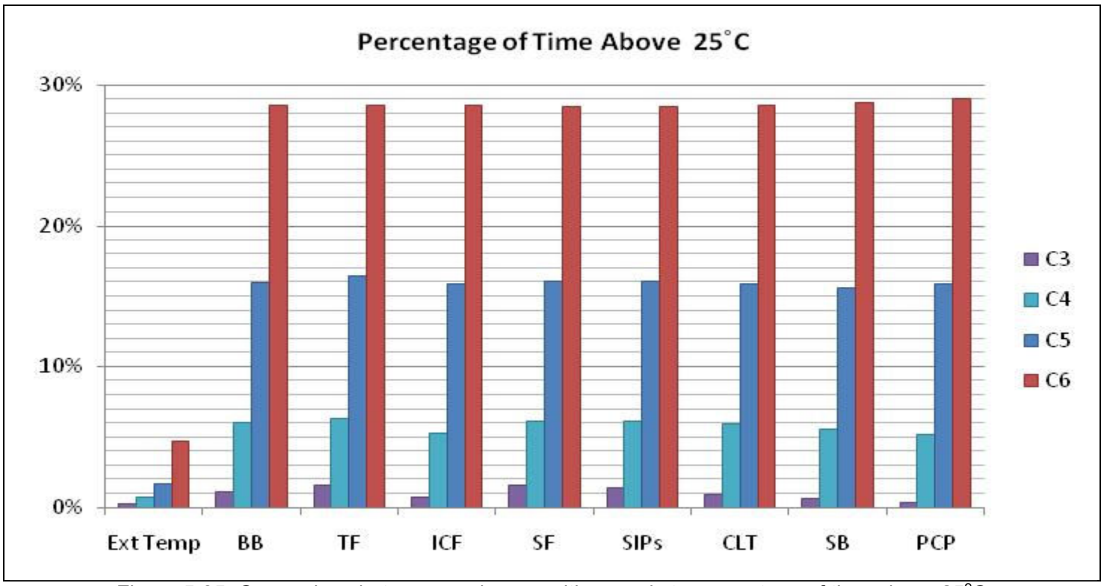


Figure 5-35: Comparison between each case with regards to percentage of time above 25°C

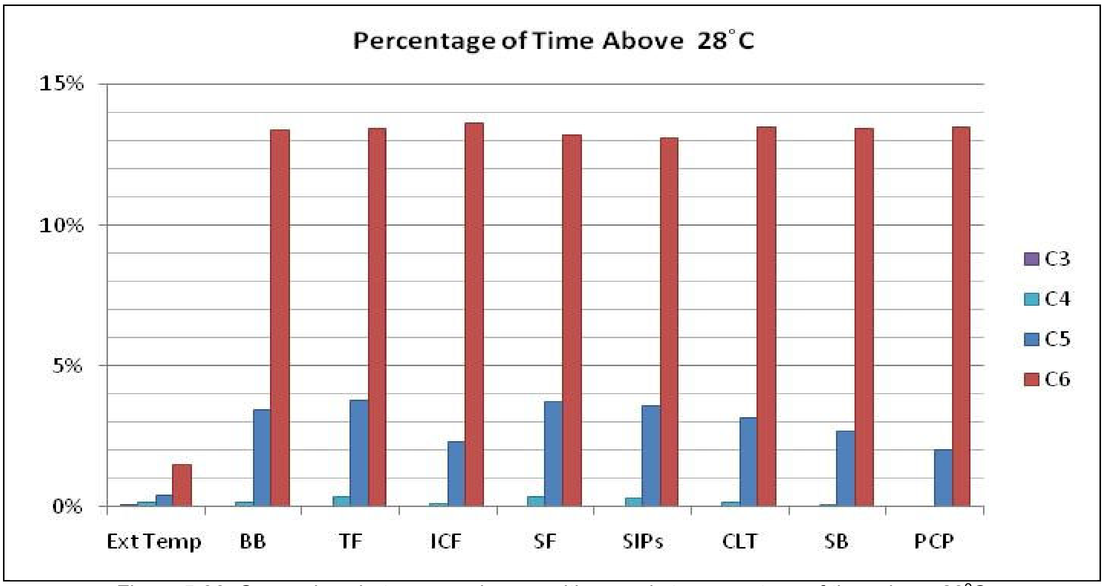


Figure 5-36: Comparison between each case with regards to percentage of time above 28°C

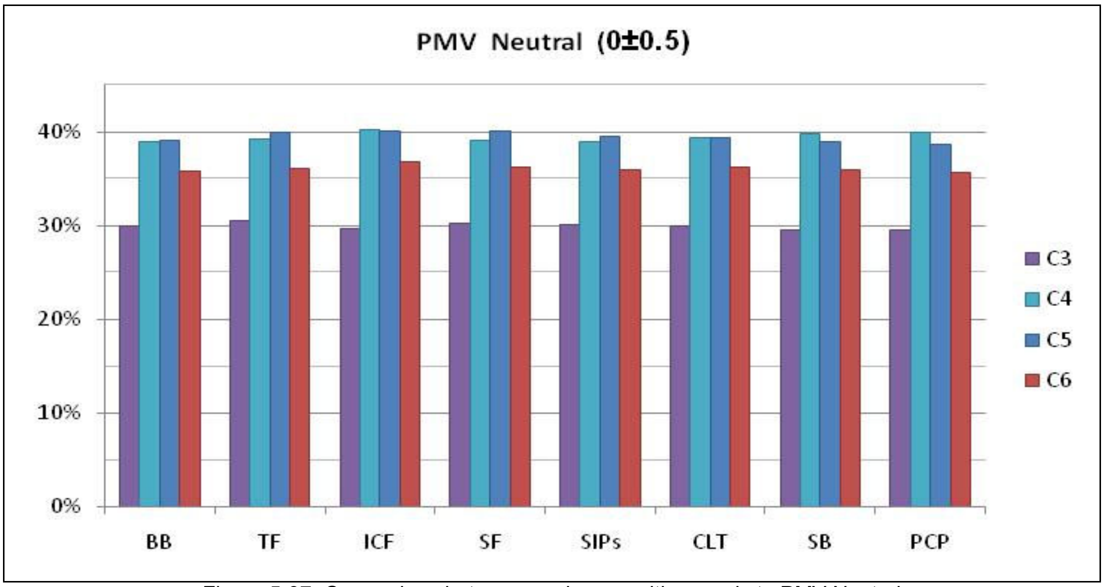


Figure 5-37: Comparison between each case with regards to PMV Neutral

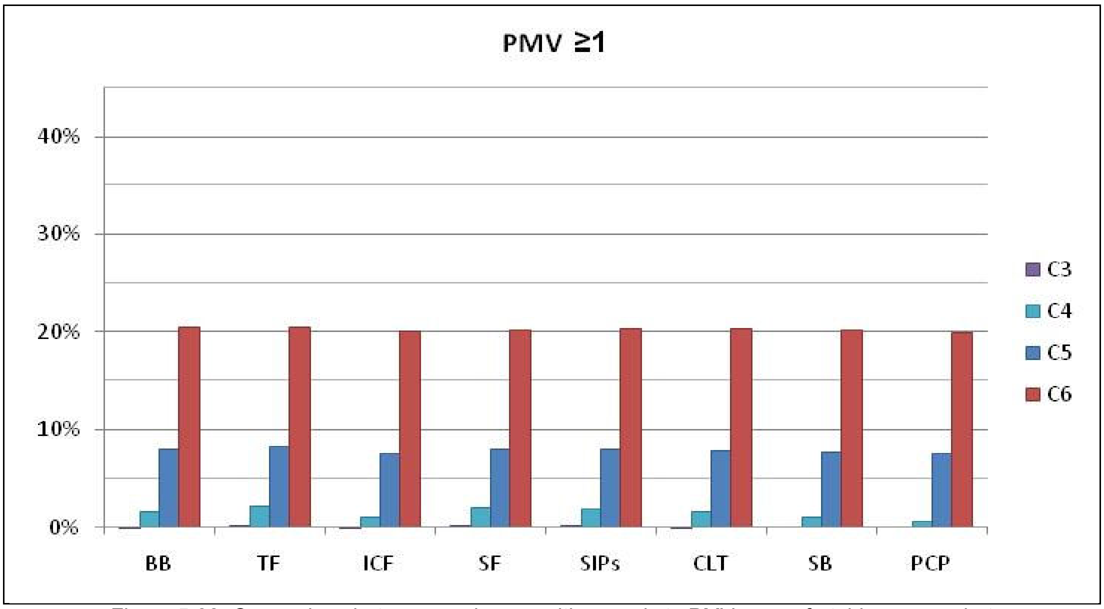


Figure 5-38: Comparison between each case with regards to PMV uncomfortably warm or hot

The most accentuated differences occurred when peak temperatures are considered with PCP being always around 2°C lower than TF and SF and up to 4°C lower than the peak external temperature. The second best performer is SB always around 1.5°C below TF and SF followed by BB and CLT, which again had similar performances around 1°C lower than TF and SF.

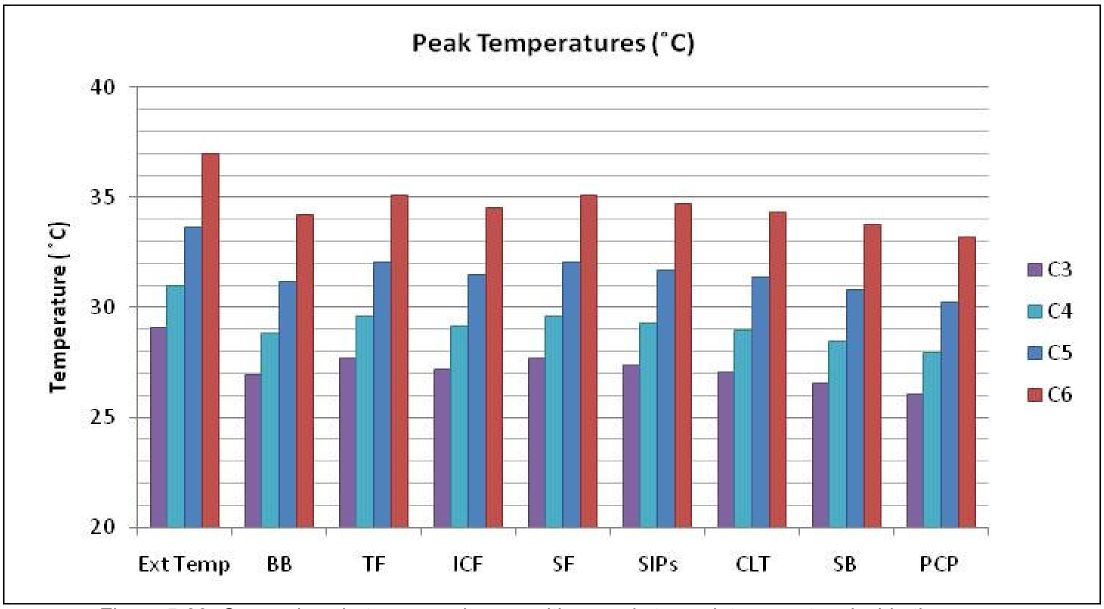


Figure 5-39: Comparison between each case with regards to peak temperature inside the space

In summary, Case 7 comprises full summer shading (which has been used since Case 0), part time occupancy (which has been applied since Case 3), winter heating (since Case 3) and summer natural ventilation (the window starts to open at 22°C and is 100% open at 28°C). Case 7 assumes the high-emissions 2080 climate change scenarios.

As it can be seen in Figure 5-40 and Figure 5-41, even with all the mitigation strategies described, summer overheating has not been completely eliminated even though ventilation improved greatly the situation. Just PCP and SB are within acceptable levels of overheating while BB and CLT are just below the border line (1% above 28^{o}C) and ICF and SIPs just above it. SF and TF presented unsatisfactory levels of overheating.

Regarding peak temperatures, once more PCP stayed around 2^{o}C below SF and TF and BB and CLT around 1^{o}C below (Figure 5-42). However, all cases reached temperatures above 28^{o}C.

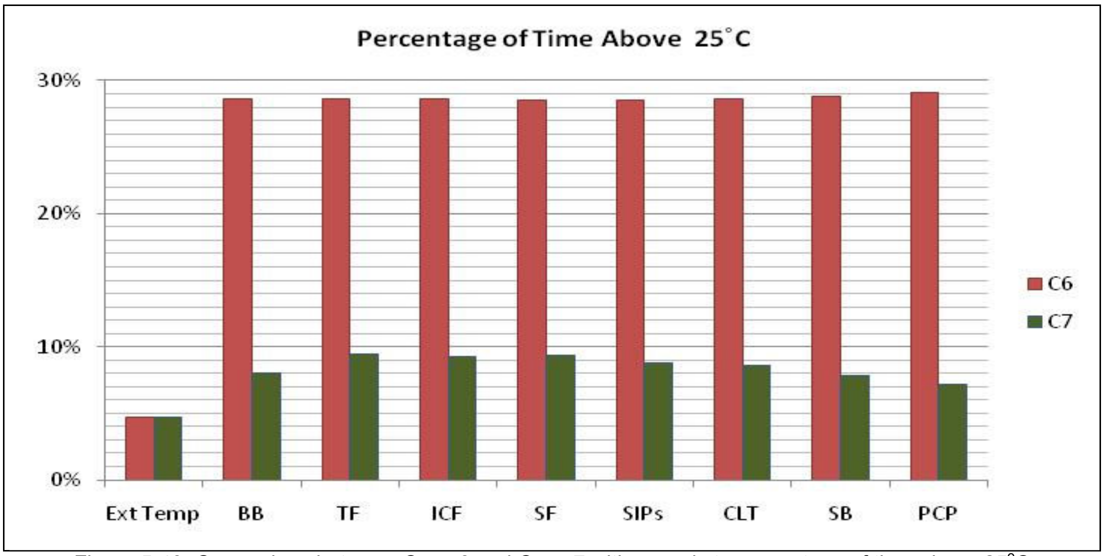


Figure 5-40: Comparison between Case 6 and Case 7 with regards to percentage of time above 25^{o}C

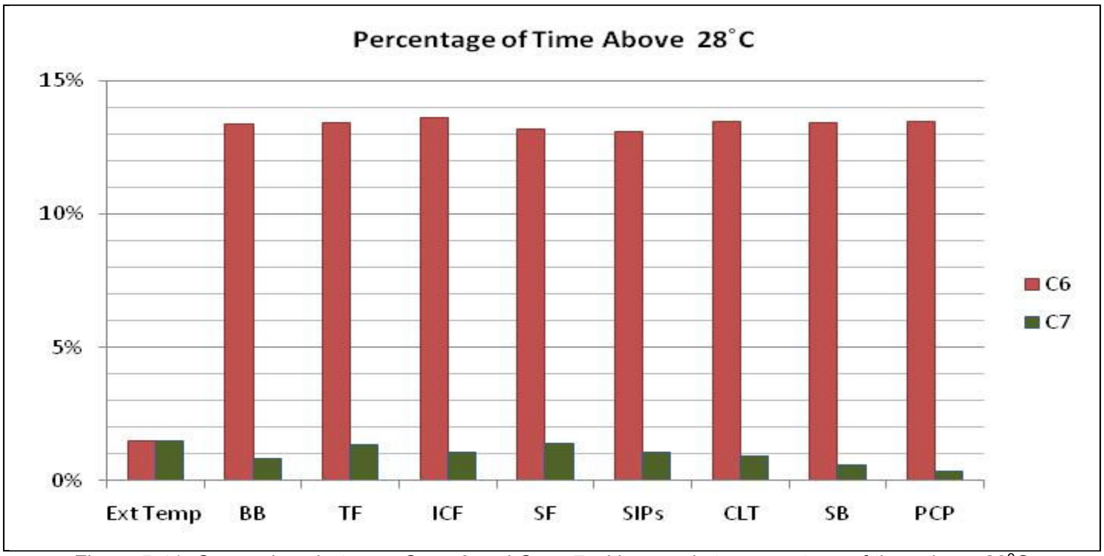


Figure 5-41: Comparison between Case 6 and Case 7 with regards to percentage of time above 28^{o}C

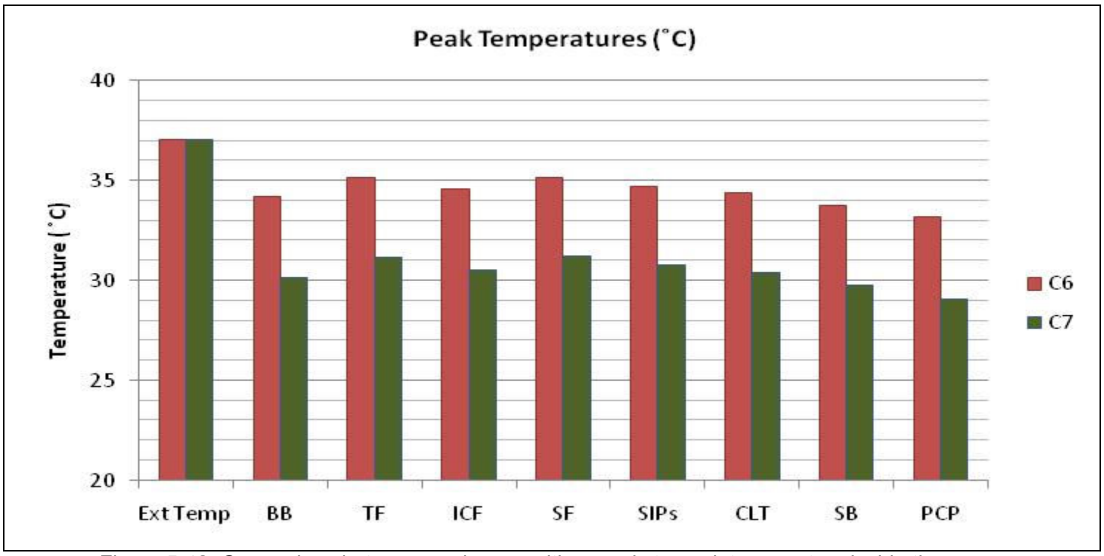


Figure 5-42: Comparison between each case with regards to peak temperature inside the space

5.6 CONCLUSIONS AND FURTHER WORK

> *"I am not suggesting that the thermal mass theory is incorrect or that the science is rubbish. I am simply pointing out that some of the claims made by the 'heavy massers' are exaggerated. It's very similar to the arguments about whether underfloor heating uses more or less energy than radiators. The answer to both questions is it depends. Constantly occupied buildings benefit from thermal mass, whilst intermittently occupied ones are better built as lightweight structures with quick radiator heating systems. Note that the pro-thermal mass studies, as far as I can tell, are always carried out assuming the buildings are in constant use. I think you would get very different results from computer modelling if your occupancy assumptions were changed to match a DINKY household. Then thermal mass could easily be shown to be a net energy burden. It all depends on the parameters you set."*
>
> Mark Brinkley, housebuilding expert author at the UK Timber Frame Association website[52]

Temperatures in the UK are rising and this trend is likely to continue. In the East Midlands, where Nottingham is, up to 4^{o}C rise is expected, which may mean not only overheating issues in buildings but also make cooling strategies such as night time ventilation difficult in hot periods. This is likely to cause a rise on the use of air-conditioning in British houses.

Eight different wall construction types were selected representing the most common types used in housing construction in the UK. These are distinguished by differing quantities of thermal mass and diverse thermal properties. The only fixed parameter across all wall types was a U-Value of 0.12W/m^{2}K.

The parameters admittance, decrement factor and time constant do not seem to advantageously characterise a construction type with regards to thermal mass. For example, SIPs presented a reasonably high admittance but had a significantly poorer performance than BB and CLT (both of which had similar admittance to SIPs) when summer overheating is considered. Decrement factor and time constant values also do not match the results of the simulations in view of best and worst performers.

A simple model was built to allow for easy understanding of the impact of each wall type. Suggestions for further work include experimentation with different room and window sizes and their impact on the performance of the room.

Sensitivity analysis was found to be a relevant method to approach the development of project specific design strategies allowing for a characterization of each input and its influence on the output. However, sensitivity analysis cannot directly inform an optimum solution as each parameter requires a pre-understanding of concepts from the designer. In addition, it is a time-consuming method that might not be suitable in a design office environment due to time constraints. A second suggestion for further work is the

[52] Available at www.timber-frame.org/html/understanding-the-issues/thermal-mass-in-housing [Accessed on the 26th of July 2009]

development of a guide that could be used by designers to inform the early stages of their projects without having to undertake dynamic analyses.

Mark Brinkley, quoted above, is right when he says it all depends on the parameters you set. That is one of the reasons why a model with minimum parameters was used in the chapter. As the results have shown in this chapter, there is benefit with regards to summer overheating from using a construction type with high thermal mass. In the case of the model used here, the difference in the peak temperature between the top performer (PCP) and the worst performers (TF and SF) was always at least 2^{o}C, despite the change in other inputs such as occupancy and ventilation. This shows that there is a limit to the benefits offered by the material alone.

It is clear that thermal mass alone offers limited benefits and should always be considered with other passive strategies. The fact that conductive heat transfer is very low due to the low U-Values of the envelope means that the building will be less susceptible to higher external temperatures and more reliant on good design that considers passive mitigation strategies. It becomes even more essential to allow solar gains just when those are desirable, control internal gains and carefully consider ventilation strategies without forgetting factors such as the urban heat inland and security.

Mark Brinkley also pointed out that modelling should be undertaken considering more realistic user pattern. However, this type of data is extremely rare for housing and currently projects such as the Creative Energy Homes (described in Chapter 1) are addressing this issue.

In this chapter occupants were assumed to either be at home full time or to be out in daytime for 12 hours. This had an impact on the results of the simulations. For example, Case 3 presented reduced overheating due to part time occupancy but also presented proportionally higher heating demands. Despite the fact that the Case 3 house is just being heated up for half of the time (12h) while Case 2 house is permanently heated, the difference in heating demand is small suggesting that constant heating might not mean much higher energy bills. Wall type PCP presented the lowest energy demand for heating but that difference is more significant when heating is used full time. With part time heating all the wall types had a similar performance.

Further work could include detailed assessment of each wall type, especially those with high thermal mass, to determine the impact of the quantity of material mass in the results. Liaising with suppliers is recommended in order to understand the full limitations of each wall component and study other possible solutions. Another suggestion is work that involves identifying a relationship between the proportion of glazing per floor area and the relation of that to quantity of thermal mass.

The issue of balancing building requirements in terms of thermal comfort with building design and material selection is a major challenge for which there is no easy answer. There is no ‘one size fits all’ type of solution and each project should consider, in addition to the other passive design strategies, a careful selection of construction method that might be traditional or modern or even hybrid.

This is especially true when future climate scenarios are considered. There is a high risk of overheating in houses and this risk will not be mitigated by one solution alone. Each design has to be optimised to address the needs of the occupants and the users should be ‘educated’ to accept higher temperatures and understand their houses. In the future, with warmer weather, designers will also have to consider other strategies, passive, active or hybrid, such as the ones being studied in this work (EAHEs and PCMs in Chapters 3 and 4). These strategies were applied to the two houses which are the case studies in this thesis described in the next two chapters.

6 THE STONEGUARD RESEARCH HOUSE

The Stoneguard Research House is one of houses in the Creative Energy Homes built using Modern Methods of Construction and making use of strategies such as Phase Change Materials and Earth-Air Heat Exchangers. This Chapter focuses on a critical appraisal of the house's thermal performance, which is dynamically simulated and on the performance prediction of designed strategies that have not been implemented in the house yet.

6 THE STONEGUARD RESEARCH HOUSE

> *"The conflicting demands for huge numbers of new homes and the need to meet the world's environmental challenges for generations to come must be reconciled and we believe that Stoneguard House will be in the forefront of this process."*
>
> Stoneguard MD Mike Hinman, 2008[53]

The Stoneguard Research House is an innovative home created to address some of the challenges facing the construction industry to tackle the issues discussed in Chapter 1 by achieving high efficiency and fast construction. This was the first house envisaged in what eventually became the Creative Energy Homes project. The road where it is located, 'Green Close', was created to give access to this house.

This house, designed by the architect Guillermo Guzman, had many design variations until the industry partner, Stoneguard[54], came on board to support and develop the project. As the company was launching the Protec steel framing system, the proposal changed to adapt to this construction method. In addition to Stoneguard, many companies came on board bringing their expertise under one roof for the first time and problems were turned into opportunities and new products. These will be independently monitored and their effectiveness evaluated over the coming years.

The construction uses Modern Methods of Construction (MMC) such as steel frame and polystyrene formwork filled with green concrete. These techniques may facilitate high levels of environmental performance, speed up the house building process and reduce wastage and defects as explained in Chapter 1.

The house was firstly called C60 which stands for Carbon 60 as the dwelling was designed to address the target of 60% reductions on Carbon Dioxide (CO_2) by 2050 set by the Government's Energy White Paper (DTI, 2003: p. 11). The 2007 Energy White Paper kept the overall target of at least a 60% reduction in CO_2 by 2050 (DTI, 2007: p. 8, 24, 34). However, in November 2008, the UK's Climate Change Bill became law with a new target of 80% reduction in carbon emissions by 2050 (Turner, 2008). The latest policies for buildings reveal the government's intention for all new homes to be zero carbon by 2016 with a progressive tightening of the energy related building regulations: 25% reduction by 2010, 44% by 2013 and up to the zero carbon targets in 2016 (as mentioned in Chapter 1).

[53] Available at www.stoneguard.co.uk/research-house/pages/stoneguard.htm [Accessed on the 10th f August 2009]

[54] More information can be found at www.stoneguard.co.uk [Accessed on the 10th of August 2009]

Unfortunately the progress of the house was affected by the recent credit crunch when the main sponsor went into liquidation and its completion has been postponed. Consequently this work could not benefit from monitored data of the house. It has, however, analysed its performance by means of computer simulations and on-site experimentation which are described in this chapter. The house's design will be adapted to meet the new government targets before its construction is completed.

6.1 THE HOUSE DESIGN

The Stoneguard House aimed to be innovative in its construction method and to make use of as many technologies as necessary to achieve a high standard and comfortable life style. The proposal is a steel frame house that will be highly insulated and extremely airtight. Another major feature of the house is the integrated sunspace that aims to provide free passive solar heating in the winter and high levels of natural daylight. In addition the designer's intention was to make this large area a pleasant liveable space to be used during all seasons of the year.

The shadows caused by the surrounding trees and buildings and the movement of the wind were factors that influenced the final design. The organization of the plan places service spaces together to the north of the plan, leaving the best orientation to capture solar energy for the main spaces.

The four-bedroom house, constructed over three levels, includes a basement with garage and a roof space. The total floor area is around 230m^2 (170m^2 of heated space). The main entrance is located in the sunspace that provides an intermediate space between outdoor and indoors. The figures below show the house plans and sections. For larger versions of the plans with dimensions please refer to Appendix 6.A.

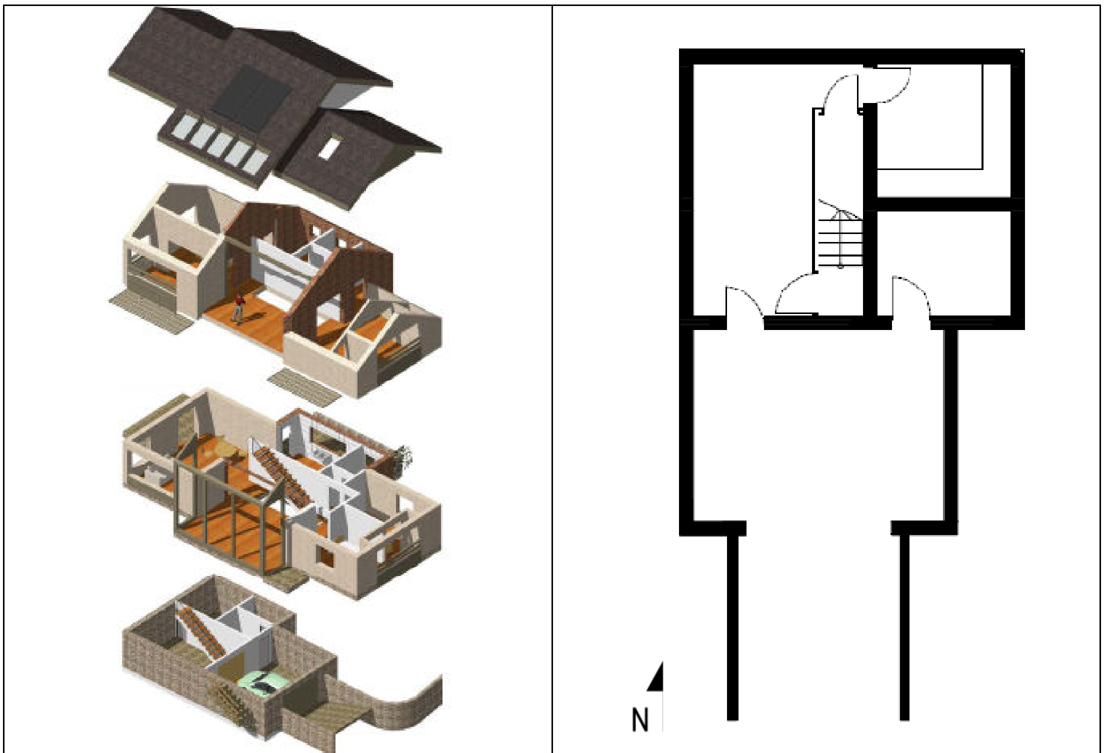


Figure 6-1: The Stoneguard House artistic perspective[55] and the Basement Plan

[55] Available at www.creative-energy-homes.co.uk [Accessed on the 10th of August 2009]

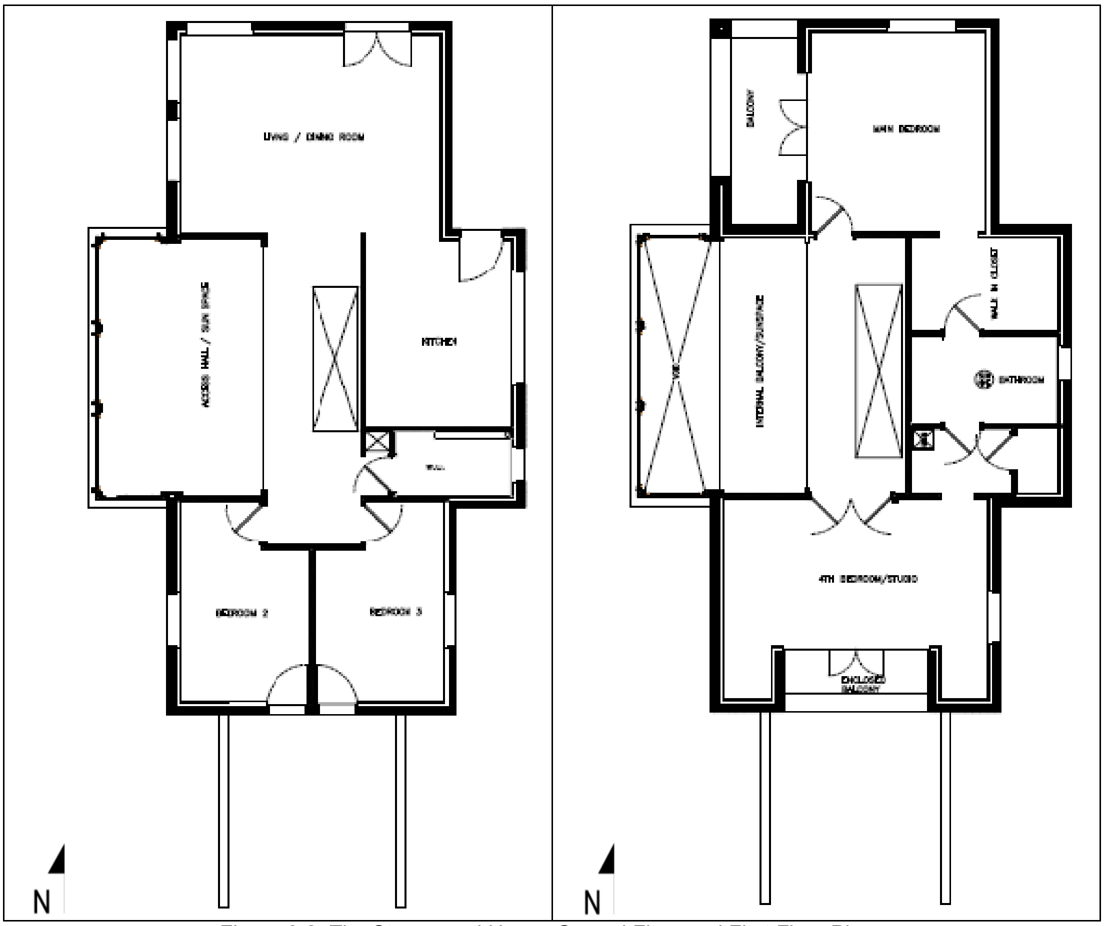


Figure 6-2: The Stoneguard House Ground Floor and First Floor Plans

The home has a hybrid ventilation system which combines natural ventilation, mechanical ventilation and an Earth-Air Heat Exchanger (EAHE). The size and function of the triple-glazed windows were selected by the architect with the intention of making the best use of daylight, to provide air circulation and a view to the outside. An energy-free sunpipe was placed where satisfactory natural lighting levels were difficult to achieve.

The Stoneguard House combines a highly insulated envelope, triple-glazed windows, the large sunspace and other strategies to reduce the need for active heating. Whenever the passive measures are not sufficient to keep the house warm, an underfloor heating system will be used, primarily supplied by a ground source heat pump system provided by Dimplex[56]. The house has roof mounted solar air collectors connected to a heat exchanger placed in the loft (a system known as Sunwarm[57]) that can be used according to the house requirements for hot water, space heating, air cooling and ventilation, as well as improving indoor air quality by filtering the air. The top of the sunspace has a connection to the heat exchanger so excess heat can be extracted and used for other purposes. The energy to run

[56] More information can be found at **www.dimplex.co.uk** [Accessed on the 11th of November]

[57] More information can be found at www.sunwarm.com [Accessed on the 11th of November 2009]

the afore mentioned technologies and the house's lighting and appliances is provided by an array of photovoltaic panels (2.8 kWp) provided by Evoenergy[58] and a micro wind turbine

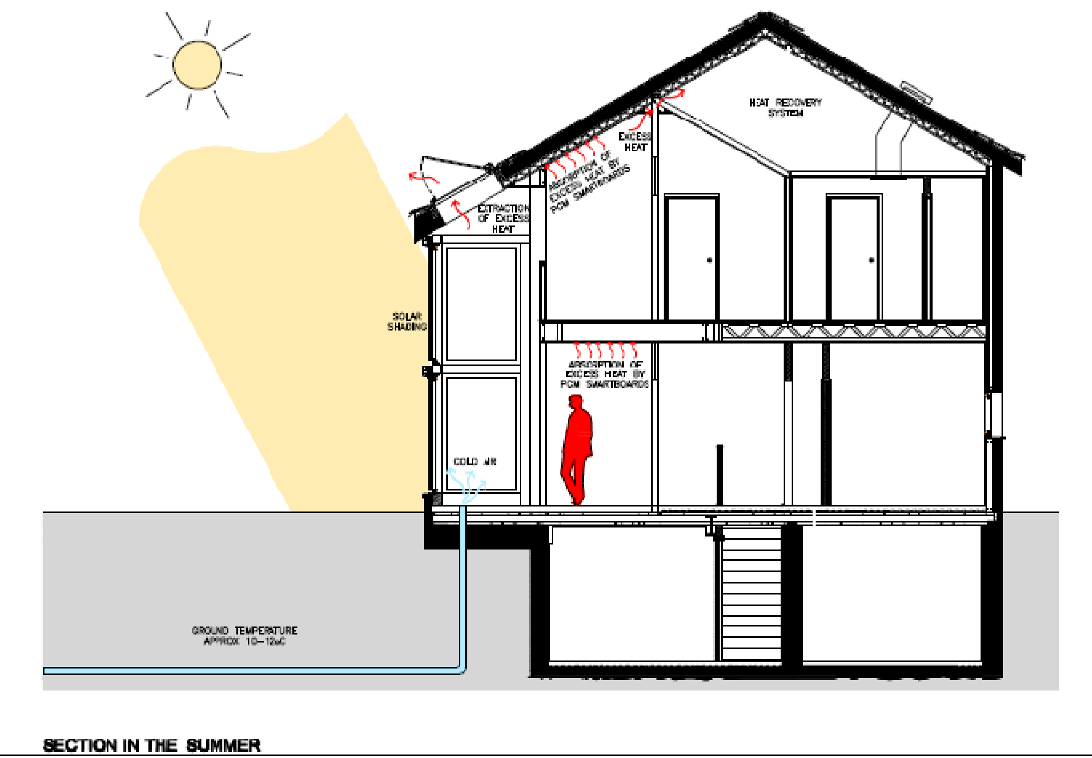


Figure 6-3: Diagrammatic section showing summer strategies

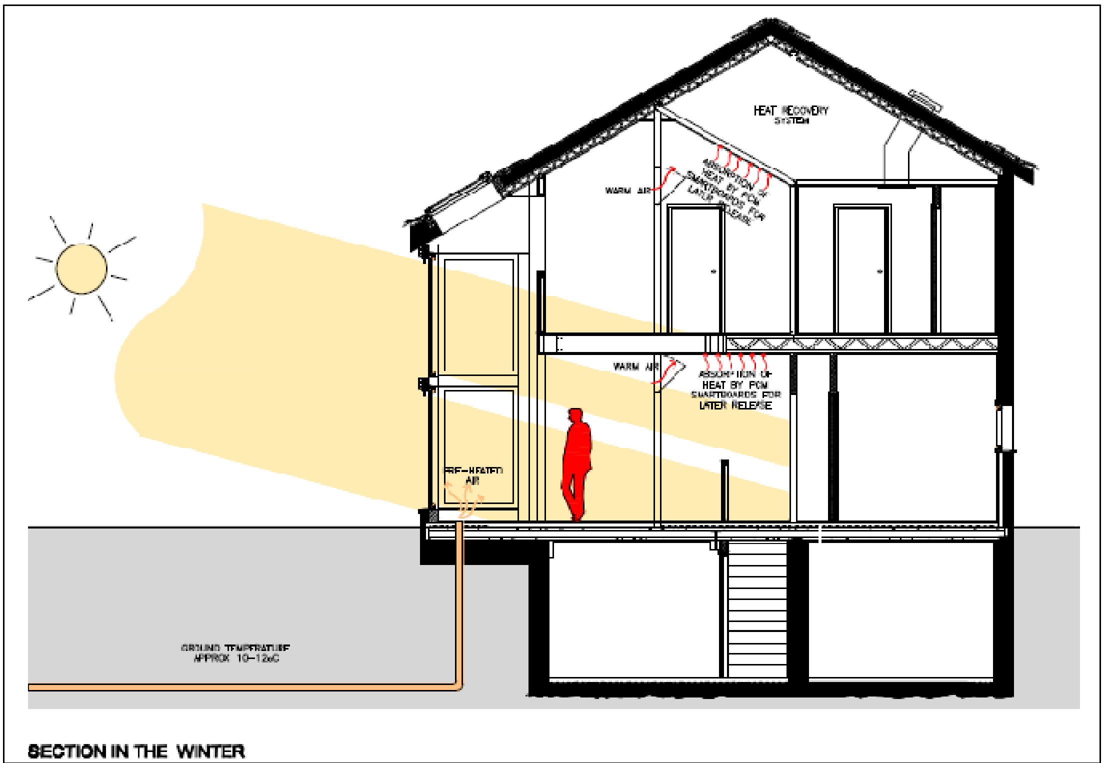


Figure 6-4: Diagrammatic section showing winter strategies

[58] More information can be found at www.evoenergy.co.uk/CaseStudies.aspx [Accessed on the 11th of November 2009]

.An Earth Air Heat Exchanger (EAHE), described in the next section, was installed to provide the sunspace with cooling during summer days and with pre-heated air in winter, which can be further heated up by solar radiation. Windows connect the sunspace to the house allowing for warm air to be directly delivered to the main circulation of the house. The sunspace ceiling received Phase Change Material (PCM) boards.

According to housing best practice, windows should be large enough to provide adequate day lighting to at least 15% of a room's floor area[59]. Traditionally, houses would have their windows distributed more or less uniformly around the perimeter of the building. However, houses designed using passive solar design strategies can have south facing glazing comprising 50% to practically 100% of the total facade area as long as solar gains are controlled (EST, 2005). The Stoneguard house presents much larger windows on the south than any other façade (Table 6-1) hence there is a need to control gains and prevent overheating.

Table 6-1: Proportion of windows area in the Stoneguard House

		Glazing Area (m^2)	Approximate Ratio Glazing on each facade/ Total glazing area
Ground Floor	**South**	25.62	55%
	North	4.83	10%
	East	6.41	13%
	West	10.34	22%
First Floor	**South**	10.86	49%
	North	2.72	12%
	East	6.40	29%
	West	2.10	10%
	Total Glazing Area	70.68	32% of the total floor area

6.1.1 Materials and Construction Method

The house materials were selected to minimize environmental impact and/or improve the house efficiency and life cycle. Concrete with 30% recycled aggregates (ground granulated blastfurnace slag, GGBS, a by-product of the iron industry) was used for precast foundations and the Insulated Concrete Formwork (ICF) basement. A precast concrete slab and staircase finished this level.

The building's lightweight steel frame structure was produced off-site in modular panels reducing waste on site and speeding up on-site construction, but keeping the design flexible.

[59] Sustainable development guide at www.plan4nottingham.com [Accessed on the 10th of August 2009]

In addition, the steel frame is made from 90% recycled sources (according to the manufacturer) and permits the plan to be flexible, allowing different uses for the spaces and even a possible extension of the house, potentially expanding the building's life cycle as walls can easily be moved. The steel frame was filled with mineral wool and finished with plasterboard or PCM boards in the sunspace's ceiling. Externally the frame received polystyrene panels with Sto[60] rendering. Steel frame was used to build the ground and first floor walls and the structure. The roof is highly insulated and its structure allows roof-mounted renewable energy systems. It is made of Unipur[61] structural insulated panels that comprise integral timber rafters fixed to, and stabilised by, a rigid facing board and filled with polyurethane foam which is sprayed in the factory.

The windows and external doors (with the exception of those in the sunspace) are made of a composite of timber and aluminium and triple glazed with argon filling. The Internorm[62] Edition 4 passive house standard triple glazed windows are extremely energy efficient with a very low u-value of 0.71W/m^{2}K. Integrated internal blinds have been incorporated in all the south, southeast and southwest windows to provide controllable solar shading. The exceptions are the roof Velux [63] windows and the sunspace glazing, which were manufactured by Veka[64]. Veka uses partially recycled PVC. External electrically operated solar louvers were considered to shade the sunspace when required but those were not installed by the time this work was finished.

As the house has not been finished, the following specification is design stage only. For this study it has been assumed that all floor finishings are wood as the actual finish will be decided at a later date. It has also been assumed that plasterboard is the standard internal finishing of all walls and ceilings. The rest of the materials were based on the house plans, on site observation and/or conversations with the site manager.

The geometry of the Stoneguard House is complex and consequently there are various types of floors, walls and ceilings in addition to different combinations of those. As a consequence, internal floors and walls might have insulating importance (e.g. the floor between the unheated basement and the heated ground floor). The house's construction elements are illustrated in Table 6-2. For details on each layer please refer to Appendix 6.B. Although the house's design can reduce energy consumption for heating when compared with conventionally built homes, it may also present overheating during the summer as the

[60] More information can be found at www.sto.co.uk [Accessed on the 12th of August 2009]

[61] More information can be found at www.unilin.nl/en [Accessed on the 12th of August 2009]

[62] More information can be found at www.dynamight-internorm.co.uk [Accessed on the 12th of August 2009]

[63] More information can be found at www.velux.co.uk [Accessed on the 12th of August 2009]

[64] More information can be found at www.vekauk.co [Accessed on the 12th of August 2009]

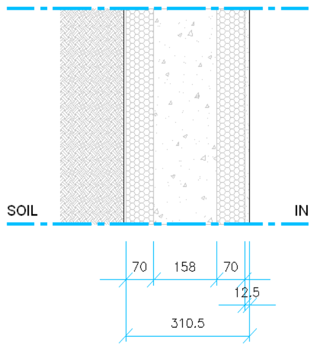
light structure has no thermal mass and the large glazed areas allow high levels of solar gains if those are not controlled.

Figure 6-5: The construction of the Stoneguard house basement with help of undergraduate students of architecture (pictures by the author and by the photographer Robert Paulden)

Figure 6-6: The Stoneguard House steel frame panels being prepared in the factory and installed on site with the help of undergraduate students of architecture (pictures by the author and by the photographer Robert Paulden)

Table 6-2: The elements of the Stoneguard House envelope

W ext 1 -BASEMENT EXTERNAL WALL (ICF), UNDERGROUND



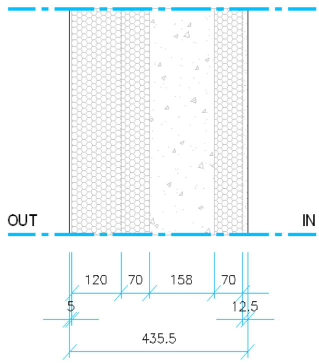
OUT

a. Membrane
b. 70mm Extruded Polystyrene (EPS)
c. 158mm Heavyweight concrete
d. 70mm Extruded Polystyrene (EPS)
e. 12.5mm Plasterboard

IN

Decrement Factor (0-1)	0.01
Time Constant (hours)	76.5
Admittance (W/m^2K)	0.86
U-Value (W/m^2K)	0.11
Thickness (mm)	310.5

W ext 2 -BASEMENT EXTERNAL WALL (ICF), EXPOSED



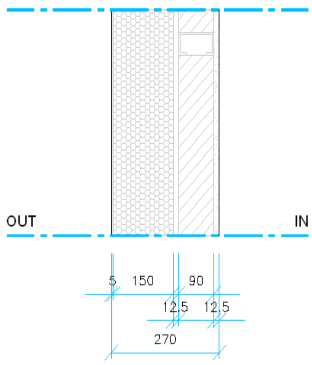
OUT

a. 5mm Rendering
b. 120mm Extruded Polystyrene (EPS)
c. 70mm Extruded Polystyrene (EPS)
d. 158mm Heavyweight concrete
e. 70mm Extruded Polystyrene (EPS)
f. 12.5mm Plasterboard

IN

Decrement Factor (0-1)	0.03
Time Constant (hours)	113.3
Admittance (W/m^2K)	0.86
U-Value (W/m^2K)	0.13
Thickness (mm)	435.5

W ext 3 - GROUND AND FIRST FLOOR EXTERNAL WALLS (SF)



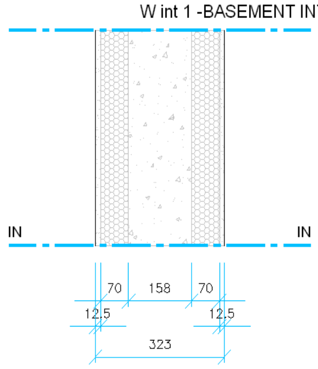
OUT

a. 5mm Rendering
b. 190mm Extruded Polystyrene (EPS)
e. 12.5mm Cement Particle Board
f. 90mm Rockwool
g. 12.5mm Plasterboard

IN

Decrement Factor (0-1)	0.4
Time Constant (hours)	5.6
Admittance (W/m^2K)	1.01
U-Value (W/m^2K)	0.14
Thickness (mm)	270

W int 1 -BASEMENT INTERNAL WALL (ICF)



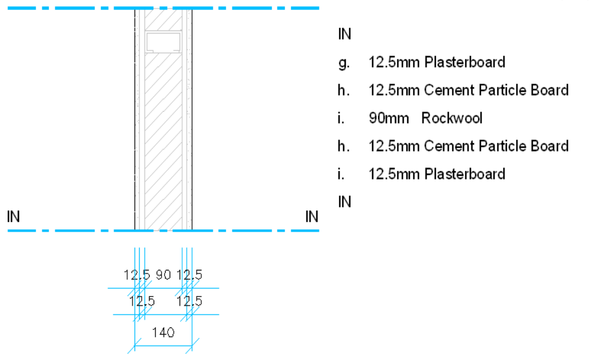
IN

a. 12.5mm Plasterboard
b. 70mm Extruded Polystyrene (EPS)
c. 158mm Heavyweight concrete
d. 70mm Extruded Polystyrene (EPS)
e. 12.5mm Plasterboard

IN

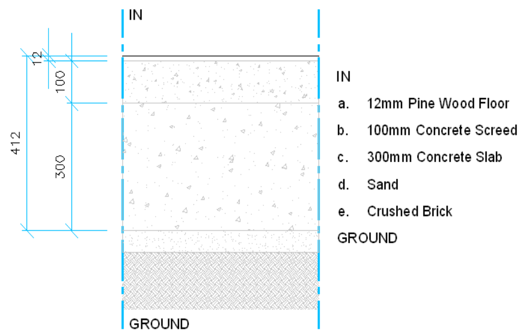
Decrement Factor (0-1)	0.05
Time Constant (hours)	77.8
Admittance (W/m^2K)	0.86
U-Value (W/m^2K)	0.24
Thickness (mm)	323

W int 2 - GROUND AND FIRST FLOOR INTERNAL WALLS (SF)



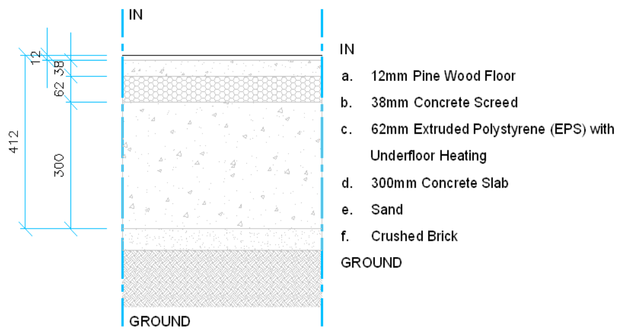
Decrement Factor (0-1)	0.89
Time Constant (hours)	0.0
Admittance (W/m^2K)	1.4
U-Value (W/m^2K)	0.34
Thickness (mm)	140

F ext 1 - UNHEATED BASEMENT FLOOR



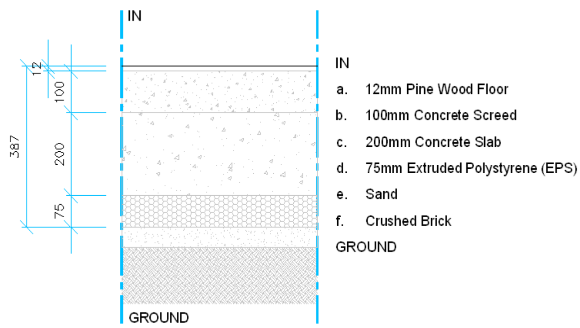
Decrement Factor (0-1)	0.0
Time Constant (hours)	78.7
Admittance (W/m^2K)	4.15
U-Value (W/m^2K)	0.61
Thickness (mm)	214

F ext 2 - HEATED BASEMENT FLOOR



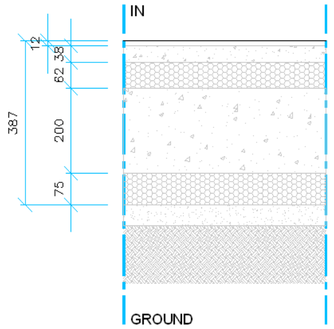
Decrement Factor (0-1)	0.0
Time Constant (hours)	205.6
Admittance (W/m^2K)	3.61
U-Value (W/m^2K)	0.30
Thickness (mm)	412

F ext 3 - UNHEATED SUNSPACE FLOOR



Decrement Factor (0-1)	0.0
Time Constant (hours)	104.5
Admittance (W/m^2K)	4.15
U-Value (W/m^2K)	0.27
Thickness (mm)	387

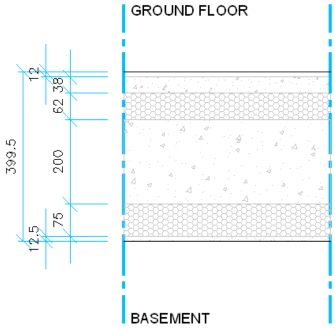
F ext 4 - HEATED LIVING ROOM FLOOR



IN
a. 12mm Pine Wood Floor
b. 38mm Concrete Screed
c. 62mm Extruded Polystyrene (EPS) with Underfloor Heating
d. 200mm Concrete Slab
e. 75mm Extruded Polystyrene (EPS)
f. Sand
g. Crushed Brick
GROUND

Decrement Factor (0-1)	0.0
Time Constant (hours)	173.2
Admittance (W/m^2K)	3.61
U-Value (W/m^2K)	0.18
Thickness (mm)	387

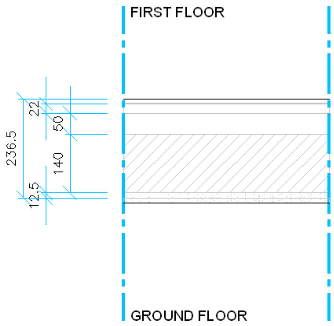
F int 1 - HEATED GROUND FLOOR/ BASEMENT CEILING



GROUND FLOOR
a. 12mm Pine Wood Floor
b. 38mm Concrete Screed
c. 62mm Extruded Polystyrene (EPS) with Underfloor Heating
d. 200mm Concrete Slab
c. 75mm Extruded Polystyrene (EPS)
d. 12.5mm Plasterboard
BASEMENT

Decrement Factor (0-1)	0.0
Time Constant (hours)	117.3
Admittance (W/m^2K)	3.61
U-Value (W/m^2K)	0.23
Thickness (mm)	399.5

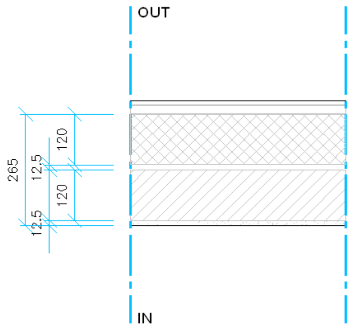
F int 3 - FIRST FLOOR/ GROUND FLOOR CEILING



FIRST FLOOR
a. 12mm Pine Wood Floor
b. 22mm Plywood with Underfloor Heating
c. 50mm Air Cavity
d. 140mm Rockwool
e. 12.5mm Cement Particle Board
f. 12.5mm Plasterboard
GROUND FLOOR

Decrement Factor (0-1)	0.72
Time Constant (hours)	0.82
Admittance (W/m^2K)	1.47
U-Value (W/m^2K)	0.21
Thickness (mm)	236.5

ROOF



OUT
a. Clay Roof Tile
b. Roofing Felt
c. 120mm Extruded Polyurethane (PUR)
e. 12.5mm Cement Particle Board
f. 120mm Rockwool
g. 12.5mm Plasterboard
IN

Decrement Factor (0-1)	0.34
Time Constant (hours)	7.0
Admittance (W/m^2K)	1.56
U-Value (W/m^2K)	0.12
Thickness (mm)	265

6.1.2 SAP Rating

The Standard Assessment Procedure, mentioned in Chapter 1, provides a home energy rating that seeks to calculate a score between 1 to 100+ (100 representing zero energy cost, over 100 net exporter of energy) for the annual energy cost considering the house's fabric characteristics, its heating and hot water system, internal lighting and renewable energy systems. A working spreadsheet was developed in Excel (Microsoft Office Package) based on the SAP 2005 manual (BRE, 2005).

The first difficulty faced was the lack of flexibility for the incorporation of innovative strategies and technologies. The house has a combination of technologies and ventilation strategies working together that SAP 2005 failed to consider. The EAHE and the PCM were also not taken into consideration. In fact, even the sunspace, which is a relatively basic passive solar strategy, cannot be accounted for in this method of assessment. Currently, this is being reviewed by the government but when this house design received its planning permission this was the customary procedure and a brief study was developed to investigate its strengths and weaknesses regarding these issues.

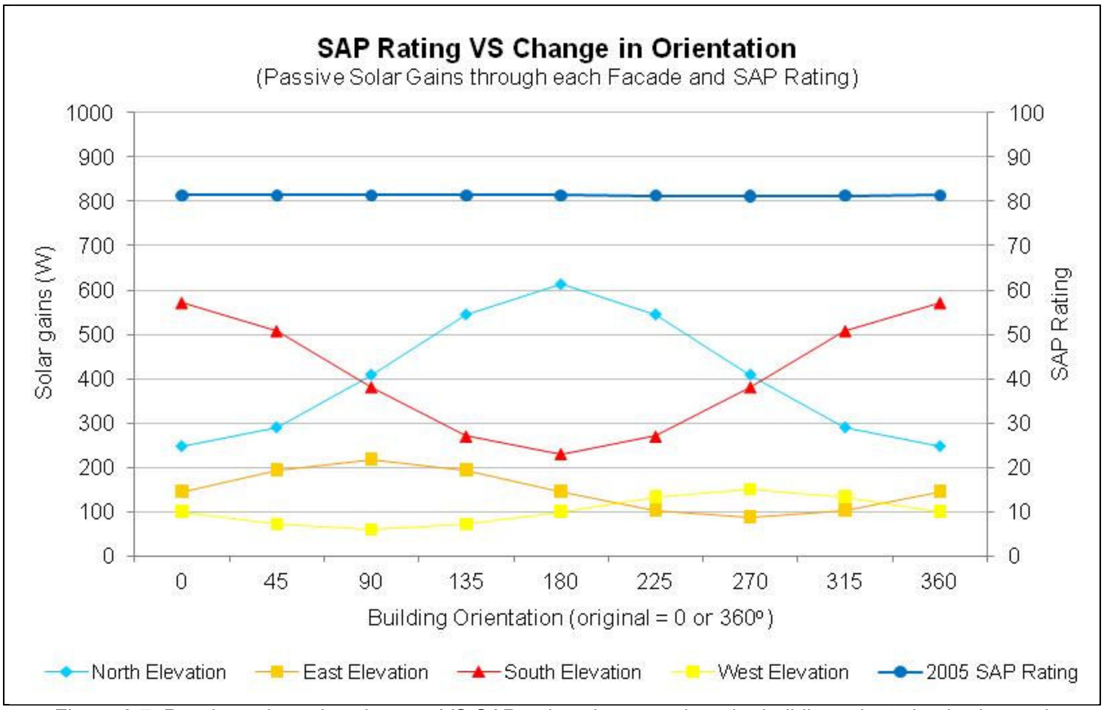


Figure 6-7: Passive solar gains changes VS SAP rating changes when the building orientation is changed

The second difficulty was the fact that SAP 2005 did not give significant importance for passive design strategies. As an example, the large southern facing conservatory which is expected to deliver enormous amount of passive heating to the house is not considered appropriately by SAP. Rather than benefit in performance, it brought the rating down due to the large glazed area behind it. The Stoneguard House SAP 2005 rating was 81.57 (draft stage) which is band ‘B’, lower than expected in a house that aims to be a low energy home or a net exporter of energy. This is due to the reasons described above. Figure 6-7 illustrates the variation in solar gain if the Stoneguard House was rotated and how little the SAP rating would change even if the sunspace was north facing.

SAP 2005 provides a method for assessing summer overheating but it is not an integral part of the estimation and does not affect the final ratings. It uses admittance of the constructions to find degree days of overheating. The new SAP 2009 will use admittance in calculations for summer cooling and for winter heating loads. In the next section the results of a full dynamic modelling of the house will be described and overheating will be assessed.

6.1.1 PCM Pre-Assessment

The PCM used in the Stoneguard house was the BASF Knauf Micronal PCM board described in section 4.4.1 of this work. 100m^2 of the board were distributed in the sunspace’s ceiling, which is the area with the largest proportion of glazing per floor area. The installation of PCM boards in the living room ceiling was also envisaged but not carried out. The product used was the Micronal DS 5000 X with a melting point of 23^{o}C incorporated in Knauf lightweight plasterboards as suggested by BASF. Each 1m^2 of the board contains 3kg of PCM and each 1kg of the PCM has a latent heat storage capacity of 110kJ.

The improvement in summer performance of the sunspace that the BASF Knauf Micronal PCM board could provide was investigated using ‘PCM Express’, created by Valentin EnergieSoftware in a partnership with BASF and the Fraunhof Institute for Solar Energy (ISE) in Freiburg.

The software is relatively simple and the inputs are limited to room geometry (always a rectangular room with each surface having to be either completely exposed to outside temperature or completely sheltered), fabric properties, weather data and a few building service parameters. The results are always a comparison between the room without PCM and the room with PCM.

The first exercise (Case 1) compared the sunspace with and without the Micronal PCM (melting point 23^{o}C) without the aid of ventilation or mechanical systems. The results can be seen in Figure 6-8, Figure 6-9 and Figure 6-10. According to the software, in these conditions the space presents significant overheating issues with temperatures reaching 42^{o}C. The PCM is able to reduce the peak temperature by up to 2^{o}C.

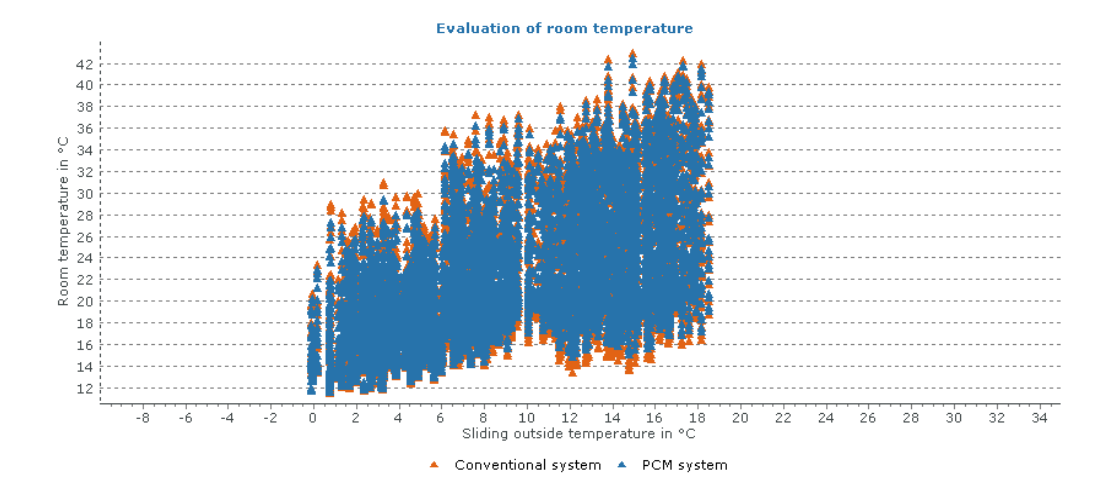


Figure 6-8: Comparison of temperatures between a room without PCM (conventional) and with PCM in Case 1

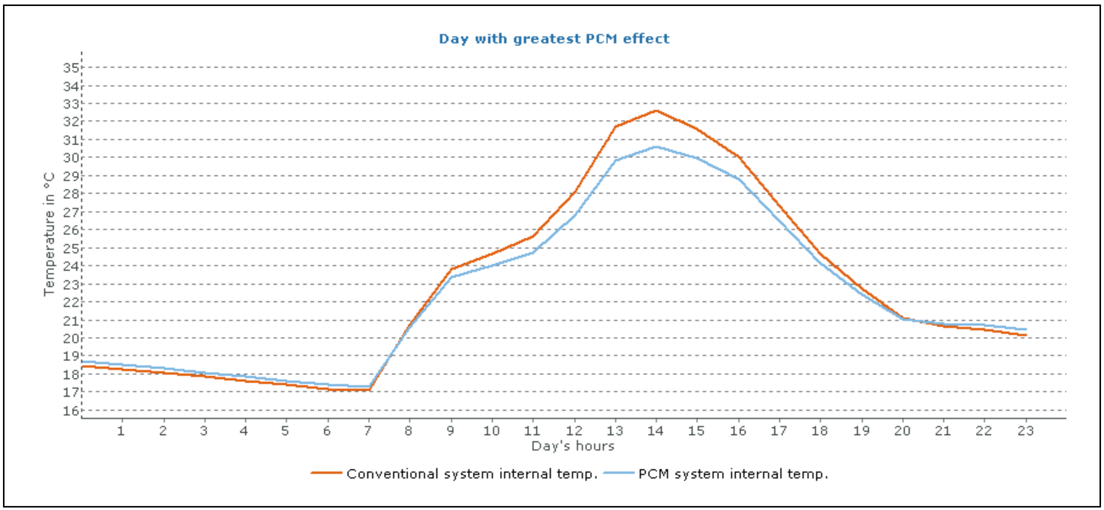


Figure 6-9: Comparison of the day with the greatest PCM effect in Case 1

Case 2 (Figure 6-11) is the same room as Case 1 but with added natural ventilation by the opening of windows. As may be seen, peak temperatures in the model without PCM were reduced to 36°C and in the model with PCM to 35°C. Case 3 (Figure 6-12) is the same room and conditions as Case 2 but with added heat recovery system, night time ventilation and an EAHE (it is not clear how the software considers the benefits of the system). In case 3, peak temperatures without PCM were reduced to 34°C and to 33°C in the PCM room where temperatures stayed around the PCM melting point (20-24°C) for much longer.

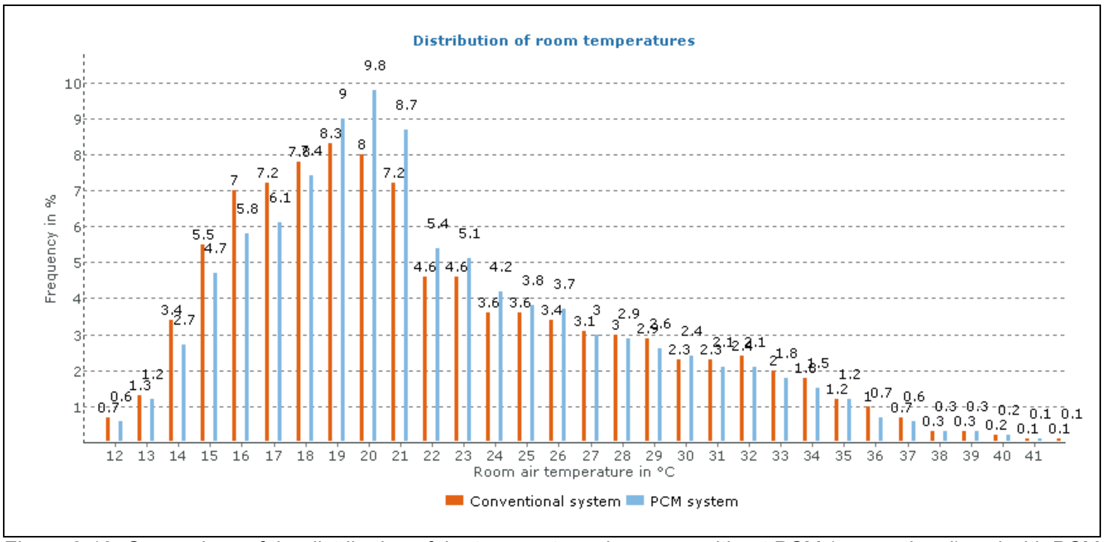


Figure 6-10: Comparison of the distribution of the temperatures in a room without PCM (conventional) and with PCM in Case 1

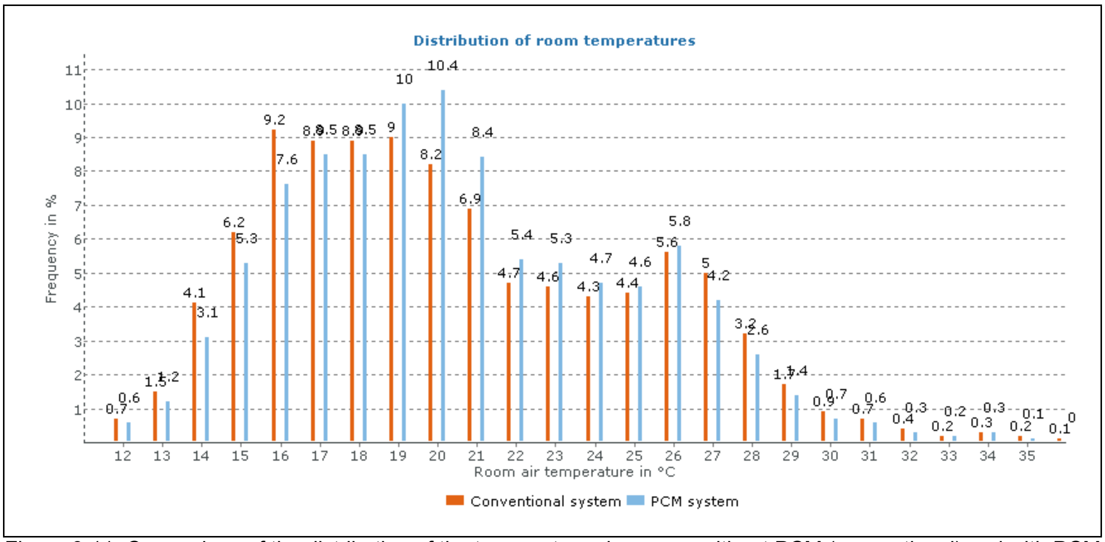


Figure 6-11: Comparison of the distribution of the temperatures in a room without PCM (conventional) and with PCM in Case 2

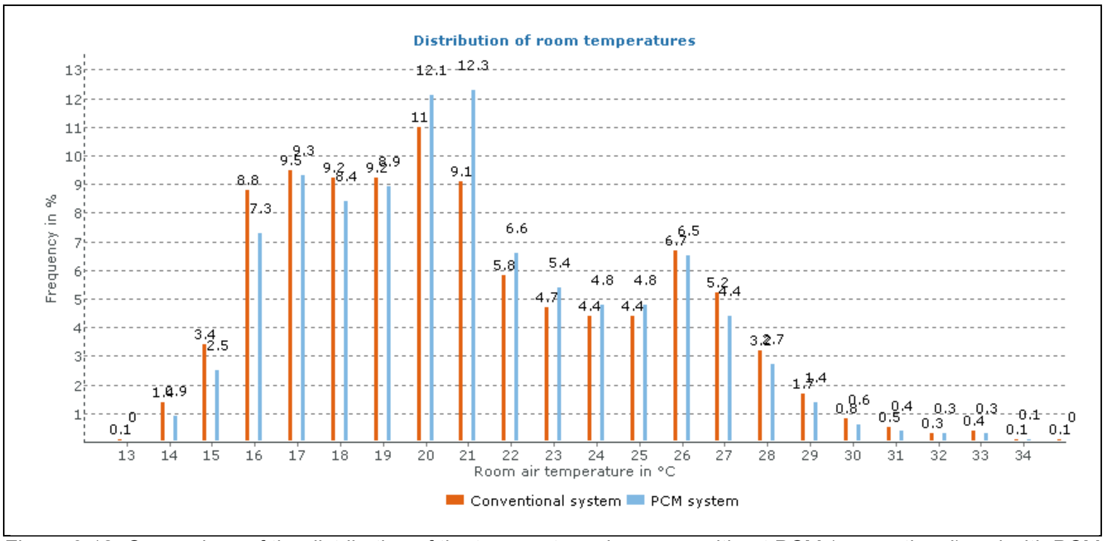


Figure 6-12: Comparison of the distribution of the temperatures in a room without PCM (conventional) and with PCM in Case 3

It is clear from the graphs above that the PCM used in these specific quantities (around 145kg below the sloping roof) contributes towards comfort but is not enough to deal with the excess heat in that area and shows quick saturation in all the cases. It can be seen in the graphs that, above the PCM melting temperature, conventional and PCM rooms present similar results.

Figure 6-13 shows a comparison of each case and the percentage of time when temperatures between 21 and 26^{o}C and above 26^{o}C occur. Unfortunately the resulting data cannot be extracted from the software so it cannot be analysed with the same criterion used in Chapter 5. Nevertheless all cases indicate temperatures above 26^{o}C for more than 10% of the time. It must be remembered that the geometry of the room was simplified and it is not possible to consider shading. Further on in this chapter the house will be analysed dynamically in Tas and the issue of overheating will be reassessed in detail. Unfortunately Tas does not simulate the behaviour of PCM so its benefits cannot be properly explored.

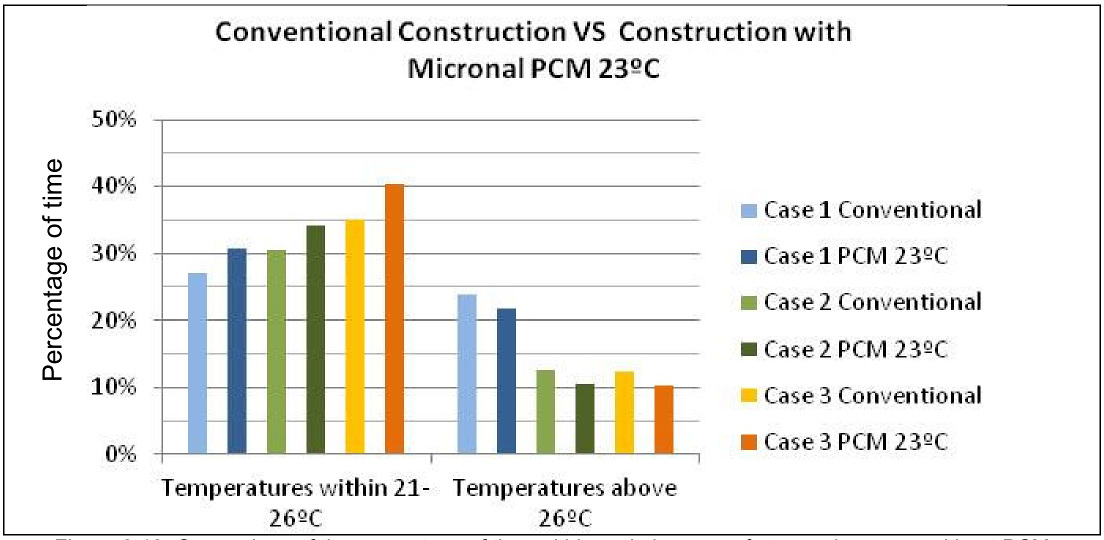


Figure 6-13: Comparison of the percentage of time within and above comfort zone in a room without PCM (conventional) and with PCM in Cases 1, 2 and 3

6.1.2 The EAHE Design and Construction

The design of the Stoneguard EAHE has been described in previous work (Rodrigues, 2005). The first design proposed an array of 3 PVC pipes of 100mm of diameter, positioned 1.58m from each other and summing to 42m of length to provide the house with 50% of its cooling needs. This design would allow the pipes to be jet-washed with the inlets located close to the basement's walls and outlets in the house's sunspace. Figure 6-14 shows the initial EAHE system proposed.

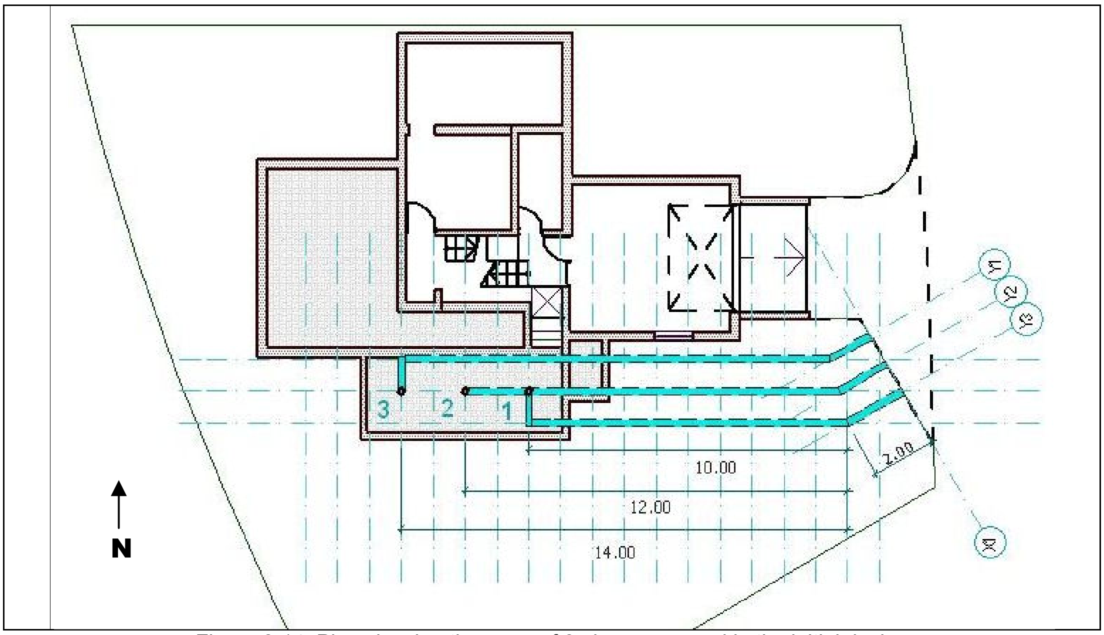


Figure 6-14: Plan showing the array of 3 pipes proposed in the initial design

When the construction of the house started, the position of the house had to be changed due to unforeseen problems on site so the EAHE as initially designed could not be built. A decision made on site with the agreement of the construction company to install a 1 pipe system that would be as long as possible given the constraints of budget and site and which would be used to allow further investigation of the performance of EAHEs in this location. The final layout of the Stoneguard House EAHE can be seen in Figure 6-15, Figure 6-16 and Figure 6-17. This layout was only possible because the house's plot is on the university's campus and the limits of the plot did not have to be respected. In a real situation such a long pipe would not be suitable for the plot but in this case a long narrow trench was easier and cheaper to excavate than a large hole to place the pipes in an array or in parallel lines.

The EAHE currently installed is made of a single PVC pipe with a diameter of 110mm and a length of 85m. PVC was chosen for a number of reasons: availability, price, durability and water tightness. Furthermore, PVC exchanges heat at a very low rate enabling the soil around the pipes not to become saturated (Kennett, 2005). The pipes were buried at a depth of approximately 3m except when closer to the house where it followed the foundation depth of approximately 2.5m. The pipe was sloped towards 2 soak-aways as seen in Figure 6-15 and Figure 6-18. The soak-away aids the removal of condensed or drawn water from the system to the ground. At a regular distance of 10m along the pipe there are vertical reference pipes with their tops above ground level to allow measurements to be taken for research purposes. The excavation and construction of the pipes can be seen in Figure 6-18. The excavation of the trench started from the hole made for the house's foundation and the pipes were joined together outside the trench for safety reasons (risk of the trench collapsing on a person). The pipes were then lowered into the trench with the help of cords, soak-aways were put in place and the system was backfilled on the same day. After backfilling, the ground was flattened and the vertical inspection pipes were capped.

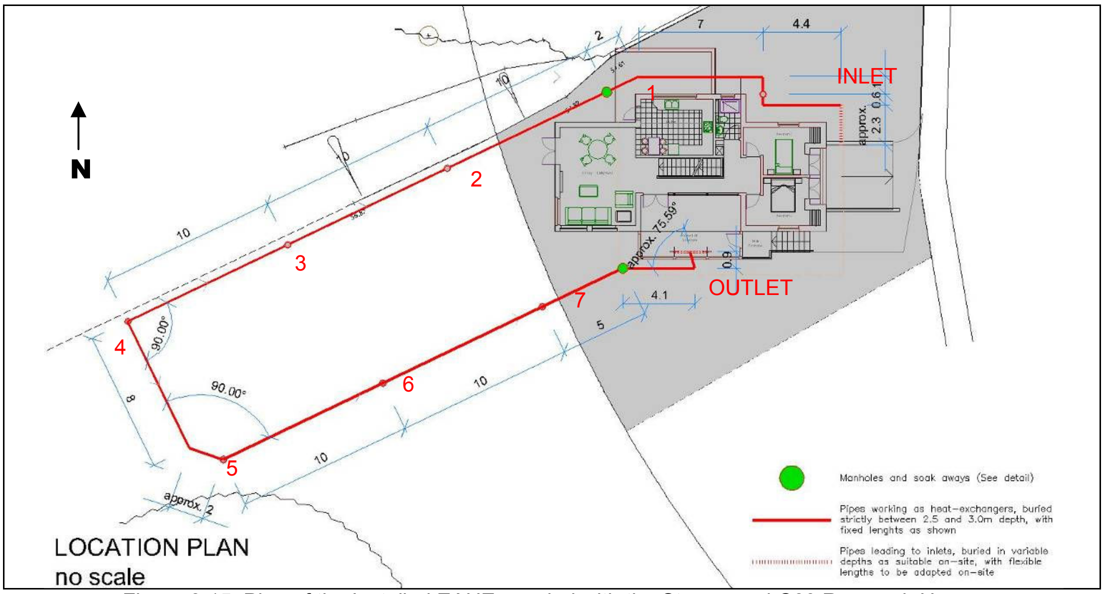


Figure 6-15: Plan of the Installed EAHE coupled with the Stoneguard C60 Research House

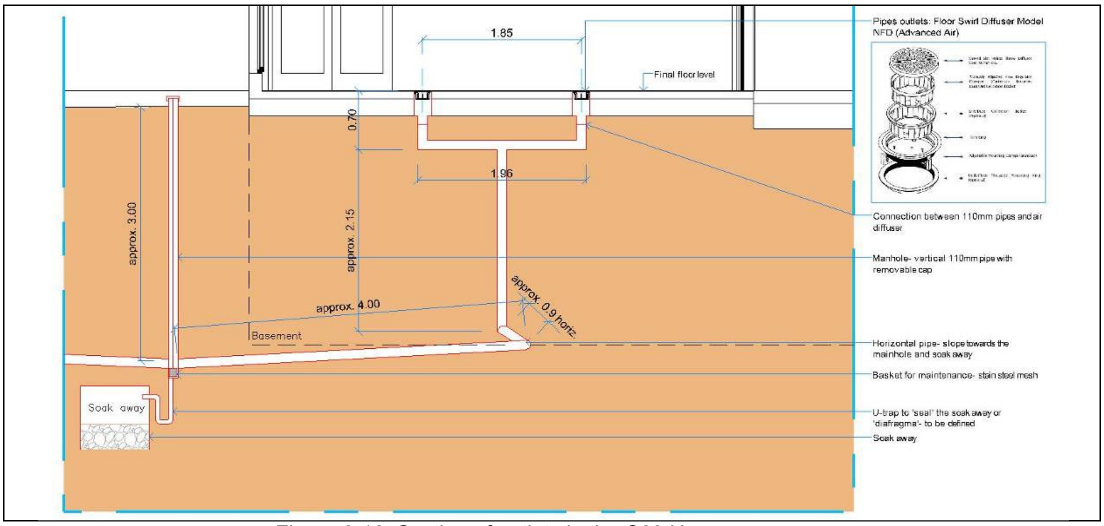


Figure 6-16: Section of outlets in the C60 House sunspace

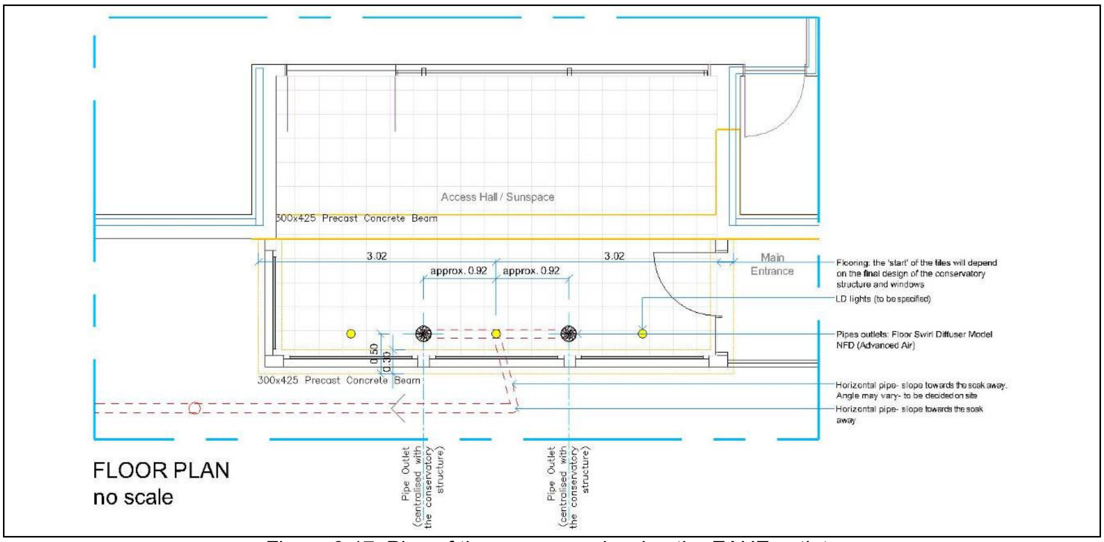


Figure 6-17: Plan of the sunspace showing the EAHE outlets

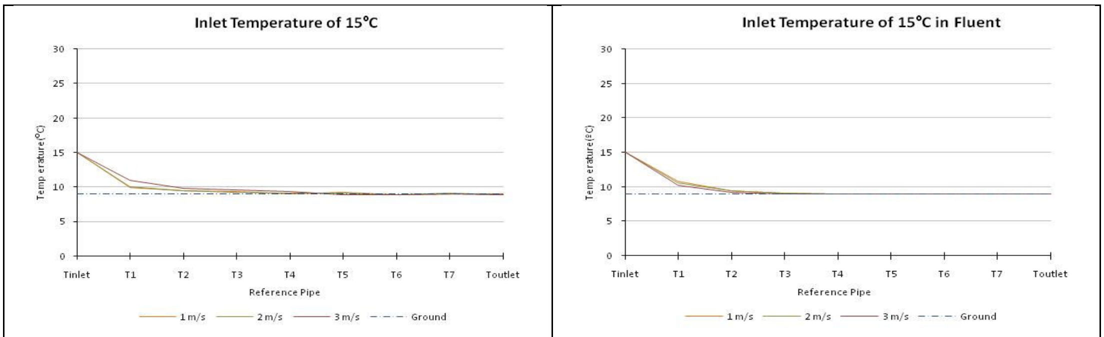
Figure 6-18: The construction of the Stoneguard House EAHE

The system was simulated using Computer Fluid Dynamics (CFD) and a preliminary test was done on site with the help of a heater. These are described in the next section.

6.1.3 EAHE Preliminary Tests

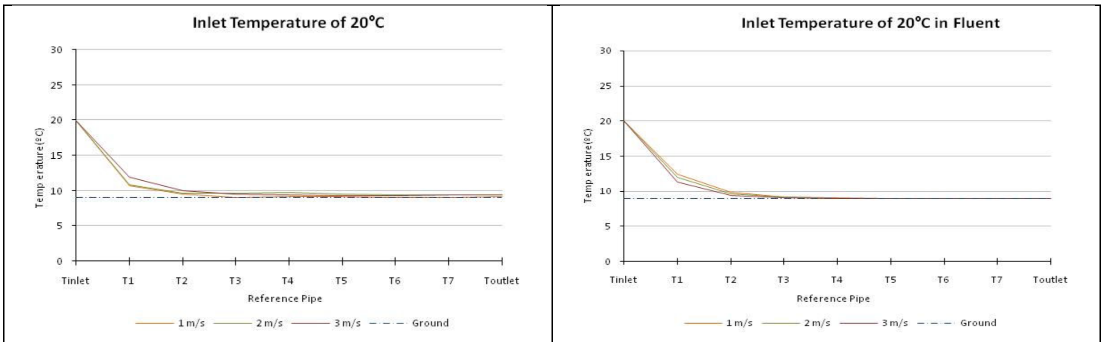
A fan attached to a heater was used to heat air and push it through the pipe. Measurements were taken for 3 air velocities (1m/s, 2m/s and 3m/s) at inlet air temperatures of 15^{o}C, 20^{o}C, 25^{o}C and 30^{o}C. The temperature was read at each of the 7 vertical pipes and at the outlet for each of the above cases. The number of each vertical pipe and the position of the inlet and the outlet can be seen in Figure 6-15. The pipe was also dynamically simulated in Fluent version 4.5[65].

Equation 3.1 was used to calculate the rate of cooling of the pipes. The onsite results and the computer simulations can be seen in Figure 6-19, Figure 6-20, Figure 6-21, and Figure 6-22. The Fluent results agree with the measurements taken on site, which suggests that Fluent could be an efficient modelling tool for EAHE, it is worth remembering however that neither the test nor the simulations are taking thermal saturation of the pipe and surrounding soil into account, something that is likely to occur in practice when the system works for long periods of time.



On site results | Fluent results

Figure 6-19: Results for inlet temperature of 15^{o}C



On site results | Fluent results

Figure 6-20: Results for inlet temperature of 20^{o}C

[65] Fluent is a computer fluid dynamics software provided by Ansys. More information can be found at www.ansys.com/products/fluid-dynamics/fluent [Accessed on 27th of September 2009]

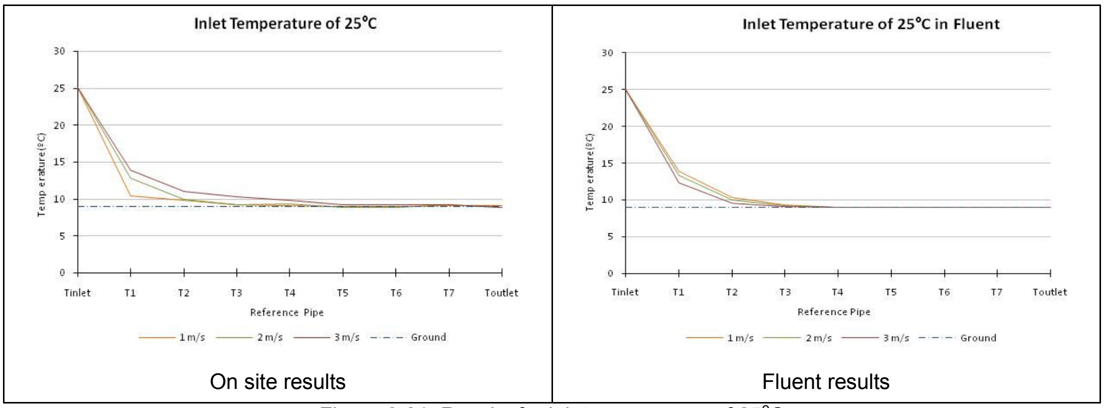


Figure 6-21: Results for inlet temperature of 25°C

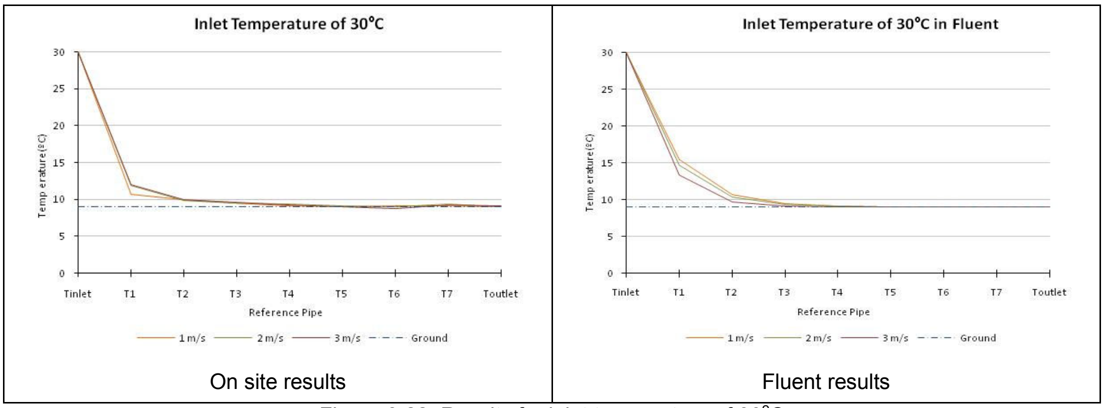


Figure 6-22: Results for inlet temperature of 30°C

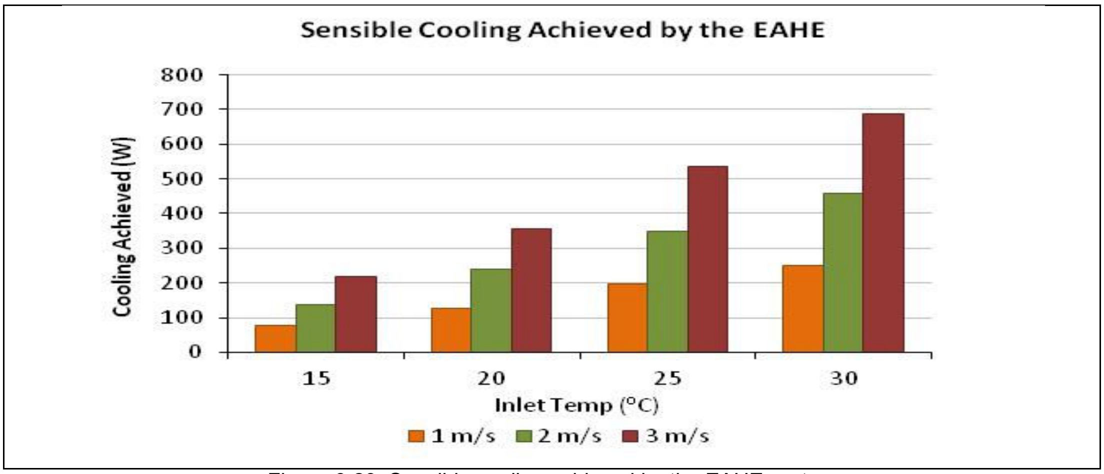


Figure 6-23: Sensible cooling achieved by the EAHE system

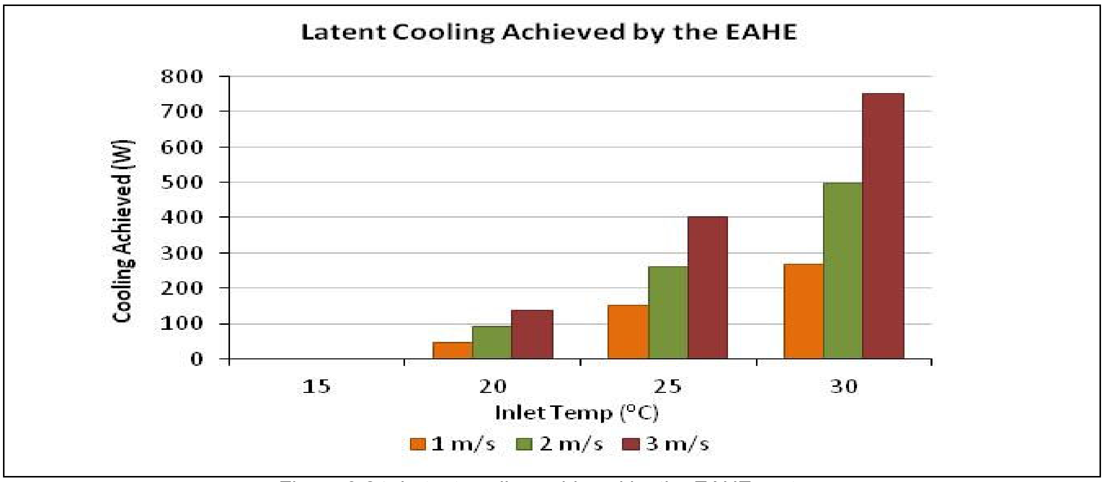


Figure 6-24: Latent cooling achieved by the EAHE system

Latent heat of condensation is the energy released when water vapour condenses to form liquid droplets. In order to determine if any condensation occurred inside the pipes and consequently determine the latent heat transfer, a psychometric chart was used. The study has shown that there was condensation when the inlet temperature was 20°C, 25°C and 30°C. The total energy potentially saved by latent heat transfer, can be seen in Figure 6-24.

Based on 200 hours of cooling needs and considering that the energy used by the fan was 36W, an example of the potential free cooling and consequent financial savings prove the EAHE system was worth building (Table 6-3).

The results show that the temperature of the inlet air in every flow modelled or assessed on site eventually reaches the temperature of the ground. With every inlet temperature the rate at which the air is heated or cooled slightly decreases as the velocity of the inlet air increases. This was expected due to the residence time of the air: as slow moving air is in the EAHE for a longer period it is able to transfer more heat than fast moving air per unit length.

Table 6-3: Potential savings on energy and CO_2 emissions of the Stoneguard EAHE (T_{inlet} is the temperature at the inlet and T_{outlet} is the temperature at the outlet as measured)

Temp. (°C)		**Velocity of air** (m/s)	**Net energy saved (instant)** (W)	**200h of cooling** (kWh)	**CO_2 emissions saved** (kg)
T_{inlet}	T_{outlet}				
15	8.9	3	195.86	39.17	16.84
15	8.9	2	114.98	22.99	9.89
15	9.0	1	54.22	10.85	4.66
20	9.4	3	334.69	66.94	28.78
20	9.4	2	309.16	61.83	26.58
20	9.1	1	149.35	29.87	12.84
25	8.8	3	916.87	183.37	78.83
25	8.8	2	585.78	117.16	50.37
25	9.0	1	326.96	65.39	28.11
30	9.2	3	1412.60	282.52	121.46
30	9.0	2	933.06	186.61	80.22
30	9.0	1	495.54	99.11	42.60

From the results it can be seen that in every case the air reaches the temperature of the ground somewhere between 40 and 50m if not before. This suggests that the EAHE could be shorter for the purpose of cooling of the house. It is possible that in exceptionally hot weather or when the EAHE is used for long periods of time some of the extra length will be required to further cool the air, but in the UK it is rare that temperatures exceed 30°C and even then it is likely that shorter pipe lengths would cool the air sufficiently. The long pipe might also be an advantage if it is used for full seasons but this will not be known until long term tests are done. Nevertheless the pipe's design serves its research purpose allowing further investigation of its performance.

As seen in Figure 6-23, the higher the flow rate the better the cooling achieved because more air is being delivered to the house. These results indicate that even more cooling could be achieved if the air flow rate is increased as the pipe is long enough to accommodate this (the extra pipe length can cool the extra volume of air). Long pipes might also make up for long periods of use which may cause thermal saturation of the soil around the first sections of the system. However, with shorter pipes a lower flow rate is likely to present better results due to the time the air spends in contact with the pipe (known as residence time).

The Fluent modelling achieved similar results to those obtained from the text on site although the results obtained on site have shown a slightly greater cooling, which could be due to irregularities in the ground temperature. When the accuracy of the on-site measurements is also taken into consideration the difference is even less significant. A longer period of monitoring is necessary, especially when the house is ready, so the influence of the occupancy can be accounted for. Long term monitoring of the system is envisaged for the next few years once the house is ready. Short periods of monitoring over the summers of 2008 and 2009 were carried out and are presented in the next section.

6.1.4 EAHE On-site Monitoring

The house design envisaged complete monitoring system, which was not installed by the time this work was finished. Consequently, it was not possible to examine any real data from the house except the functioning of the EAHE, which was monitored in an experimental manner.

A section of 60 meters of the system was monitored over two summer periods, 2008 and 2009. The air at the outlet and outside in a shaded part of the site was monitored using 14 k-type (chromel–alumel) thermocouples with shielded finish and connected to the analogue inputs of a datalogger (Datataker DT 505 series 2). Humidity at the outlet was monitored but external humidity was only recorded over certain periods. The error in temperature readings through thermocouples was considered to be ±1ºC and they were all tested for their accuracy before the beginning of the experimentation. Data were gathered every 10 or 30 minutes.

When running continuously, the system did not perform as the preliminary tests had predicted (Figure 6-25). Even though this experiment was done using a shorter section of the pipe, the preliminary test had shown that the air would reach around 10^{o}C after 40 to 50m. This can be attributed firstly to long term monitoring showing the effect of thermal saturation of the ground and secondly to errors due to the apparatus used to conduct the experiment.

The heater without a mixing box might have been inadequate to simulate warm inlet air but by the time this on-site monitoring was done there was no reason to repeat the previous experiment. These errors were considered in the future experimental work undertaken.

The other aspect to be considered is that the preliminary test had a fan pushing the air through the system. This experiment had the fan pulling the air through the pipes which means that despite the fact that the vertical reference pipes were blocked some external air might have been pulled through them mixing up with cooler air. It was not possible to test the airtightness of the system so this could not be confirmed. In an EAHE both solutions might be used, the fan at the inlet or at the outlet depending on the required configuration.

Figure 6-26 shows the results from a very warm day when the fan was running at 2m/s from 9am to 6pm. The maximum temperature difference achieved in this period of monitoring (10 days) was 16.5^{o}C and the system was able to deliver air at 15^{o}C throughout the period. Figure 6-27 shows the average external temperatures, average outlet temperatures and the rate of the sensible cooling delivered by the system in this period. Unfortunately the external humidity sensor did not record data over that period.

These results show that the system installed by the author works effectively and could aid the mitigation of the overheating in the Stoneguard House once the house and the EAHE are ready.

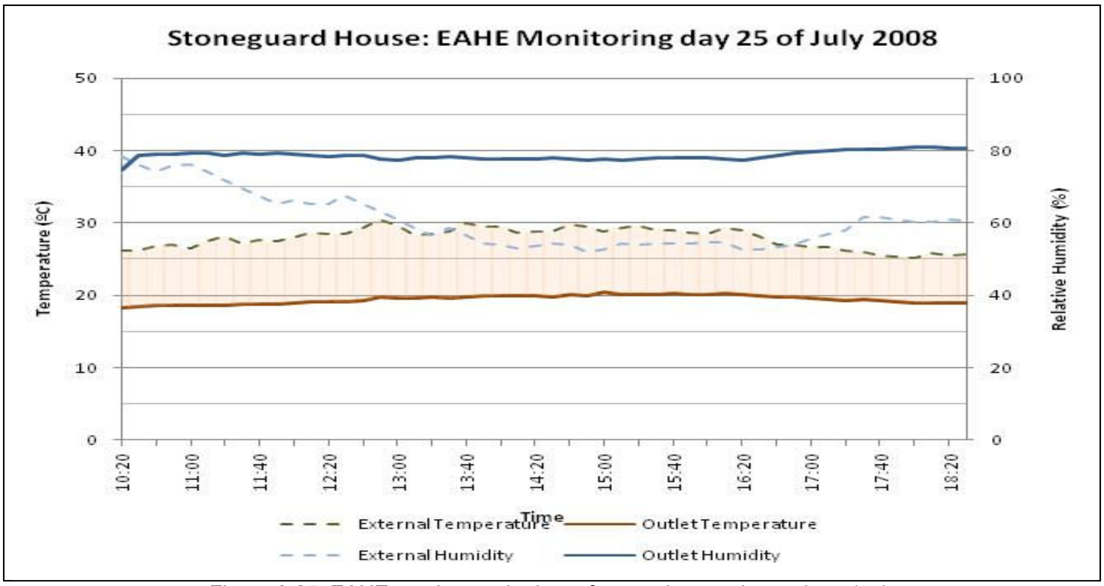


Figure 6-25: EAHE on-site monitoring – fan running continuously at 1m/s

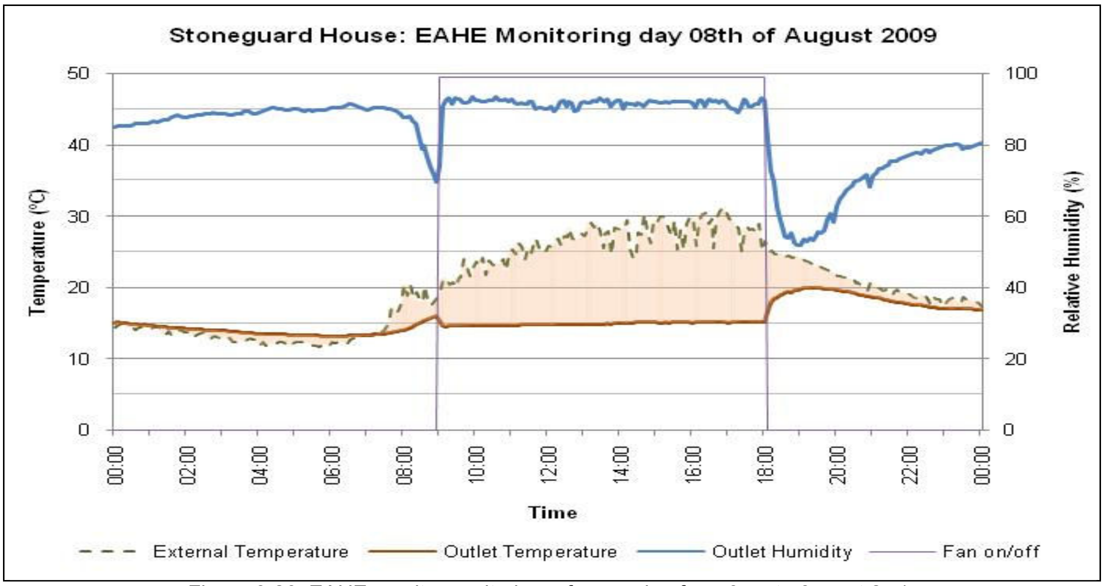


Figure 6-26: EAHE on-site monitoring – fan running from 9am to 6pm at 2m/s

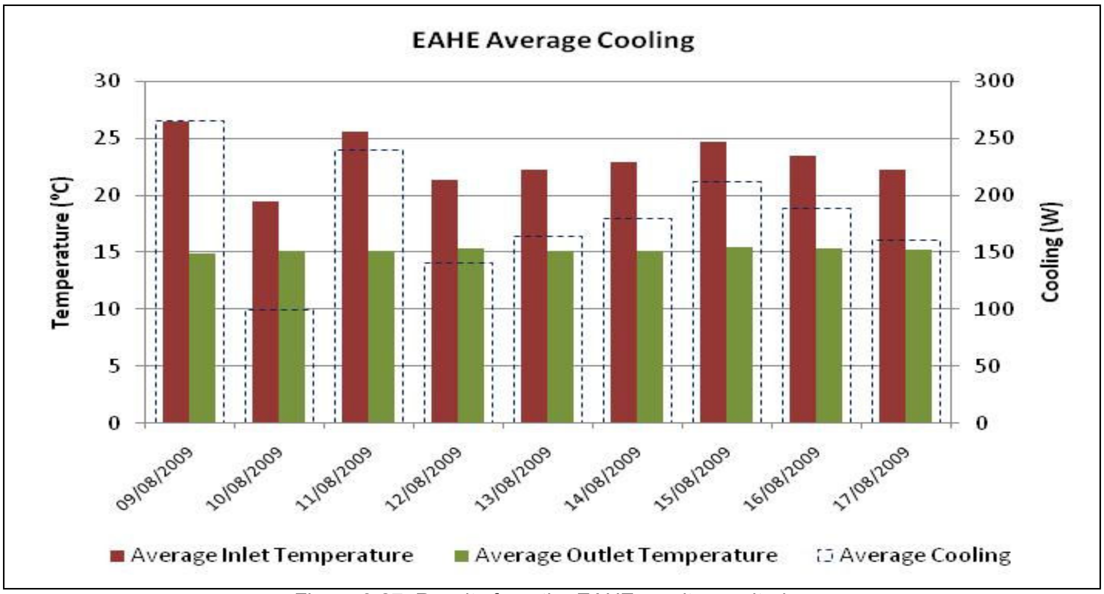


Figure 6-27: Results from the EAHE on-site monitoring

6.2 THE BASE CASE SIMULATION MODEL

A computer model of the house based on the design at the time of this writing was built in Tas in order to assess its performance regarding overheating (note that the house is still not complete and some design aspects may change before the final completion). The materials of the envelope followed those described in section 6.1.1 which are largely the materials actually used but with a few assumptions made due to the incompletion of the house. Images of the model can be found in Appendix 6.B.

6.2.1 Scope and Method

The house did not have shading at the time this work was carried out so Base Case does not comprise any shading devices. Shading on the south facade is expected to be designed and incorporated once the house is complete. In Case 0 shading was added by means of external louvers on the sunspace south façade and blinds from 8am to 8pm in windows types W1 and W6 (south and west facades).

The aim of these simulations was to validate the model and understand the basic thermal performance of the dwelling using a simpler model that had no additional gains or strategies. The model is developed in the next section with occupancy, lighting, ventilation and active space conditioning devices to simulate behaviour that reflects its real functioning.

Table 6-4: Base Case simulations

		Base Case Weather data 2002, infiltration 0.05ACH, no shading, no internal gains	**Case 0** As Base Case + shading
		BC	**C0**
Stoneguard House as constructed	**SH**	BC SH	C0 SH

6.2.2 Assumptions

As many input parameters in dynamic simulation represent quantities that are difficult or impossible to measure, especially with regards to occupancy, assumptions were used. These have a large influence in the results so in this first set of simulations they were kept as simple as possible.

1. Weather: the weather data used was the CIBSE Design Summer Year Weather Data (DSY) for Nottingham based on the year 2002 described in section 5.1.2 (Chapter 5).

2. Calendar: it is assumed that summer (or no heating period) is from the 1st of May to the 30th of September and winter (heating period) is from the 1st of October to the 30th of April.
3. Internal Gains: no internal gains were assumed in this first simulation.
4. Ventilation and infiltration:
   - Infiltration: in this first set of simulations, infiltration was assumed to be very low at 0.05ACH at atmospheric pressure in line with best practice in passive design.
   - Ventilation: no ventilation was assumed.
5. Comfort Temperature Range: as described in Chapter 5, thermal comfort is subjective and sometimes more acute temperatures are desirable. In this work the benchmarks suggested by CIBSE, described in Table 5-2 (Chapter 5), were used. The simulation results are illustrated by means of the number of hours in a year when temperatures in the room go above 25^{o}C and above 28^{o}C. In addition, the Predicted Mean Vote (PMV) method was used to estimate the percentage of people who feel comfortable in each condition.
6. Heating: no heating was assumed.
7. Cooling; no cooling was assumed.

6.2.3 Results

Figure 6-28 shows the results for the Base Case regarding temperature in the main rooms of the house. The Base Case was found to present severe overheating with the living room exhibiting temperatures above 25^{o}C for more than 34% of the year and temperatures above 28^{o}C for almost 18% of the year. The bedrooms also presented overheating although to a smaller degree and the sunspace was above 25^{o}C for practically 50% of the year. The basement, which receives no solar radiation, was found to be below 18^{o}C for more than 80% of the year.

Once shading was added in Case 0, there was significant improvement, not just in the zones directly affected by solar radiation, but also to the zones adjacent to the sunspace (Figure 6-29). Shading brought overheating in the living room down to around 13% of the year above 25^{o}C and just over 3% above 28^{o}C. All the bedrooms were still found to be above 25^{o}C between 10 and 20% of the year despite significant improvement, especially in those with south facing glazing. Even though the sunspace's south facade is largely shaded over the hottest period of the year, there is still substantial overheating in the area, with temperatures above 25^{o}C over 25% of the year and above 28^{o}C around 17% of the year.

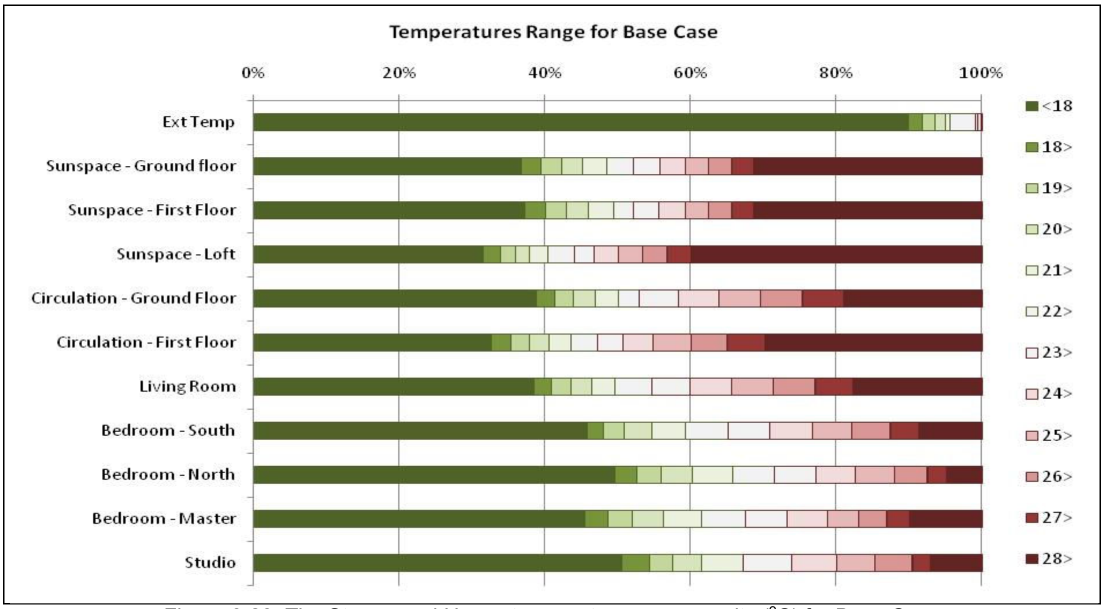


Figure 6-28: The Stoneguard House temperature range results (°C) for Base Case

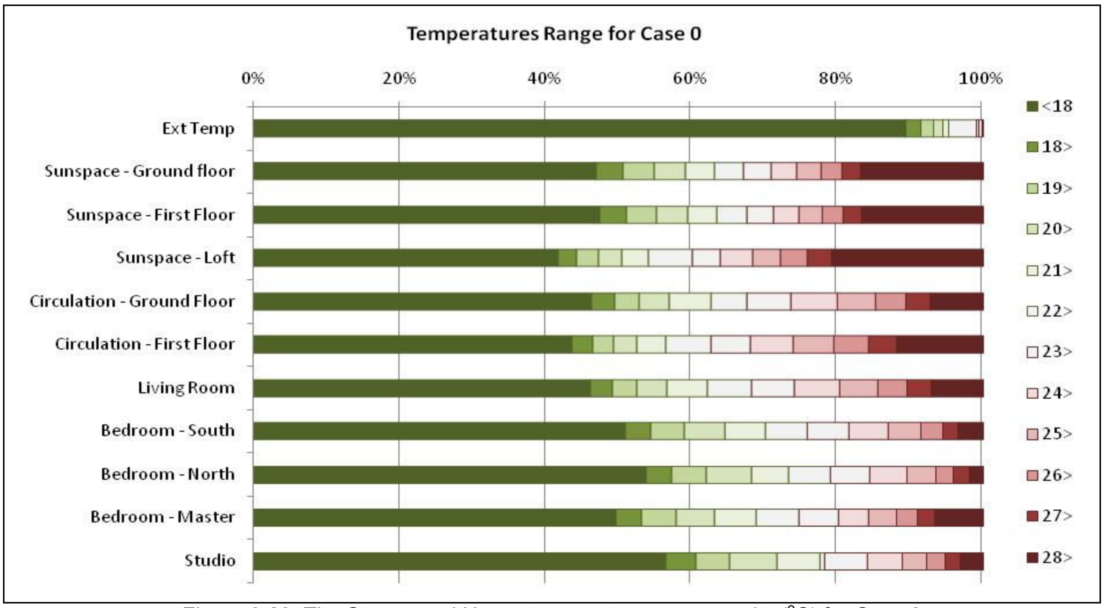


Figure 6-29: The Stoneguard House temperature range results (°C) for Case 0

Figure 6-30 refers to Base Case and illustrates how the house's temperatures are a result of the quantity of solar radiation received in each space. In fact, the house was found to be very reliant on the external conditions, with very fast response to any temperature change. This can be attributed to the materials used as well as the design.

As the envelope is well insulated (although not as well as the examples in Chapter 5), whenever there is availability of solar radiation the house is much warmer than the outside. However, the peak temperatures reach levels around 40°C in the circulation zone (just behind the sunspace) and the living room (which is open to the ground floor circulation zone). The sunspace reaches a staggering 60°C in this simulation as it is acting as a greenhouse. This might seem exaggerated but it is probably close to reality as no shading or ventilation were assumed. Nevertheless the results show the potential for overheating in that space and the need for strategies that both diminish gains and provide cooling.

As may be seen in Figure 6-31, even though the shading was designed for the summer period, it also had an impact on the winter period bringing the highest temperatures down to within comfort zone. Conversely, it did not affect significantly the lowest temperatures as those are closely related to outside temperatures. Note that 'GF' stands for Ground Floor and 'FF' for First Floor.

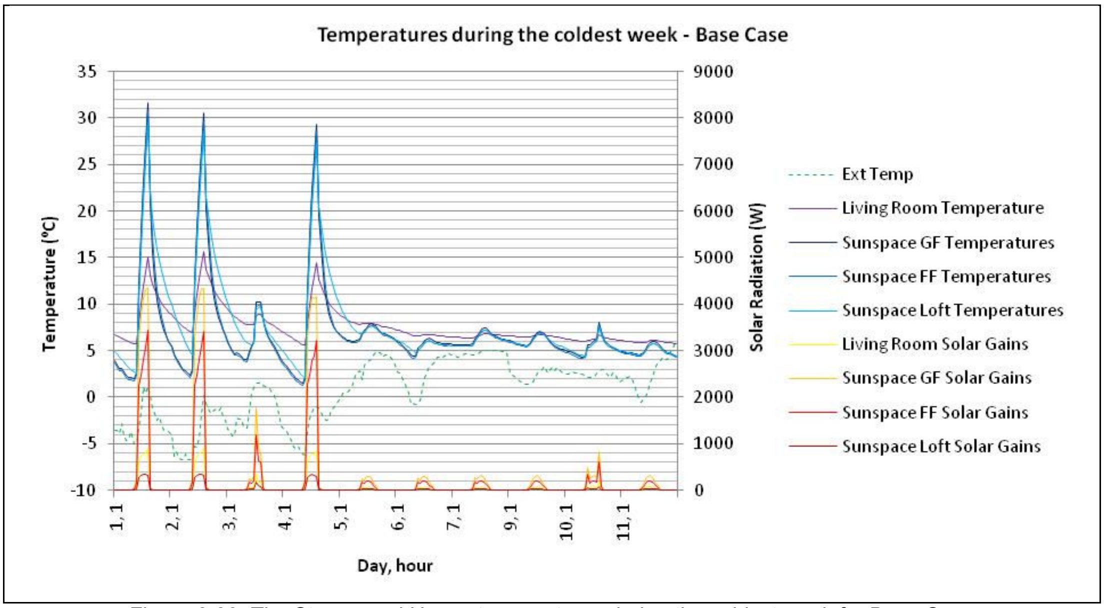


Figure 6-30: The Stoneguard House temperatures during the coldest week for Base Case

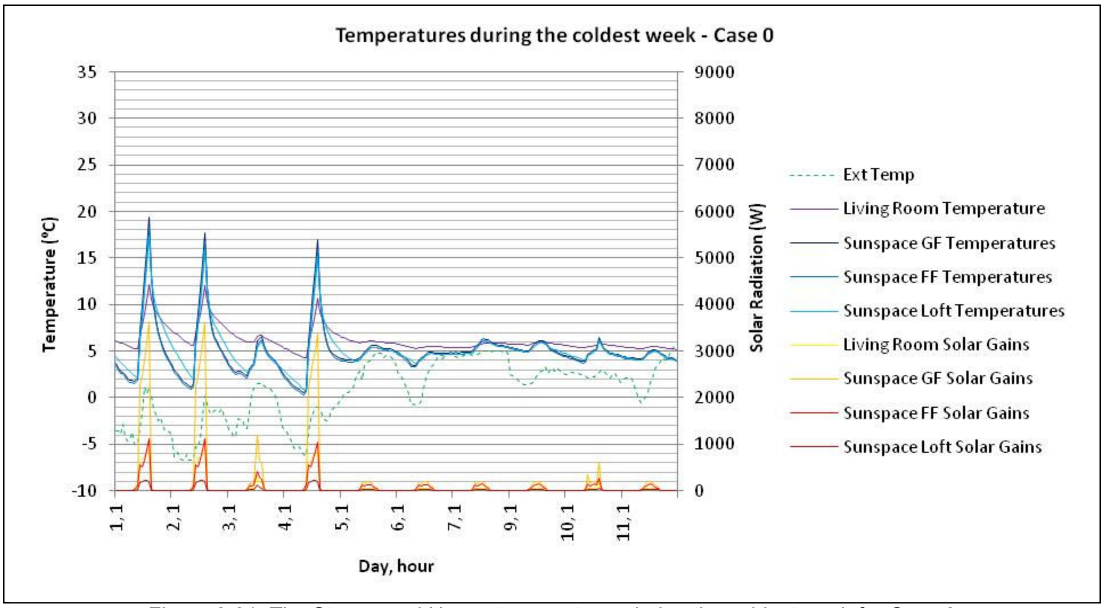


Figure 6-31: The Stoneguard House temperatures during the coldest week for Case 0

Overall Case 0 represented a considerable improvement over the Base Case regarding overheating (Figure 6-32 and Figure 6-33) as expected. However, it did not completely mitigate it so ventilation will be considered in the next case. In winter time, shading had a small negative impact on the temperatures with all main zones presenting temperatures below 18^{o}C for more than 40% of the year.

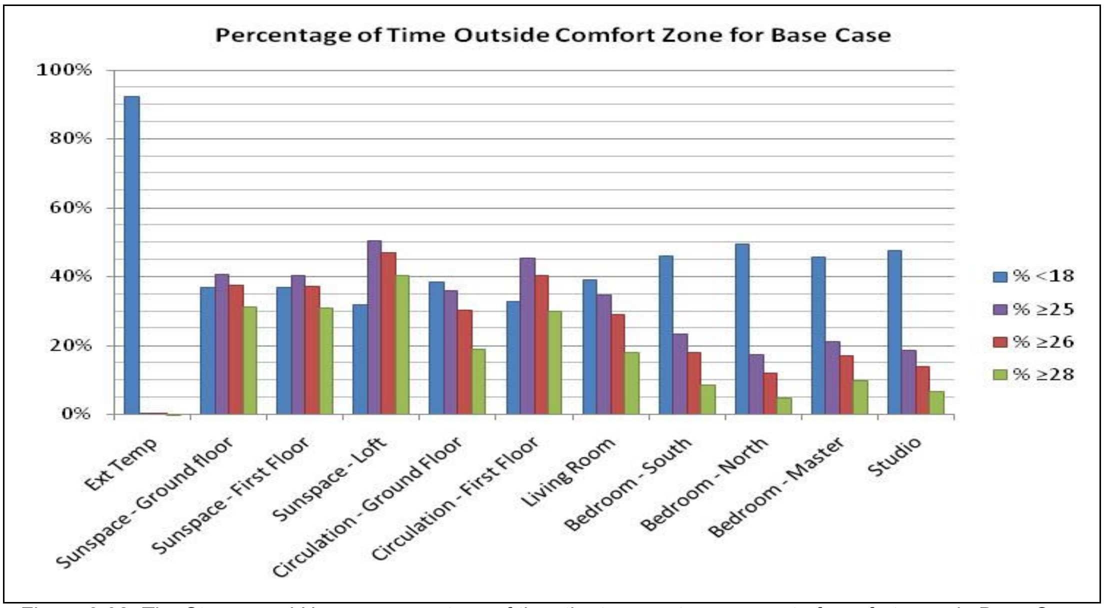


Figure 6-32: The Stoneguard House - percentage of time the temperatures are out of comfort zone in Base Case

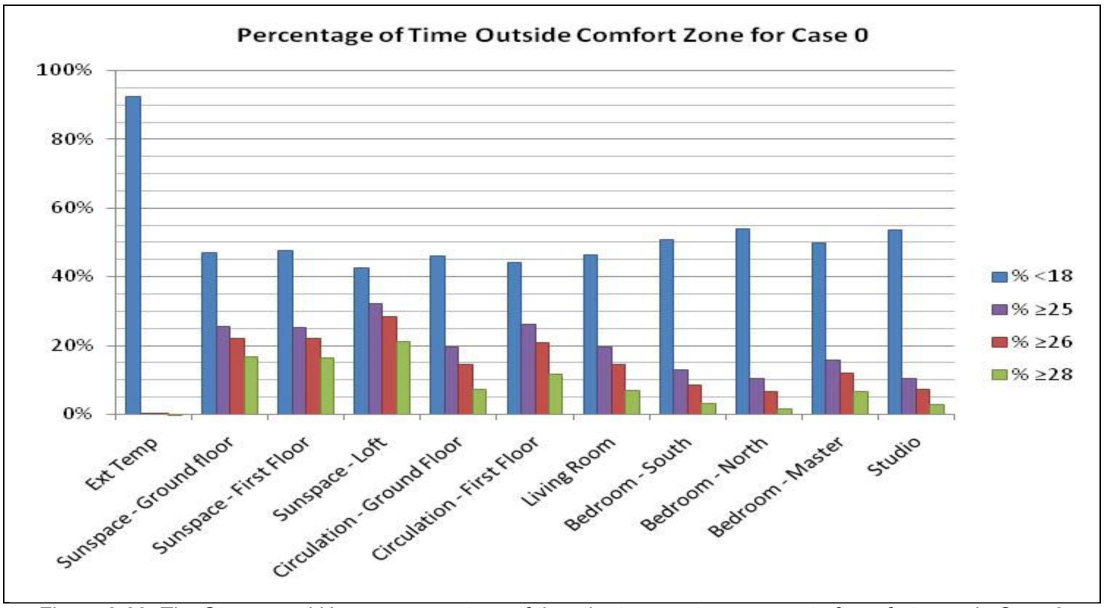


Figure 6-33: The Stoneguard House - percentage of time the temperatures are out of comfort zone in Case 0

6.3 MODEL WITH SHADING, OCCUPANCY AND HEATING

This section uses the model of the previous section with added parameters in order to simulate the Stoneguard House as close as possible to reality. As shown in the previous section, the house presents severe overheating risks if mitigation strategies are not in place. This section will use the model with shading, added ventilation and the EAHE. Although the latter cannot be modelled in Tas, its benefits can be accounted for by a strategy called inter-zone air movement.

6.3.1 Scope and Method

The objective of this section is to simulate the Stoneguard House as a fully functioning dwelling accounting for occupancy and to use the results to determine any overheating issues in the present climate. The next section will simulate the model in future weather climate.

Table 6-5: Summary of Cases 0, 1, 2, 3 and 4

		Case 1 As Case 0 +occupants, heating, infiltration 0.2ACH	**Case 2** As Case 1 + ventilation	**Case 3** As Case 2 + EAHE	**Case 4** As Case 3 but with Precast concrete panel walls
		C1	**C2**	**C3**	**C4**
Stoneguard House as constructed	**SH**	C1 SH	C2 SH	C3 SH	C4 SH

6.3.2 Assumptions

The house's geometry was kept the same. Case 1 introduced internal gains and a higher infiltration, Case 2 added natural ventilation and Case 3 simulated the benefits of the EAHE. The assumptions were based on the following:

1. Weather: as Base Case.
2. Calendar: as Base Case.
3. Internal Gains: as the CIBSE guide does not provide gains for dwellings, the following values were assumed:
   - Occupants: 4 people were assumed to use the house, a couple using the master bedroom and one person in each of the bedrooms. All of them were assumed to be out during the day and in different locations during the evenings. The sensible heat gain assumed for each person was 70W and the latent heat gain was 50W. Occupancy in circulation spaces was ignored. Occupants were assumed to use the spaces according to the schedules in Table 6-6.

- Lighting: is assumed to be provided by low-energy compact florescent bulbs resulting in the following thermal loads when in use:
    - Kitchen: 75W
    - Living and dining rooms: 50W
    - Bedrooms: 50W
    - Circulation: 50W
    - Toilet and bathroom: 25W
- Equipment gains: a TV was assumed to be used for 3 hours in the evenings in the living room producing a gain of 150W. The house's service equipment for heating and hot water are located in the basement so 10W of gain were assumed in that space in a 24h regime. In the loft, where the heat exchanger connected to the solar collectors is located, 3W of gains were assumed in a 24h regime.

Table 6-6: Schedules of spaces internal gains (1=on, 0=off)

Name	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
24 hours	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8am to 8pm	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
Heating (12h)	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
Bathroom occupancy, lighting	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
Bedrooms lighting	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
Living occupancy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0
Living lighting (summer)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
Kitchen occupancy, lighting	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
TV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0

Table 6-7: Stoneguard House appliance gains

Appliance		**Power** (kW)	**Usage** (assumed)	**Daily total energy** (kWh)
Kettle (on hob)	Per 1.5 litre boil	3.00	4 times/ day	0.60
Microwave/ Oven	When on	0.80	30 minutes/ day	0.40
Cooker	When on	0.79	30 minutes/ day	0.40
Dishwasher	Per 1h cycle	1.00	Twice weekly	0.29
Fridge	Per hour	0.03	All year	0.62
Total				2.31

- Appliances: gains from appliances in the kitchen were assumed on a 24 hours regime so the gains from fridge, cooker and oven, dishwasher and kettle were assumed to together continuously deliver an average of 10W. This is described in Table 6-7.

4. Ventilation and infiltration:
   - Infiltration: was assumed to be 0.2ACH at atmospheric pressure. This value includes the minimum infiltration used in the previous simulation plus enough fresh air for the occupants. By the time this work was finished, no pressurization test was carried on in this house.
   - Ventilation: it was assumed that air movement occurred both from outside to the house and within the house (i.e. between the sunspace and the circulation zones).
     - Sunspace external windows (24 hour regime): In summer, the external windows in the sunspace (the side windows and the Velux roof windows) were set to start opening automatically (as the design anticipates automation for these windows) when the sunspace reached 24^{o}C and be fully opened when the sunspace reached 28^{o}C. The windows were set to close should the wind reach 3m/s or the external temperature become warmer than the internal temperature. In winter they were set to open if the circulation zone reached a temperature above 24^{o}C so the house can make use of the sunspace heat but not get overheated by it.
     - Sunspace internal windows to circulation (24 hour regime): In winter, the apertures will begin to open if the temperature in the sunspace exceeds 18^{o}C and will be fully opened if the temperature reaches 21^{o}C. The aperture will begin to close if the temperature either in the sunspace or in the circulation reaches 24^{o}C. In summer they remain closed.
     - The other windows in the house (living room, kitchen and bedrooms) were set to start opening when temperatures reached 24^{o}C and be fully opened (50% of the area) when it reached 28^{o}C. These settings were applied just for the summer when occupants were in the space. The windows were set to close should the wind reach 3m/s or the external temperature become warmer than the internal temperature. The windows in the bathrooms, walk-in closet and studio were assumed to be kept closed as these zones are more rarely used.
5. Comfort Temperature Range: as Base Case.
6. Heating: heating was assumed during the heating period (1st of October to the 30th of April) for 12 hours (from 5pm to 5am). The thermostat was set to a lower limit of 19^{o}C and an upper limit of 21^{o}C and radiators were used as emitters. It was assumed that, when the heating was on, the whole house would be heated (except for the sunspace, loft and basement). If each space could be heated separately when used, much energy could be saved, however, this has not been done in the house yet and it is not clear if it will be done.

7. Cooling: Case 3 takes into account the EAHE delivering $1m^3/s$ at 10^oC inside the sunspace which is approximately 1.2kg of air per second. As the volume of the sunspace is very large (around $140m^3$) the EAHE at this rate is able to provide the space with 25ACH of fresh air. The temperature of the air being delivered was chosen based on the fact that the previous monitoring was undertaken in a shorter section of the pipe and that it is not possible to vary the air temperature to appropriately simulate the EAHE. The mechanical ventilation and heat recovery system (Sunwarm) could not be simulated.

Case 4 is exactly as Case 3 but the external steel frame walls have been substituted by a concrete precast wall (Figure 5-18 in Chapter 5) with similar U-Value to the original walls.

The sunspace was assumed to have no occupancy, lighting or equipment gains despite the fact that it was designed to be a usable space. This is because assuming internal gains in that space would not refer to any known data source. Based on experience, this space will be used if it offers a pleasant and comfortable environment. According to Base Case and Case 0, the sunspace often presents uncomfortable temperatures.

6.3.3 Results

As expected, Case 1 presented slightly more overheating in the occupied areas due to internal gains if compared to Case 0 (Figure 6-34). In Case 1, the living room is above 25^oC for more than 23% of the year and above 28^oC for more than 10%. The numbers are similar for the circulation just behind the sunspace. The sunspace itself is above 25^oC around 24% of the year and above 28^oC around 15%. The top of the sunspace (named sunspace-loft), is not a liveable area but shows the temperature stratification in the zone, staying above 25^oC for 33% of the year and above 18^oC for over 21%.

Even though ventilation improved the situation, it was not enough to eradicate overheating completely as may be seen in Figure 6-35. In Case 2, the living room is above 25^oC for around 12% of the year and above 28^oC for almost 3%. The sunspace is above 28^oC for more than 8% of the year. In both cases there is overheating in the bedrooms if the CIBSE suggested summer operative temperatures in bedrooms are 23-25^oC with the maximum being 26^oC for 1% of the time (Table 5-2, Chapter 5) are used as a benchmark.

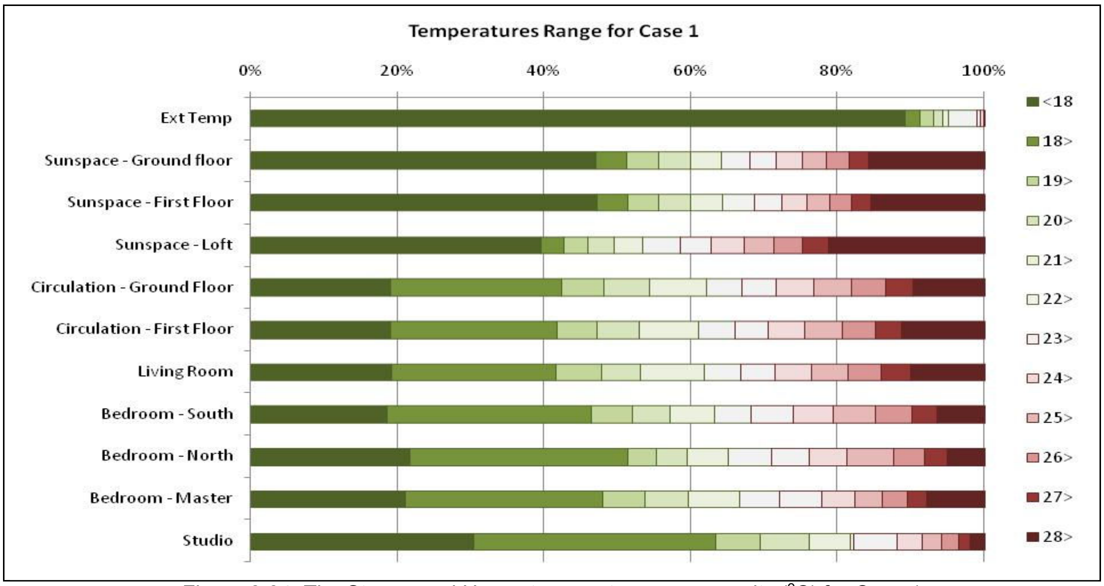


Figure 6-34: The Stoneguard House temperature range results (°C) for Case 1

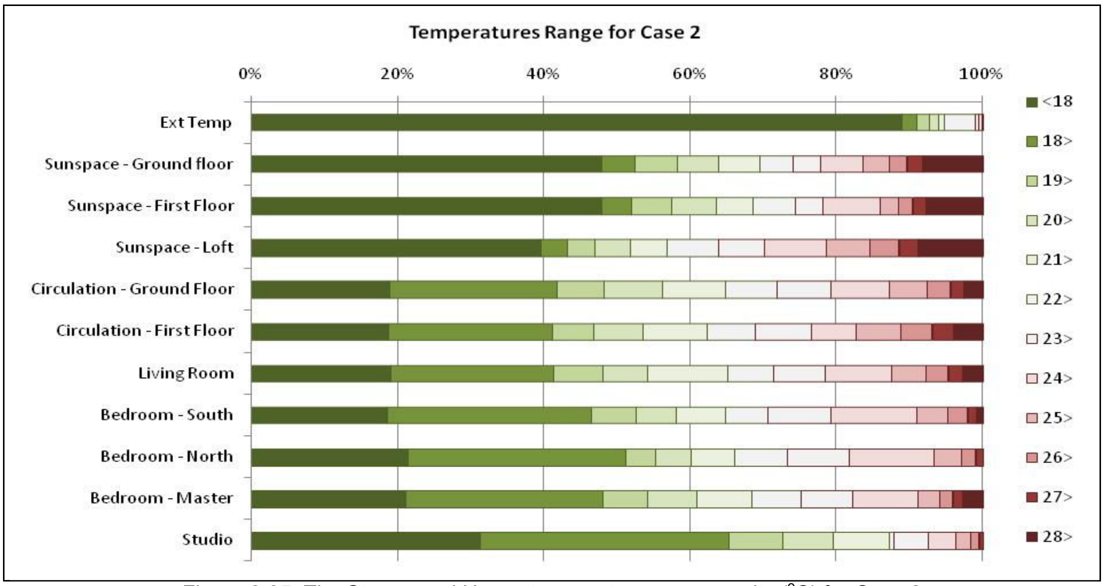


Figure 6-35: The Stoneguard House temperature range results (°C) for Case 2

The energy demand for space heating for Cases 1 and 2 was found to be similar, around 16kWh/m² net habitable floor area per annum or 21kWh/m² treated floor area per annum. Consequently the house does not achieve Passivhaus standards for space heating (15kWh/m² treated floor area per annum) as expected due to U-Values (all elements would need to be below 0.15W/m^{2}K as mentioned in Chapter 1). The fact that the results are similar also means that the internal ventilation strategy (from sunspace to circulation) did not affect the results greatly. This might be due to the dwelling design: the windows are not designed to encourage air movement from the sunspace to the circulation and to the other zones. There is, however, a mechanical ventilation and heat recovery system (MVHR) in the project that is not been considered here. This heat exchanger will be housed in the space above the walk-in closet and upstairs bathroom and is expected to extract warm air from the sunspace to reuse its heat and boost ventilation.

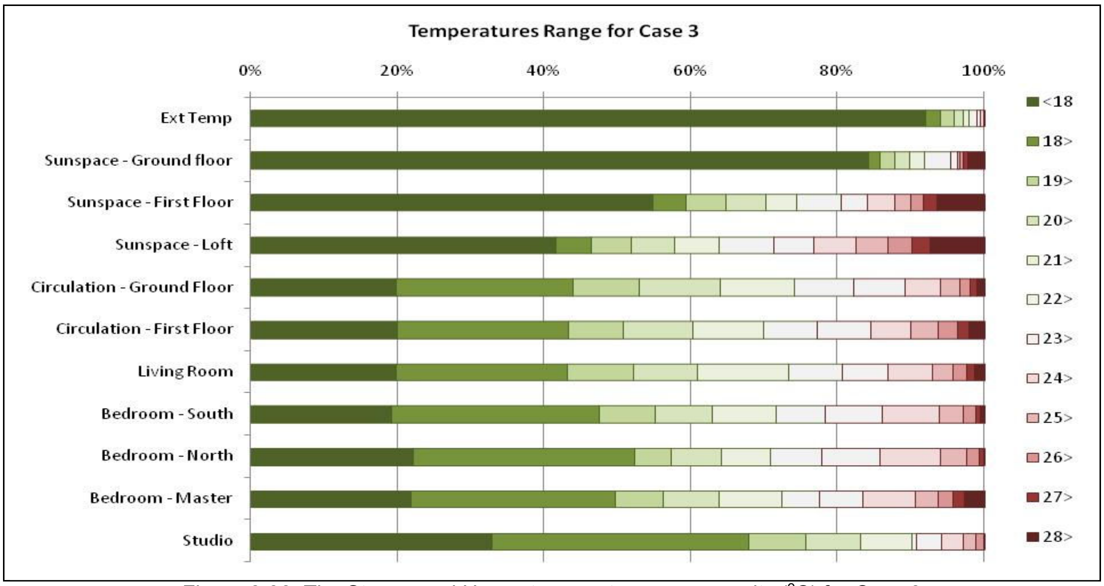


Figure 6-36: The Stoneguard House temperature range results (°C) for Case 3

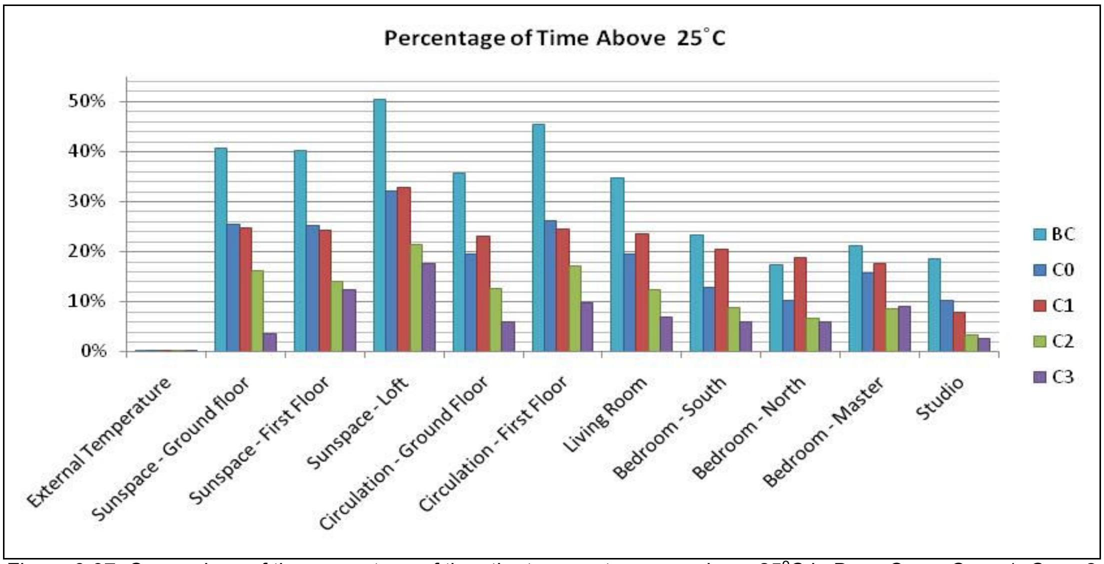


Figure 6-37: Comparison of the percentage of time the temperatures are above 25°C in Base Case, Case 1, Case 2 and Case 3

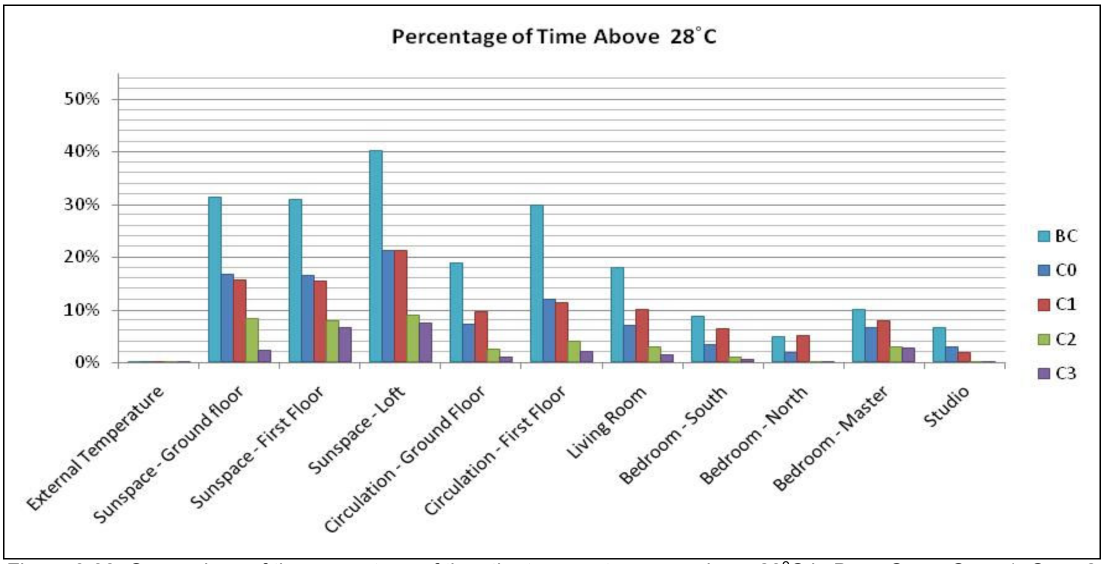


Figure 6-38: Comparison of the percentage of time the temperatures are above 28°C in Base Case, Case 1, Case 2 and Case 3

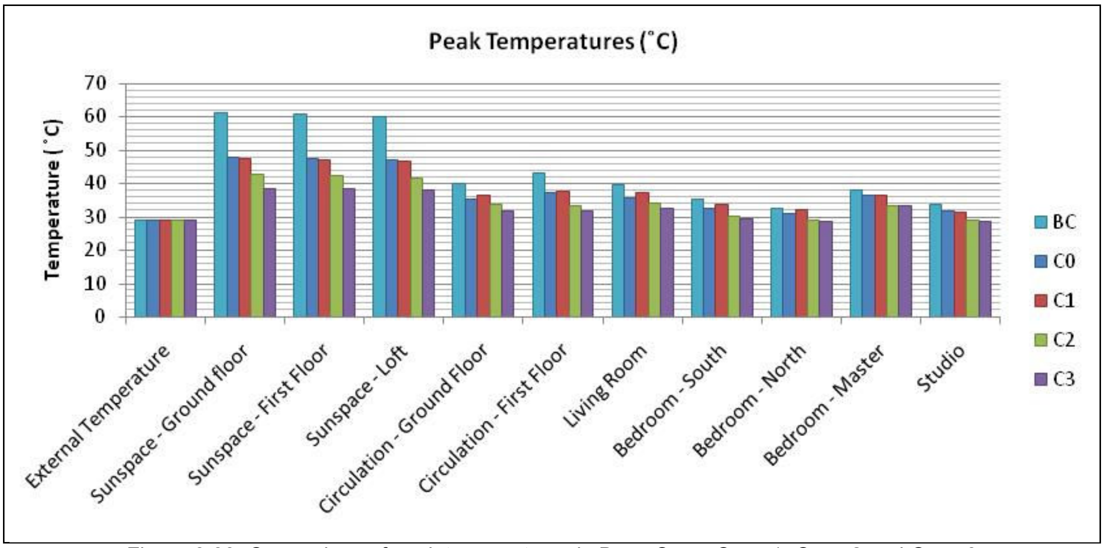


Figure 6-39: Comparison of peak temperatures in Base Case, Case 1, Case 2 and Case 3

In Case 3 the EAHE was simulated by means of cold air being delivered to the sunspace's ground floor. This is not an accurate way to simulate an EAHE but Tas does not allow for the simulation of such systems. The delivery of fresh air from the EAHE to that zone improved conditions but once more did not eradicate overheating. Temperatures above 28^{o}C in the sunspace were reduced to about 4% of the year and in the living room to 1.3% of the year. Bedrooms to the north and south reach temperatures above 26^{o}C for 2% of the year and the master bedroom for more than 6% of the year.

In summary, with shading, ventilation and the EAHE, overheating was diminished but not eliminated, especially in the bedrooms. Nevertheless, the level of overheating presented, although above the CIBSE criteria, could be tolerable for occupants (an example of this will be described in the next chapter). Long term monitoring and post-occupancy evaluation of the house (which are to be undertaken) are the only way to confirm this.

Figure 6-39 compares the peak temperatures in each case. The biggest reduction was seen with the addition of shading. Ventilation also causes an impact but on a smaller scale. Overall, peak temperatures are still very high and even in Case 3, the sunspace reaches 40^{o}C. In addition to the strategies simulated, the sunspace also contain PCM boards as described in section 6.1.1. These are expected to reduce the peak temperatures as demonstrated. However, PCM cannot be simulated in most building thermal simulation software tools including Tas, which is one of the problems of trying to model the effects of these materials.

Case 4 is similar to Case 3 but with the substitution of the external steel frame walls for precast concrete walls. Temperatures above 28^{o}C in the sunspace were reduced to about 2% of the year and in the living room to 0.5% of the year. Bedrooms to the north and south reach temperatures above 26°C for 1% of the year and the master bedroom for just above 3% of the year (Figure 6-40).

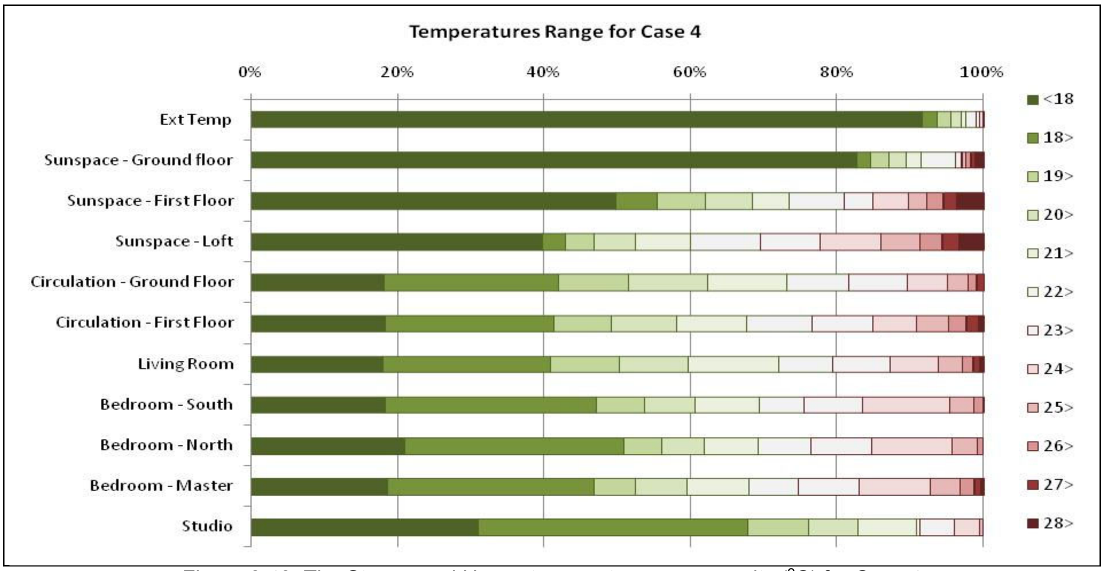


Figure 6-40: The Stoneguard House temperature range results (°C) for Case 4

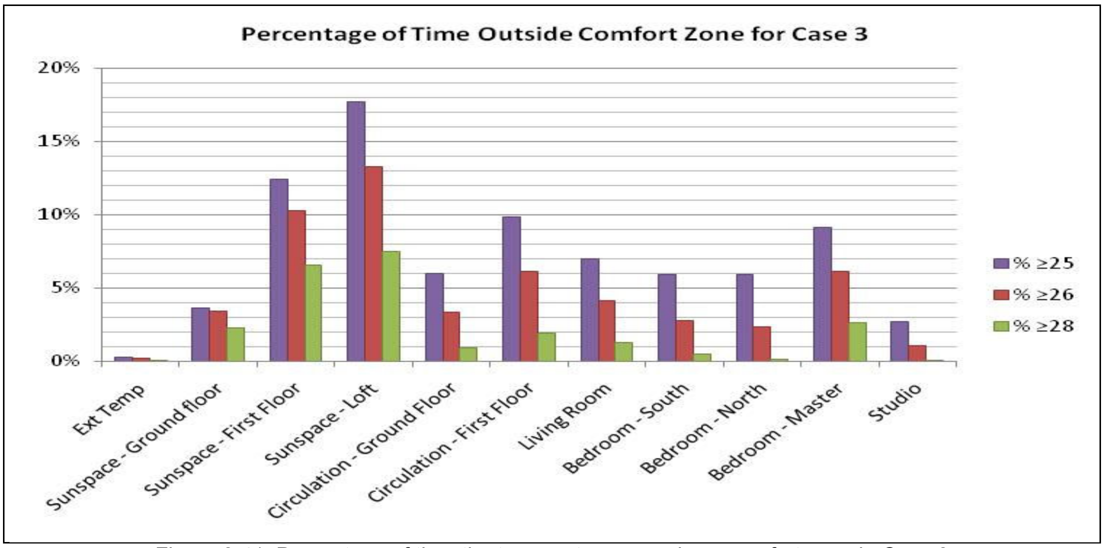


Figure 6-41: Percentage of time the temperatures are above comfort zone in Case 3

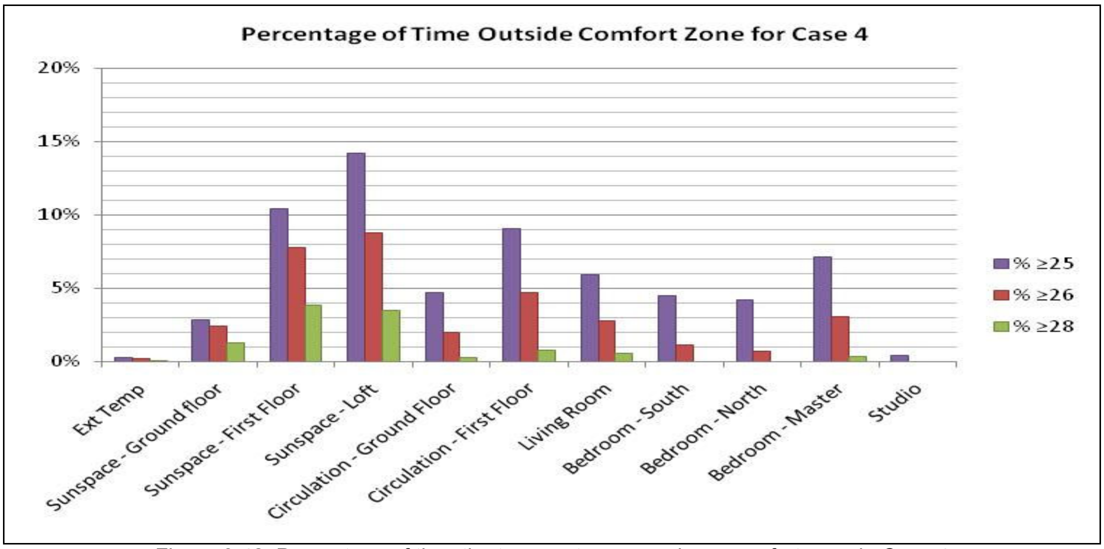


Figure 6-42: Percentage of time the temperatures are above comfort zone in Case 4

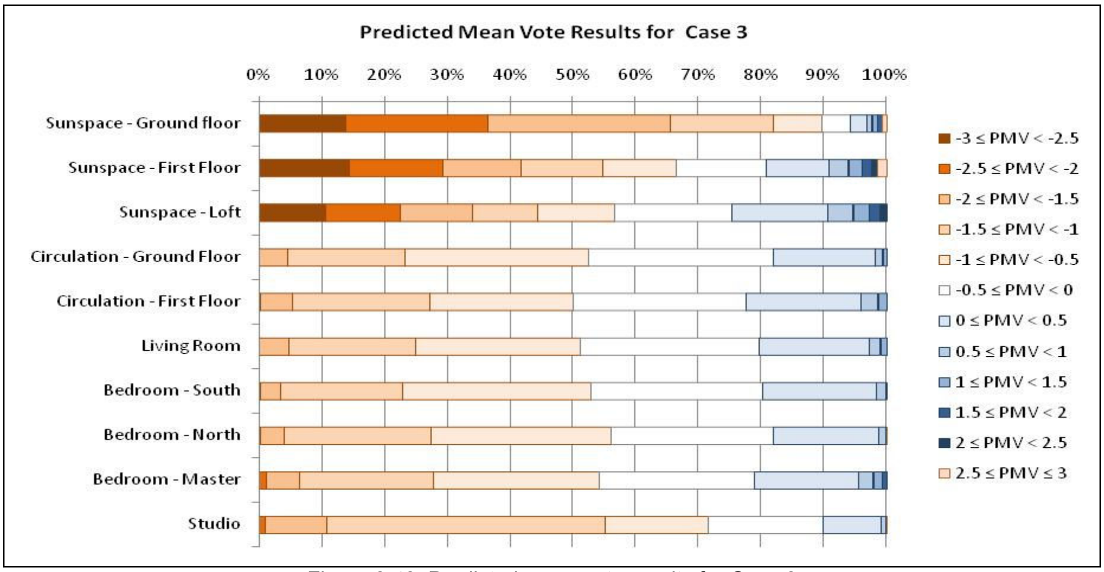


Figure 6-43: Predicted mean vote results for Case 3

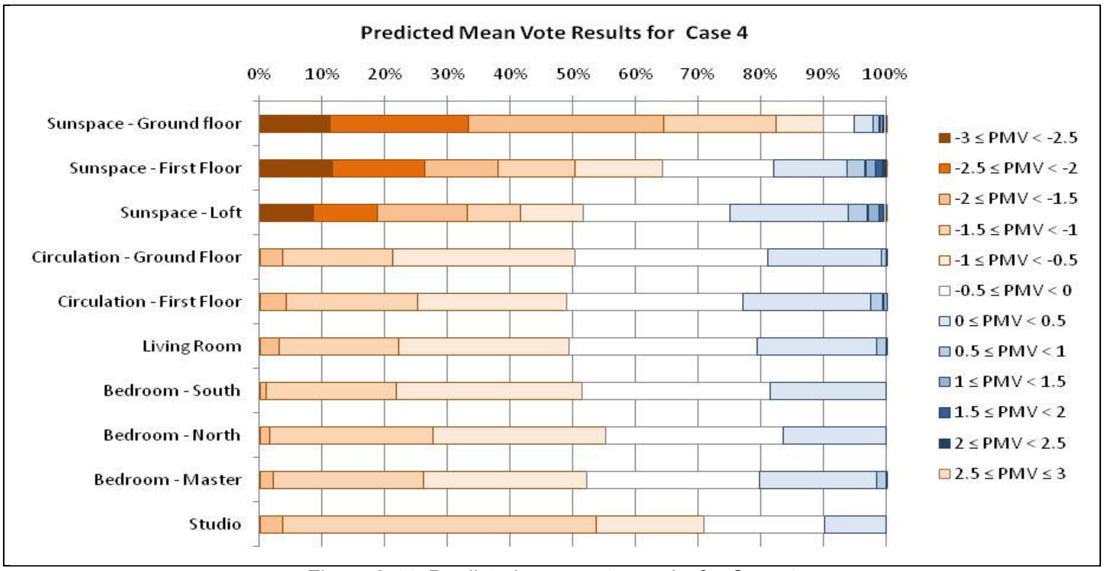


Figure 6-44: Predicted mean vote results for Case 4

If the house had thermal mass available in its envelope, the modelling shows that overheating would have been eradicated from all the spaces except the sunspace. Although a lot of improvement can be seen, the sunspace still presents some overheating despite the addition of shading, ventilation, high mass internal walls and the EAHE. It must be noted that the sunspace does not have a large wall surface available for thermal mass as the front, back and half of each side of it are made of glazing units. It might have been possible to improve its conditions further with the substitution of some of the glazing for high thermal mass walls. Figure 6-44 shows that, except for the sunspace, the other zones present acceptable levels of comfort in Case 4.

Although real occupancy conditions cannot be achieved in simulations, Case 3 is expected to be the closest to the house's real performance and so will be taken for further simulations in future climate scenarios.

6.4 STONEGUARD HOUSE IN FUTURE WEATHER SCENARIOS

As was demonstrated in section 6.3, the Stoneguard House is expected to present some overheating in today's weather due to its very low thermal mass envelope. However, this issue is not extensive if shading, ventilation and the other strategies described are applied to the house. This section will simulate the house in a future that comprises warmer temperatures due to climate change.

6.4.1 Scope and Method

The objective of this section is to investigate how the house that presented little overheating in today's weather will perform under 2020, 2050 and 2080 weather scenarios. These cases will be compared with Case 3, which is the case expected to be the closest to the house's actual performance.

Table 6-8: Summary of Cases 5, 6, and 7

		Case 5 As Case 3 but with 2020 weather data (high-emissions)	**Case 6** As Case 5 but with 2050 weather data (high-emissions)	**Case 7** As Case 5 but with 2080 weather data (high-emissions)
		C5	**C6**	**C7**
Stoneguard House as constructed	**SH**	C5 SH	C6 SH	C7 SH

6.4.2 Assumptions

The assumptions of this section are the same as Case 3 except for the change on the weather data.

1. Weather: the weather data used was the CIBSE Design Summer Year Weather Data (DSY) for Nottingham 'morphed' into weather data for 2020, 2050 and 2080, created using the UKCIP process described in section 5.1.3 (Chapter 5).
2. Calendar: as Base Case.
3. Internal Gains: as Case 3.
4. Ventilation and infiltration: as Case 3.
5. Comfort Temperature Range: as Base Case.
6. Heating: as Case 3.
7. Cooling: as Case 3.

6.4.3 Results

In Case 5 (Figure 6-45), the living room is above 25°C for 12% of the year and above 28°C for almost 3% of the year. The sunspace is above 25°C for about 10% of the time and above

28°C for around 7% of the year. These numbers do not consider the sunspace loft because it is not habitable and because the heat exchanger is expected to extract some of that heat. Bedrooms north and south present temperatures above 26°C for over 6% of the year while the master bedroom exceeds that temperature for almost 10% of the time. In summary, the house will be overheated to uncomfortable levels by 2020 if the climate change scenario data used become reality.

In Case 6 (2050), the bedrooms are uncomfortable for around 15% of the year while the living room is above 28°C for almost 6% of the year (Figure 6-46). In Case 7 (2080), these numbers rise to 24% and 12.5% respectively. It is probable that a mechanical cooling system will be necessary for the well-being of the occupants.

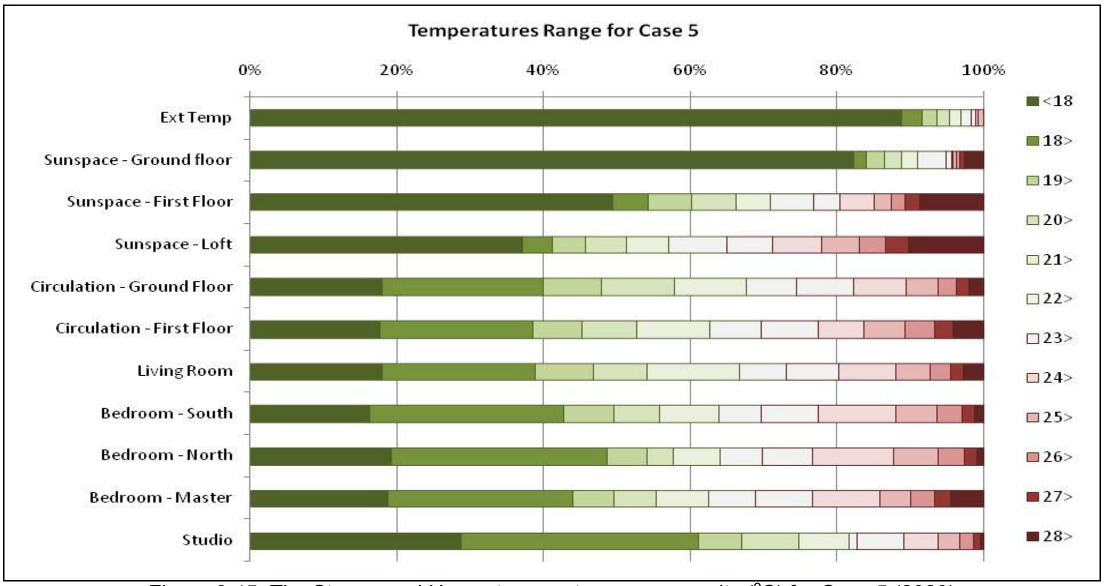


Figure 6-45: The Stoneguard House temperature range results (°C) for Case 5 (2020)

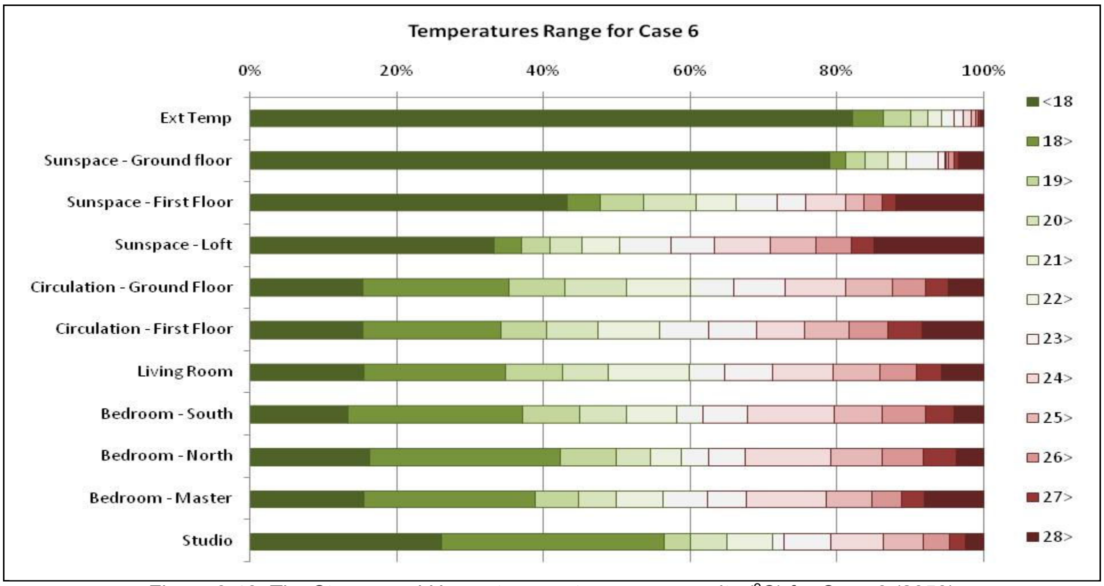


Figure 6-46: The Stoneguard House temperature range results (°C) for Case 6 (2050)

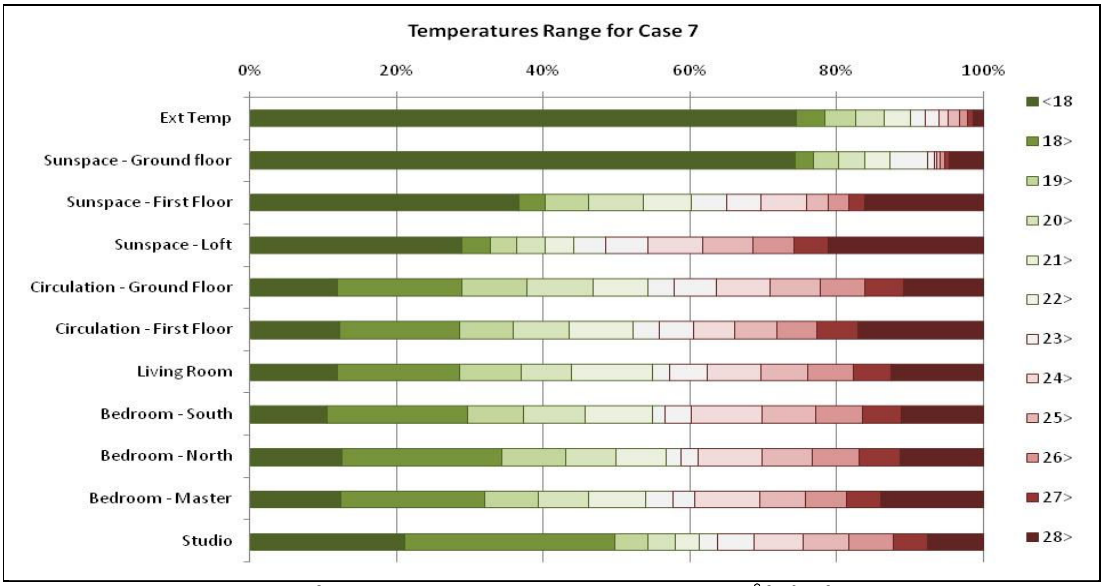


Figure 6-47: The Stoneguard House temperature range results (°C) for Case 7 (2080)

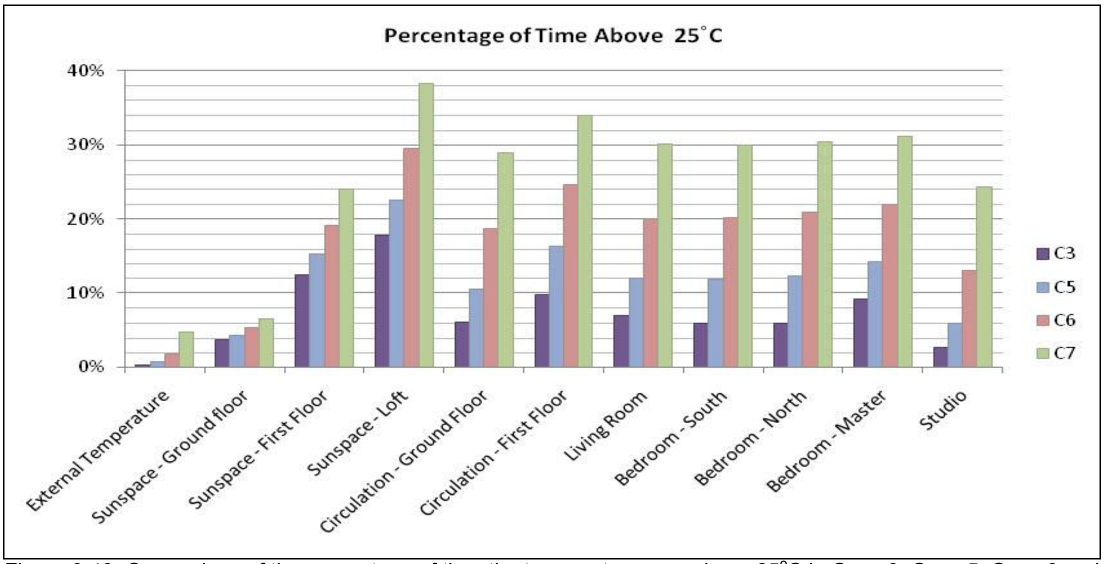


Figure 6-48: Comparison of the percentage of time the temperatures are above 25°C in Case 3, Case 5, Case 6 and Case 7

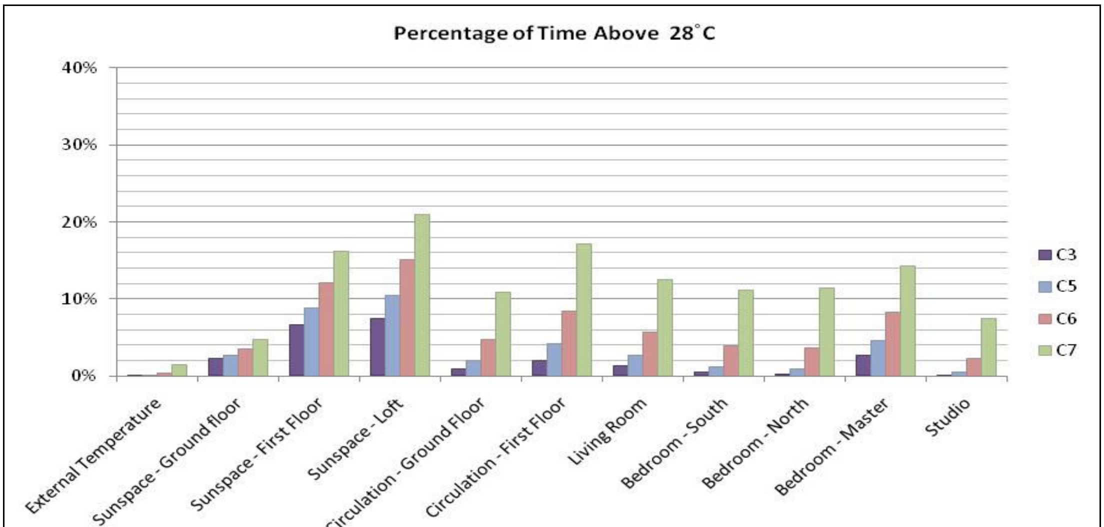


Figure 6-49: Comparison of the percentage of time the temperatures are above 28°C in Case 3, Case 5, Case 6 and Case 7

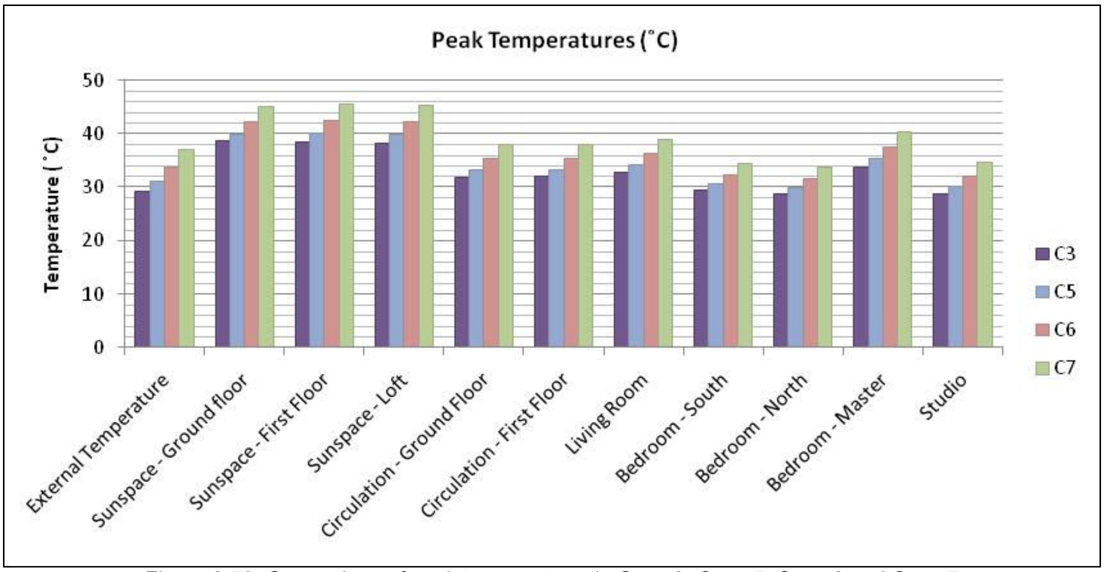


Figure 6-50: Comparison of peak temperatures in Case 3, Case 5, Case 6 and Case 7

6.5 THE EXPERIENCE OF BUILDING THE STONEGUARD HOUSE

Implementing sustainable design and renewable energy technologies is not always easy. Although most British professionals involved in construction are relatively aware of what is involved in such concepts and the demand for energy efficient buildings is on rise (Sponge, 2006), it is noticeable the lack of understanding of the implications on achieving this aim.

Through the difficult and sometimes very frustrating construction process of the Stoneguard House a lot was learnt. The house was initially planned to be built in 10 months and by the time this work was finished, more than 3 years had passed since the start of its construction and it was still not finished. It is worth talking about some of the issues that led to such delay as they could have a direct influence on the house's performance.

The first and most important issue was that the house project was never pursued to detail design in full. As discussed, the use of MMC puts great reliance on the project and, consequently, on the designers. This house is an example of what happens when that is not followed: the benefits of fast and high quality construction on site are lost. The house took much longer than predicted and too many decisions had to be made on site by a site manager rather than by a designer. This not only increased costs, but also led to a series of interface problems between construction systems and technologies.

Another issue was the construction of the EAHE. The original design was not approved due to last minute changes of the house's position. As explained previously, the pipes were to be laid in the hole dug for the house's foundations. As the foundation works were due to start a last minute decision had to be made and the final design is a consequence of those decisions. The EAHE system was considered of secondary importance and therefore had to follow the schedule of other parts of the building and not enough time was allowed for the new design to be simulated before construction. More importantly there was the difficulty of getting the idea of the EAHE across to the builders. Put in simple words, 'drainage pipes' were to be used as 'air ducts' and to be placed as deep in the ground as cost allowed. The reasoning behind the system was not understood and as a consequence the installed pipes were kept open in the weather for months despite the author's explanations of the need to keep them dry and clean. This might mean hygienic problems in the future when the system is in use.

The need for drainage of condensation water in the pipes was also not completely comprehended and the system had to be completely redone as the proposed slope was not followed in the first installation. This led to an increase in the costs and other time and stress related issues. Soak-aways were another issue and although 4 were initially requested just 2 were actually built as shown in Figure 6-15.

Another very important aspect to consider is air leakage, known to be a problem in the UK construction industry. A large part of the house's cost was invested in high performance insulation materials to achieve low U-Values in the building's envelope. However, that investment might be wasted if excessive air leakage is not avoided. It was noticed that this concept is almost completely unknown by builders, which then leads to the high infiltration rates that the UK industry so commonly presents (Stephen, 2000). Consequently, time was spent not just on the project details but also on explaining to the on-site labour why such details were important. As a result, new layers such as membranes were proposed in the walls and floors and attention was given to the link between the different components (i.e. steel framing to concrete slab). Similar thoughts were given to avoid thermal bridging, which in steel construction can be an extensive problem. Unfortunately, as the dwelling construction stopped, it is likely that the project team will change and such efforts will be lost.

The link between different technologies for hot water and space heating was another problem. Most of the products available on the market are not flexible enough to adapt to new technologies or even to existing technologies combined in a different way. An example was the link between the OSMA under floor heating system and the Dimplex heat pump. The OSMA Pocketed Polystyrene and Thermoboard systems save time by manufacturing insulation and wood panels with pre-cut channels for easy installation of the water pipes. This system requires a temperature of 45^{o}C in order to work efficiently but the heat pump could just deliver 35^{o}C. The companies liaised with one another for further investigation and the strategies were combined.

The late decision to install an array of PV modules nearly caused a problem as the Unilin roof system does not provide more than a 30mm truss for it to be fixed. Fitting it retrospectively would be unfeasible as finding the 30mm truss could be very difficult. In addition, the roof tiles used did not allow for standard clamps to be used. Fortunately a set of metal brackets and especially made clamps were made on time and the array was installed appropriately.

New products were also developed when the need arose. For instance, Logix, the company responsible for the ICF system that formed the basement walls, created a new product using Neopor, an improved polystyrene product produced by BASF, supplier of the PCMboard. The new product is similar in shape and form to the original but has a U-Value 20% better.

Concluding, regardless of the time spent by the design team designing and detailing the project, the building might not achieve the expected result if the construction team is not aware of the issues they are trying to cover. Moreover, the construction team should be motivated and driven by the same objectives as the design team. It was felt that, in this house, they lacked understanding of certain important concepts in sustainable design. However, they were interested and willing to learn from this project. If the UK construction industry expects to improve building energy efficiencies, more attention should be given to the link between design and construction teams.

During the exhaustive process of translating the design ideas into an efficient building, the majority of the problems were turned into opportunities of networking between companies and adaptableness of strategies and systems which, by becoming more flexible, became even more valuable. The sponsoring company and the construction team had a valuable experience where not only much was learnt, but also horizons were broadened.

6.6 CONCLUSIONS

The Stoneguard House was designed to showcase modern construction methods and innovative technologies and to achieve a dramatic reduction in carbon emissions without compromising the user's comfort. The house puts together a series of different strategies (passive and active) that differentiate the design from standard dwellings but also caused difficulties when it came to integrating different products and systems. Most of the problems were turned into opportunities, allowing the suppliers to interact and create new products.

In this house, many things were not specified clearly at the design stage and instead were decided on site. For example, the wall fabric and its properties were not fully resolved before the construction started. Consequently there are too many different construction types leaving space for mistakes and lots of joints, both of which are likely to result in thermal bridging and air infiltration.

The house encompasses a large south facing sunspace and most of the house fabric is constructed using material with low thermal mass or with insulated thermal mass (such as ICF). The elements with the highest thermal mass form the ground floor and are below the ground floor (basement). The house is likely to present severe overheating if mitigation strategies are not in place and spaces, such as the living room, could be above comfort zone for more than 30% of the year. Without the strategies, the sunspace could be uncomfortable (and consequently unused) for most of the year. It is worth noting that the sunspace is the main entrance of the house and just behind it the most important circulation zones in the home are placed. In addition, it was found that this space has great influence on the comfort of adjacent spaces, such as the living room and all bedrooms. Therefore the control of overheating here is crucial.

Overall, the house in today's weather presented overheating to a reasonable level, which might be acceptable. If the house had been built using a material with higher thermal mass (such as precast concrete panels) than overheating could be mitigated. In future climate scenarios the house is likely to be uncomfortable even with shading, ventilation and the EAHE, so the addition of a cooling strategy might be necessary.

It is of concern that despite the addition of mitigating strategies (shading, ventilation, no internal gains, delivery of cold air by an EAHE and even the addition of high thermal mass walls) the sunspace still presents overheating in today's weather and even more in future weather scenarios. The PCM boards added to the ceiling might help the reduction of peak temperatures but the ceiling surface area is small in comparison with the sunspace volume so a signifcant improvement should not be expected. As no high windows are provided to extract the warm air (except for the velux windows at a lower level), the comfort of the sunspace will put great reliance on the MVHR system to be installed in the loft space. The sunspace does, however, buffer certain parts of the house in the summer and in the winter and provides the occupants with a large entrance hall.

The on-site monitoring of the EAHE presented results that, even if not totally in agreement with the preliminary tests, are positive. The system should aid the reduction of overheating even though it cannot eliminate it completely. In the future, the EAHE of this house is likely to be frequently used.

Unfortunately it was not possible to analyse on-site monitored data of the full house. The next chapter will analyse the BASF House making use of both, computer simulations and data collected on site.

7 THE BASF PROTOTYPE HOUSE

The BASF House, part of the Creative Energy Homes, was built using Modern Methods of Construction and encompassed Phase Change Materials and Earth-Air Heat Exchangers together with great reliance on passive design measures. A critical evaluation of the house's thermal performance over the summer of 2009 was undertaken. Subsequently, the house was dynamically simulated in future warmer climates and with various possible solutions for the overheating issue that was revealed by the appraisal. The prototype house is found to have opportunities for improvement of its design before being taken into a larger scale housing development.

7 THE BASF PROTOTYPE HOUSE

> *"In building the BASF House in Nottingham, we took into consideration a number of issues affecting the construction industry: tightening of carbon emissions used in buildings, shortage of affordable housing, shortage of skilled Labour, lack of available building land and energy performance."*
> Claire Farrar, leader of the BASF House project, for BASF[66]

The BASF house, designed by Derek Trowell Architect and built by BASF with the support of the University of Nottingham, was the second house to start on the Creative Energy Homes project and its construction is completed. It is a compact experimental house that functions as a conventional dwelling and, by the time this work was finished, it had been inhabited for approximately one year. The main aspects outlined on the house's brief were that firstly the home is intended to be energy efficient achieving Code for Sustainable Homes Level 4 and secondly the house is intended to be economical and affordable. The idea was to address the issues discussed in Chapter 1 in a house that is also inexpensive to construct.

Figure 7-1: The BASF House (left) next to its neighbour, the Eon House, built to 1930s standards (uninsulated)[67]. The BASF House is highly insulated so little heat escaped by conduction through the roof allowing snow to settle.

The house was designed to be a terrace house although just one unit has been built as a prototype. It puts great reliance on passive design and the south facing sunspace is a

[66] Available at http://www.energyefficiency.basf.com/ecp1/EnergyEfficiency/en/content/show_houses/UK/01_Relevant_Issues/Relevant_Issues [Accessed on 20th of August 2009]

[67] More information can be found at www.creative-energy-homes.co.u [Accessed on 20th of August 2009]

primary contributor to heating and ventilation. The techniques chosen for the building of the house are all Modern Methods of Construction (MMC). The materials are polystyrene formwork filled with concrete to the ground floor walls and above ground floor level, a prefabricated timber insulated sandwich panel is used. These have been chosen due to their practicality, high performance and the ability to prefabricate off-site speeding up the construction. The whole house was constructed in 25 weeks at a cost of £70k (according to BASF based on a 20 house development; value to be confirmed).

This house was designed to a detailed specification and its thermal performance was assessed prior to the start of the construction in earlier work undertaken by the author (Rodrigues and Schiano-Phan, 2007). The results were used to inform changes in the design. Performance data from the occupied house have been collected since January 2009. Consequently, the focus of this chapter is slightly different from the previous chapter as real data will be used to validate the results of the simulations.

7.1 THE HOUSE DESIGN

The BASF House has an untraditional look due primarily to its ventilation strategies and selection of materials. It is a 3-bedroom house composed of around 100m^2 divided into ground and first floors.

The ground floor includes a 'buffer space' on the north side that acts as an entrance lobby, houses the control system and is also used as storage for bikes and biomass fuel. This floor has an open plan except for two rooms, the WC and the utility room, where the equipment (such as the biomass boiler, solar thermal hot water cylinder and rainwater harvesting control system) are housed. The house is naturally ventilated and the staircase is located in the middle of the plan allowing for warm air to flow to the first floor by stack effect. Air is exhausted by windows placed close to the roof ridge line on the north facade. The first floor has two main south bedrooms, one smaller north bedroom and a family bathroom. There are no windows on the East and West façade so the house can be built as a terrace or semi-detached house in future developments.

The southern elevation comprises a fully glazed double-height sunspace contained within the house volume. This was designed to contribute to the home space heating requirements in winter. The space has a number of different opening apertures to ensure that both of the glazed screens to the sunspace can be opened or closed to facilitate heating or cooling. It also has external shading and internal manually controlled blinds. When working in the house in spring time (beginning of May of 2008), the author experienced temperatures in the sunspace up to 44.5^{o}C without ventilation. Plans and sections of the house can be seen in Figure 7-2, Figure 7-3 and Figure 7-4. For larger versions of the plans with dimensions please refer to Appendix 7.A in the end of this chapter.

This house should be considered as a system that combines diverse strategies such as shading, sunspace, compactness of design, highly insulated building fabric, double-glazing windows, Phase Change Materials (PCM), an Earth Air Heat Exchanger (EAHE) and natural ventilation by stack effect to achieve thermal comfort. In winter, in order to ensure the comfort of the occupants, the biomass boiler can be activated to deliver heat through a trench located on the ground floor along the sunspace. Air from the EAHE is delivered either to the sunspace to be further heated by the sun or to the trench to be further heated by the boiler. Warm air from the sunspace can be delivered to the house through openings at ground and first floor. In summer, the sunspace windows can be opened and the higher windows on the top of the house can be used to extract warm air encouraging stack effect and avoiding overheating. Further cooling can be supplied by the EAHE and excess heat can be absorbed by the PCM. Both strategies are described in detail further in this chapter.

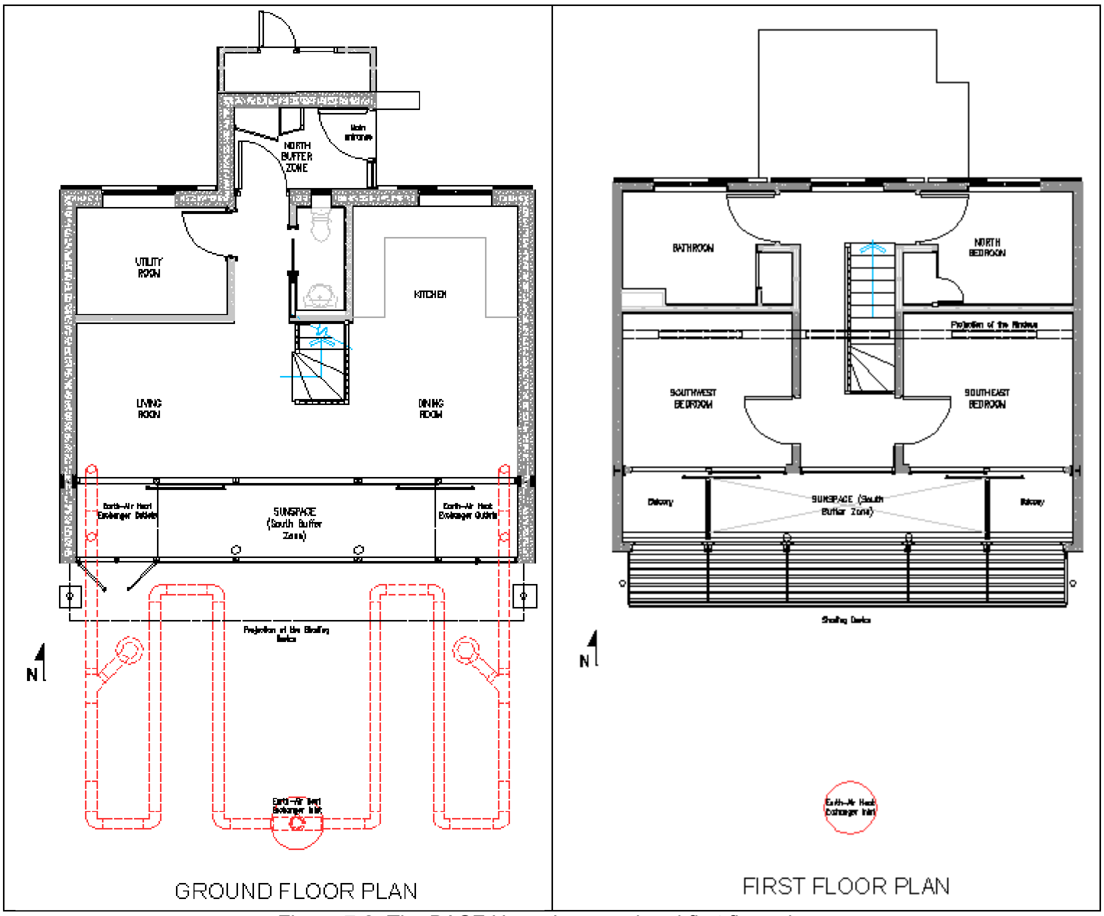


Figure 7-2: The BASF House's ground and first floor plans

The opening and closing of the central windows can be manually controlled or activated automatically by the Webbrick[68] home automation system. The system can also control the EAHE, the boiler, lighting and electricity. Sensors have been distributed in the house measuring temperature, humidity, energy use and other aspects of the house performance. A full post-occupancy evaluation is being undertaken as part of another project at University of Nottingham.

Some of the conclusions of the previous work carried out by the author (Rodrigues and Schiano-Phan, 2007) when the house's thermal performance was simulated included a predicted energy use of 15kWh/m^2 per annum for space heating (which complies with Passivhaus requirements). However, the work clearly showed that this was highly dependent on the use of the house, thus highly dependent on occupants. Another suggestion made in the work was the addition of space heating by radiators fed by the biomass boiler in the bedrooms. The simulations have shown that if bedroom doors were kept closed these spaces could not benefit from the heating provided only at ground floor level. The bedrooms were predicted to reach temperatures below comfort for long periods of time in overcast

[68] More information can be found at www.webbricksystems.com [Accessed on the 21st of August 2009]

periods and, if an efficient heating system was not provided, there was the risk of the use of less efficient systems such as electrical heaters by the users. The suggestion was not followed which, on the author's opinion, was a contradiction to the house's flexible and user-interactive design. However, the specification of pipes for the future provision of radiators was made in case of necessity.

Nina Hormazábal is a researcher investigating the influence of occupants in the performance of sustainable homes and is one of the home's tenants. Hormazábal has reported the use of electrical heaters in the bedrooms during winter as "after overcast days the bedrooms are really cold". The home's tenants also mention overheating in summer and highlight the importance of the ventilation strategy and the possibility of user control. The mentioned Webbrick system can control the opening of some of the windows but the users prefer to suspend it and manually operate them, mainly because, as the system responds to temperature, windows could open at any time day or night, disturbing their sleep.

Although it seems that the suggestion to provide radiators in the bedrooms was correct, there is another aspect to be considered. Hormazábal has made a study of the systems installed in the house and has concluded that, due to the fact that the biomass boiler is oversized for the house's requirements (as there was no better suited product to meet such a small demand), its efficiency can be very low in winter when it is used for space and hot water heating. In addition, Hormazábal reports that the maintenance and internal cleaning of the boiler is not just difficult, but also hazardous due to fumes and toxins (Hormazabal and Gillott, 2009). Consequently, a complete review of the home's main space heating system might be necessary.

The BASF house was designed to be a showcase of different materials supplied by BASF and its partners. These are described in the next section.

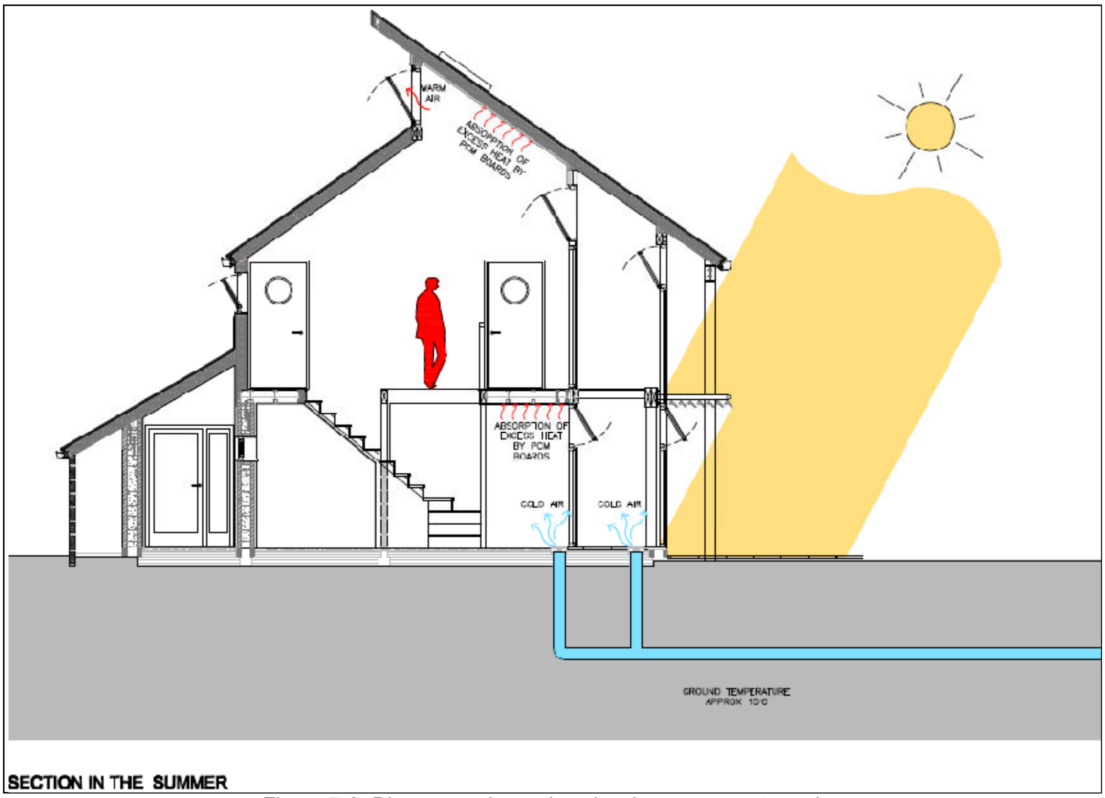


Figure 7-3: Diagrammatic section showing summer strategies

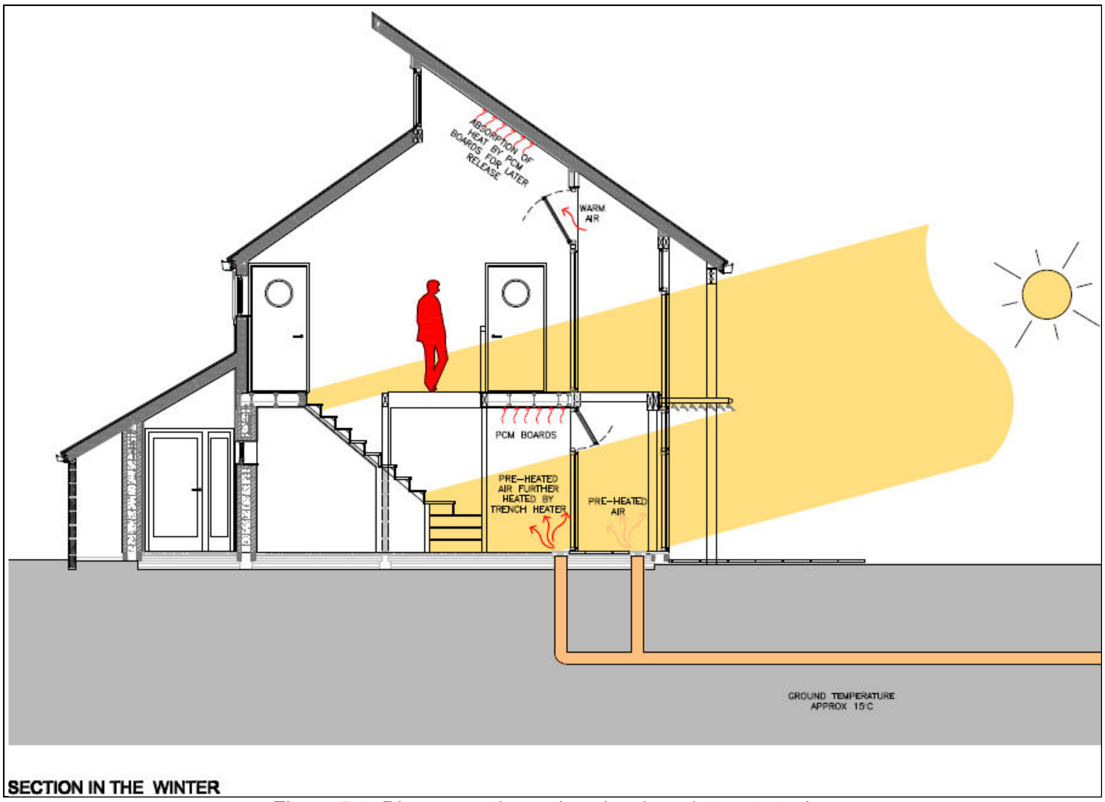


Figure 7-4: Diagrammatic section showing winter strategies

7.1.1 Materials and Construction Method

The foundations used a system designed by Roger Bullivant[69] which included steel trays filled with concrete and surrounded by a type of insulation developed by BASF called Neopor. Neopor is a type of extruded polystyrene sheet (EPS) enhanced with graphite for a lower conductivity and higher density. Neopor was also used to produce the insulated concrete formwork (ICF) blocks by Logix[70] that compose the ground floor walls. This partnership between BASF and Logix was a result of the process of product development described in Chapter 6. In addition, the concrete used to fill the ICF was Rheocell[71], which also has enhanced thermal properties. Consequently, the ICF used in the BASF House has a slightly better performance than the one used in the Stoneguard House. An extra layer of insulation was added on all walls and roof to ensure a U-Value of 0.15W/m^{2}K.

The first floor walls and the roof were constructed using structural insulated panels (SIPs) and took just a couple of days to be built on-site. The main difficulty faced due to the combination of the different constructive methods was the interface between them. This will be discussed in more detail in section 7.6 of this chapter, but in the infrared picture (Figure 7-5) a thermal bridge can be seen where ground floor walls and first floor walls meet.

The ground floor wall was finished with a reinforced rendering and the first floor walls and roof were finished with a metal cladding by Corus[72] covered with BASF coatings for solar heat management. The windows, external doors and curtain walling were provided by Rehau[73] and made in PVC-U (polyvinyl chloride un-plasticised). The windows are double glazed argon filled with a U-Value of 1.66W/m^{2}K. The external curtain wailing is double glazed (for structural strength), air filled with a U-Value of 2.7W/m^{2}K and the internal is argon filled with a U-Value of 1.7W/m^{2}K. The materials of the BASF house are illustrated in

Table 7-1 and in Figure 7-5.

[69] More information can be found at www.roger-bullivant.co.uk [Accessed on the 24th of August 2009]

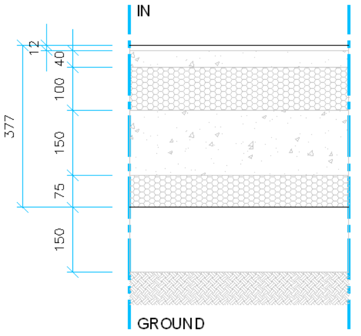
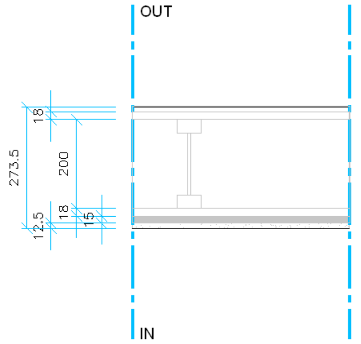
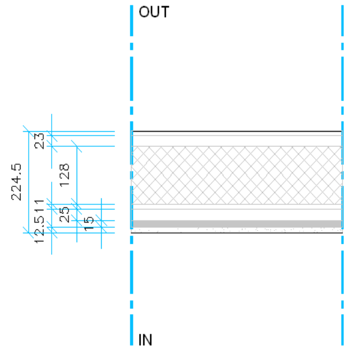
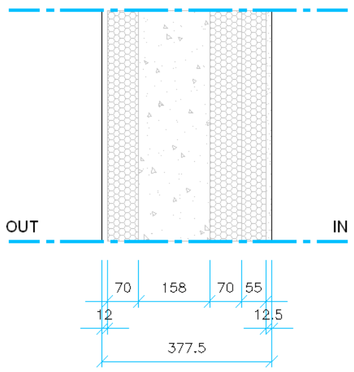
[70] More information can be found at www.logix.uk.com [Accessed on the 24th of August 2009]

[71] More information can be found at www.house.basf.co.uk [Accessed on the 24th of August 2009]

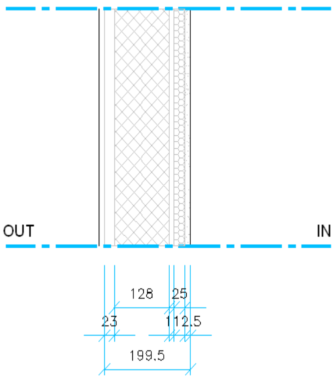
[72] More information available at www.colorcoat-online.com/en/products/exterior_products/ colorcoat_urban [Accessed on the 24th of August 2009]

[73] More information available at www.rehau.co.uk [Accessed on the 24th of August 2009]

Table 7-1: The elements of the Basf House envelope

<table>
<tr><td rowspan="5">GF - GROUND FLOOR (precast concrete beams)

IN
a. Carpet or PVC (kitchen)
b. 40mm Concrete Screed
c. 100mm Extruded Polystyrene (EPS)
d. 150mm Concrete beams
e. 120mm Extruded Polystyrene (EPS)
f. 150mm Air Gap
g. Ground
GROUND</td><td>Decrement Factor
(0-1)</td><td>0</td></tr>
<tr><td>Time Constant
(hours)</td><td>164.3</td></tr>
<tr><td>Admittance
(W/m^2K)</td><td>2.36</td></tr>
<tr><td>U-Value
(W/m^2K)</td><td>0.14</td></tr>
<tr><td>Thickness
(mm)</td><td>422 + Air Gap</td></tr>
<tr><td rowspan="5">FF - FIRST FLOOR/ GROUND FLOOR CEILING (timber deck)

OUT
a. Carpet or PVC (bathroom)
b. 18mm Oriented Strand Board (OSB)
c. 200mm Timber I-Joists Finnjoists
d. 18mm Oriented Strand Board (OSB
e. 15mm PCM board
f. 12.5mm Plasterboard
IN</td><td>Decrement Factor
(0-1)</td><td>0.91</td></tr>
<tr><td>Time Constant
(hours)</td><td>1.24</td></tr>
<tr><td>Admittance
(W/m^2K)</td><td>1.48</td></tr>
<tr><td>U-Value
(W/m^2K)</td><td>1.08</td></tr>
<tr><td>Thickness
(mm)</td><td>273.5</td></tr>
<tr><td rowspan="5">ROOF

OUT
a. Corus Metal Cladding with BASF Coolpaint
b. Roofing Felt
b. 23mm Oriented Strand Board (OSB)
c. 128mm Extruded Polyurethane (PUR)
d. 11mm Oriented Strand Board (OSB
e. 25mm Air Cavity
f. 15mm PCM board
g. 12.5mm Plasterboard
IN</td><td>Decrement Factor
(0-1)</td><td>0.73</td></tr>
<tr><td>Time Constant
(hours)</td><td>3.0</td></tr>
<tr><td>Admittance
(W/m^2K)</td><td>1.7</td></tr>
<tr><td>U-Value
(W/m^2K)</td><td>0.158</td></tr>
<tr><td>Thickness
(mm)</td><td>224.5</td></tr>
<tr><td rowspan="5">GFW ext - Ground Floor Wall External (ICF)

OUT
a. 12mm Reinforced Rendering
b. 70mm Extruded Polystyrene (EPS)
c. 158mm Heavyweight Concrete
d. 70mm Extruded Polystyrene (EPS)
b. 55mm Extruded Polystyrene (EPS)
c. 12.5mm Plasterboard
IN</td><td>Decrement Factor
(0-1)</td><td>0.04</td></tr>
<tr><td>Time Constant
(hours)</td><td>104.9</td></tr>
<tr><td>Admittance
(W/m^2K)</td><td>0.9</td></tr>
<tr><td>U-Value
(W/m^2K)</td><td>0.158</td></tr>
<tr><td>Thickness
(mm)</td><td>377.5</td></tr>
</table>

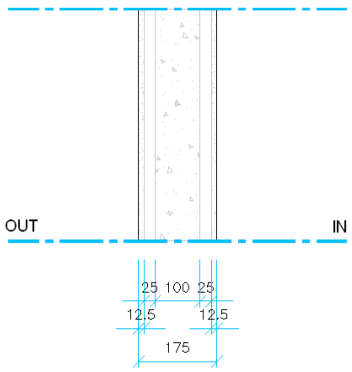
FFW ext - First Floor Wall External (SIPs)



OUT
a. Corus Metal Cladding with BASF Coolpaint
b. 23mm Oriented Strand Board (OSB)
c. 128mm Extruded Polyurethane (PUR)
d. 11mm Oriented Strand Board (OSB)
e. 25mm Extruded Polystyrene (EPS)
f. 12.5mm Plasterboard
IN

Decrement Factor (0-1)	0.73
Time Constant (hours)	3.42
Admittance (W/m^2K)	1.7
U-Value (W/m^2K)	0.15
Thickness (mm)	199.5 +cladding

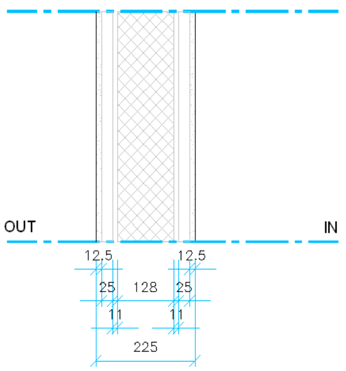
GFW int - Ground Floor Wall Internal (concrete blocks)



OUT
c. 12.5mm Plasterboard
d. 25mm Service Void
e. 100mm Lightweight Aircrete Concrete Block
b. 25mm Service Void
c. 12.5mm Plasterboard
IN

Decrement Factor (0-1)	0.93
Time Constant (hours)	1.73
Admittance (W/m^2K)	2.46
U-Value (W/m^2K)	1.23
Thickness (mm)	175

FFW ext - First Floor Wall Internal (SIPs)



OUT
f. 12.5mm Plasterboard
g. 25mm Service Void
h. 11mm Oriented Strand Board (OSB)
i. 128mm Extruded Polyurethane (PUR)
j. 11mm Oriented Strand Board (OSB)
k. 25mm Service Void
l. 12.5mm Plasterboard
IN

Decrement Factor (0-1)	0.91
Time Constant (hours)	1.38
Admittance (W/m^2K)	2.03
U-Value (W/m^2K)	0.17
Thickness (mm)	225

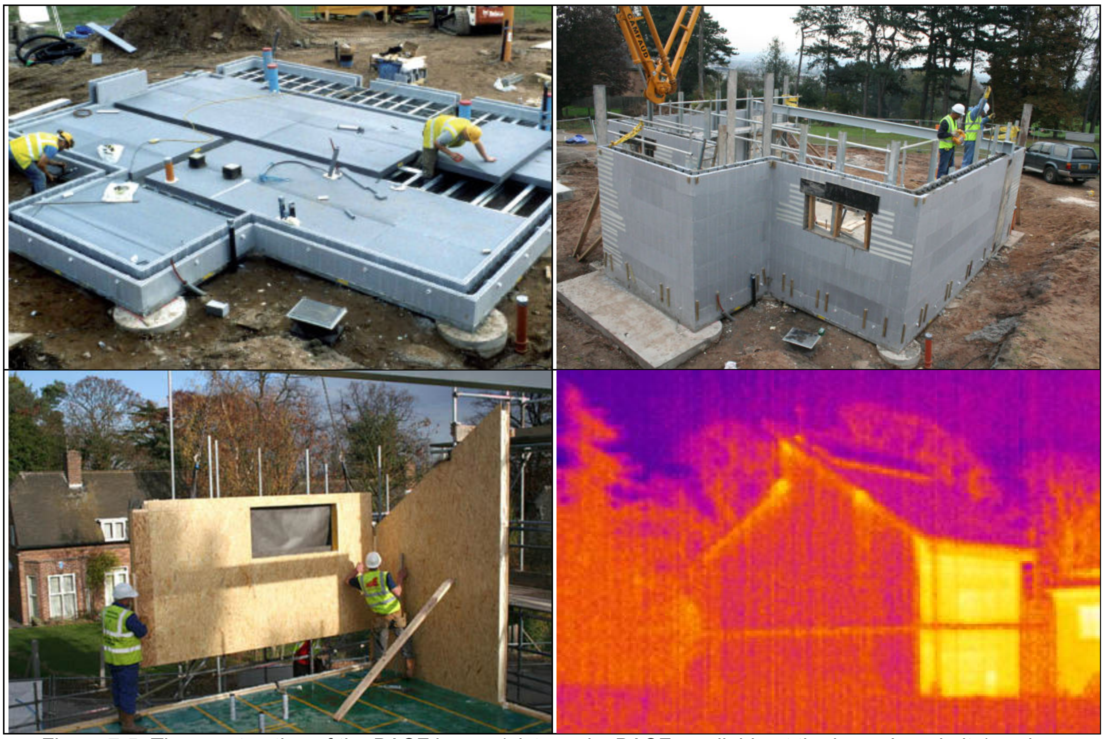


Figure 7-5: The construction of the BASF house (pictures by BASF, available at the house's website) and an infrared picture taken when the house was in use

In order to avoid overheating, the house was provided with PCM boards and a commercial EAHE, which are described in the next sections.

7.1.2 Energy Efficiency Assessment

In March of 2008, a Standard Assessment Procedure (SAP) was undertaken for planning approval. At this stage, the minimum air permeability of $10m^3/hm^2$ at 50Pa (as specified in Part L discussed in Chapter 1) and the minimum efficiency of 65% for the boiler (main heating system) had to be assumed. As a result, the house was rated in SAP at 68.43 which is band 'D'.

A new report was produced in June 2008 after the house's completion with a new value for air permeability of $3.38m^3/hm^2$ (as measure on site during a pressurisation test) and 89% for the boiler's efficiency. This resulted in a new SAP rating of 87.04 which falls into band 'B' (Figure 7-6). This demonstrates the huge impact these two parameters have in the rating.

This house meets the requirements for Code for Sustainable Homes (CfSH) level 4 and aims to achieve Passivhaus standards with regards to the space heating criterion, annual use of energy and fabric characteristics. It does so, however, without the mechanical ventilation system and the very low level of air permeability required, which are fundamental parts of the Passivhaus standard as discussed in Chapter 1. The monitoring and evaluation of the house, discussed later in this chapter, aspires to prove that this is possible. The reports produced by the assessor mentions a small risk of overheating, which is not higher due to the possibility of cross ventilating the house. The EAHE and the PCM boards installed in the house are not taken into account in the rating systems.

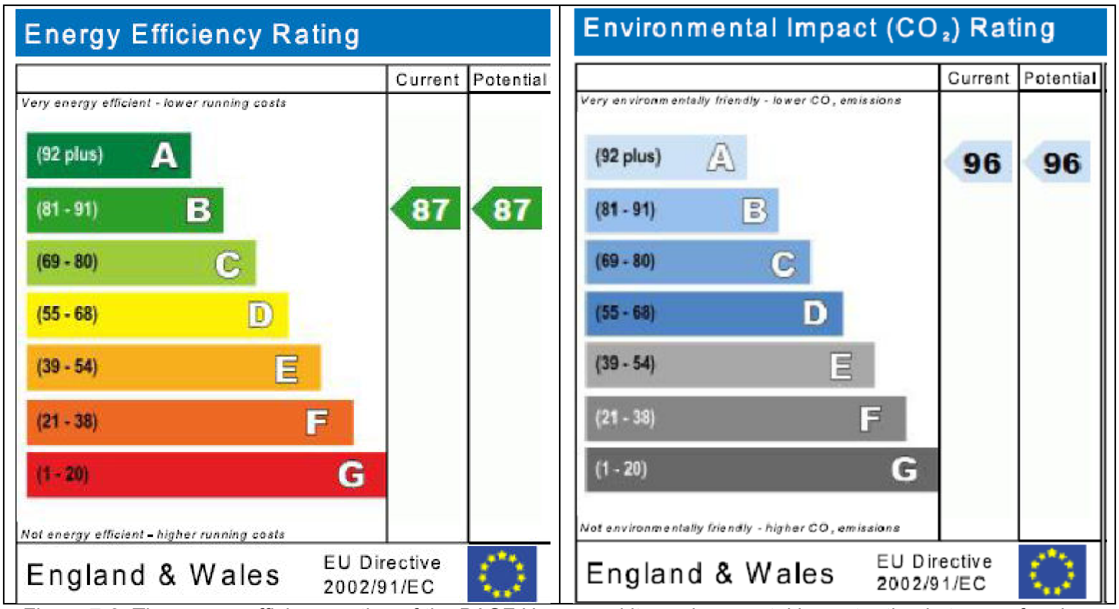


Figure 7-6: The energy efficiency rating of the BASF House and its environmental impact rating in terms of carbon dioxide emissions

7.1.3 PCM Pre-assessment

In the BASF House, 100m^2 of PCM board was distributed between the living room, bedrooms southwest and southeast and the sunspace. The product used was the BASF Knauf Micronal DS 5000 X Smartboard (described in section 4.4.1) with a melting point of 23^{o}C as suggested by BASF. Each 1m^2 of the board contains 3kg of PCM and each 1kg of the PCM has a latent heat storage capacity of 110kJ.

The improvement that was potentially provided by the PCM boards in the performance of the mentioned spaces was investigated using PCM Express, created by Valentin EnergieSoftware in a partnership with BASF and the Fraunhof Institute for Solar Energy (ISE) in Freiburg. The software is relatively simple and the inputs are limited to room geometry (always a rectangular room with each surface having to be either completely exposed to outside temperature or completely sheltered), fabric properties, weather data and a few building service parameters. The results are always a comparison between the room without PCM and the room with PCM. The software does not allow for the simulation of sunspaces.

Differently from Chapter 6 when the sunspace of the Stoneguard House was simulated, here a composite of a ground floor and a first floor rooms was modelled with the dimensions of the actual house without the sunspace. The south façade of both floors was made of 90% low energy double glazing windows. The first exercise (Case 1) compared the spaces with and without the Micronal PCM (melting point 23^{o}C) without the aid of ventilation or mechanical systems. Room 2 (first floor) was taken as an example and can be seen in Figure 6-8, Figure 6-9 and Figure 6-10. According to the software, in these conditions there is some overheating with temperatures reaching 30^{o}C in the ground floor and 33^{o}C in the first floor. Without the aid of ventilation, PCM could not improve the room conditions significantly: the conventional construction is within 21-26^{o}C for 52.5% of the time whilst the PCM construction is 52.2%. The day with the greatest effect shows just over 1^{o}C of difference.

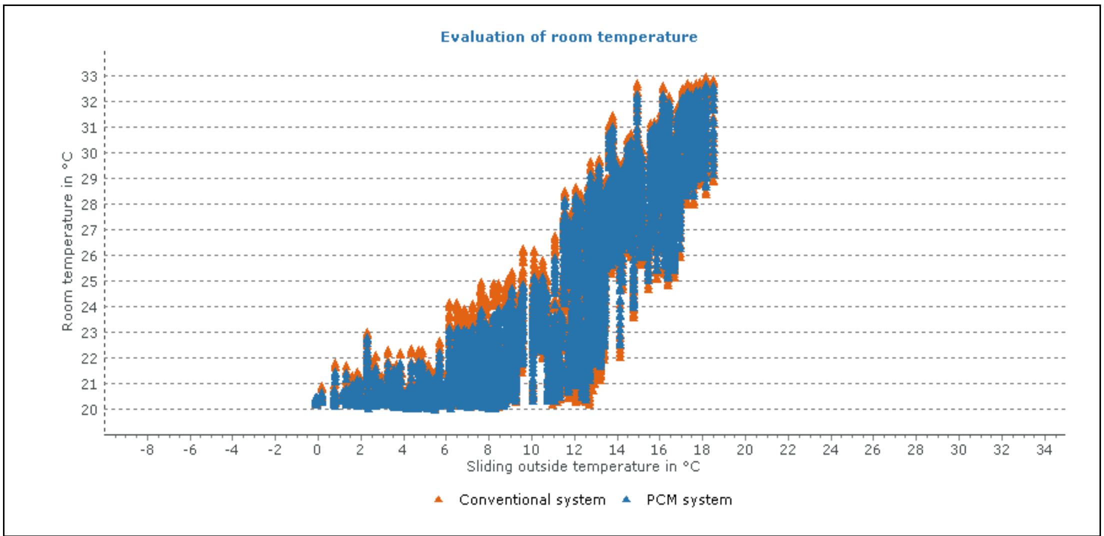


Figure 7-7: Comparison of temperatures between a room without PCM (conventional) and with PCM in Room 2 (first floor)

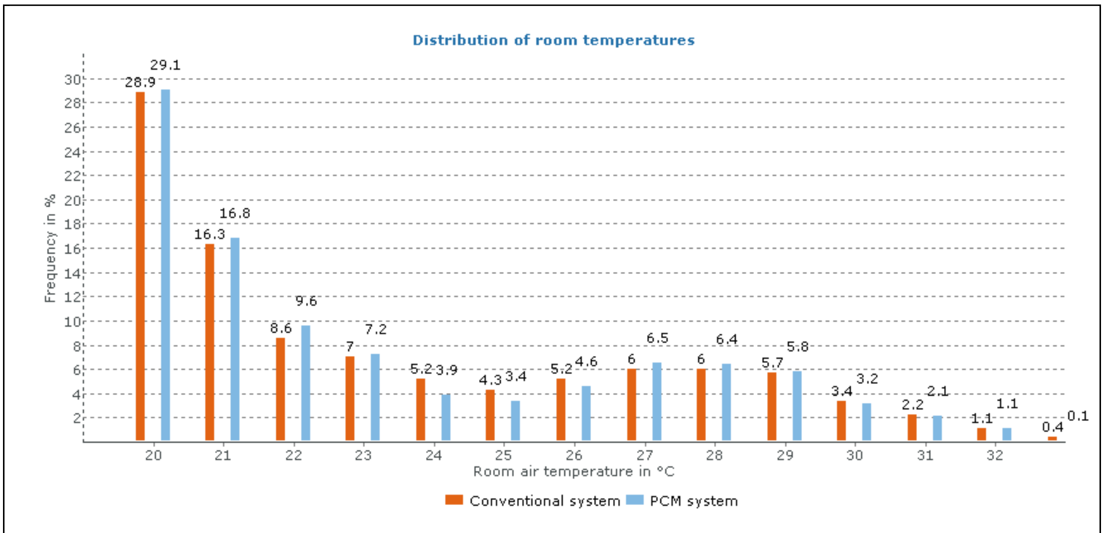


Figure 7-8: Comparison of temperatures between a room without PCM (conventional) and with PCM in Room 2 (first floor)

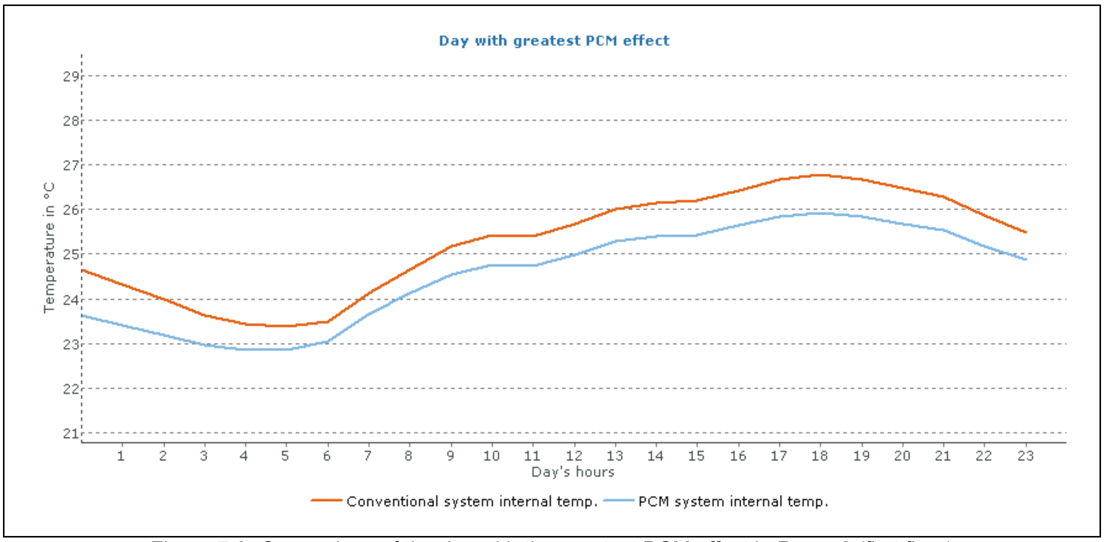


Figure 7-9: Comparison of the day with the greatest PCM effect in Room 2 (first floor)

Case 2 (Figure 6-10, Figure 6-11 and Figure 6-12) is the same model as Case 1 but with added natural ventilation. As it can be seen, peak temperature was reduced to less than 27°C. However, the PCM was not able to improve the conditions when compared to a room without it: the conventional system is between 21 and 26°C for 43.5% of the time whilst the PCM rooms are within those temperatures for 42.4% of the time. The greatest PCM effect now is around 2°C of temperature difference.

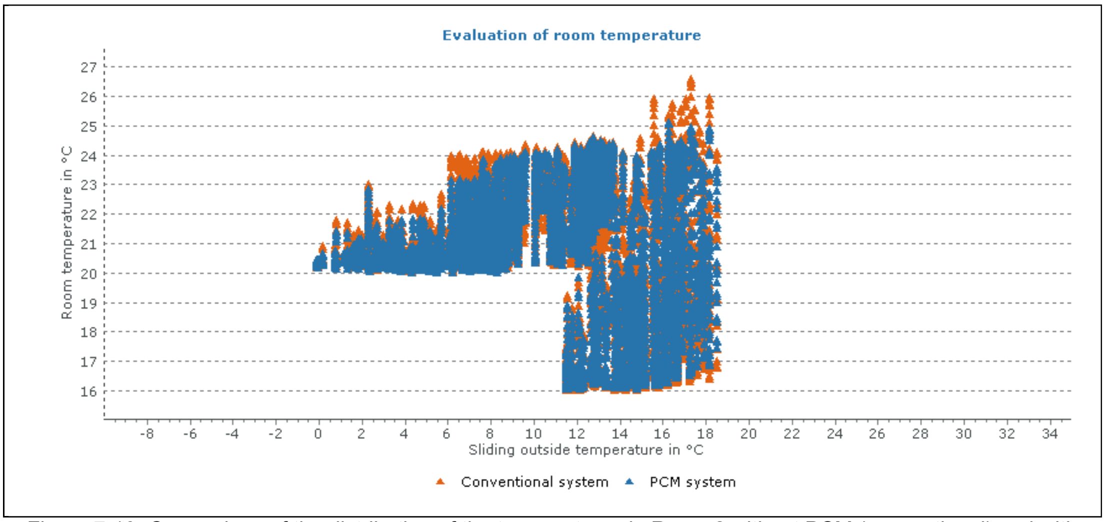


Figure 7-10: Comparison of the distribution of the temperatures in Room 2 without PCM (conventional) and with PCM in Case 2

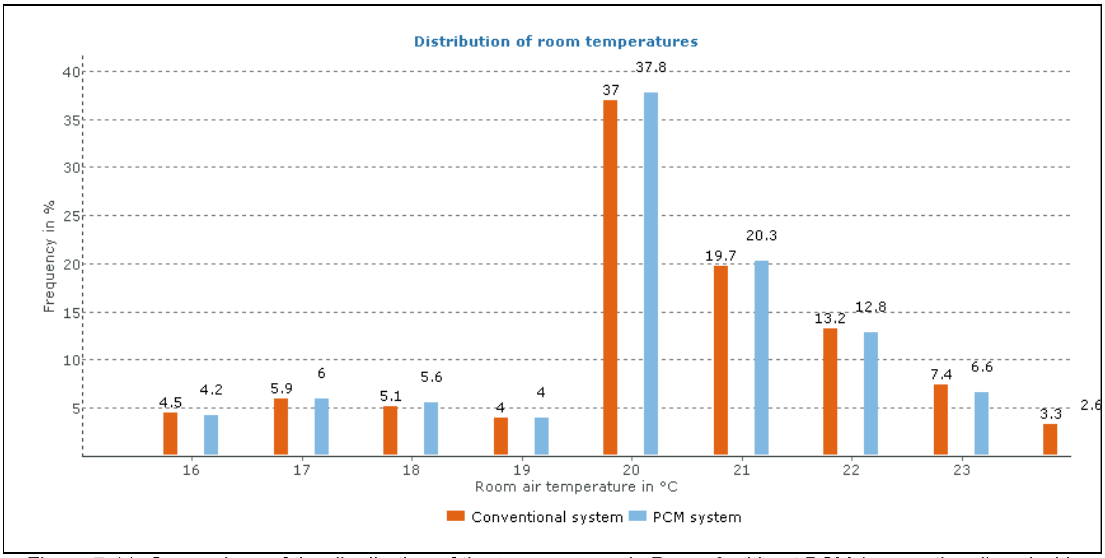


Figure 7-11: Comparison of the distribution of the temperatures in Room 2 without PCM (conventional) and with PCM in Case 2

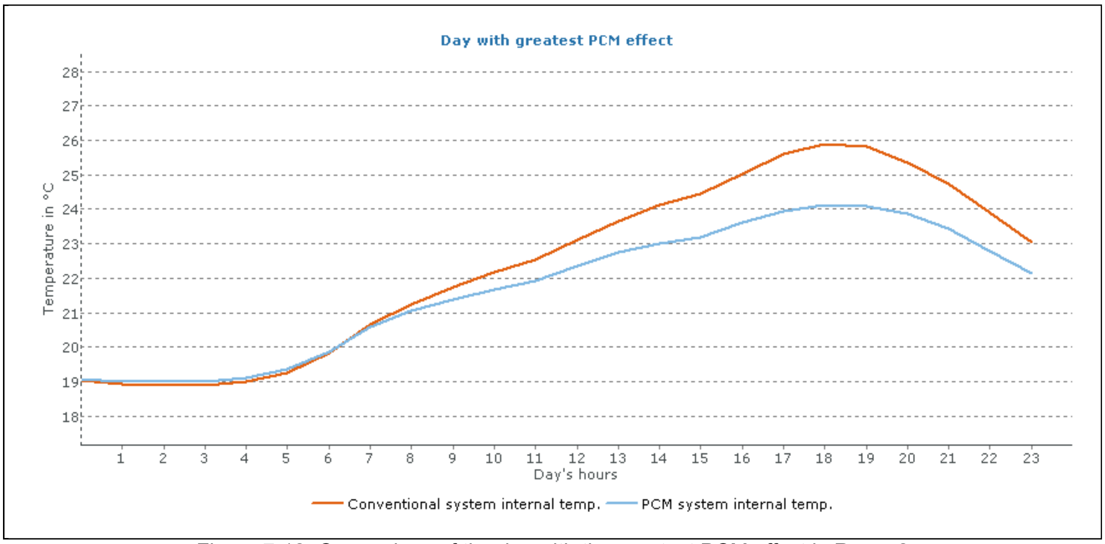


Figure 7-12: Comparison of the day with the greatest PCM effect in Room 2

Case 3 was the same room and conditions as Case 2 but with added mechanical heat recovery, night time ventilation and an EAHE (it is not clear how the software considers the benefits of the system; the average soil temperature inputted was 13°C ±2°C). In case 3 peak temperatures were reduced to about 26°C and the PCM still seems to not make a significant difference (less than 1%).

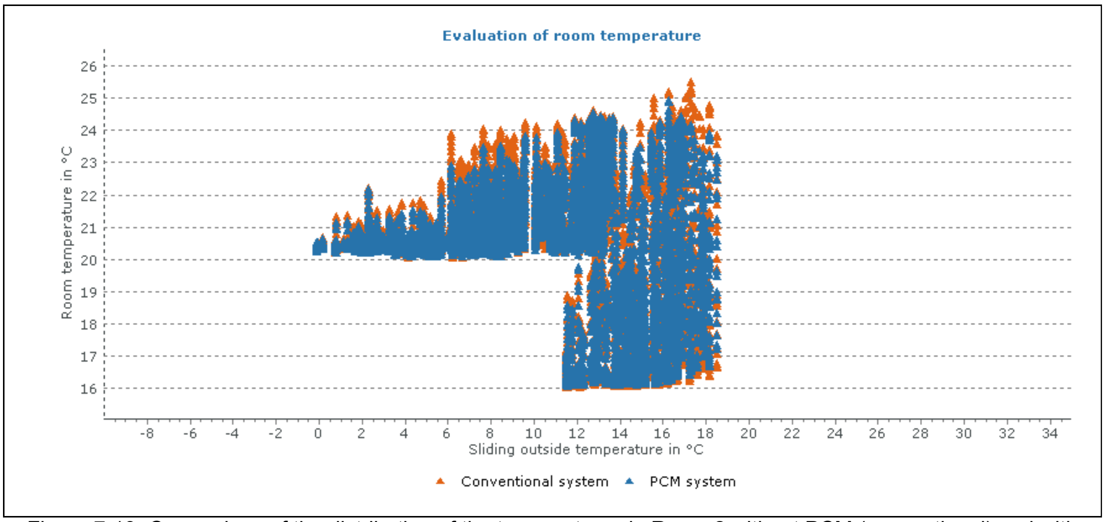


Figure 7-13: Comparison of the distribution of the temperatures in Room 2 without PCM (conventional) and with PCM in Case 3

In Case 4 all the settings were kept the same but the PCM board, which was Micronal 23°C as specified by BASF for this house, was changed to Micronal 26°C. There were very insignificant changes. In Case 5 the layer of Micronal 23°C PCM board was doubled and the improvement in comfort was just above 1% and maximum 1°C.

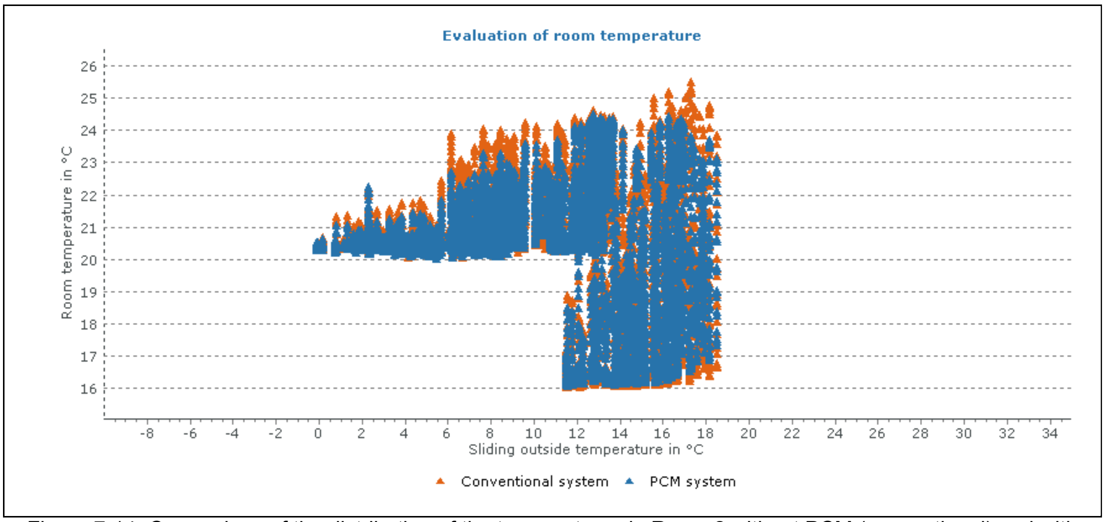


Figure 7-14: Comparison of the distribution of the temperatures in Room 2 without PCM (conventional) and with PCM in Case 6

The results were determined by a steady state mathematical model calculation within the PCM Express software. The actual yield of the house may differ greatly and the same with a dynamic simulation. According to the software, all the overheating was mitigated just with the aid of natural ventilation rather than the PCM. However, the software does not allow for input or control of natural ventilation rates so it is not clear what rates were achieved. Of course these results cannot be taken as absolute values as the model is very simple and even the sunspace, which would have a great impact on the results, is not being considered.

Unfortunately, Tas cannot dynamically simulate PCM so the benefits it offers cannot be properly simulated.

The PCM Express software was still in development when the house was in its design stages. It is not clear if the software was actually used to inform the installation of PCM in the house's ceilings and what were the results of the simulations. From the simulations undertaken in this work the house does not seem to benefit greatly from the PCM. However, a study of the data collected in the house over summer 2009 and a dynamical simulation will demonstrate that there is risk of overheating in the house and the spaces might be benefiting better from the PCM than calculated by the PCM Express software.

7.1.4 EAHE design

The system recommended for the BASF house was a commercial system called Awadukt Thermo produced by Rehau. The system has filters in the inlet and an anti-microbial pipe inner layer (silver lining) in the pipes to avoid problems with air quality. Pipes are made of a PP (Polypropylene) material with improved heat conductivity to enhance heat transfer. Any condensation is pumped to a soak-away. The total length is around 36m and it is buried at a depth of 1.5m. The pipes layout can be seen in Figure 7-15 below.

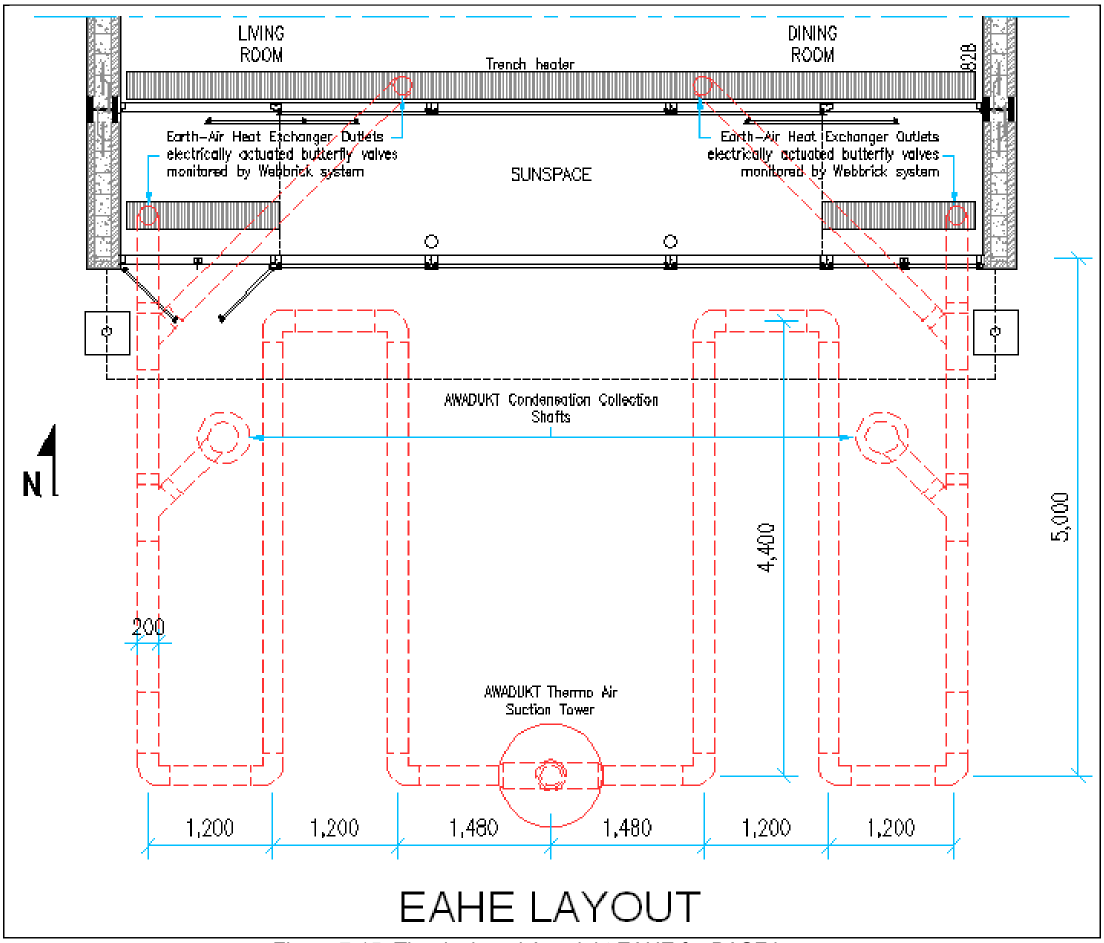


Figure 7-15: The designed Awadukt EAHE for BASF house

Figure 7-16: The installation of the Awadukt EAHE in the BASF house plot

The pipe was simulated using the company's software Rehau Awadukt Thermo UK using the following parameters:

- Soil type: Standard (density 1800kg/m³, thermal conductivity 1.45W/mK and temperature conductivity 6.015e-7m²/s).
- Air flow rate: 174m³/h (0.06kg/s).
- Depth of ground water level: 30m.
- Fan efficiency: 60%.

The predicted performance for summer and winter can be seen in Figure 7-17 and Figure 7-18 below. The resultant air velocity is 1.8m/s against a pressure drop of 17.3Pa. The results for winter show a minimum outlet temperature of 1.1°C (when the external temperature is below -10^{o}C) and a net heat gain of 519.7kWh/a. In summer the maximum outlet temperature is 20.0°C and the net cooling is 247.5kWh/a.

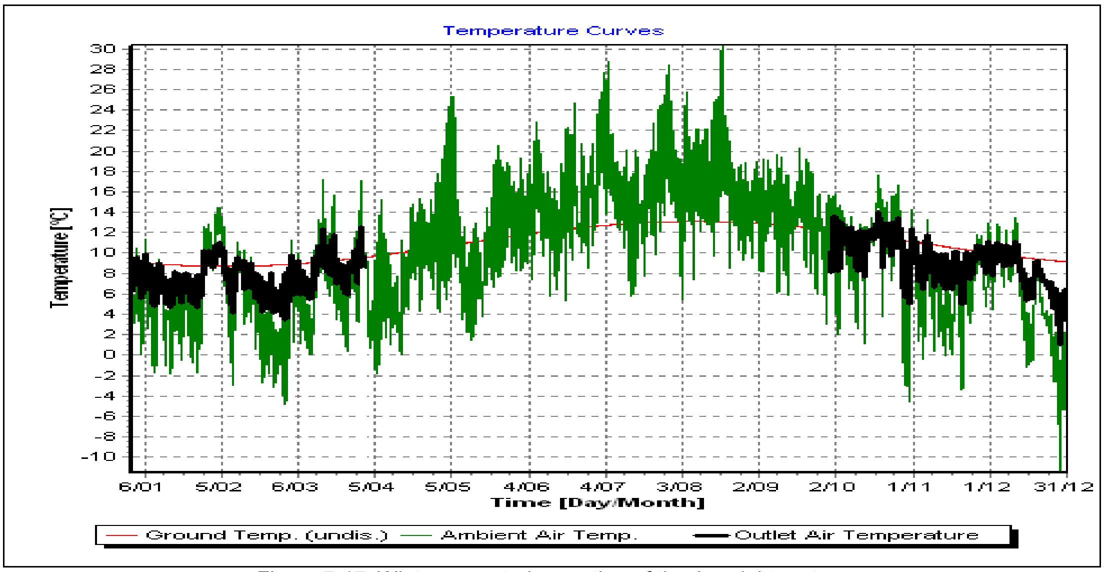


Figure 7-17: Winter expected operation of the Awadukt system

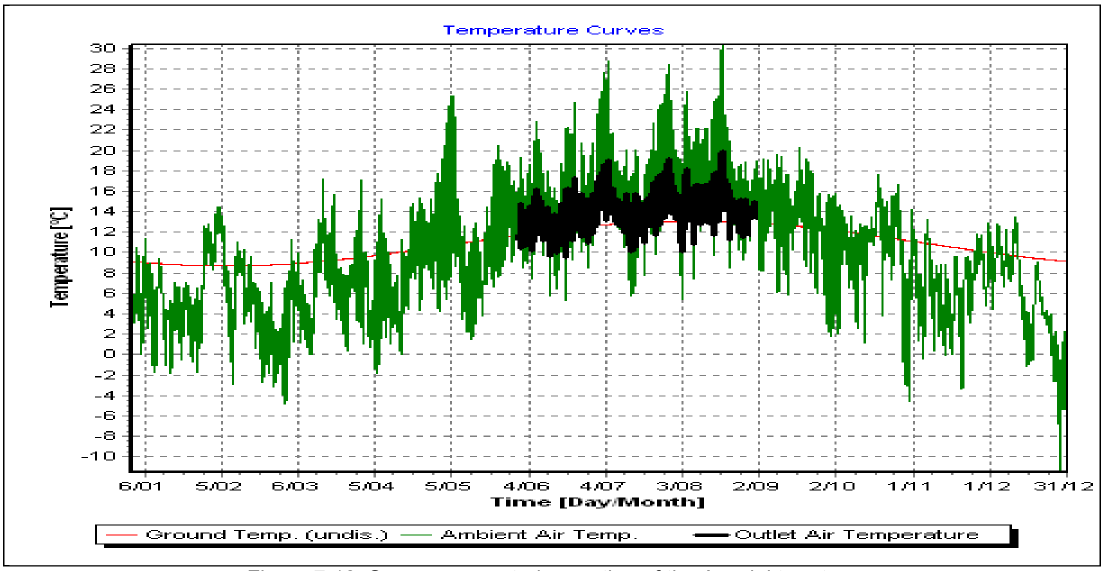


Figure 7-18: Summer expected operation of the Awadukt system

7.2 THE EXPERIENCE OF BUILDING THE BASF HOUSE

The construction process of the BASF house was easier and faster than the Stoneguard House. A well detailed project and the use of ICF and SIPS has significantly reduced the amount of waste generated on site and speeded up the house's construction, which was finished in 25 weeks to a good quality standard. The design's passive approach plus minimum use of renewable energy technologies mean that, in a typical 20 homes development, the BASF house could be built for £70,000 according to the company. This provides designers and house builders with a realistic airtight, thermal efficient building at an affordable build cost.

The pre-assessment of the house, which considered thermal performance, was done by the author and informed effective design changes such as the way the windows opened in order to expose the house's ceiling were PCM boards were placed and the introduction of the biomass boiler in the heart of the house (rather than in the north buffer as initially designed). Figure 7-19 shows the temperatures measured in the wall between the living room and the utility room, on the living room surface of the concrete block. As it can be seen the wall is always warmer and so radiates heat generated by the equipment in the utility to the living room. In addition, the utility room door can be kept opened. This heat should increase in winter when the boiler is likely to be used more often.

The pre-assessment also created an interesting debate about the use of the house and what is expected from occupants and made the external design team aware of the issues. There is a lot to be studied in this area as there are no conclusive answers.

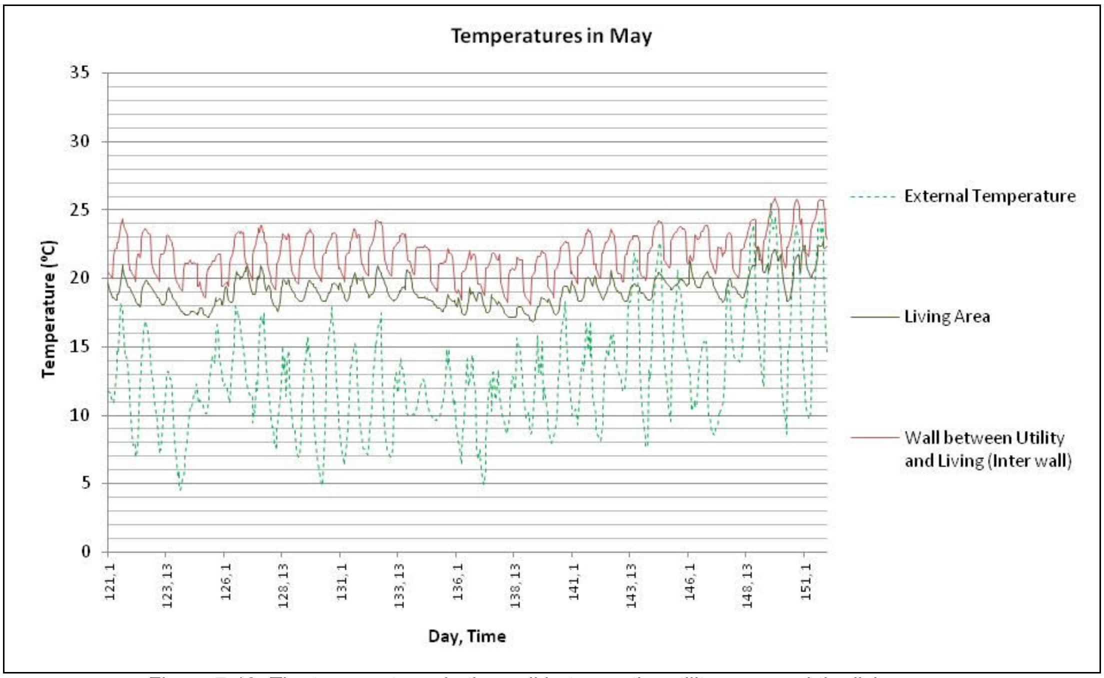


Figure 7-19: The temperatures in the wall between the utility room and the living room

Great attention was given to mitigation of thermal bridging and to air permeability. Due to the house's simple geometry and the focus on details, susceptible areas were addressed more easily. Nevertheless, as shown in Figure 7-5, thermal bridging has still happened due to material choice. Additionally, despite the efforts off-site, there were still infiltration problems. The first pressurization test had shown vulnerable areas that were addressed subsequently. The final test resulted on $3.38m^3/h/m^2$ at 50Pa which according to the BRE database is within the most airtight houses in the UK (Stephen, 2000). As discussed in Chapter 1, this number is far from the maximum proposed by stricter standard such as Passivhaus. This emphasises the previously discussed argument that if lower infiltration rates are to be achieved in the UK then more on-site quality control and training of labour to a higher standard should occur.

Windows are obviously one of the most important aspects of passive design as they 'control' most of the solar gains, daylight and ventilation aspects of any design. However, even in this house where most of the things were detailed before the construction, the windows were left to the end and detailed by the supplier without the input of the environmental design team. The consequence is, as demonstrated in this chapter, that the windows do not function as expected jeopardizing the performance of the full strategy. In addition, the large window frames were not taken into account during the design stage so they physically block the pleasant view from the bedrooms, balconies and living area.

From its opening in January of 2008 until June of 2008 the house was inhabited for a couple of months and frequently used for meetings and demonstrations. Overall the internal conditions were described by users as comfortable on both, warm and cold days. Occupants have expressed contentment for being able to interact with the house and the outside environment directly by controlling openings and blinds.

From June 2008 the house has been inhabited by 2 or 3 people as described. In addition to the collection of indoor climate data, since January 2009 energy use is being recorded and occupier's behaviour has been closely monitored. This real life experiment will provide the University of Nottingham, BASF and industry with vital data on the advantages and disadvantages of living in a low energy home. The sensors and monitoring equipment were provided by WebBrick Systems and were chosen for their affordability, flexibility, expandability and accuracy. The system oversees and controls the ventilation, heating, lighting, security, and blinds. Smart meters have been installed to measure the use of resources in the house, i.e. electricity and water, with the data being presented on a touch screen panel mounted in the kitchen. This same touch screen also provides a user interface with a menu of options for controlling the home. Further detailed work on post-occupancy house performance and user satisfaction is going to be carried out over the next few years by the University of Nottingham and will be published at a later date.

The fact that the team who installed the monitoring system was not acquainted with subtle aspects of passive design left a few important gaps in the house's monitoring system. More attention was given to the space heating and hot water technologies rather than its passive strategy. Aspects such as the natural ventilation strategy and the use of the sunspace for heating were almost neglected. In a house where care was taken to reduce the heating demands to a minimum without compromising cooling demand and user interaction one would expect those strategies to be more closely watched.

Even though the construction team was not familiar with some of the issues that the house's project was proposing to cover, it was felt that they were enthusiastic about tackling them on site. The close interaction between sponsoring company, university consultants, construction team and other suppliers meant that this project ran smoothly and all the problems presented positive results and new partnerships. In addition the experience of the construction team was very constructive and much was learnt.

7.3 BASF HOUSE MONITORED DATA

There are 19 temperature sensors installed in different locations in the BASF house, some of them measuring air temperature, one measuring PCM surface temperature and others installed in various items of equipment. In addition, the WebBrick system encompasses 3 humidity sensors, 9 energy meters, a lux meter and a pyranometer. Unfortunately there are no sensors recording the opening and closing of walls or windows. Figure 7-20 illustrates the position of the temperature and humidity sensors as built.

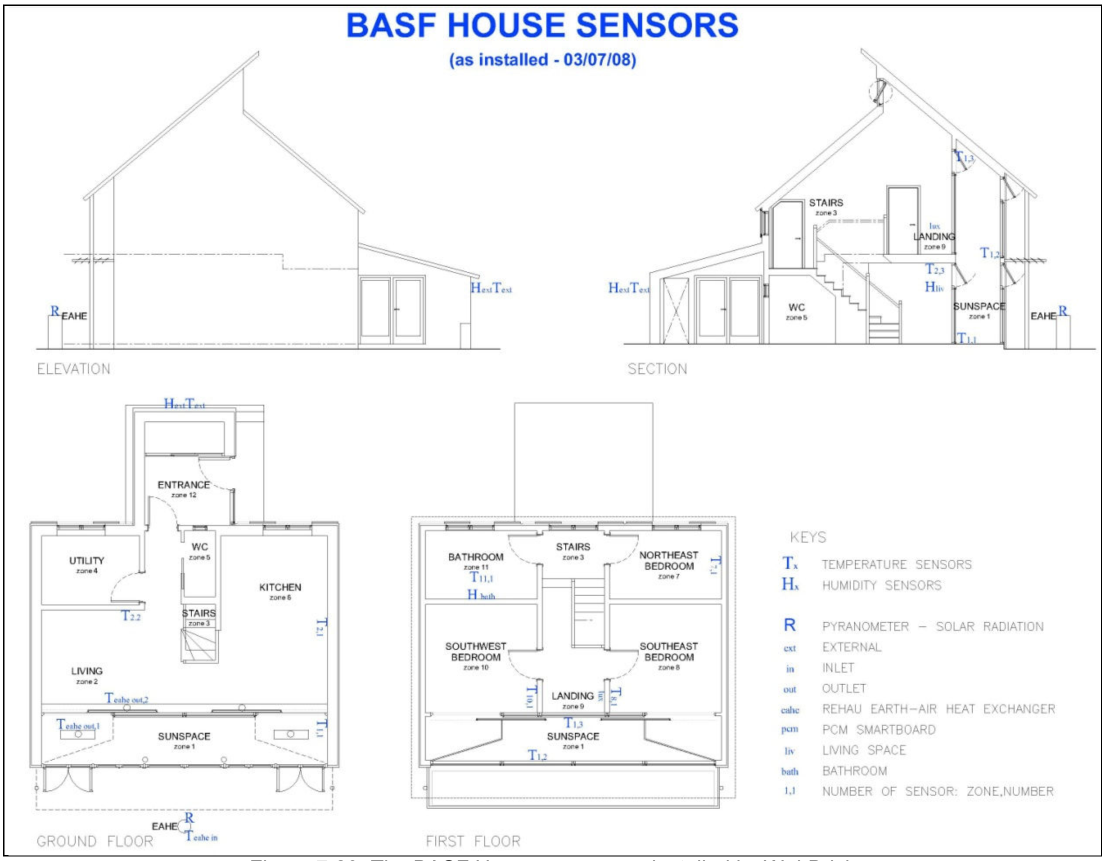


Figure 7-20: The BASF House sensors as installed by WebBrick

The house is occupied by research students working in the Department of the Built Environment at University of Nottingham. A couple used the southwest bedroom and a single student occupied the southeast one in the investigated period. It is difficult to find a pattern of use of the house as the users worked a few minutes away from the house so they were able to 'visit' the house during day time and even work in there. The house also receives hundreds of visitors per week.

7.3.1 Base Case Scope and Method

WebBrick has installed Dallas DS18B20 temperature sensors that offer an accuracy of ±0.5^{o}C. When installed, they were calibrated and tested. The temperature data are being recorded every 6 minutes and a comma separated data file has been produced every day since April 2009. From January to April 2009 there were some data available but the set is incomplete due to problems with the data recording.

As this work focuses on overheating, data from May to August of 2009 was downloaded, processed and analysed in a way to make its results comparable to the computer simulations that are described in the next section. The data were reduced to a reading for every hour for every sensor, including external temperatures that were later used to produce a new weather data set. This set of data collected on-site was called the Base Case.

7.3.2 Base Case Results

Different aspects of the data were investigated. Its frequency of temperatures below, within and above comfort zone was analysed (Figure 7-21) in order to be compared with the results from computer simulations in the next section of this chapter.

As discussed in previous chapters, the CIBSE benchmark for overheating in the living room is 26^{o}C, which should not be exceeded; if that benchmark is exceeded, it should not be for longer than 1% of the time above 28^{o}C. In bedrooms the desirable temperature is 23^{o}C and the temperatures should not exceed 25^{o}C but if they do they should not stay above 26^{o}C for more than 1% of the time.

This data analysis shows that there is no overheating in the living area (living room, dining room and kitchen) and overheating levels in the sunspace are below expected and at acceptable levels (especially if the first floor of the sunspace is not considered habitable). However, it shows overheating in the bedrooms (Figure 7-21) and also a difference between the southwest (25% of the time over 25^{o}C) and southeast (23% of the times over 25^{o}C) bedrooms. This is due to a number of reasons: firstly the southwest bedroom was either occupied by 2 people or empty for periods while the southeast bedroom was occupied by just one person. Secondly, they are used in different ways: when the users were around, the door of the southwest bedroom was kept open during the daytime so it received greater quantities of warm air from the rest of the house. When the users were away the door and windows were kept closed in that bedroom. The top windows of the southeast bedroom were more frequently opened. Unexpectedly overheating is seen even in the north bedroom, possibly because its door is also kept open most of the time (the bedroom was unoccupied and being used for storage during this period).

These bedrooms are occupied by students who also may use them in the day (especially because the house is shared so the bedroom is effectively the only totally private space) so overheating may be an issue not just at night. Nevertheless analysis of the data has shown that overheating happens also at night, especially in the southwest bedroom were the peak temperature between 7pm and 6am over the whole period (May to August) was found to be 31.8°C. This bedroom was found to reach temperatures above 23°C between 7pm and 6am for 9% of the period and above 26°C for 3.6%. This is considered overheating according to the CIBSE criteria.

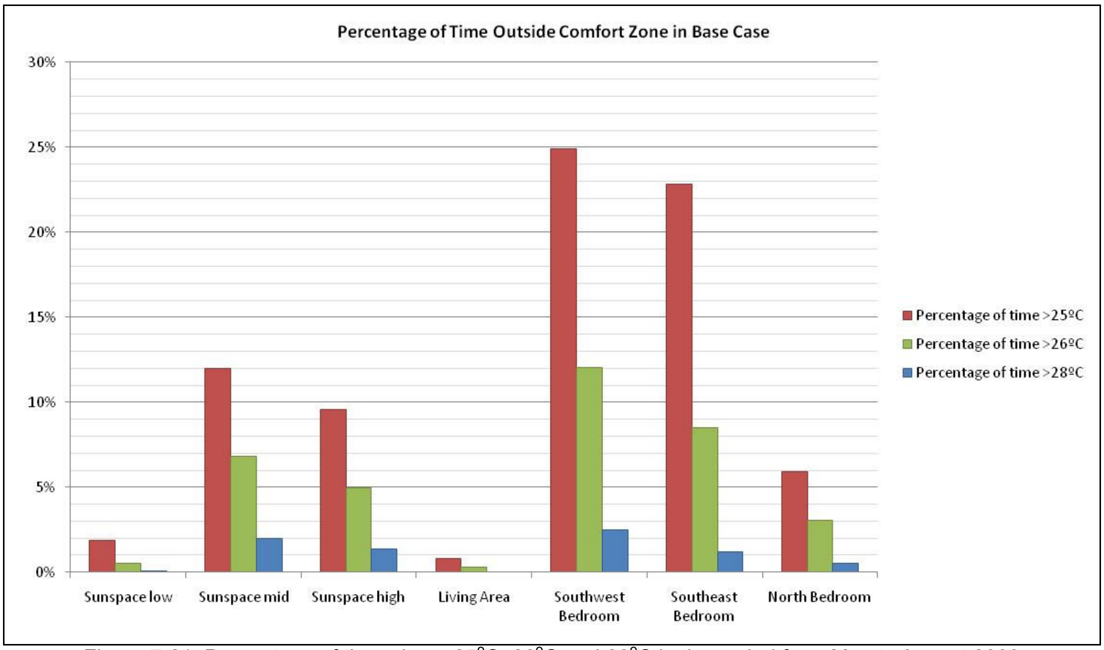


Figure 7-21: Percentage of time above 25°C, 26°C and 28°C in the period from May to August 2009

The temperature difference between the ground floor and the first floor of the sunspace is also remarkable. In addition to the expected stack effect, other factors influenced these outcomes: the delivered fresh air from the EAHE at around 16°C (Figure 7-22 and Figure 7-27) at ground floor level, the accessibility of the ground floor windows, which tended to be used much more than the first floor windows, and the size of openings. The ground floor of the sunspace has an openable area to the outside of around 8m^2 whilst the first floor has an effective opening area of 0.64m^2. To the house's interior, the sunspace has an effective opening area of 6.7m^2 to the living area (ground floor), just 0.4m^2 to the circulation on the first floor (through where the warm air is expected to be extracted) and around 4m^2 to each bedroom. At a higher level, inside each bedroom there is a window with 0.3m^2 of effective opening and in the circulation space another window with the same area. This puts great reliance on the use of the bedroom windows and sliding door to ventilate the sunspace, which might cause problems such as the overheating of the bedrooms (as demonstrated here) and/or noise and privacy issues.

The month of July was chosen as an example as the peak temperatures of the studied period occur in the first 2 weeks of this month (Figure 7-22, Figure 7-23, Figure 7-24 and Figure 7-25). Figure 7-25 shows how the south bedrooms temperatures stay above 24°C even at night.

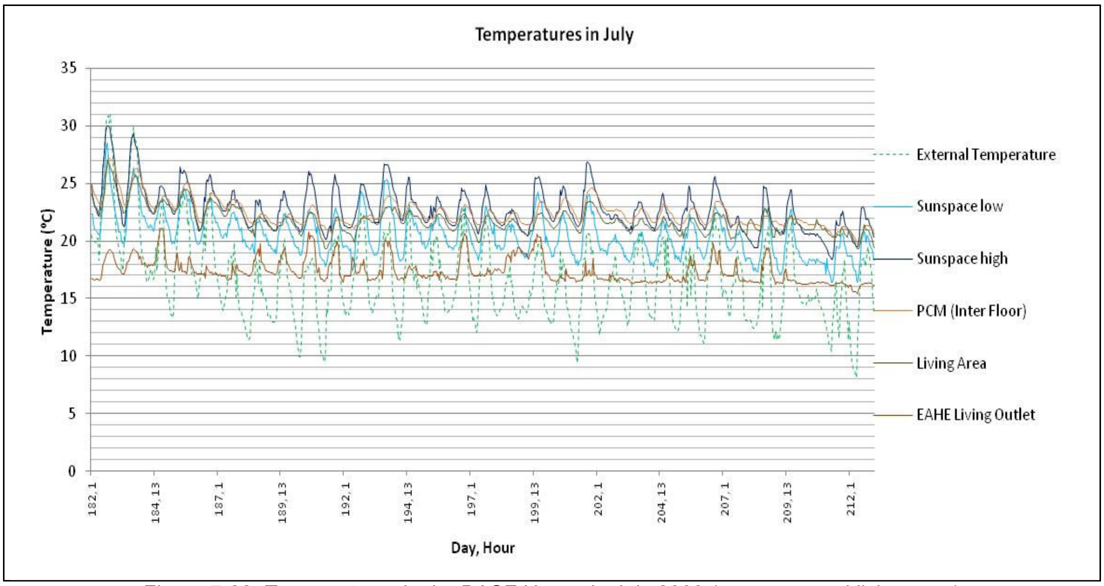


Figure 7-22: Temperatures in the BASF House in July 2009 (sunspace and living area)

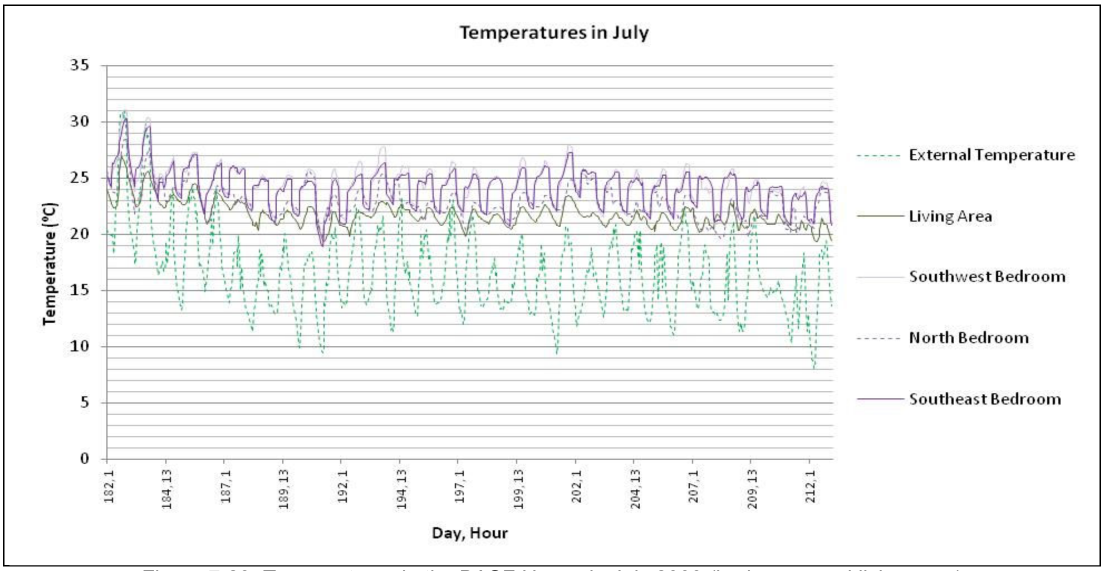


Figure 7-23: Temperatures in the BASF House in July 2009 (bedrooms and living area)

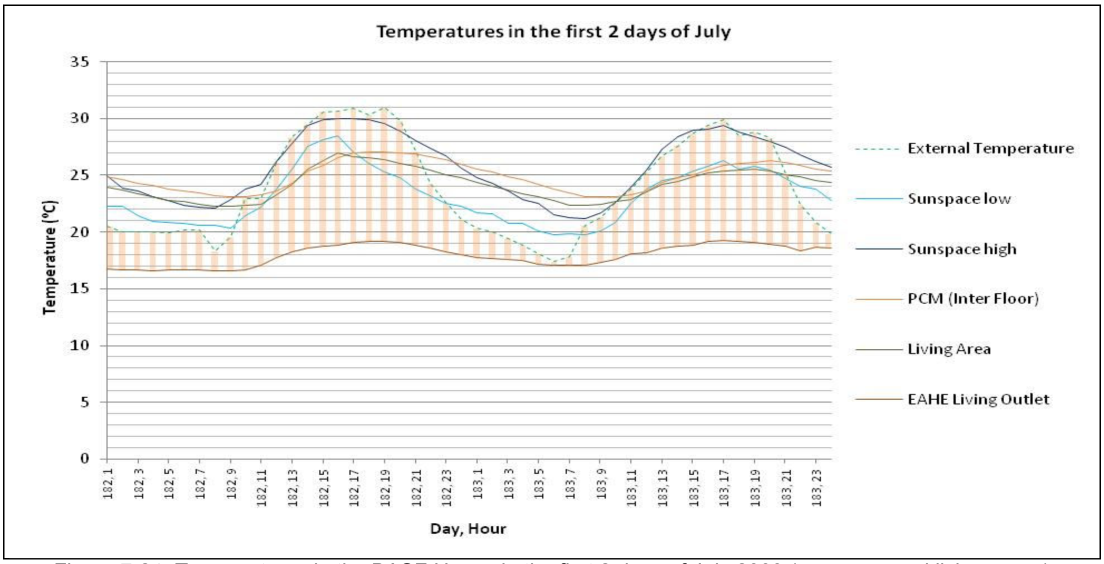


Figure 7-24: Temperatures in the BASF House in the first 2 days of July 2009 (sunspace and living areas)

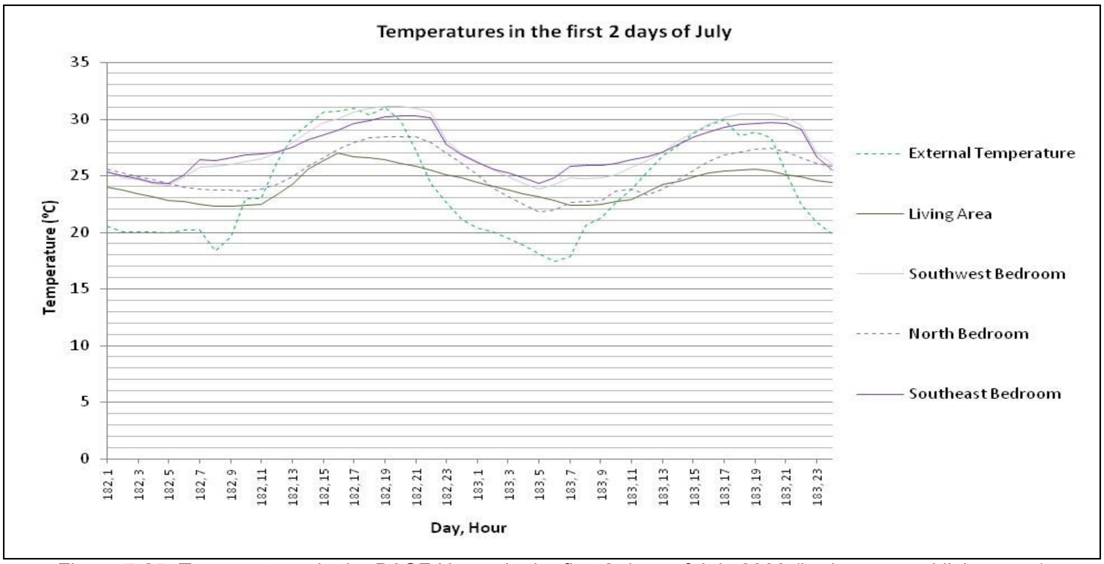


Figure 7-25: Temperatures in the BASF House in the first 2 days of July 2009 (bedrooms and living area)

Throughout July the temperatures in the top of the sunspace did not go below 20°C and reached 30°C. Figure 7-22 and Figure 7-23 show clear stratification of warm air in the sunspace with average temperature differences around 2 to 3°C. It is worth noting that at this time of year the sunspace was fully shaded (consequently there were no contributions from direct solar gains) and that ventilation was controlled by the occupants. In addition, the sunspace has PCM boards on the ceiling and has received cold air from the EAHE whenever that was activated by the users. Unfortunately the system does not record when the EAHE fan was on or off but in Figure 7-22 one can distinguish periods when the EAHE outlet in the living area presents a flatter pattern. In Figure 7-24 the contribution of the EAHE can be clearly seen. However, it is not clear how this contribution influences the living area temperature. Figure 7-27 shows the 4 months of data including the EAHE outlet temperature and the temperature recorded on the bottom surface of the PCM board, positioned on the ceiling of the living area (the temperature sensor is sandwiched between PCM and plasterboard added for fire protection).

As may be seen in Figure 7-22 and Figure 7-24, the PCM closely follows the living area temperature pattern although there is a small time delay which results in about 1°C difference in the coolest periods (nights). Even though one can look at the temperatures of the PCM board on the living room ceiling (Figure 7-24) it is not possible to quantify its contribution to the indoor environment as there are no other areas that can be compared with (ideally an equal house without PCM and the same pattern of usage would be needed).

Nonetheless a study of the percentage of time the PCM was within its phase change zone (as stated by the manufacturer BASF, please refer to Figure 4.12) shows that it did not spend enough time below that zone to completely solidify on a daily basis (although it is difficult to tell if the PCM is liquid or solid within that temperature range). This can be seen in Figure 7-27: the PCM was between 19 and 24°C for almost 90% of the studied period which may suggest that it was not effective in helping control the indoor temperature each day. This emphasises the need for cooling in order to discharge the heat from the PCM and the importance of the system presented in Chapter 8.

The PCM may, however, have contributed to a comfortable indoor temperature in different ways. It may have helped on a seasonal basis but a longer period of data would be needed to confirm this hypothesis. It also may have helped by generating a surface with a stable temperature possibly altering thermal transfer through that element and the thermal sensation due to surface radiant temperatures; but once more this cannot be proven.

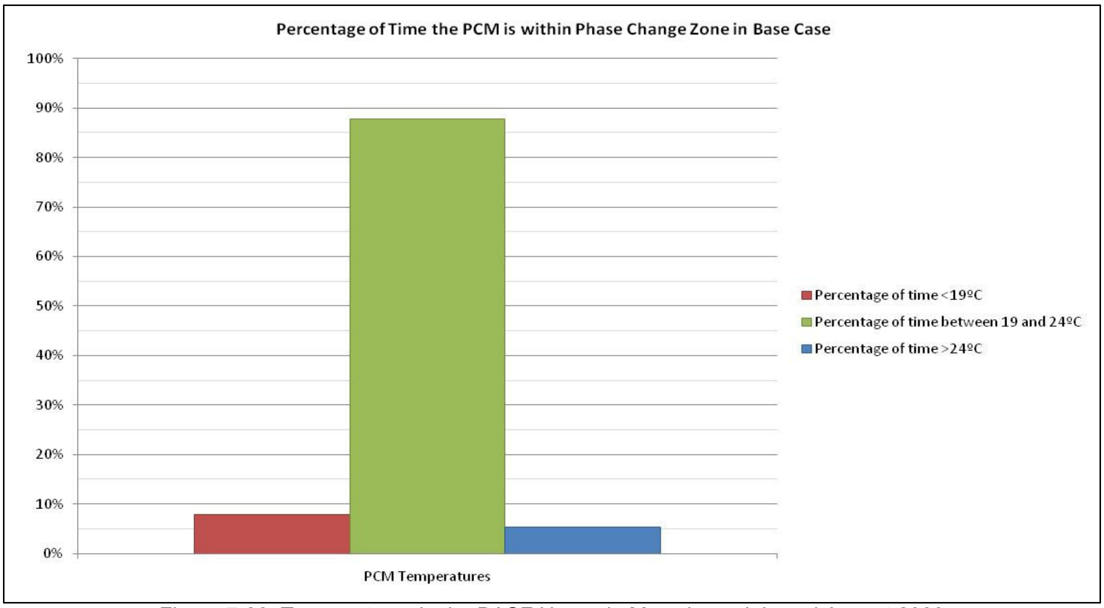


Figure 7-26: Temperatures in the BASF House in May, June, July and August 2009

The bedrooms presented similar pattern of behaviour even though the north bedroom was always colder (Figure 7-23 and Figure 7-25). If compared with the bedrooms, the living area presented a much 'flatter' pattern with less temperature variation between day and night (around 2^{o}C). The south bedrooms presented between 4 and 5^{o}C of variation and reached 30^{o}C on the hottest day. The peak temperatures in the 3 bedrooms are similar during these 4 months, around 29 to 31^{o}C, while in the living room it is 27^{o}C. The average temperature in the north bedroom is around 22^{o}C, 1^{o}C higher than the living room and 1.5^{o}C lower than the south bedrooms. This illustrates that the high temperatures in these spaces are not due to solar radiation (as this is blocked in this period of the year) but only due to air movement and envelope exposure. Furthermore, even though temperatures in the bedrooms drop at night, they are still higher than the limits suggested by CIBSE. Regrettably there are no data to support the understanding of how the ventilation contributed to these results. Graphs illustrating the other studied months can be found in Appendix 7B in the end of this chapter.

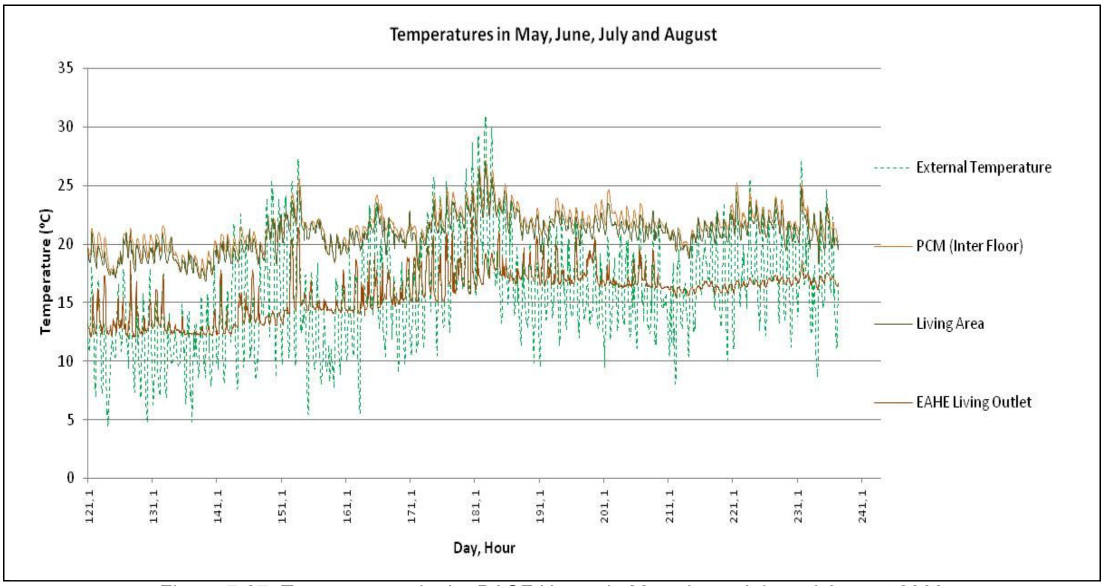


Figure 7-27: Temperatures in the BASF House in May, June, July and August 2009

The author has asked the house occupiers if they felt any overheating in the bedrooms at night and the answer was “yes but not to the point of feeling uncomfortable”. Both, Nina Hormazábal and Deborah Adkins agreed that the volume of the room helped with feeling comfortable and that the cultural factor is crucial. Nina, Chilean, says she prefers her room to be warmer and that she is more tolerant to heat than Deborah, who is English, and places “a greater importance on air quality and ventilation than temperature and opens the windows even in cooler periods”. Both say they would keep the sliding doors and sunspace internal windows opened at night in warmer periods but rarely the high level window due to noise pollution from the main road not far away.

Despite the fact that the small sample might be not indicative of a cultural pattern, these comments raised two interesting issues. Firstly it suggests that people with different cultural background might feel comfortable at different conditions and might use similar rooms in a different way. Secondly, they both mention the large volume of the room as being a contributor to comfort. There is no doubt that a room with larger volume would present less overheating than one with a smaller volume when subjected to the same inputs. However, it must be noted that the air temperatures were measured at the occupiers’ level, which means that they are readings of the temperatures the occupiers were actually experiencing. In addition, the only windows that were kept regularly opened were the internal ones (the top ones that could encourage more stack ventilation were rarely used according to the users) meaning little air movement inside the space. Consequently the volume of the room was of little thermal importance in the readings and possibly more significant from a visual point of view. The southeast bedroom and the higher level of the sunspace can be seen in Figure 7-28.


Figure 7-28: The higher level of the sunspace and the southeast bedroom of the BASF House (images courtesy of BASF)

7.3.3 EAHE Monitored Data

Once the system was commissioned, short periods of measurements were taken during 4 spring days, 29th and 30th of May and 4th and 5th of June, 2008. This allowed for some degree of soil saturation to be assessed as well as temperature performance. Humidity measurements could not be taken at this stage. Longer periods of monitoring could not be undertaken as the house was occupied and the users did not require the use of the system.

The air at the outlet and outside in a shadowed place was monitored using 14 k-type (chromel–alumel) thermocouples with shielded finish and connected to the analogue inputs of a datalogger (Datataker DT 505 series 2). The error in temperature readings through thermocouples were considered to be ±1ºC and they were all tested for their accuracy before the beginning of the experimentation. The fan was kept on from 10:30am to 6:30pm at a fixed velocity of 4.7m/s, which is equivalent to approximately 0.04m^3/s. This is lower than the air flow rate used in the preliminary assessment in section 7.1.4 but the fan settings did not allow for varying it at that stage; this has been changed and now the users can control it. The energy required to run the fan at that speed was 18W. Data were gathered every 10 minutes.

An example of the functioning of the system can be seen in Figure 6-25. This was the warmest day (5th of June) of the monitored period. Taking this day as an example, the system provided adequate levels of fresh air with an average cooling output during the 8 hour period of 336W (2.7kWh cooling). The average inlet temperature during that period was 20.8°C whilst the average outlet temperature was 13.3°C. The average Coefficient of Performance (COP) in this day calculated using Equation 3.2 (Chapter 3) was 18.7. The maximum COP reached by the system in this monitored period was 25.4 and the average of 14 was reached over the 4 days.

The data collected show that generally the outlet temperature is just above 13°C on all the monitored days (Figure 7-30). It also demonstrates that there is some heat saturation of the pipe-work and possibly the surrounding soil as the outlet temperature tends to increase by the end of the day but always by less than 1°C.

The Awadukt system appears to be working as predicted by the company's software. However, a direct comparison is difficult as the software output is for the whole year. Ideally a full set of data for a year from the installed system would provide a better comparison between the software and actual data. A long term monitoring will be carried out in the next few years.

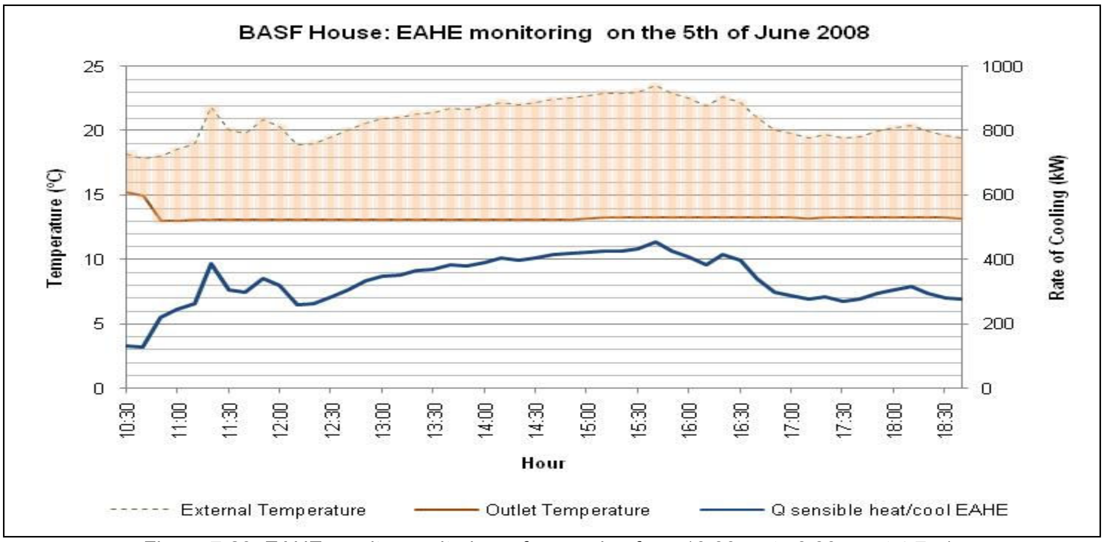


Figure 7-29: EAHE on-site monitoring – fan running from 10:30am to 6:30pm at 4.7m/s

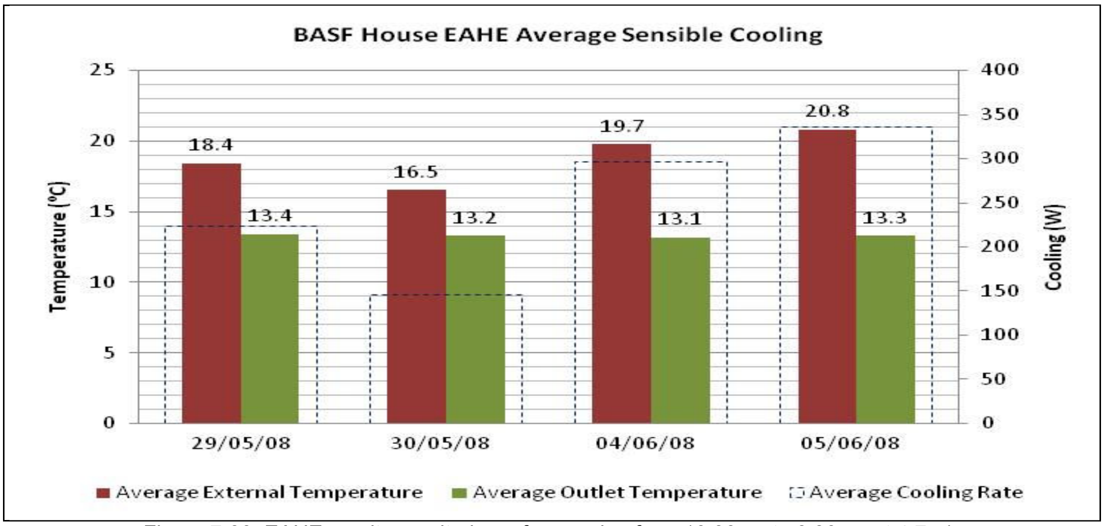


Figure 7-30: EAHE on-site monitoring – fan running from 10:30am to 6:30pm at 4.7m/s

7.4 THE SIMULATION RESULTS VERSUS MONITORED DATA

As real data was collected from the BASF House, the approach taken in these simulations was to firstly get as close as possible to what happened in reality and then simulate the house in future weather scenarios.

In order to enable the simulation to be closer to reality, a new weather data set was produced where the dry bulb temperatures of the months of May, June, July and August of the CIBSE DSY weather data (previously used) were substituted by the data collected on site in 2009. The two data sets were found to be quite different, with the real data being warmer in those months (maximum temperature 31^{o}C, average 15.6^{o}C, minimum 4.5^{o}C) than the CIBSE weather data (maximum 29.1^{o}C, average 14.5^{o}C and minimum 3.7^{o}C). A graph comparing both data sets can be seen in Appendix 7.D. The results of the simulations focused on the cited months only.

7.4.1 Scope and Method

The computer model was built as close as possible to reality including shading of the fully glazed south façade. Images of the 3D model can be found in Appendix 7.C.

The house was occupied in an unusual way (although one could argue that there is no usual way to occupy a house!) as the users worked a few minutes away and so tended to 'visit' the house during day time. In addition their work was based on research so they had no need to be at work during office hours and often worked from home. The house also received thousands of visitors since it has been opened. Consequently, rather than trying to follow a potential pattern of use, the simulation focused on the outcomes: the resultant indoor climate. Hundreds of different combinations of openings and temperatures at which they would be activated were tried until the model performed in a similar way to the house as measured in the summer 2009. These combinations were based on decisions made in an informed way, i.e. by observation and/or interviews with the occupiers. The opening sizes are based on measured effective area of opening taking into consideration the type of opening (slide, bottom hang, top hang, etc).

The Base Case is the collected data described in the previous section, the Case 0 takes into account internal gains (occupancy, equipment, appliances and lighting), heating (in winter only) and ventilation but with the windows and doors between the sunspace and the main areas kept closed at all times. In Case 1 these windows and doors were included in the ventilation strategy; Case 2 is as Case 1 but with the added benefit of cold air from the EAHE being delivered to the sunspace ground floor and the living area. The infiltration used was 0.25ACH at atmospheric pressure (converted from 3.4 m^3/hm^2 at 50Pa) as this was measured on site through an air-permeability test.

The simulations were worked out in an unusual way. The model was built up in stages and for each of those a simulation was carried out. This way the author had full understanding of the influence of each parameter, which enabled the development of Case 2. Case 2 results are as close as practical to the house's actual performance (Base Case). Case 0 and Case 1 where then re-worked backwards so every variable is the same as Case 2 except for the differences described above. The aim of these simulations was to validate the model, understand the house's basic thermal performance as close as possible to its real functioning. The results of May, June, July and August were compared with the real data collected in the house.

Table 7-2: Summary of Base Case, Case 0, Case 1 and Case 2

		Base Case Data collected on site in May, June, July and August	**Case 0** Weather data 2002+2009, infiltration 0.25ACH, shading, internal gains, basic ventilation	**Case 1** As Case 0 + openings between sunspace and main areas	**Case 2** As Case 1 + EAHE delivering air in sunspace and living area
		BC	**C0**	**C1**	**C2**
BASF House as constructed	**BH**	BC BH	C0 BH	C1 BH	C2 BH

7.4.2 Assumptions

Due to the onsite data collection, in this chapter the assumptions are as much as possible informed by the data collected, observation or informal interview with the occupants. These have a large influence in the results so in the first set of simulations (Case 0) they were kept as simple as possible. In Case 1, more parameters were added in the ventilation strategy and in Case 2 the EAHE was also added.

1. Weather: the weather data used was the CIBSE Design Summer Year Weather Data (DSY) for Nottingham based on the year 2002 described in section 5.1.2 morphed into a new weather data where the months of May, June, July and August were substituted by real data measured on site.
2. Calendar: it is assumed that summer (or no heating period) is from the 1st of May to the 31st of August and winter (heating period) is from the 1st of September to the 30th of April.
3. Internal Gains: internal gains were assumed as follows:
   - Occupants: 3 people were using the house, a couple in the southwest bedroom and one person in the southeast bedroom. They were assumed to be out during the day and in different locations during the evenings. The sensible heat gain assumed for each person was 70W and the latent heat gain was 50W. Occupancy in circulation spaces was ignored. Occupants were assumed to use the spaces

according to the schedules in Table 6-6. Although this might not match reality as mentioned above, it is as close as virtually possible as it is unpractical to follow real occupancy (especially in this house which is used in an atypical way).

- Lighting: is assumed to be provided by low-energy compact florescent bulbs and in accordance with the schedules in Table 6-6 resulting in the following thermal loads when in use:
    - Living and dining rooms: 100W
    - Kitchen: 75W
    - Bedrooms: 50W
    - Bathroom: 25W
- Equipments gains: two computers were assumed to be used for 5 hours each in the evenings in the living room producing a gain of 18W when on. The house's equipment for heating and hot water are located in the utility room so an average of 10W of gain was assumed in that space continuously over a 24h period.
- Appliances: gains from appliances in the kitchen were assumed to occur continuously over a 24 hours period so the gains from fridge, cooker and oven, dishwasher and kettle were assumed to together deliver an average power of 10W.

4. Ventilation and infiltration:
    - Infiltration: infiltration was assumed to be at 0.25ACH as measured on site.
    - Ventilation: the assumed ventilation strategy can be seen in Figure 7-31 and Figure 7-32 which was developed in order to achieve similar performance to the house as monitored. In Case 0, a simpler ventilation strategy was assumed (in blue). In Case 1, ventilation was assumed both from outside to the house and within the house (i.e. between the sunspace and the other zones- blue + pink). In case 2, the EAHE was added (purple). The basic concepts behind the strategies were: in winter, allow warm air from the sunspace to percolate to the house and keep all the other windows closed except if the sunspace is overheated; in summer, Case 0 closed the relationship between sunspace and the main areas to study the impact of it in the results. Case 1 in summer allowed air to escape through the bedrooms and circulation to the high level windows in an attempt to reduce overheating.
5. Comfort Temperature Range: The benchmarks suggested by CIBSE and described in Table 5-2 (Chapter 5) were used as a starting point. The simulation results are illustrated by means of number of hours in a year when temperatures in the room go above 25^{o}C and above 28^{o}C. The simulated data are compared with the onsite collected data using this method.

Table 7-3: Schedules of spaces internal gains (1=on, 0=off)

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
24 hours	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Heating (12h)	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
Bathroom occupancy, lighting	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
Bedrooms lighting	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
Living occupancy and winter lighting	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0
Living lighting (summer)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
Kitchen occupancy, lighting	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
Computers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0

Table 7-4: BASF House kitchen appliance gains

Appliance		**Power** (kW)	**Usage** (assumed)	**Daily total energy** (kWh)
Kettle (on hob)	Per 1.5 litre boil	3.00	4 times/ day	0.60
Microwave/ Oven	When on	0.80	30 minutes/ day	0.40
Cooker	When on	0.79	30 minutes/ day	0.40
Dishwasher	Per 1h cycle	1.00	Twice weekly	0.29
Fridge	Per hour	0.03	All year	0.62
Total				2.31

6. Heating: in all cases heating was assumed during the heating period (1st of September to the 30th of April) whenever needed. The thermostat was set to a lower limit of 19°C and an upper limit of 21°C and radiators were used as emitters, one in the living room (as it is where the trench heater is placed) and in the north bedroom and in the bathroom.

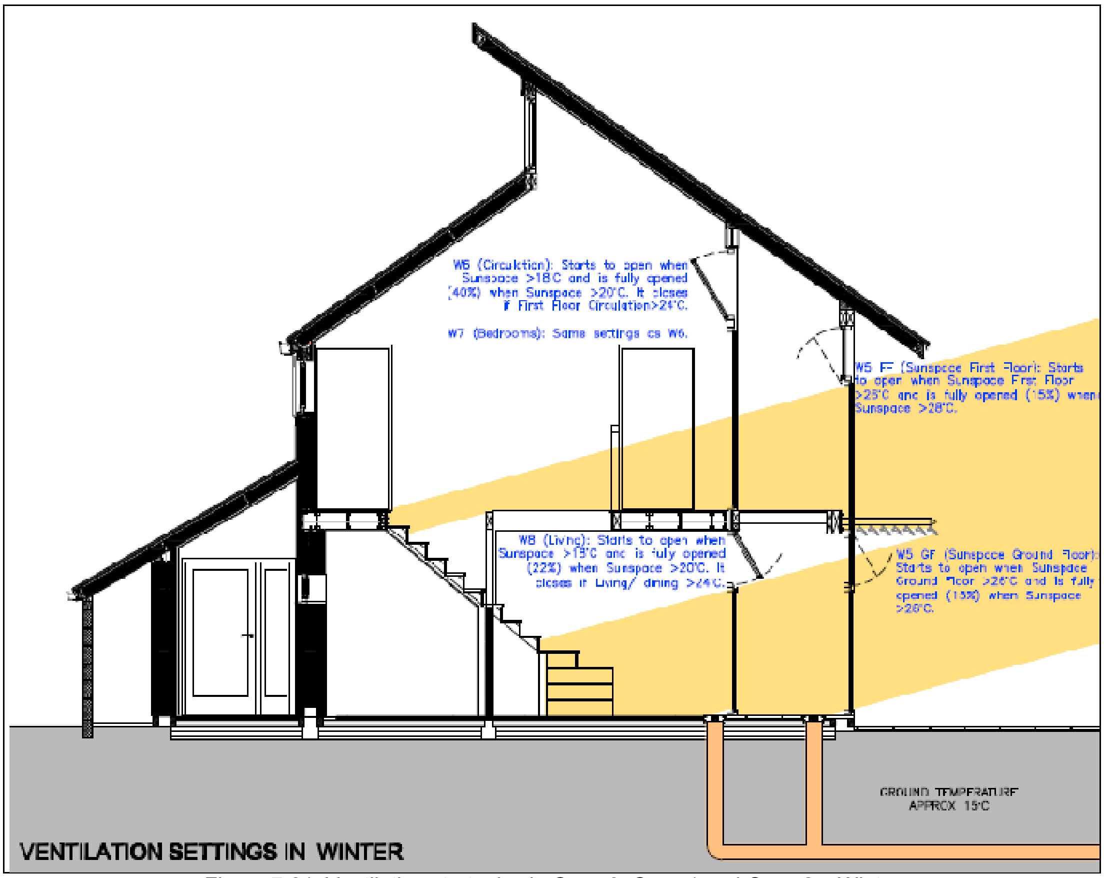


Figure 7-31: Ventilation strategies in Case 0, Case 1 and Case 2 – Winter

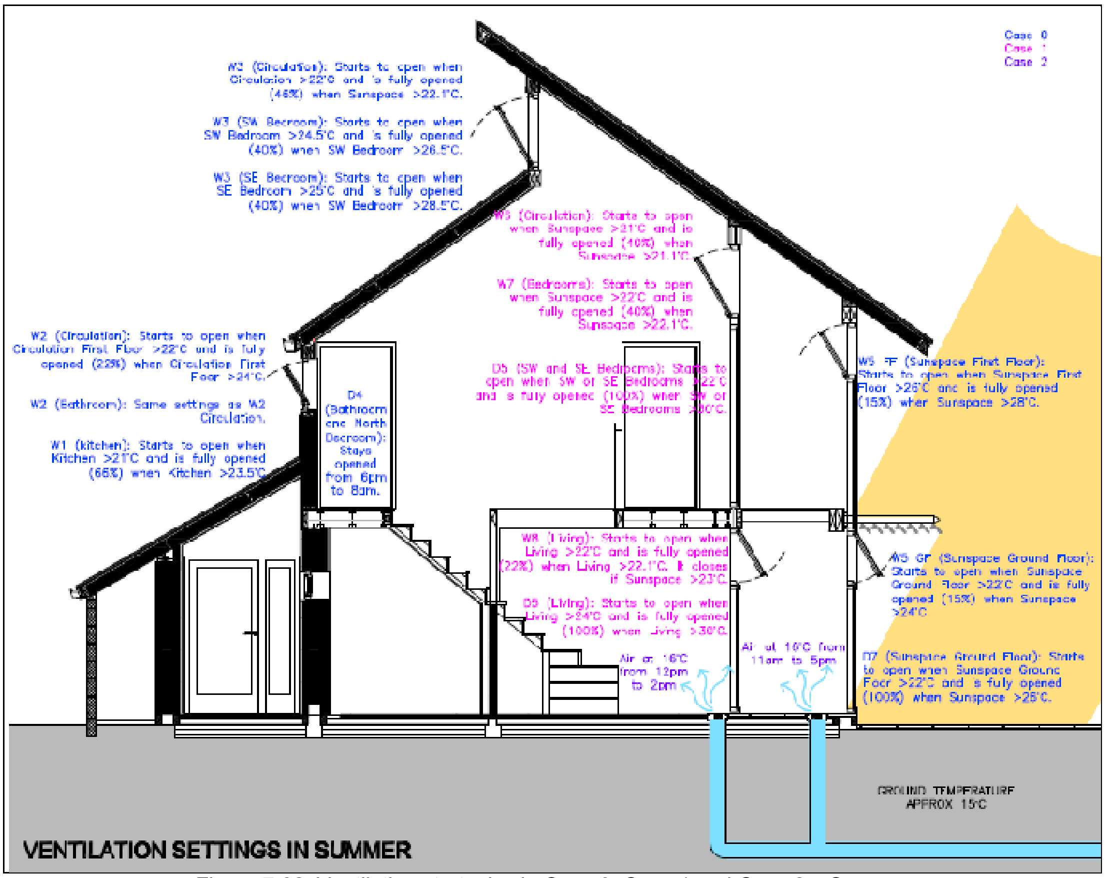


Figure 7-32: Ventilation strategies in Case 0, Case 1 and Case 2 – Summer

7. Cooling; no active cooling was assumed in Case 0 and Case 1. In Case 2, the EAHE is taken into account. Unfortunately, the house sensors do not record when the EAHE has been used. According to the house's occupiers, it was the last resource they used in case of overheating because of the noise it generated and because they prefer to keep the windows open. From the recorded data, it appears that it was used in the hottest times of the day. Consequently the EAHE in the simulations was activated from 12pm to 2pm in the living room and from 11am to 5pm in the sunspace just during summer delivering 0.05m^3/s (0.06kg/s) at 16^{o}C in each space. The air flow rate was selected to reflect the actual system and provide the sunspace with 3ACH.

The sunspace was assumed to have no occupancy or lighting as it is a space rarely used, even though it holds great importance for the maintenance of comfortable internal conditions. Circulation spaces and WC were considered to have negligible occupancy and lighting gains. The north bedroom was considered unoccupied for the whole year.

7.4.3 Results

The results presented here are just for May, June, July and August. It must be remembered that the aim of these simulations was to try to get as close as possible to the monitored results in order to simulate the house in future climate scenarios.

A comparison between Figure 7-33 and Figure 7-34 show that the introduction of ventilation within the house in Case 1 alleviated overheating in most of the spaces and especially in the first floor of the sunspace. However, in the southern bedrooms the temperatures still go above 25^{o}C for more than 30% of the period and above 26^{o}C for about 12% of the time. This demonstrates the need to use the bedroom windows for ventilation of the sunspace, which might not be the most appropriate design solution. Whilst in winter those openings allow for warm air from the sunspace to be used to warm up the bedrooms, in summer it contributes greatly to overheating as it is exemplified by this house. This problem is intensified by the fact that the openings in the sunspace at first floor level and in the circulation on the first floor and at the higher level are not big enough to extract all the warm air without the use of the bedroom windows. Solutions could include a more detailed study of window sizes and positions or the controversial inverted design when living room, dining and kitchen are placed on the first floor to make use of that warmth and bedrooms are placed on the ground floor to be kept cooler.

Once the EAHE was added (Case 2), overheating was practically eliminated from the whole house except south bedrooms where it did contribute to reducing it to an average of about 24% over 25^{o}C and 6.5% over 26^{o}C. The results for the whole period reached similar levels to the monitored data (Base Case). However, as may be seen in Figure 7-35, it got colder in areas that are directly receiving the air delivered by the EAHE even though the system is simulated at a very low air flow rate. This brings back the discussion of the limits of this kind of system to deliver the quantity of fresh air required, which is a particular problem in winter but may also exist in summer. In addition, it may also cause undesirable cold draughts when the air is delivered directly to the space. The system proposed in Chapter 8 of this work aims to overcome these limitations.

Full house computer simulation cannot replicate or be directly compared with reality for many reasons: inaccuracy of software, inputs assumed over 1 hour periods (which is very unrealistic), location of temperature measurements (computer simulations will give 1 average reading per zone per hour), inaccuracy of monitoring equipment, differences in the weather data, etc. Consequently, the focus of this section was a more holistic approach where the full performance was the objective.

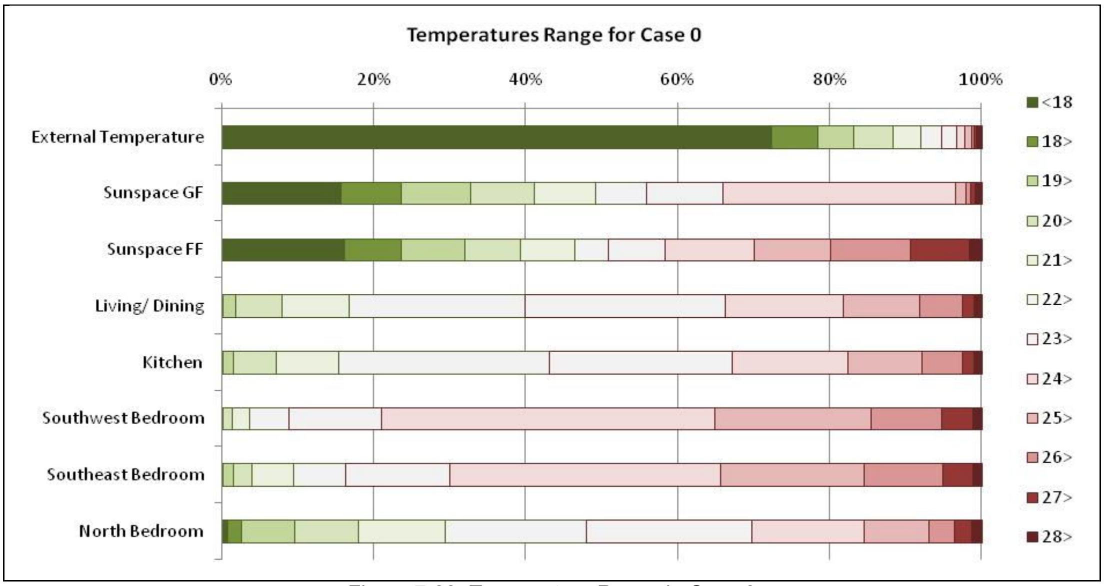


Figure 7-33: Temperature Range in Case 0

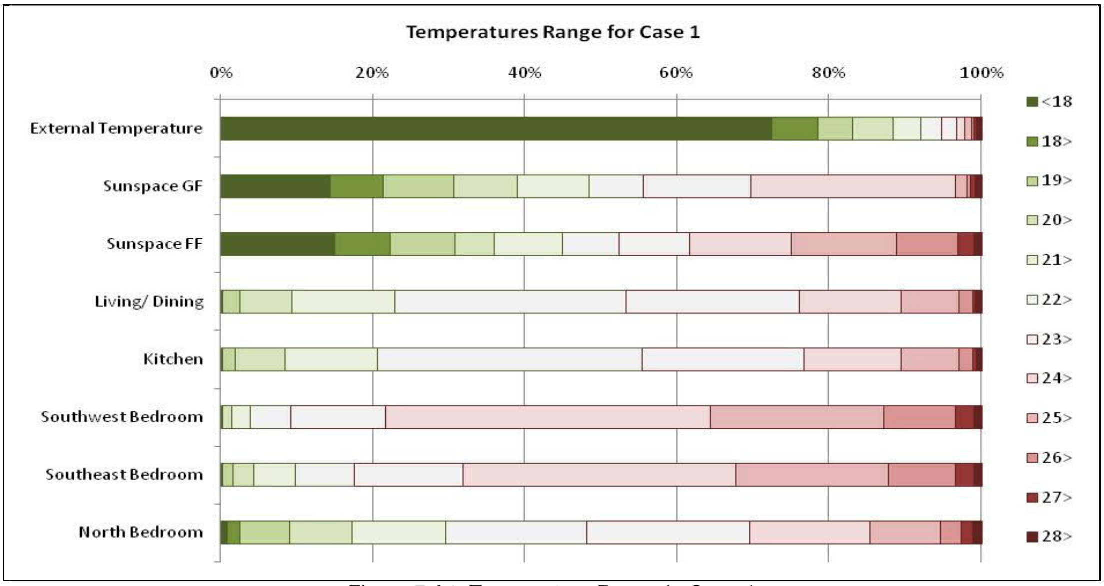


Figure 7-34: Temperature Range in Case 1

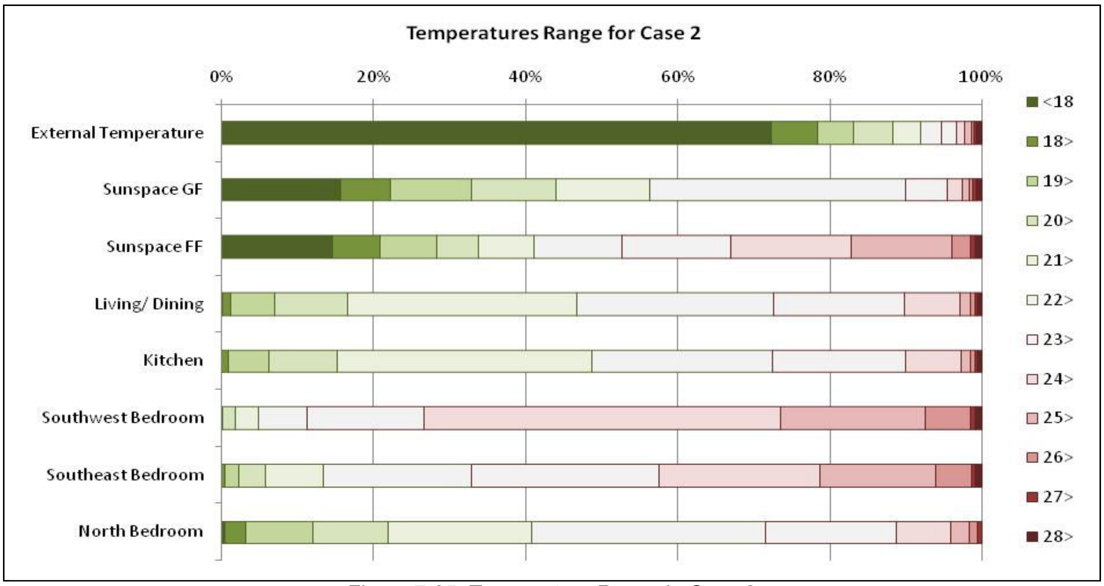


Figure 7-35: Temperature Range in Case 2

Figure 7-36 and Figure 7-37 compare the percentage of time each zone was above 25°C and 28°C in Base Case, Case 0, Case 1 and Case 2. Case 2 is quite similar to the Base Case in most areas. In the first floor of the sunspace there is a higher percentage of time above 25°C in Case 2 and a lower of time above 28°C. Despite the hundreds of combinations tried, it was not possible to come closer to the monitored data. Many factors were influential in these results so finding a specific cause is not feasible; it can be due to all or any of the reasons listed above. Please note that the figures have different scales.

As may be seen in Figure 7-38, the peak temperatures in Case 2 are fairly similar to the Base Case, although slightly higher in certain zones. Some of this difference may be attributed to the effect of the PCM boards, which are installed in all these zones but are not considered in the simulations.

A comparison of the performance on the first 2 days of July (the warmest days of the data collected) shows a remarkable similarity between the Base Case (real data) and the Case 2 (Figure 7-39 and Figure 7-40). The biggest differences seen are that the model presents a ‘flatter’ pattern in the first floor of the sunspace (which reflects the results above where the model shows a greater percentage of time between 25 and 28°C) than the real data. The opposite happens in the living area. However, those differences are still within a few degrees. The temperatures in the bedrooms in the Base Case and Case 2 are exceptionally comparable, with the simulation showing a slightly flatter pattern.

The model used in Case 2 with all its assumptions was subsequently simulated in future weather scenarios in order to investigate overheating in a warmer climate. The results are described in the next section.

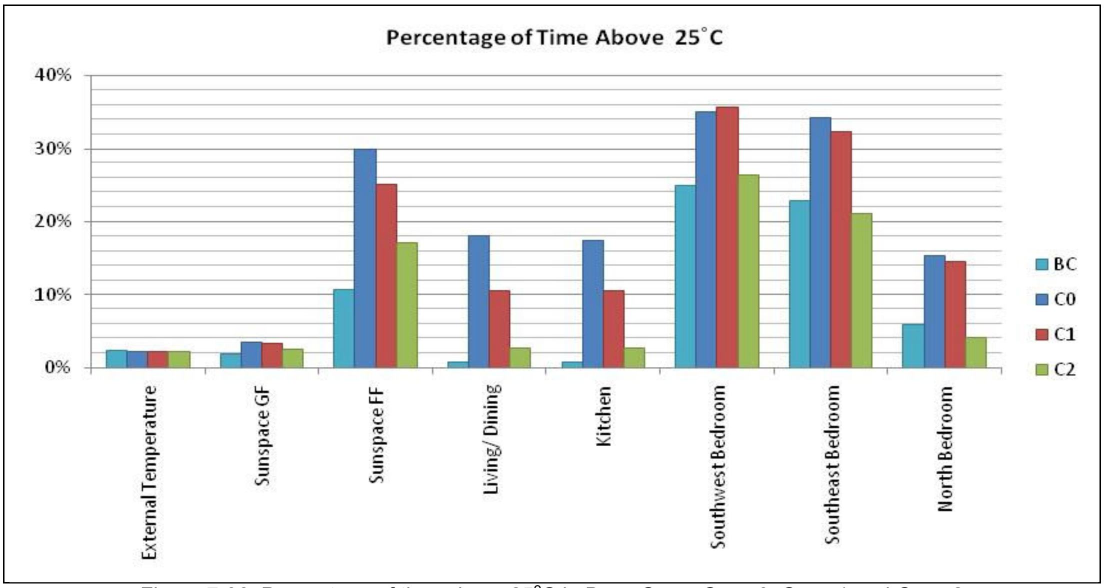


Figure 7-36: Percentage of time above 25^{o}C in Base Case, Case 0, Case 1 and Case 2

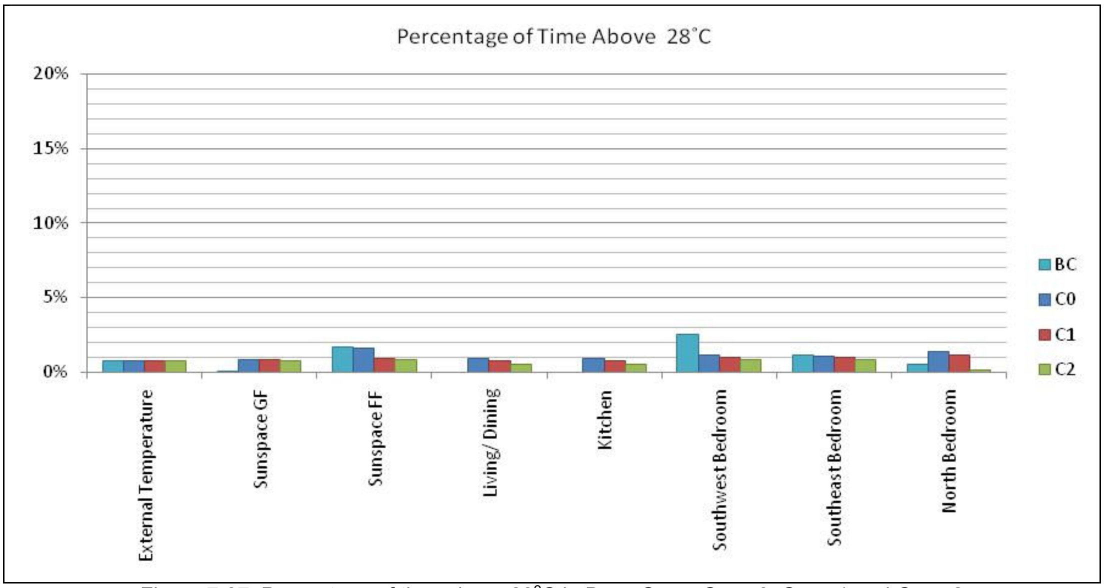


Figure 7-37: Percentage of time above 28^{o}C in Base Case, Case 0, Case 1 and Case 2

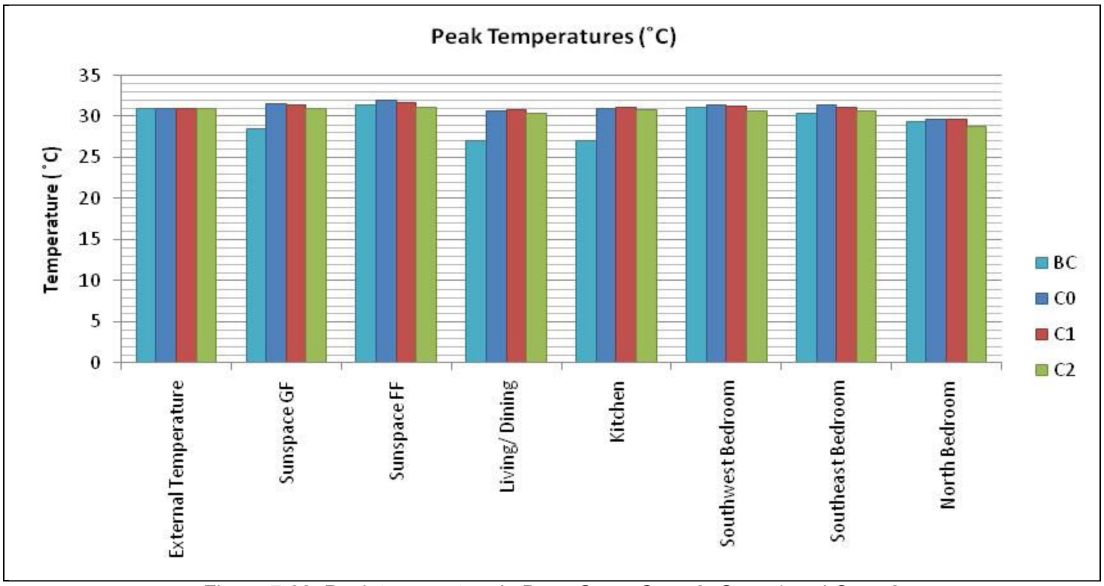


Figure 7-38: Peak temperature in Base Case, Case 0, Case 1 and Case 2

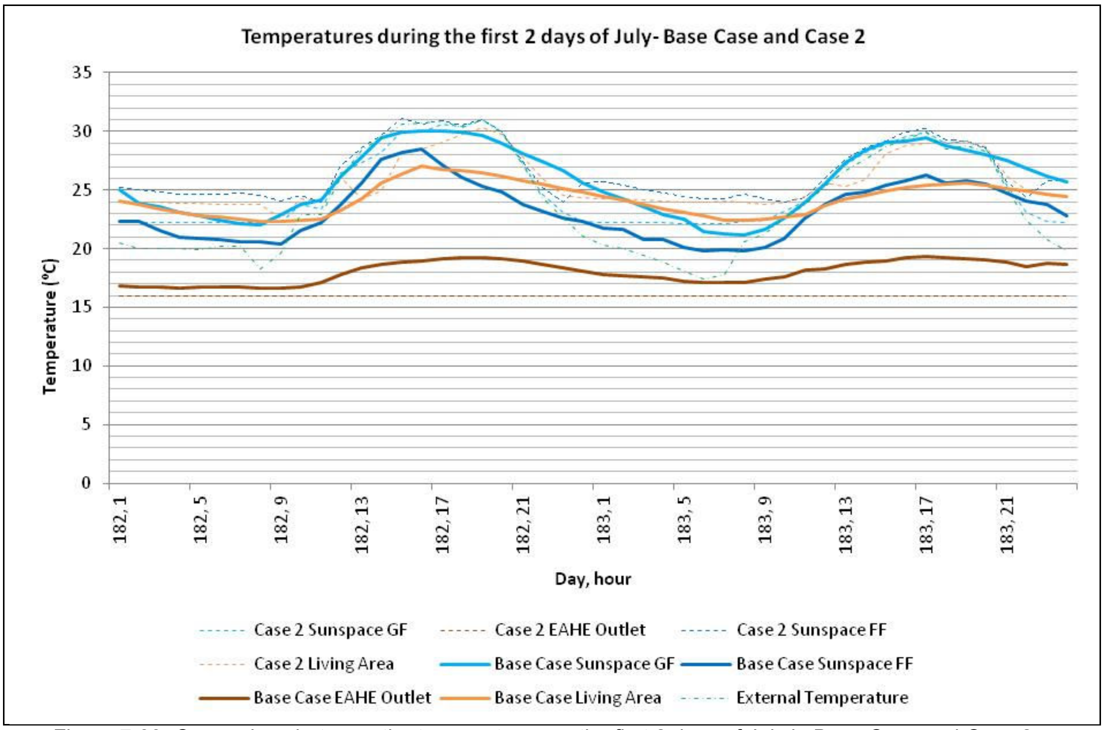


Figure 7-39: Comparison between the temperatures on the first 2 days of July in Base Case and Case 2 – Sunspace and Living

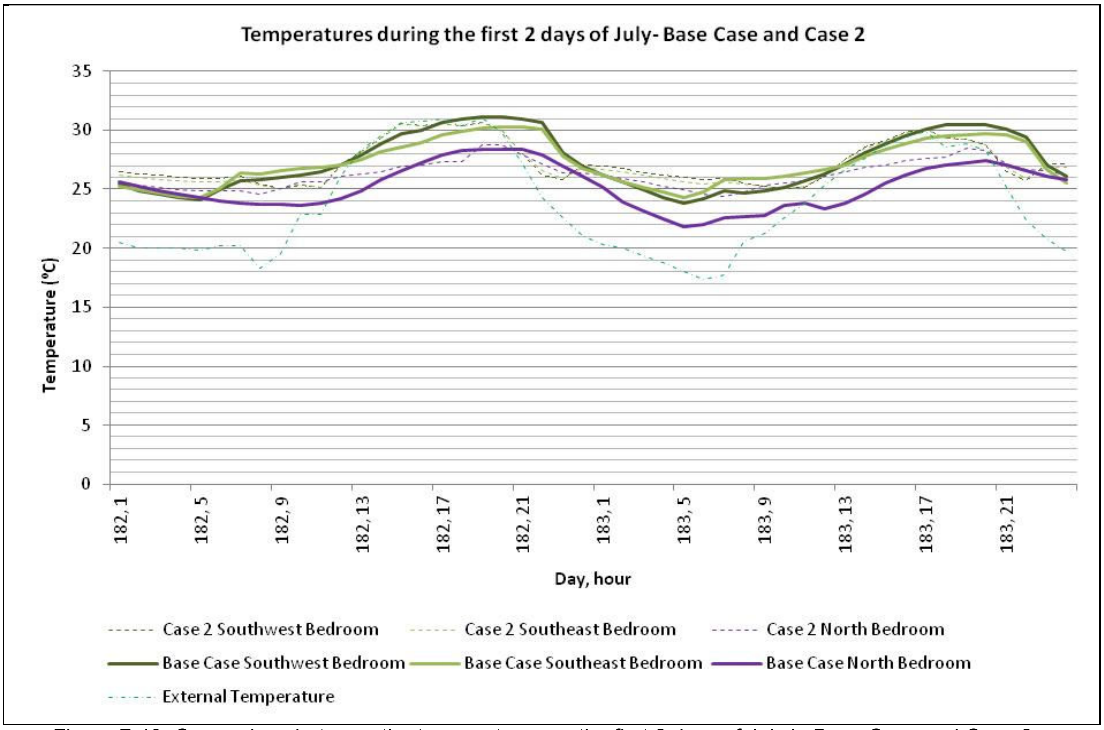


Figure 7-40: Comparison between the temperatures on the first 2 days of July in Base Case and Case 2 – Bedrooms

7.5 BASF HOUSE IN FUTURE WEATHER SCENARIOS

The BASF House does suffer overheating if the CIBSE guidelines are taken as a benchmark. However, occupants are satisfied with the thermal comfort of the house even in the bedrooms where the issue is more significant. In the previous section, a computer simulation model was built that predicts similar performance to that experienced in the house in 2009. This section will use this model to investigate the house's performance in 2020, 2050 and 2080 using the UKCIP climate change scenarios described in Chapter 5.

7.5.1 Scope and Method

The objective of this section is to investigate how the house that presented little overheating in today's weather will perform in 2020, 2050 and 2080. These cases will be compared to Case 2, which is the case expected to be the closest to the house's actual performance and has the same settings and assumptions used here.

Three sets of simulations were undertaken: firstly the house was simulated as it is in the different climate scenarios (Case 3, 4 and 5) then changes were made to the envelope in order to investigate if the selection of materials had a large influence on the degree of overheating experienced. As demonstrated in Figure 7-5, the use of ICF for the ground floor and SIPs for the first floor caused a thermal bridge all around the house as there is a mismatch of the insulating layers. In Chapter 5, ICF was proven to perform well thermally regarding the avoidance of overheating. Consequently, the house was simulated as if it had been built entirely as the ground floor (ICF external walls and concrete blocks as internal walls) in today's weather (Case 6) and in 2080 (Case 7).

Subsequently, all the walls were changed to Precast Concrete Panels (PCP) with similar composition as section 6.2.8 (Chapter 5) but with a 160mm layer of polyurethane so the U-Value is similar to the house as it is. As overheating was still a significant issue, the EAHE was activated 24 hours at the same rate as previously used forming Case 10.

Table 7-5: Summary of Cases 3, 4, and 5

		Case 3 As Case 2 but with 2020 weather data (high-emissions)	**Case 4** As Case 2 but with 2050 weather data (high-emissions)	**Case 5** As Case 2 but with 2080 weather data (high-emissions)
		C3	**C4**	**C5**
BASF House as constructed	**BH**	C3 BH	C4 BH	C5 BH

Table 7-6: Summary of Cases 6 and 7

		Case 6 As Case 2 (house as it is used today) but with all walls made of ICF	**Case 7** As Case 5 (2080) but with all walls made of ICF
		C6	**C7**
BASF House with all walls changed to Insulated Concrete Formwork (ICF)	**BH ICF**	C6 BH ICF	C7 BH ICF

Table 7-7: Summary of Cases 8, 9 and 10

		Case 8 As Case 2 (house as it is used today) but with all walls made of PCP	**Case 9** As Case 5 (2080) but with all walls made of PCP	**Case 10** As Case 9 (2080 PCP) but with EAHE activated 24 hours
		C8	**C9**	**C10**
BASF House with all walls changed to Precast Concrete Panels (PCP)	**BH ICF**	C8 BH PCP	C9 BH PCP	C10 BH PCP

Before these cases were decided, a number of other possibilities were tried. Special attention was given to night time ventilation as a means to alleviate overheating in the house's bedrooms. However, despite the large number of simulations tried, in all cases reducing day ventilation between sunspace and bedrooms/living area and implementing night time ventilation caused more overheating in the whole house. This may be attributed to 2 reasons: firstly, as an obvious result of warmer climate, there will be fewer opportunities for effective night time ventilation. Secondly, due the house's design, ventilation in the bedrooms has to come from the sunspace (except for the high level window which is not used by the occupants due to noise as stated). Consequently, if the temperature in the sunspace cannot be kept at a comfortable level then it might cause problems elsewhere in the house.

7.5.2 Assumptions

The assumptions in this section are the same as Case 2 except for the change on the weather data and on the wall materials as explained in the previous section. Because the model assumes that opening of windows occurs in connection with temperature rise and fall, it was felt that the same regime could be kept for future scenarios, which means that the warmer the climate the more often windows are opened. A summary of the assumptions can be seen below.

1. Weather: the weather data used was the CIBSE Design Summer Year Weather Data (DSY) for Nottingham 'morphed' into weather data for 2020, 2050 and 2080, created using the UKCIP process described in section 5.1.3 (Chapter 5).

2. Calendar: summer (or no heating period) is from the 1st of May to the 30th of September and winter (heating period) is from the 1st of October to the 30th of April.
3. Internal Gains:
   - Occupants: 3 people with sensible heat gain for each person of 70W and the latent heat gain of 50W. Occupancy in circulation spaces was ignored. Occupants were assumed to use the spaces according to the schedules presented in section 7.4.2.
   - Lighting: is assumed to be used as described in section 7.4.2 and result in the following thermal loads:
     - Kitchen: 75W
     - Living and dining rooms: 50W
     - Bedrooms: 50W
     - Circulation: 50W
     - Toilet and bathroom: 25W

   - Equipment gains: 18W per hour from 2 computers in the living room in the evenings, 10W per hour from equipments in the utility room 24 hours.
   - Appliances: in the kitchen 10W operating continuously over a 24 hour period (Table 7-4).
4. Ventilation and infiltration:
   - Infiltration: was assumed to be 0.25ACH at atmospheric pressure as measured.
   - Ventilation: was assumed to take place both from outside to the house and within the house (i.e. between the sunspace and the circulation zones) as shown in Figure 7-31 and Figure 7-32.
5. Comfort Temperature Range: the simulations results are illustrated by means of number of hours in a year when temperatures in the room go above 25°C and above 28°C based on CIBSE benchmarks.
6. Heating: heating was assumed during the heating period (1st of October to the 30th of April) whenever needed. The thermostat was set to a lower limit of 19°C and an upper limit of 21°C.
8. Cooling: EAHE in Cases 3 to 9 was activated from 12pm to 2pm in the living room and from 11am to 5pm in the sunspace just during summer delivering 0.05m^3/s (0.06kg/s) at 16°C in each space. In Case 10 it worked at the same rates but continuously over a 24h period.

7.5.3 Results

The results from the first set of simulations, Case 3, 4 and 5, were compared with the Base Case (monitored data) and Case 2 (Figure 7-36 and Figure 7-37). As expected, overheating issues present a linear growth that follows the pattern of the morphed weather data.

In 2020 (Case 3) the overheating experienced today is accentuated but still within tolerable levels. By 2050 (Case 4), temperatures stay above 28°C for around 2% of the period (May to August) in the living and circulation areas and more than 3% in the southern bedrooms. These bedrooms present temperatures above 25°C between 38 and 44% of the time (each bedroom has a different ventilation regime) and above 26°C for more than 15% of the period. In 2080, overheating in the studied period is a serious concern, with bedrooms above 25°C for as much as 61% of the time and above 28°C for over 8% of the time. The peak temperatures in the bedrooms were above 38°C. The living area reached 36°C and exhibited temperatures above 28°C for more than 5.5% of these 4 months. It is possible that, in a warmer climate as it is expected to be in 2080, people are prepared to accept warmer temperatures in houses, especially in the living areas, or adapt themselves in search of comfort. Nonetheless, it seems that bedrooms will be a seriously problematic area in this house.

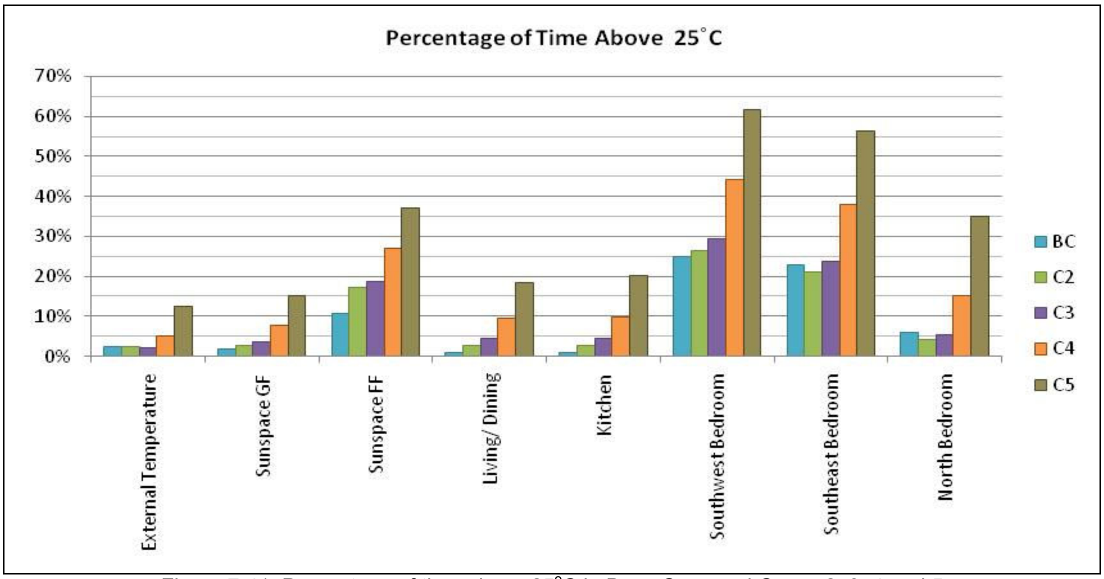


Figure 7-41: Percentage of time above 25°C in Base Case and Cases 2, 3, 4 and 5

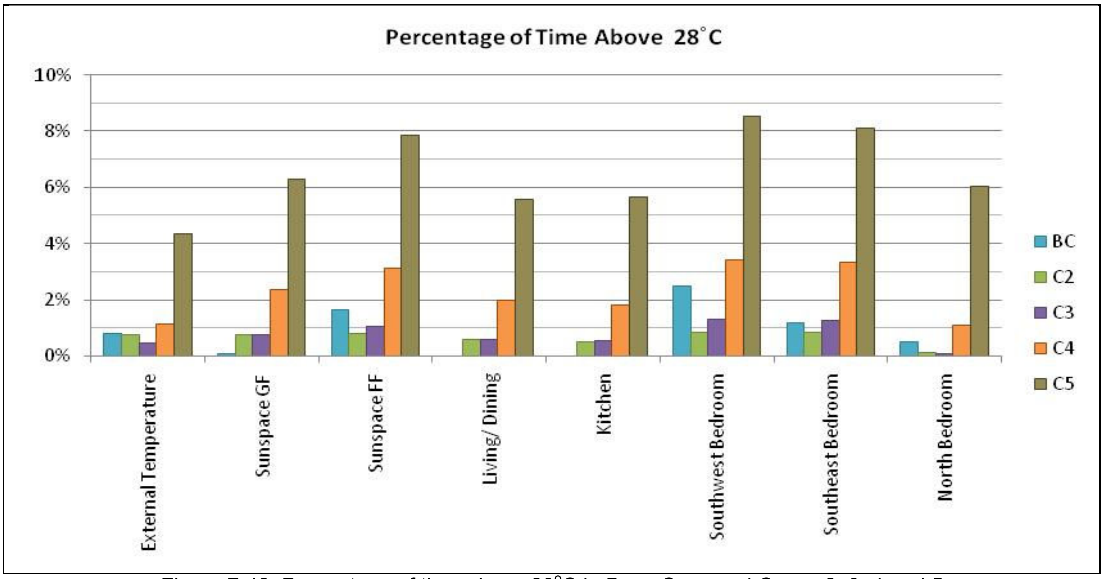


Figure 7-42: Percentage of time above 28°C in Base Case and Cases 2, 3, 4 and 5

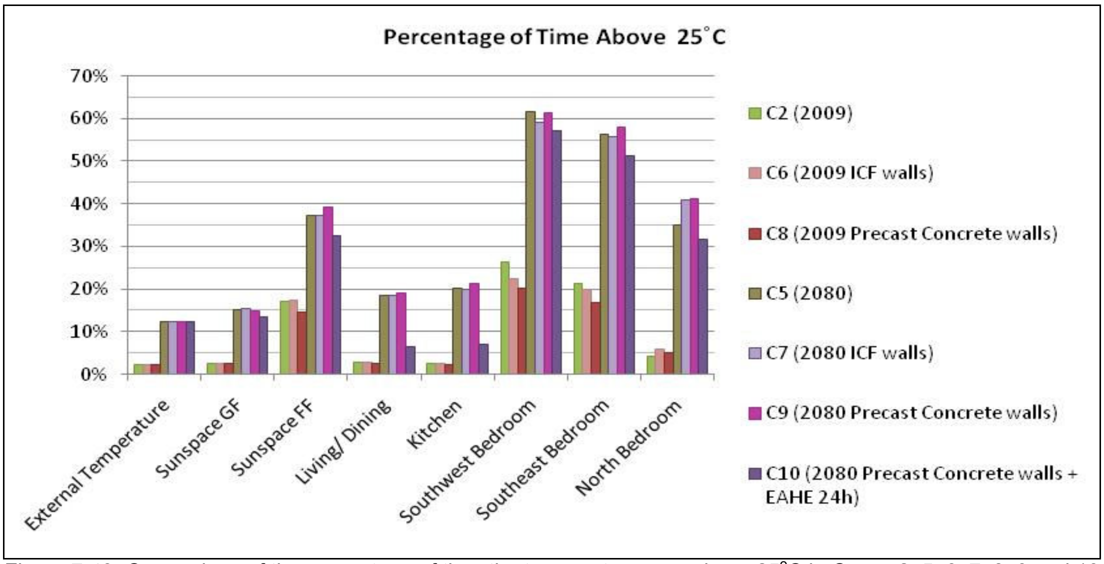


Figure 7-43: Comparison of the percentage of time the temperatures are above 25°C in Cases 2, 5, 6, 7, 8, 9 and 10

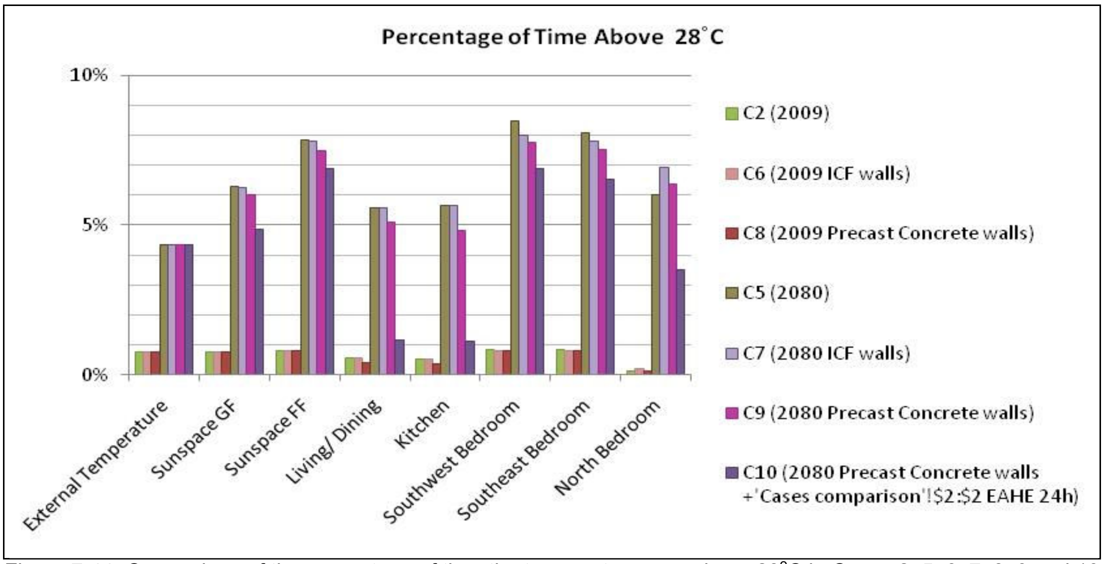


Figure 7-44: Comparison of the percentage of time the temperatures are above 28°C in Cases 2, 5, 6, 7, 8, 9 and 10

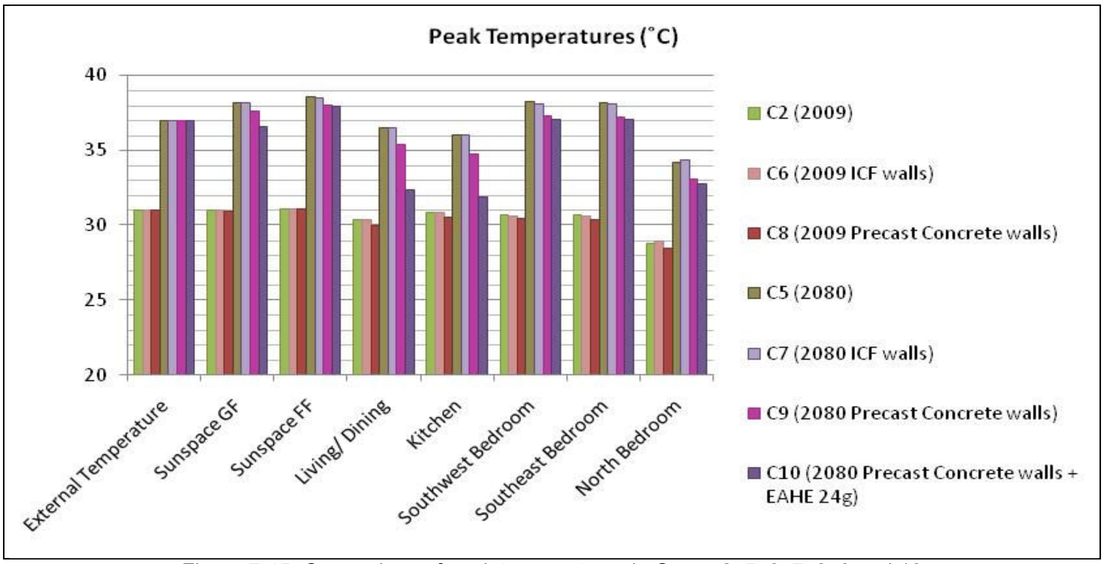


Figure 7-45: Comparison of peak temperatures in Cases 2, 5, 6, 7, 8, 9 and 10

Changing the walls to ICF reduced overheating to some extent (around 4-6% for temperatures above 28^{o}C in the southern bedrooms) in most of the first floor zones, which were previously built of SIPs in both weathers (2009 and 2080) but did not have a significant impact on peak temperature (Figure 7-43, Figure 7-44 and Figure 7-45). In today's weather, PCP had a slightly larger impact on peak temperatures (between 3 and 4% reduction in all zones except the sunspace where it reduced overheating by around 1.5%) but was similar to ICF in most areas regarding overall percentage of temperature above comfort. It did, however, offer greater reduction in areas where ventilation was larger (i.e. sunspace and southern bedrooms) which shows how high thermal mass can more effective if associated with ventilation.

Interestingly, when the walls were changed to PCP and the house was simulated in 2080, there was an increase in the percentage of temperatures above 25^{o}C (by around 4% in the living areas as compared to Case 5 but larger if compared to ICF) but a reduction on both, temperatures above 28^{o}C and peak temperatures (around 9% and 3% respectively in the living area and southern bedrooms as compared to Case 5). This is a reflection of the effect that thermal mass can have in reducing peak temperatures and creating a 'flatter' temperature curve.

The activation of the EAHE for 24 hours during the whole period (Case 10) helped to reduce overheating in all areas of the house including those that do not receive the cold air directly when compared to Case 9 (Figure 6-46 and Figure 7-47). It brought overheating levels down to acceptable levels in the living areas and ground floor of the sunspace. In the southern bedrooms it reduced the percentage of time temperatures were above 25^{o}C by around 6%. However, these rooms are still at risk of being uncomfortably hot for most of the summer periods.

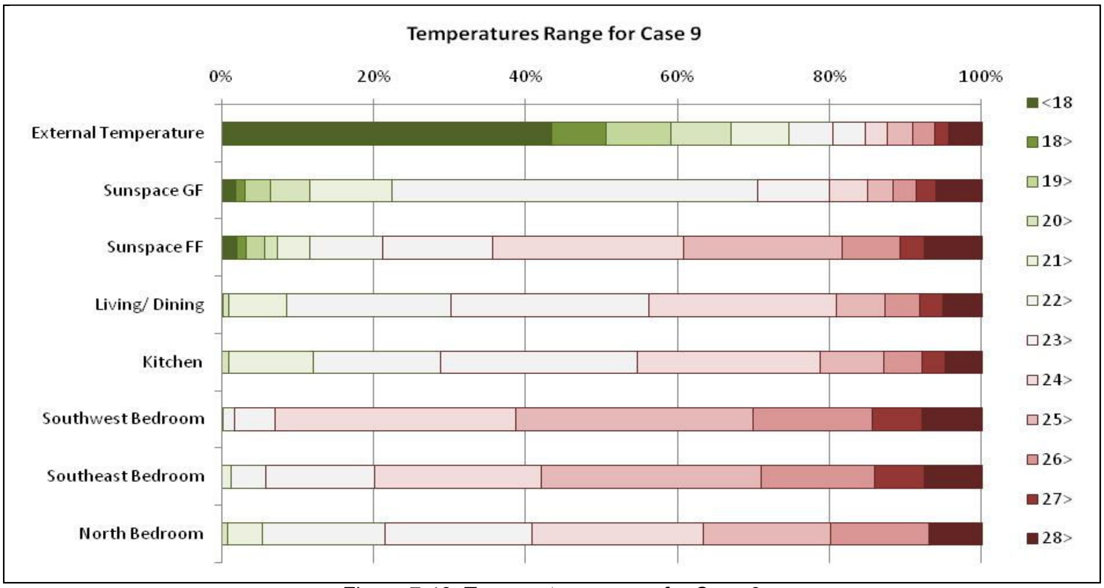


Figure 7-46: Temperatures range for Case 9

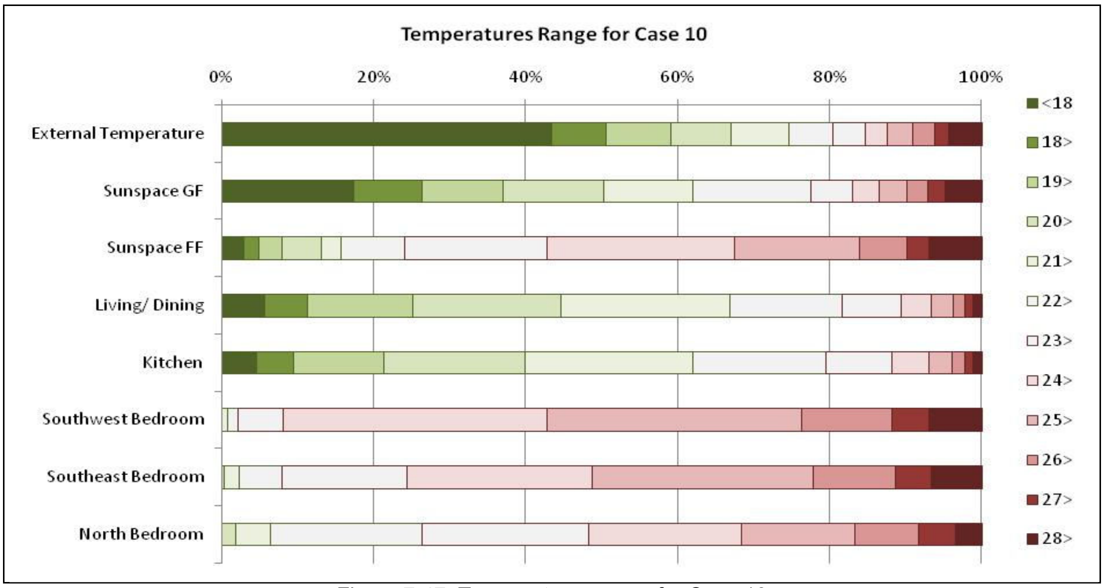


Figure 7-47: Temperatures range for Case 10

7.6 CONCLUSIONS

> *"It depends on the weather conditions, in summer there was some overheating at night, but not to the point of feeling uncomfortable, I think the volume factor helps (…). I think the culture factor in regard to tolerance of heat may be influential too."*
>
> Nina Hormazábal, tenant at the BASF House in response to the author's questioning (August 2009)

> *"I would not say that I have not experienced overheating in the bedrooms, I agree with Nina's comments that the volume factor of the rooms has a huge influence on this. I would also agree that with regards to thermal comfort that the other occupants of the house seem to have been more sensitive to climate, with myself placing a greater importance on air quality and ventilation than temperature - for example opening windows even during colder periods. "*
>
> Deborah Adkins, tenant at the BASF House in response to the author's questioning (August 2009)

The BASF House is a prototype house that was built as part of the Creative Energy Homes project using a variety of modern methods of construction. The house exploits passive design for most of its heating demand over the year and on natural ventilation and stack effect to overcome overheating problems. The southern elevation is a double height sunspace that works as a buffer for the living area and for 2 of the 3 bedrooms of the house. The ventilation of these zones, particularly of the bedrooms, uses mainly air that has to pass through the sunspace. Some of the exhausting of excessively warmed air from the sunspace is also expected to occur through these zones.

When this house was first assessed, previous to the construction work starting on site, the focus was the house's performance in winter and its heating loads. Additionally, the house was simulated using a weather data from the software's library, which was found to be colder than the CIBSE DSY weather data 2002 (available at a later date) and, particularly, much colder than the data collected on site. Consequently, overheating was not a concern and was disregarded. In addition, issues such as noise and the occupant's behaviour were not accounted for as there was no information at that time. Conversely, this work is looking specifically into overheating issues and means of alleviating it (i.e. by integrating thermal mass in the building's envelope using common materials, using PCM or the use of the soil's mass with EAHEs).

The quantity and working temperature range of the PCM installed in the house was determined by BASF. A calculation using the software developed by them to aid the wider use of their PCM products showed that the house would not benefit greatly from it as overheating was not a great issue. However, the simplicity of the model does not allow for the simulation of the sunspace, which is the main contributor to overheating in this house. The EAHE was designed by the supplier (Rehau) using software developed by them. Measurements were taken on site by the author prior to the house being occupied demonstrating that the system worked efficiently with a maximum COP of 25.4

On site data from the BASF House was collected from May to August 2009. An analysis of the data shows that the bedrooms presented overheating in this period (taking the CIBSE criteria as a benchmark) with temperatures above 25^oC more than 20% of the time, above 26^oC around 10% of this period and above 28^oC between 1 and 2% of the time. However, the occupiers say that even though it feels hot it does not bother them too much and they believe it is due to the volume of the room. As the temperatures were measured at the occupier's height, the volume should not have interfered with the thermal experience of the tenants. It might have interfered in a visual perceptive way only: occupiers might have felt it was fresher because the bedrooms feel big and airy rather than because the temperature is at a comfortable level. In addition there was little air movement at occupant's level due to the position and functioning of the windows. This brings back the discussion about thermal comfort benchmarks and reality. Firstly, comfort is highly subjective and, as the house users pointed out, possibly due to their different cultural backgrounds they are prepared to accept different levels of overheating. Secondly, it depends on other factors such as the overall space experience, daylight, visual contact with the outside and opportunities to interact and control your own environment. Thirdly, people do not want to ignore their thermal senses: provided that there is no thermal stress, overheating might be welcomed as a reminder of the summer outside.

According to the CIBSE criteria the bedrooms were above thermal comfort benchmarks not just during summer 2009 but also in all the simulations. This can be attributed to a design mistake because the sizes of the high level outlets for exhausting of warm air from the sunspace are not correct. In addition, they are not often used, especially at night, because of noise issues. The bedroom sliding doors to the sunspace can be used as part of the ventilation strategy but this is not desirable because the whole house strategy should not rely on someone keeping his/her bedroom door opened as this creates privacy and noise issues. Indeed generally the house ventilation strategy should not rely on the use of the bedrooms as this is very subjective and may jeopardize the design's performance.

Due to the lack of temperature sensors at high levels, it is not possible to identify stratification of warm aim in the core of the house. Also, there are no sensors in the circulation zone, where most of the stack effect happens. Further monitoring work should include temperature sensors in these areas and sensors capable of recording the time of the opening of windows and doors. There are sensors at different levels in the sunspace and a temperature difference of around 2-3^oC can be seen between the ground and first floors. Further work using computer fluid dynamics (CFD) software could simulate that air movement and help understand the temperature difference at these different levels.

Although surface temperatures of the installed PCM board have been recorded, the data do not allow for comparison against an area without PCM and so its benefits cannot be measured. However, it was possible to see that the PCM stayed within its phase change temperature range for almost 90% of the studied period. That might mean that the PCM did not have an opportunity to discharge the heat and re-solidify to be ready for a new cycle, which should ideally happen on a daily basis. This emphasises the need for additional cooling of the boards and for a system as the one presented in the next chapter of this thesis. So a question remains unanswered: can the PCM board effectively contribute to a comfortable indoor environment? In the next chapter, the functioning of the Micronal PCM will be explored by means of experimentation in a lab environment and in a rig exposed to the weather. In order to effectively prove the functioning of the PCM in a real life application two identical rooms and/or houses would need to be built and compared. Longer periods of data and/or more comprehensive monitoring systems might help to confirm if the PCM was beneficial to the house on a seasonal basis and/or by diminishing heat transfer through the element where it is installed.

The EAHE's temperature outputs have been recorded and the system works well even though it presents some thermal saturation of the soil when working for long hours. However, the house tenants mentioned that the EAHE is rarely used (which can be seen in the monitored data).

A model of the house was built in Tas and modified until the performance of the model was similar to the house in May, June, July and August 2009. Subsequently, the model was used to simulate the house in 2020, 2050 and 2080 using the UKCIP climate change scenarios. Of course overheating became a even bigger issue in the future as it was already a problem in today's weather albeit to a small degree. Knowing that one of the reasons for the problem in the bedrooms was that the sunspace relied on extraction of warm air through these spaces as the central windows cannot cope alone, different simulations were tried keeping the connection between them closed in the day and opening at night but these did not overcome the problem. Night time ventilation as a cooling technique in the UK is well tested and recognized as successful. However, in this house it was not effective for 3 reasons: wrong inlet/outlet dimensions, insufficient exposed thermal mass and the higher night time temperatures in future climate scenarios.

Consequently, next it was supposed that the lack of exposed thermal mass (the first floor is built using SIPs panels) could be contributing to the high temperatures in the bedrooms so the SIPs walls were substituted by ICF and PCP. Theoretically, the ceilings are thermally massive as they contain PCM which should have somewhat contributed to the monitored results even if their effect is not quantifiable. The house with ICF walls reduced overheating to a limited extent in all the first floor zones but did not reduce peak temperatures. PCP reduced both, percentage of time above 28^{o}C and peak temperatures, especially in the warmer climate (2080) and in the zones with larger ventilation rates but it also increased slightly the percentage of time above 25^{o}C if compared to the ICF simulation. This illustrates the effect of the thermal mass of the concrete on flattening the sinusoidal variation of diurnal temperatures. In addition to the benefit of the thermal mass, if the walls in the ground and first floor were built using the same method, the thermal bridge that occurred in the joint of them could have been avoided.

In the 2080 simulations there was serious overheating in the house. To explore a method for addressing this, a new case was created where the EAHE is activated 24 hours in the summer period. Although this did help to alleviate the problem it did not mitigate it completely, especially in the southern bedrooms that do not receive this air directly. In addition, the cold draughts that the EAHE would cause might result in occupant discomfort. The system proposed in the next chapter might eliminate that problem. Overall, the EAHE of the BASF House will probably gain more importance and be used more frequently with the warmer temperatures brought by climate change. It is the author’s opinion that the system’s functioning will be crucial to support the house’s indoor thermal comfort in the future.

It is clear that the risk of overheating in houses in the UK exists now and may become a bigger issue in the future. Although there are ways to mitigate it, it can currently be avoided with a combination of techniques such as high thermal mass (either from common building materials or from PCMs) combined with ventilation and possible active strategies such as EAHE. More importantly, it is the design that dictates the effectiveness of these techniques. In the case of the BASF House, there are opportunities to improve the prototype before it is applied to commercial house developments and these include the choice of materials and the size and position of the windows.

It is possible that, in a warmer climate as it is expected to be in 2080, people are prepared to accept warmer temperatures in houses, especially in the living areas. Nonetheless, it seems that bedrooms might be a seriously problematic area in this house.

8 A NOVEL EAHE+PCM HYBRID SYSTEM

As a result of the review of existing literature described in previous chapters, a novel hybrid system incorporating Earth-Air Heat Exchangers (EAHE) and Phase Change Materials (PCM) was proposed and tested by means of laboratory and outdoor experimentation in a purposely built chamber. The system has shown great potential and further work is suggested for a full scale development.

8 A NOVEL EAHE-PCM HYBRID SYSTEM

> *"A fact is a simple statement that everyone believes. It is innocent, unless found guilty. A hypothesis is a novel suggestion that no one wants to believe. It is guilty, until found effective."*
> Edward Teller (1908 - 2003)

We have not just accepted but have also been experiencing the effects of climate change worldwide. One might never be able to confirm if the entire change on the planet's balance was caused by man-made emissions of green-house gases but we do know that we have contributed to it and are still contributing. We also are experiencing the rise of temperatures.

The energy dispensed to condition buildings around the world is worryingly large and increasing every year. The inappropriate design of buildings, the augmentation of ambient temperature due to climate change and the problems caused by urban density mean that almost 50% of houses around the world use some type of energy-expensive conventional air-conditioning system (Santamouris, Pavlou et al., 2007) as mentioned previously in this work. Unfortunately most people cannot afford to run traditional air-conditioning systems for economic reasons and many have died in heat waves for that reason. In addition, these systems are high emitters of carbon dioxide gases and so high contributors to climate change.

People generally do not like to use conventional air-conditioning mainly because of its inflexible conditions and in the UK almost 90% of occupants prefer buildings without it (Littlefair, 2005: p. 11). Keeping a building's internal condition within an expanded comfort zone means not just energy savings but also the reassurance and delight brought by the stimulation of our thermal sense as discussed in Chapter 5. Additionally, the importance of the sense of touch and the fact that a person's contact with a building is through its surfaces should not be neglected. Alternatives to conventional systems have to be adopted.

This chapter proposes a new way of conditioning spaces that eliminates the inconvenience of the bad distribution of the temperature common in conventional air-conditioning systems and encourages a healthy fluctuation of internal temperatures. The system combines large surfaces containing phase change material (PCM) with the potential conditioning of an Earth to Air Heat Exchanger (EAHE). This way the wall or ceiling is the source of cool or warmth to the inner space.

In the previous chapter the functionality and benefits of the chosen PCM (BASF Micronal) were not proven due to lack of a 'control room' to enable comparison of the results. This chapter also describes experiments that were undertaken to establish its performance before the full hybrid system as tested.

8.1 THE PRINCIPLES OF THE PROPOSED SYSTEM

As seen in Chapter 3, EAHEs can successfully condition outdoor air to the ground's temperature at the depth where the system's pipes are buried and so provide readily available on site energy. The system's efficiency is dependent on physical, thermal and hydraulic parameters. There are limitations to the use of this strategy such as those summarised below:

- Might present risks for indoor air quality because of condensation and/or water ingress in the pipes and consequent potential for microbial growth.
- Tend to present issues with humidity control inside the conditioned space.
- Relies on good design to efficiently temper the indoor air as the location and size of the air outlet in the space determines how the tempered air is effectively used.
- Its performance could be improved by increasing the air flow but that is limited by the quantity of fresh air required inside the space to be conditioned.
- Might cause discomfort due to excessive air movement because of nuisance draughts, noise and blowing of papers.
- Expensive to build.

The system that is being proposed uses PCM embodied in wallboards. Small amounts of PCMs can have the effect of large amounts of conventional thermal mass with the added advantages of being light and having a sharp temperature change as seen in Chapter 4. PCM is able to shift the time of the peak temperature and diminish space temperature swings broadening the exploitation of solar radiation in the space. However, once more there are limitations to be considered such as the ones listed below:

- It needs to be in contact with hot and cold air alternatively for charge and discharge of heat (and consequently melting and solidifying) so it relies heavily on the design of openings, an effective indoor ventilation strategy and informed users.
- Its effectiveness is heavily dependent on an effective discharge method such as night time ventilation, which might not be enough or suitable if the temperature at night is relatively high.
- Depends on the indoor temperature to complete a cycle of melting and solidifying, which may lead to low internal temperatures.
- Even if the ventilation strategy is well designed, discharging the PCM only by natural air movement in the room is very inefficient so means of forcing air flow along the PCM's surface are necessary to improve its heat exchange capacity.

Based on these considerations a hybrid system was proposed. The system aims to overcome the above limitations of EAHEs by not delivering the conditioned air directly to the space diminishing concerns about air quality and discomfort caused by excessive air movement. It also allows the air flow to be much higher making the most of the EAHE system and increasing its cost-effectiveness.

In this system, the PCM has direct access to the air conditioned by the EAHE, which can easily discharge heat and induce the PCM change of phase reducing the reliance on window's design and user's control. The indoor temperature does not need to go below comfort zone as the heat exchange happens in a plenum. In addition, the higher air velocity increases the effectiveness of the heat exchange. A simplified representation of the system can be seen below in Figure 8.1.

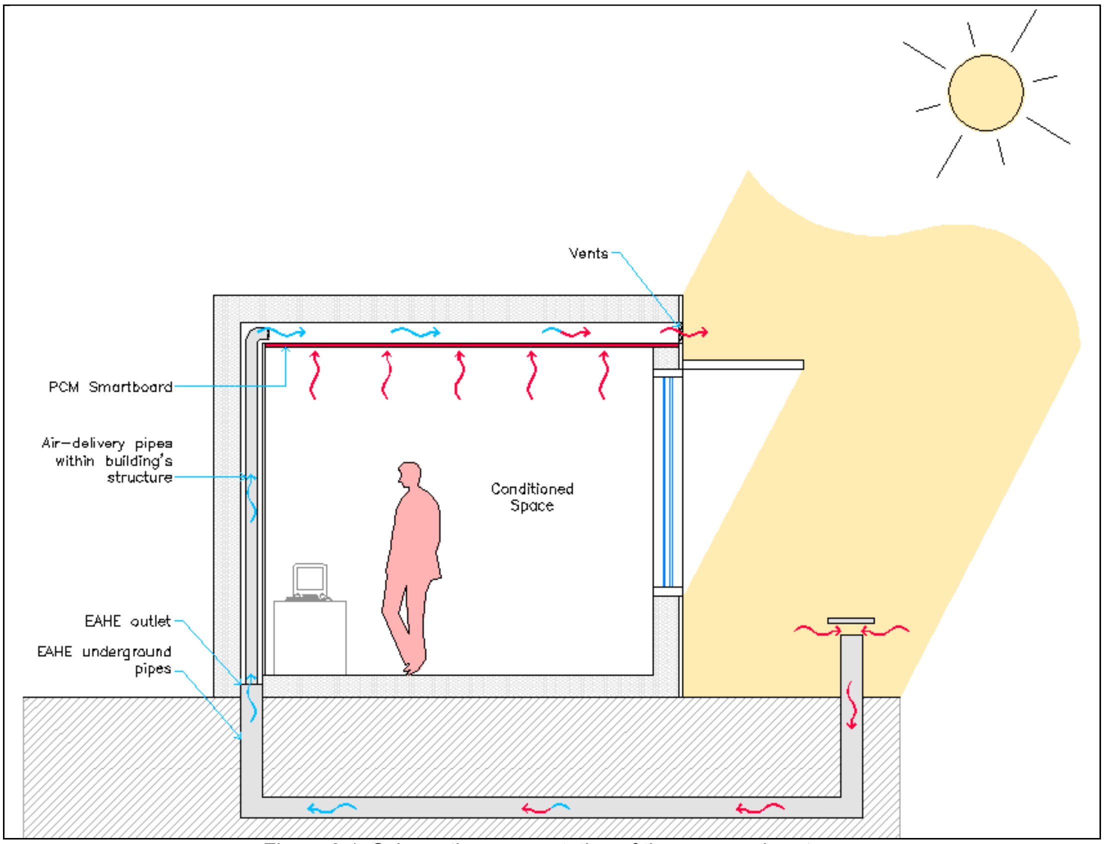


Figure 8.1: Schematic representation of the proposed system

8.1.1 Advantages and Considerations of the System

The EAHE+PCM hybrid system presents an alternative to conventional air conditioning which could be used in houses and offices in the UK and especially in warmer climates where outside air is too hot for day and/or night natural ventilation. The only moving part is a fan which should be easily accessible for maintenance and should have a control to avoid dependence on the user. When necessary the user should be able to manually control the system overriding the electronic control. The proposed hybrid system has the following advantages:

- The cycle of meting and solidification of the PCM can be induced at any time, potentially more than once a day.
- A good option for hot climates where outside air temperature is too high for natural ventilation.
- Do not rely on the large fluctuation of indoor temperature to induce PCM cycles reducing indoor temperature swings.
- Can keep the indoor temperature comfortable and evenly distributed.
- Works regardless of the outdoor temperature and regardless of time making better use of energy by shifting the peak energy need.
- Can represent vast energy savings.
- Large surfaces, either walls, floors or ceilings (preferred for being more exposed to indoor warm air) act as emitters stimulating the thermal sense and the sense of touch.

The aspects below are important considerations also taken into account:

- It could be easier to induce the solidification of the PCM by passing the EAHE air by both sides of the board expanding the heat transfer area; however, it would mean mixing the EAHE air with indoor air and finding specific times for the system to work to allow the absorption of indoor heat
- For periods when the heat stored by the PCM is required at night the exhaustion of air should be stopped so no heat is wasted. This could be controlled by electronic controls activated by temperature sensors.

The system can be flexible, working differently at various times of the year. In this way the space could benefit of the use of PCM alone, or just of the use of the EAHE as well as of the use of both together. The decision has to be made during the system's design and according to the project needs and restraints. Intelligent controls for the system are desirable.

The PCM product chosen to be tested in the hybrid system is the BASF Knauf Micronal PCM Smartboard 23 (more details on the product's enthalpy can be seen in Figure 4.12) which is the same product described in Chapter 4 and used in the Stoneguard and BASF houses. This chapter describes a series of experiments that were designed with different purposes leading up to a small scale full system test.

8.2 PCM TESTING IN INDOOR RIG

Frequently the main question a designer would ask when the use of PCM is suggested is where to install it. The Micronal PCM Smartboard facilitates the fitting of PCM in a space either on walls or on the ceiling. The Micronal as a powder or a solution can be mixed with concrete screed and used on the floor in a similar manner. However, where is it most effective?

This experiment aimed to examine the thermal behaviour of the BASF Knauf Micronal PCM Smartboard 23 and observe internal temperature swings in a chamber through a parametric study to obtain the most effective quantity ratio and surface of application of PCM in a fixed volume. This experiment was done in conjunction with a master's student at the University of Nottingham (Shah, 2007).

8.2.1 Apparatus

The experimental rig represented in Figure 8.2 is composed of a cubical room measuring 2.4x2.4x2.4m with a double glass façade on one edge. The structure resembles the modern glass façade office room where double glass façade functions as thermal buffer between inside and outside environment and at the same time collects solar gain and daylight. The walls and ceiling of test room are of lightweight construction with 100mm thick Celotex insulation (U-Values 0.22W/m²K) mounted on wooden slats and with one communication door and a glazed facade which was openable. A conventional air-conditioning unit was provided to allow for control of internal temperature.

An array of 20 metal halide gas discharge lamps with a light spectrum resembling that of sunlight was used to simulate solar radiation. These were controlled in groups of 6 or 7 by 3 switches and the array was placed at 1m distance from the glazed façade. The average radiation level on the external glass surface after a 30 minute warming period was 580W/m² (measured by a Pyranometer placed at the geometrical centre of the glass surface). The luminance inside the room measured on horizontal surface at 0.80m from ground level was 950 lux. The rig also contained an anemometer for measuring wind speed and a thermo-hygrometer for measuring air humidity levels.

The air within the chamber was monitored using 10 k-type (chromel–alumel) thermocouples with a shielded finish and connected to the analogue inputs of the datalogger (Datataker DT 500 series 2). Thermocouples were distributed across the middle of the room at three levels, lower (at 0.5m height above the floor), middle (1.2m) and upper (at 2.0 m) in order to observe the air temperature distribution due to stratification effect. Another thermocouple was placed outside the test rig and others on the studied surfaces. The position of the thermocouples can also be seen in Figure 8.2. The error in temperature readings through thermocouples were considered to be ±1ºC and they were all tested for their accuracy before the beginning of the experimentation. Data were gathered every 1 minute.

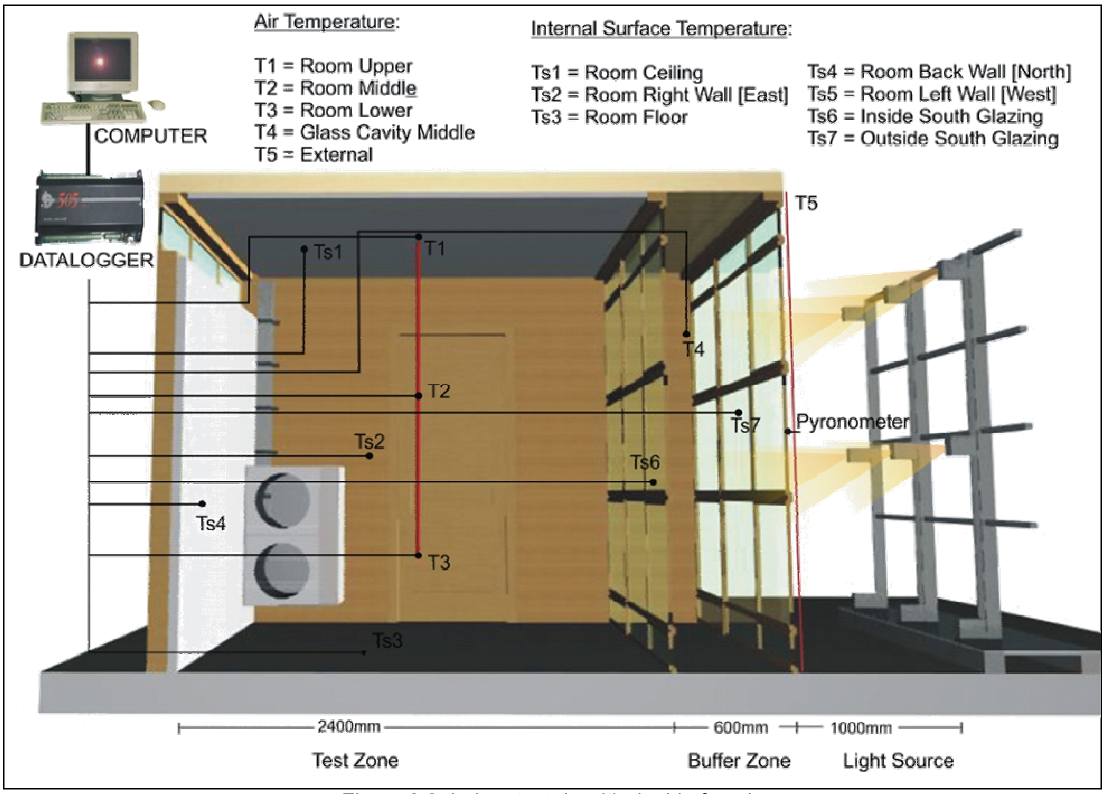


Figure 8.2: Indoor test rig with double facade

8.2.2 Scope and Method

Experimental investigation was initiated to firstly examine the contribution of phase change material to the reduction of internal temperature and secondly to investigate the potential differences in the cooling range due to changing parameters of location of the phase change material in the chamber. The chamber's temperatures were measured without any PCM. Then PCM boards were fixed directly to the wooden parts of the walls with nuts and bolts.

1. The light switches were used to vary the level of irradiation on the rig over 1 hour simulating the effect of the sun over a day.
2. Temperatures inside the indoor test rig without PCM were collected for comparative analysis.
3. Chamber was cooled down using an air-conditioning unit.
4. PCM boards were installed on the floor at a ratio of $0.5m^2/m^3$ (area of PCM/volume of chamber 1:3).
5. The light switches were used to vary the level of irradiation on the rig over 1 hour simulating the effect of the sun over a day.
6. Temperatures inside the indoor test rig with PCM were collected
7. The chamber was cooled down using the AC unit.

8. Process 4 to 7 were repeated with same quantity of PCM boards on the side 'west' wall, on the back 'north' wall and on the ceiling.

Constants:

- Initial air temperature of chamber.
- Initial temperature of PCM boards.
- Heating by radiation from lights period (1h with varying levels).
- Volume and conditions of chamber.

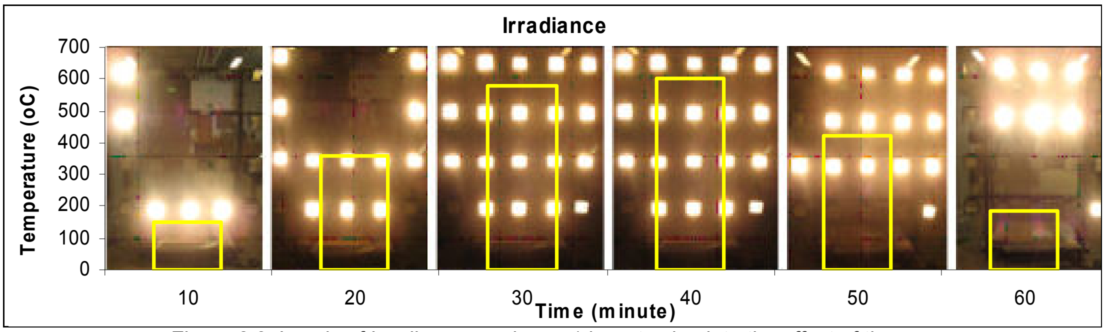


Figure 8.3: Levels of Irradiance used over 1 hour to simulate the effect of the sun

8.2.3 Results

The PCM was firstly applied on the floor then on the side of the western wall, the back northern wall and finally ceiling following the procedure explained above. An extensive parametric study was carried out and can be found at (Shah, 2007). For the purposes of this work, the results were averaged and plotted together in Figure 8.4.

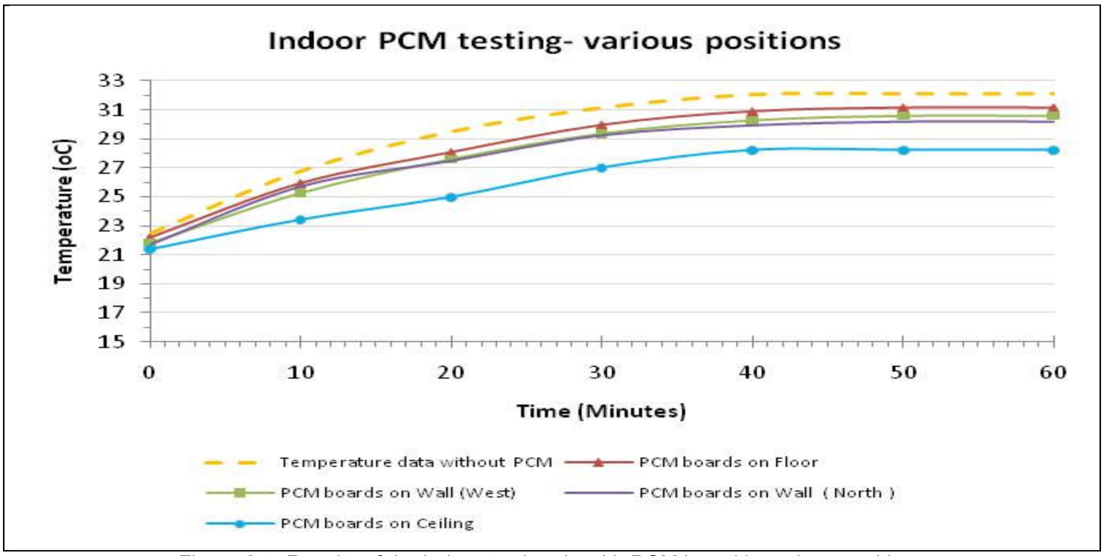


Figure 8.4: Results of the indoor testing rig with PCM board in various positions

It is clear from Figure 8.4 that the same quantity of PCM on the ceiling was a lot more effective even though the ratio of PCM area per volume of air in the chamber, $0.5m^2/m^3$, is clearly not enough to deal with all the heat energy radiated by lamps. For this reason the space remains above comfort zone for most of the time. In addition, as the chamber is in an indoor conditioned laboratory, the 'external' temperature is stable and around 24-25^oC at all times and so it is very difficult to solidify the PCM and get it ready for a new cycle. This led to a new experiment described in next section.

The effectiveness of the PCM in the ceiling can be explained by convection of the warm air ,which is then more in contact with the PCM boards enhancing heat transfer. Consequently, the least effective result was given by the PCM on the floor. This emphasizes the importance of exposing the PCM's surface to the air in order to achieve maximum heat transfer. Another advantage of installing PCM in ceilings is that this is a building surface that is usually not sheltered by furniture or finishings. Additionally, it is easy to retrofit and it not likely to be punctured too often (which can be a problem with macroencapsulated PCMs).

However, the fact that the sun was simulated by lamps also means that real solar radiation was not able to reach the PCM. In a real application it is possible that PCM on a wall exposed to solar radiation could be more effective than PCM on ceiling exposed just to warm air as heat transfer from a fluid to a solid is more difficult as explained in Chapter 2.

8.2.4 Conclusions

Although the PCM was unable to maintain the room temperature in the comfort zone (due to 3.34kW of energy coming from the $580W/m^2$ of radiation from the lamps) it was clear from results obtained that the BASF Knauf Micronal PCM Smartboard 23 was capable of reducing temperatures in the space. Nonetheless it is also clear that discharging of the PCM is essential for it to be ready for the next cycle. A new experiment was needed to appreciate the full effects of PCM in a space.

Due to stack effect, the ceiling was proven to be the most effective position for the application of the board in situations when there is no direct solar radiation on the surfaces. It also has the advantages of being more exposed as it is free from furniture and thick finishings, easy to retrofit and not likely to be punctured.

8.3 PCM TESTING IN REAL CLIMATIC CONDITIONS

In order to investigate the behaviour of the BASF Knauf Micronal PCM Smartboard 23 over a complete cycle of melting and solidification, a new experiment was designed outdoors at the University of Nottingham as part of the same work mentioned above (Shah, 2007). The box is divided in 2 identical parts to permit comparison, is fully exposed to solar radiation and allows for ventilation.

The main purpose of the outdoor test rig as discussed above was to observe if the temperature fluctuation inside the rig is affected by ambient temperature on site and solar radiation in the lightweight test chambers with and without PCM. Hence it was imperative to provide similar conditions to both the chambers.

8.3.1 Apparatus

The experimental setup consisted of one lightweight wooden cubicle measuring 1.5x1.5x1.5m divided into two identical chambers with insulated partition walls providing buffer to reduce thermal transmission between each. The south side of both the chambers comprised two identical double glazed panels installed with airtight insulated joints and the north side was openable for access and ventilation purposes.

Each window area was $0.75m^2$ and the volume of rig was $1.125m^3$ in each chamber. $3m^2$ of BASF Knauf Micronal PCM Smartboard 23 was installed in one of the chambers giving a ratio of $2.5m^2/m^3$.

The air within the chamber was monitored using 7 k-type (chromel–alumel) thermocouples with shielded finish and connected to the analogue inputs of a datalogger (Datataker DT 505 series 2). Thermocouples were placed in the middle of each chamber at 1m and at 0.2m heights. Another thermocouple was placed outside for ambient temperature. The position of the thermocouples can be seen in Figure 8.6 below. The error in temperature readings through thermocouples was considered to be ±1ºC and they were all tested for their accuracy before the beginning of the experimentation. Data were gathered every 5 minutes. All parts of the rig were covered and protected from the weather.

Figure 8.5: Outdoor PCM test box with 2 identical chambers

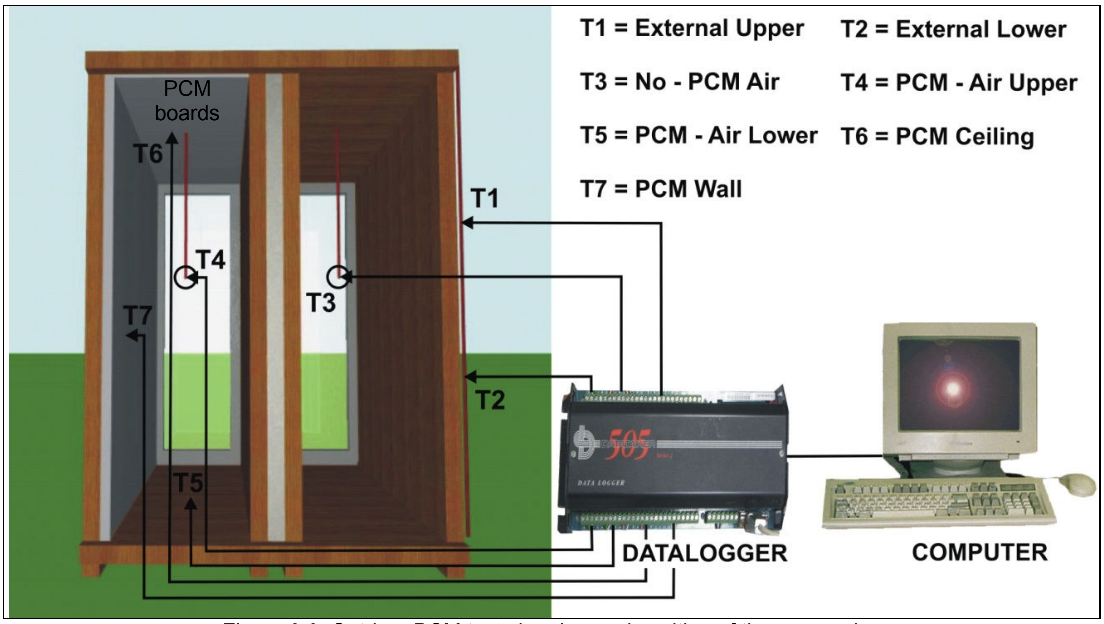


Figure 8.6: Outdoor PCM test chamber and position of thermocouples

8.3.2 Scope and Method

Because this experiment was subjected to the weather, one chamber was used for sample control.

1. PCM boards were installed in the left chamber as seen in Figure 8.6.
2. The rig was subjected to external environment for a week with 0.5ach of ventilation at night (8pm to 8am).
3. Temperatures of each chamber and external conditions were collected every 5 minutes and saved to a computer.

Constants:

- Volume and conditions of chambers.
- Quantity of PCM.
- Same exposure to solar radiation and external temperatures for each chamber.

8.3.3 Results

The experiment was conducted for a week in mid August of 2007 and sought to observe the effect of the PCM on the temperature swing in the lightweight test rig. Figure 8.7 represents the temperature variation in each chamber over a 3 days period.

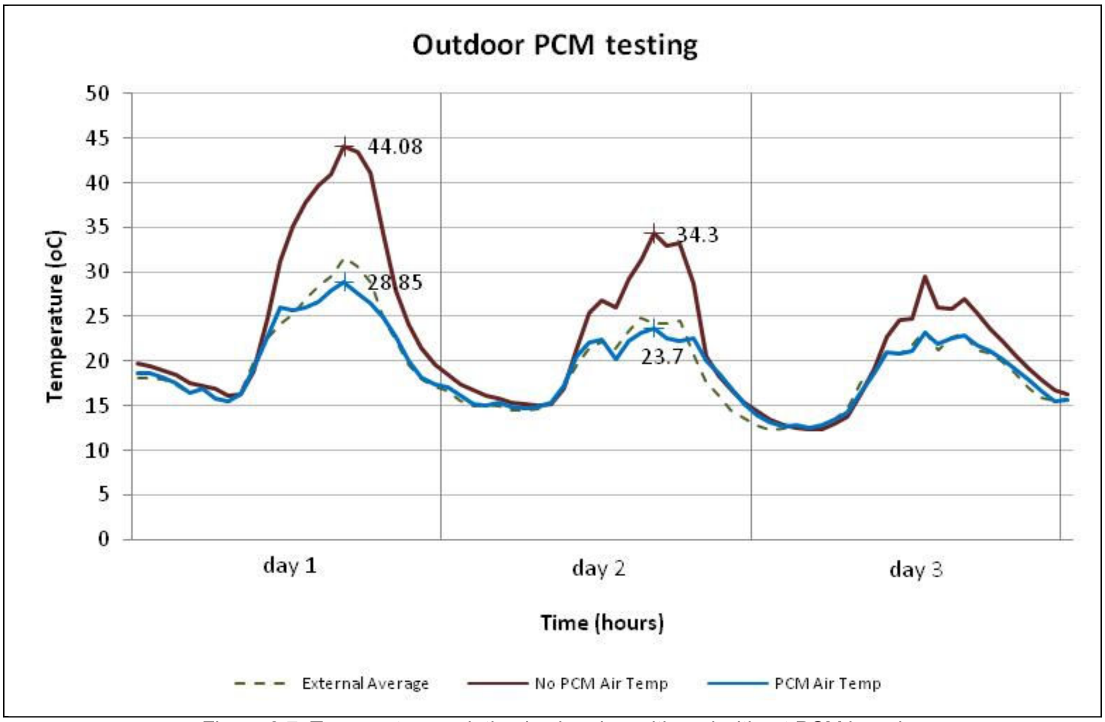


Figure 8.7: Temperature variation in chamber with and without PCM board

Due to solar gains, the temperature in the box increases in the day and drops at night following the ambient air temperature. When the internal air is still heating up, both chambers show a similar temperature. From around 20^{o}C the difference between chambers becomes obvious: the chamber with PCM remains below 30^{o}C while the one without peaks at 44^{o}C. Even though the quantity of PCM was not enough to absorb all excess heat in the first day, it still has greatly improved the conditions in the chamber. At night the benefit of using PCM cannot be seen because of excess heat loss in the chambers as the walls are not insulated.

A closer look at what happens in the chamber with the PCM board in 2 of those days produced Figure 8.8. The graph shows the air and PCM surface temperatures. The benefits of the PCM board can be appreciated as their surface temperature stays in the comfort zone (at the PCM's melting/ solidifying temperature) for much longer as indicated by the yellow arrow. As mentioned before, this can add to the user's thermal experience of the building. Once latent heat has been totally discharged from the PCM, its temperature starts to drop quickly.

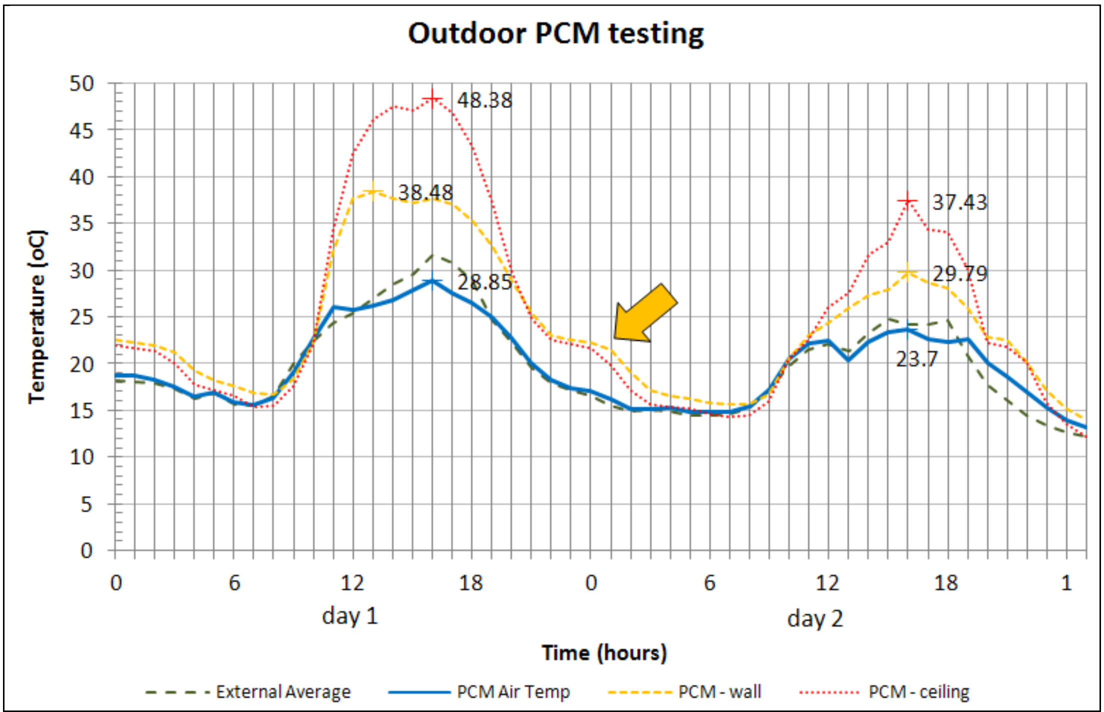


Figure 8.8: Temperature variation of air and surfaces in chamber with PCM board

It can also be observed that the air temperature and the ceiling temperature differ by 20°C which is an enormous difference, especially in such a small chamber. Such high surface temperatures can be attributed to conduction through the box envelope (which was not insulated) as it was exposed to high solar radiation. In addition, between wall and ceiling there is a 10°C difference showing again that the ceiling can have enhanced heat transfer. The high temperature indicates that the PCM is saturated with heat and so completely melted. The solidification process can be clearly seen in the graphs but not the melting process.

8.3.4 Conclusions

The chamber with the BASF Knauf Micronal PCM Smartboard 23 has shown a much better performance than the chamber without it. During the day it was able to keep the air temperature at a comfortable level almost all the time. At night both chambers experienced a high temperature drop because the box was not insulated.

The surfaces with PCM maintained a constant temperature for longer, at the PCM's phase change zone. This could be explored to improve the thermal experience of the building user. The PCM's latent heat capacity was exhausted fairly soon showing the importance of combining it with other design strategies. The ceiling's surface temperature was found to reach 10^{o}C more than the wall's surface temperature and 20^{o}C more than the air temperature in the chamber. The next experimental setup should consider an insulated rig to reduce conduction through the envelope, which has caused an undesirable effect in this experiment.

8.4 PCM TESTING IN THE ENVIRONMENTAL CHAMBER

An experiment was designed to explore the function of the selected BASF Knauf Micronal PCM Smartboard, the heat conduction across the board and its sensitivity to different airflows. The EAHE cooling power was simulated by a water chiller connected to a heat exchanger.

In summary this experiment was designed to investigate the possibility of combining EAHE and PCM. It aimed to:

- Understand the operation of the selected PCM board.
- Study different air-flows and their impact on the cooling of the PCM.
- Study the heat exchange across the PCM board.
- Study the impact of having two layers of PCM boards and/or one layer of plasterboard over the PCM board (as required in the UK for fire regulations).

8.4.1 Apparatus

The experiment was set up in the Environmental Chamber in the School of the Built Environment, University of Nottingham. This chamber offers the possibility of strictly controlling the ambient temperature and humidity and it is highly insulated from the external laboratory environment.

The use of an air-conditioning unit to supply the rig with cold air was initially proposed. The AC unit was placed outside the chamber and a flexible pipe connected it to the rig through a hole in the chamber's wall. The AC unit did not work as expected because of its inconstancy to supply a smooth flow of cold air so it was substituted by a heat exchanger connected to a water chiller.

Metal diffusers were built to facilitate the air distribution inside the plenum. Due to space constraints the diffusers were not as long as required to allow an even distribution of the air so an air-filter was also implemented in the inlet side of the plenum in an attempt to improve air delivery. As this was proven not to be efficient, the air filter was later removed.

The wooden plenum was 1000x500x100mm and insulated with Celotex. The PCM board was fixed to the bottom of it. On the outlet side another diffuser and a fan with a controller were installed. Air pipes and diffusers were also highly insulated. Figure 8.9 and Figure 8.10 illustrate the set up of the experiment.

The air within the chamber, pipes and plenum was monitored using 14 k-type (chromel–alumel) thermocouples with shielded finish and connected to the analogue inputs of a datalogger (Datataker DT 505 series 2). Thermocouples were placed on each side of the PCM board, in different locations in the plenum, at the pipe's inlet and outlet and in the chamber. Humidity in the chamber was kept constant at 60%. The position of the thermocouples can be seen in Figure 8.10. The error in temperature readings through thermocouples were considered to be ±1ºC and they were all tested for their accuracy before the beginning of the experimentation. Data was gathered every 30 seconds.

An anemometer was used to set the air velocity in the pipes with the help of the fan. The anemometer's probe was installed in a hole in the outlet pipe and was also used to check the air distribution at different locations through 5mm holes in the box and insulation. The anemometer had a recent calibration certificate and was therefore deemed to be accurate.

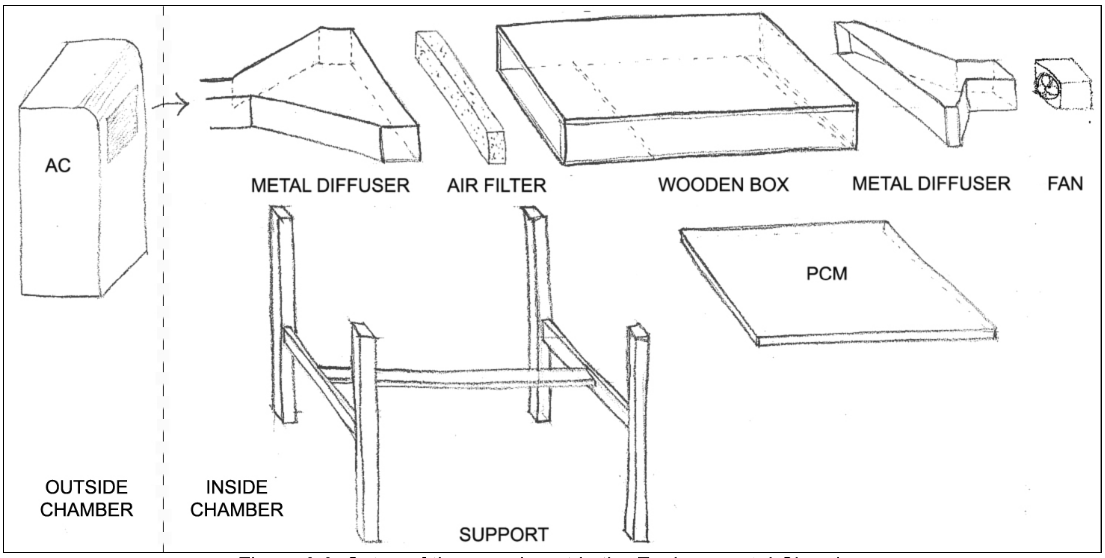


Figure 8.9: Setup of the experiment in the Environmental Chamber

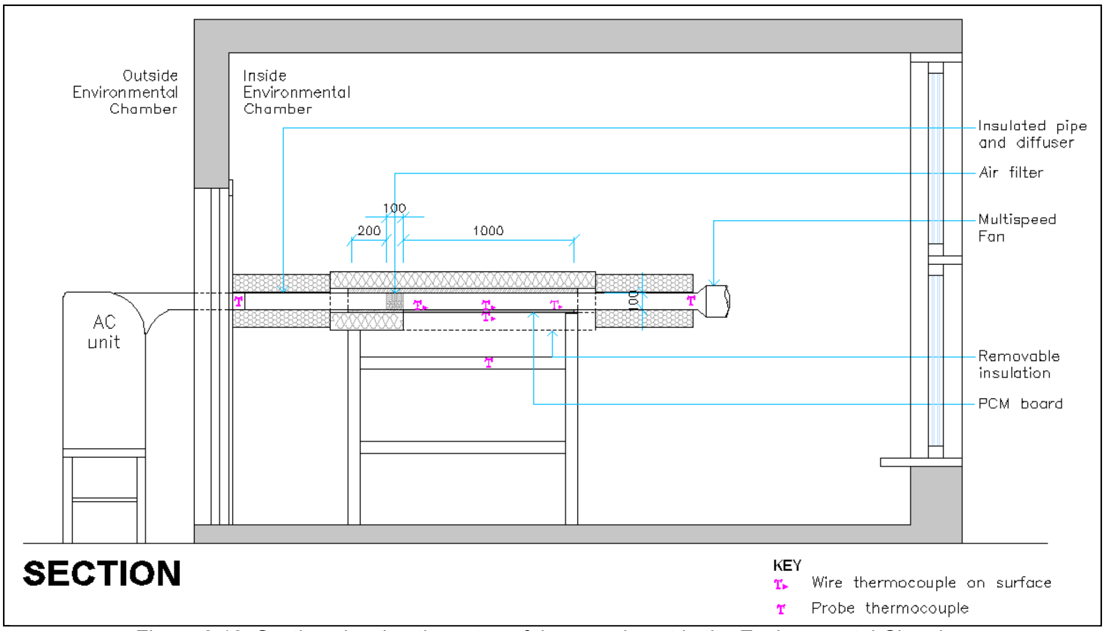


Figure 8.10: Section showing the setup of the experiment in the Environmental Chamber

8.4.2 Scope and Method

Five experiments were undertaken as described below.

1. First Experiment: Air distribution test
    a. The box as shown above was setup firstly without and then with the air filter.
    b. The fan was used to drive the air flow in the box at different speeds.
    c. Air velocity was measured at different points in the plenum.
2. Second Experiment: Air-conditioning unit trial
    a. The box without the air filter was set up and connected to the air-conditioning unit.
    b. The fan was used to drive the air flow in the box at different speeds.
    c. Air temperature was measured at different points in the plenum and saved every 30 seconds.
3. Third Experiment: PCM Enthalpy
    a. The box without the air filter was set up.
    b. A BASF Knauf Micronal PCM Smartboard 23 board was cut to size (1000x500mm), installed under the box and left exposed to the chamber's environment on both sides.
    c. The chamber temperature was set to 10^{o}C until all thermocouples (surfaces and air) were reading 10^{o}C.
    d. The chamber was then set to warm up to 34^{o}C.
    e. Air and surface temperatures were collected and saved every 30 seconds during the warm up process.
    f. Once all thermocouples were reading above 30^{o}C, the chamber was set to cool down to 10^{o}C.
    g. Air and surface temperatures were collected and saved every 30 seconds during the cooling process.
4. Fourth Experiment: Heat transfer across 1 board
    a. The box without the air filter and connected to a heat exchanger and water chiller was set up.
    b. PCM was left exposed to the chamber's environment.
    c. The chamber was set up to 34^{o}C.
    d. Once all thermocouples were reading above 30^{o}C, the board was insulated underneath and so protected from the chamber's environment. The whole box was then wrapped with cling film to minimize air infiltration.
    e. The fan was turned on at 1.5m/s (air flow rate 0.012m^3/s).
    f. Air and PCM board surface temperatures were collected and saved every 30 seconds during the cool down process.
    g. The process was repeated with the fan at 2.0m/s (0.016m^3/s), 2.5m/s (0.02m^3/s) and 3.0m/s (0.024m^3/s).

5. Fifth Experiment: Heat transfer across 2 boards
    a. An extra PCM board was fixed on the top of the first.
    b. The box without the air filter and connected to a heat exchanger and water chiller was set up.
    c. PCM was left exposed to the chamber's environment.
    d. The chamber temperature was set to 34^{o}C.
    e. Once all thermocouples were reading above 30^{o}C, the board was insulated underneath and so protected from the chamber's environment.
    f. Fan was turned on at 1.5m/s (air flow rate 0.012m^3/s).
    g. Air and PCM board surface temperatures were collected and saved every 30 seconds during the cooling process.
    h. The process was repeated with the fan at 2.0m/s (0.016m^3/s), 2.5m/s (0.02m^3/s) and 3.0m/s (0.024m^3/s).

Constants:

- Relative Humidity in the Chamber was kept at 60% in all experiments.

8.4.1 Results

For each experiment the results are described below. The results of the first and second experiment were deemed invalid and therefore they are not demonstrated here. They did, however, provide the author with information that was significant for the development of the subsequent experiments.

1. First Experiment: Air distribution test

It was found that the air filter did not aid the distribution of air inside the plenum so it was discarded and the subsequent experiments were done without it. The areas on the plenum boundaries were ignored as they did not receive enough air-flow. All the readings were taken on locations with similar air-flow.

2. Second Experiment: Air-conditioning unit trial

Because the air-conditioning unit is controlled by a thermostat, its flow was not held constant regardless of the setting that was used. It tended to keep on just until the surrounding air reached the set temperature and then go automatically off until the surrounding air was above that temperature. This was found not to adequately simulate the behaviour of an EAHE and so the AC unit was discarded. A heat exchanger connected to a water chiller was constructed and installed in the rig and its performance was found to be satisfactory for the requirements.

3. Third Experiment: PCM Enthalpy

In Chapter 4, Figure 4.12 shows the BASF Knauf Micronal PCM Smartboard 23 enthalpy according to the company. As was described before, when latent heat transfer is occurring, the PCM's temperature is held almost constant. This effect can be appreciated below. In Figure 8.11 and Figure 8.12 the light grey shaded band indicates the 'mushy' period according to the company's data and the darker grey shaded band indicates the temperature where most of the latent heat transfer would occur when the PCM is melting or solidifying. As it can be seen below those did not fully match with what was actually measured. Nevertheless it is quite close and most of the differences are within the ±1°C of possible error.

As care was taken so both thermocouples (top and bottom of PCM board) where installed in a similar manner and calibrated against each other, the difference seen below might be attributed to the chamber's conditions as the conditioned air seemed to reach the bottom of the board first.

The processes of melting and solidifying of the PCM, took just less than 1 hour each (the grey band indicates the phase change temperature band). It must be emphasized that there was no aid of increased air flow on the PCM board; it was simply exposed to the environmental chamber's atmosphere.

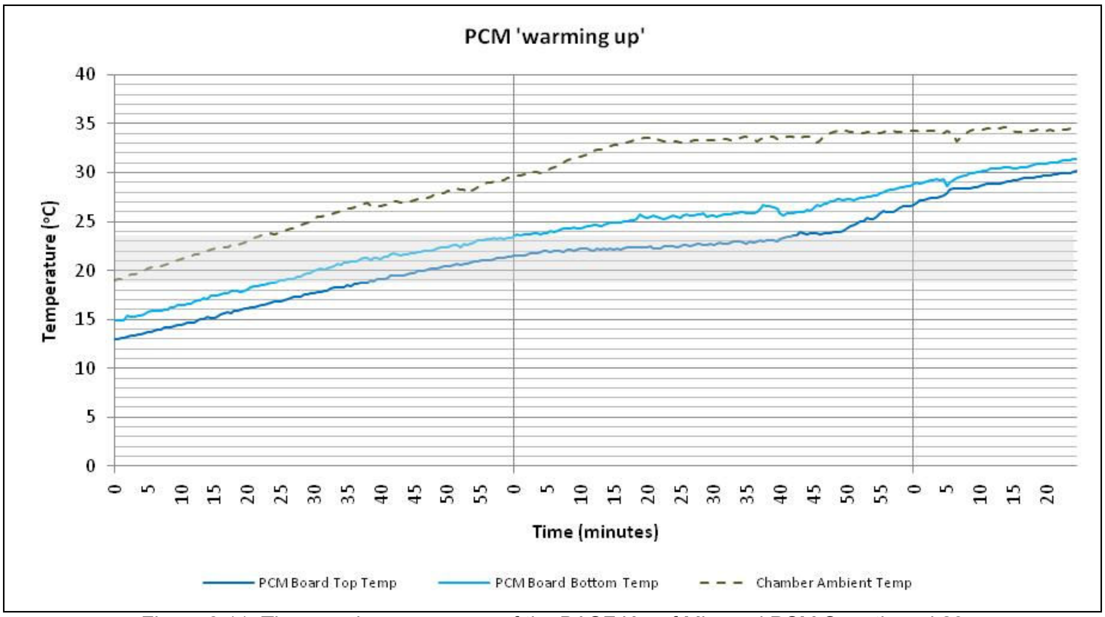


Figure 8.11: The warming up process of the BASF Knauf Micronal PCM Smartboard 23

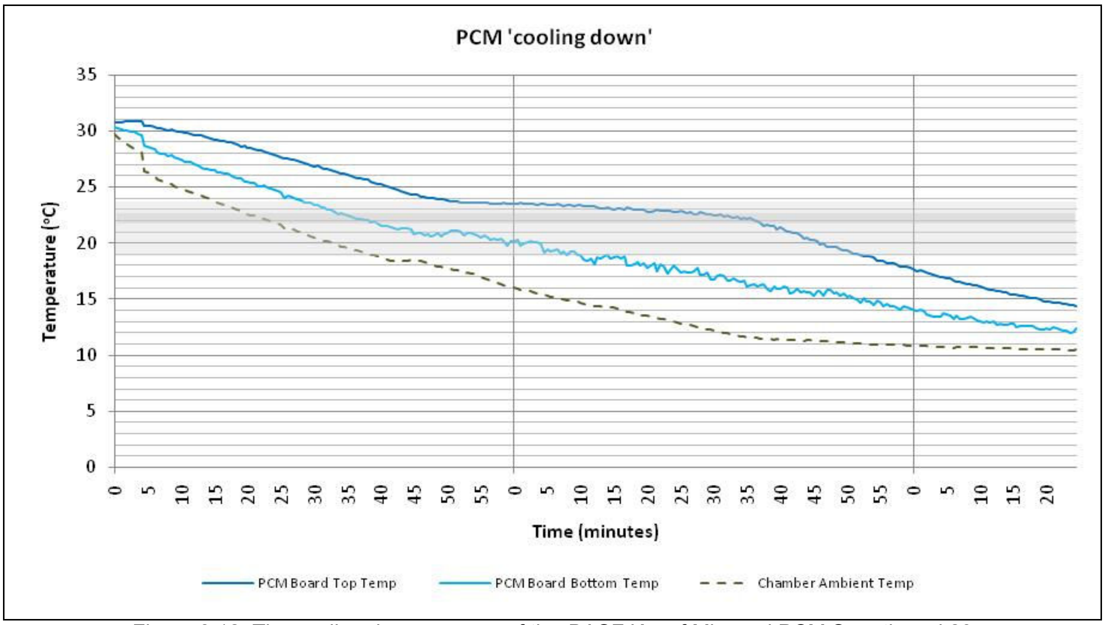


Figure 8.12: The cooling down process of the BASF Knauf Micronal PCM Smartboard 23

4. Forth Experiment: Heat conduction across 1 board

The fourth experiment was repeated several times with different air velocities. Figure 8.13 below shows the results of one of these sets of data. As it can be seen, the chamber's temperature was kept around 35^{o}C while the PCM board was cooled down by the air flow just on the top of the board driven by the fan. The fan was turned on at minute 5 when a sudden drop of the inlet temperature can be seen. The temperature rise between inlet and outlet is not particularly significant as it suffered the influence of the chamber's hot environment. The insulation was not thick enough to completely stop heat conduction through the box's walls and air infiltration also occurred.

There is a thermal delay across the board and, as expected, the bottom of the board remains at a higher temperature for a longer period of time but eventually both surfaces cool down below the phase change level. This shows clearly that it is possible to discharge the heat from the PCM causing it to solidify again just by having a forced air flow on one of the board's sides.

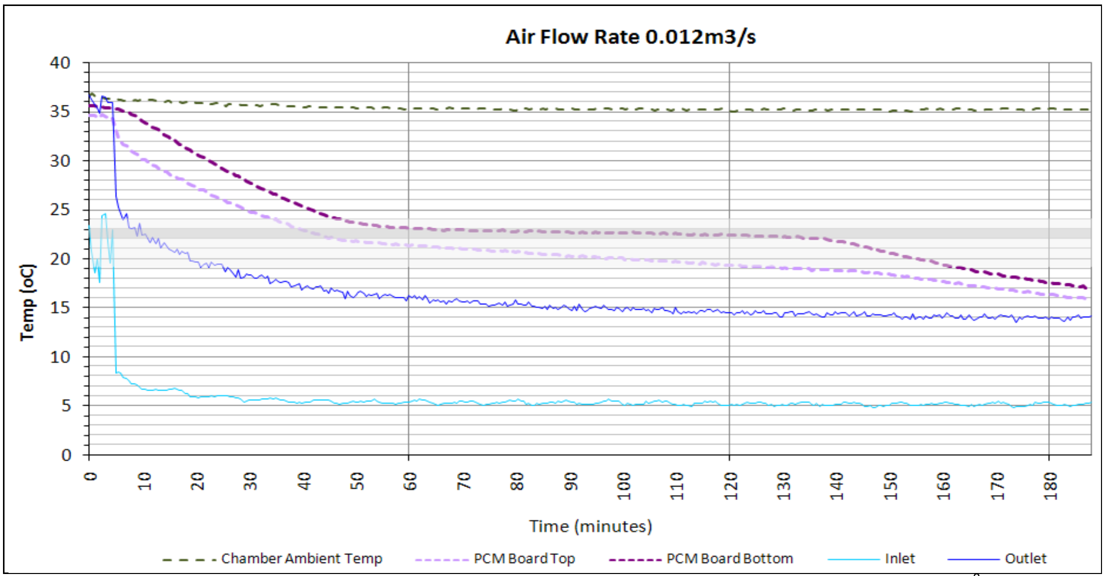


Figure 8.13: Heat removal across 1 PCM board at air velocity of 1.5m/s (air flow rate 0.012m^3/s)

In each case, the time the board spent within its phase change zone was calculated to allow for comparison. This was done firstly counting how many minutes were spent between 19 and 24°C (Figure 8.14) and then between 21 and 23°C (Figure 8.15).

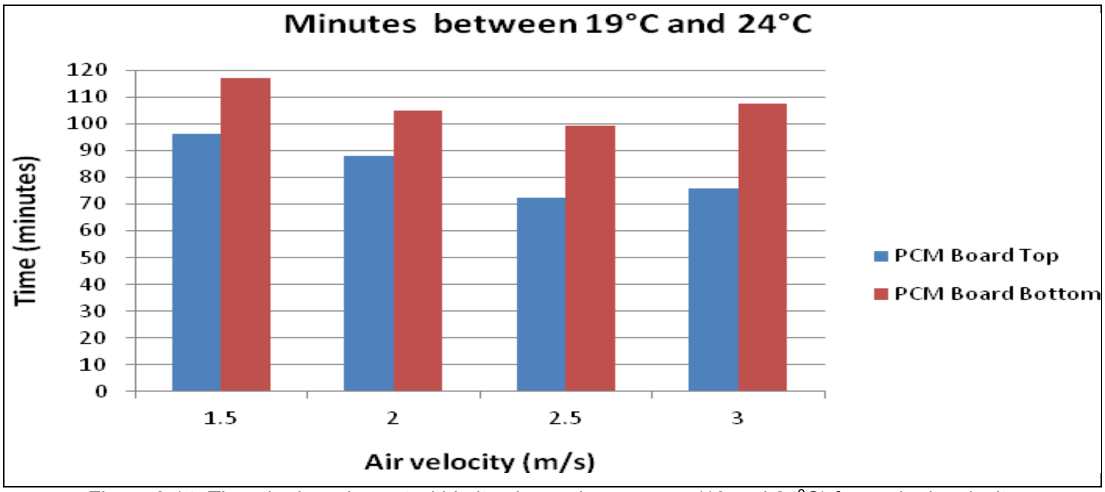


Figure 8.14: Time the board spent within its phase change zone (19 and 24°C) for each air velocity

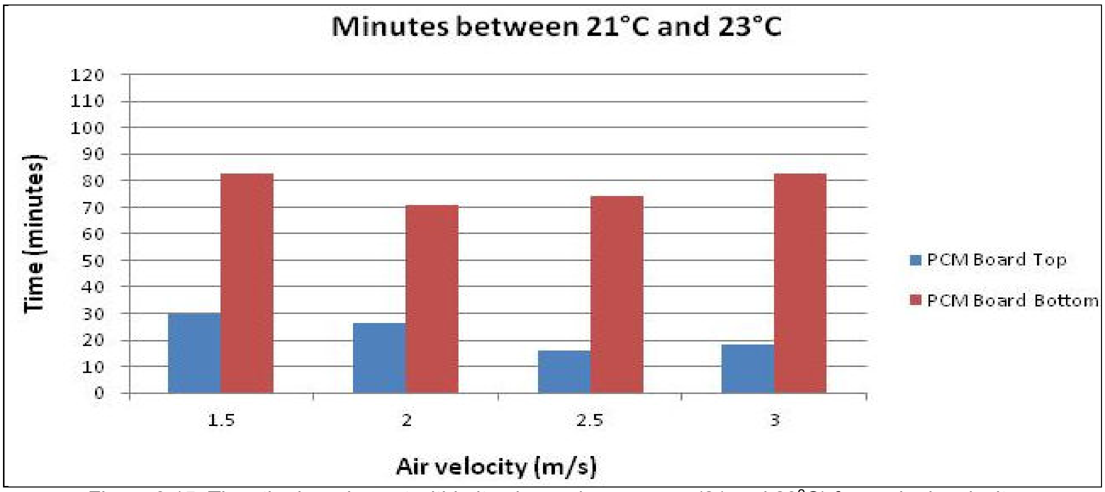


Figure 8.15: Time the board spent within its phase change zone (21 and 23°C) for each air velocity

When taking into account 19 to 24°C, the time difference between top and bottom of the board was not very large although in every case the bottom of the board always took longer to cool down. If 21 to 23°C are considered, then a big difference can be seen and it is clear that the bottom of the board had a much more stable temperature than the top. This is one of the potential benefits of the proposed system as explained before, in achieving a conditioned surface.

Because the variation caused by the different air flows was not great, there is not clear benefit from using either of the tested ones. The lowest air flow promotes more residence time whilst the highest air flow promotes more air changes and both situations can improve heat exchange between air and board. Generally it took between 1:40 and 2 hours for the PCM in the board to solidify again. In a real application this 20 minutes difference is not very significant as usually one would design the system for a 24 hour cycle, exploiting night and day differences on the use of the building and external temperature. In addition, other factors might have influenced the result, such as air flow turbulence and air infiltration in the system. It is interesting to note though that at an air velocity of 3m/s the time within phase change started to increase again.

5. Fifth Experiment: Heat conduction across 2 boards

The fifth experiment was also repeated several times with different air velocities. This experiment differs from the previous because it has 2 layers of the PCM board. Figure 8.16 below shows the position of the thermocouples used.

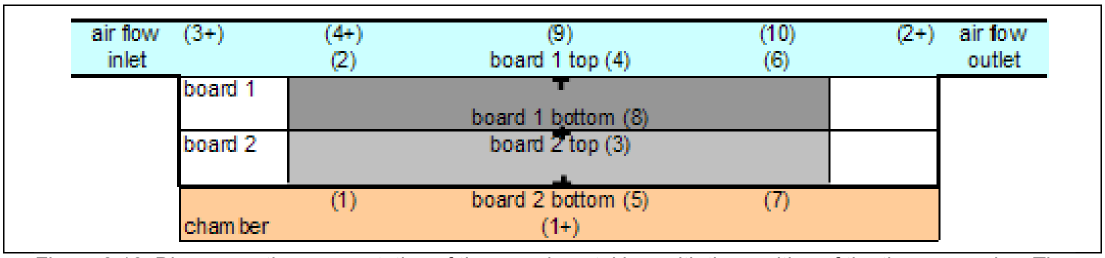


Figure 8.16: Diagrammatic representation of the experimental box with the position of the thermocouples. The number between brackets is the number of the thermocouple.

Figure 8.17 below shows the results of one of these sets of data. As it can be seen, the chamber's temperature was kept around 35°C while the PCM boards were cooled down by the air flow driven by the fan and applied only on the top of the top board. The fan was turned on at minute 5 when a sudden drop of the inlet temperature can be seen. Here the temperature rise between inlet and outlet is once more not particularly significant as it suffered from the influence of the chamber's hot environment; nevertheless it gives an indication of the air temperature rise.

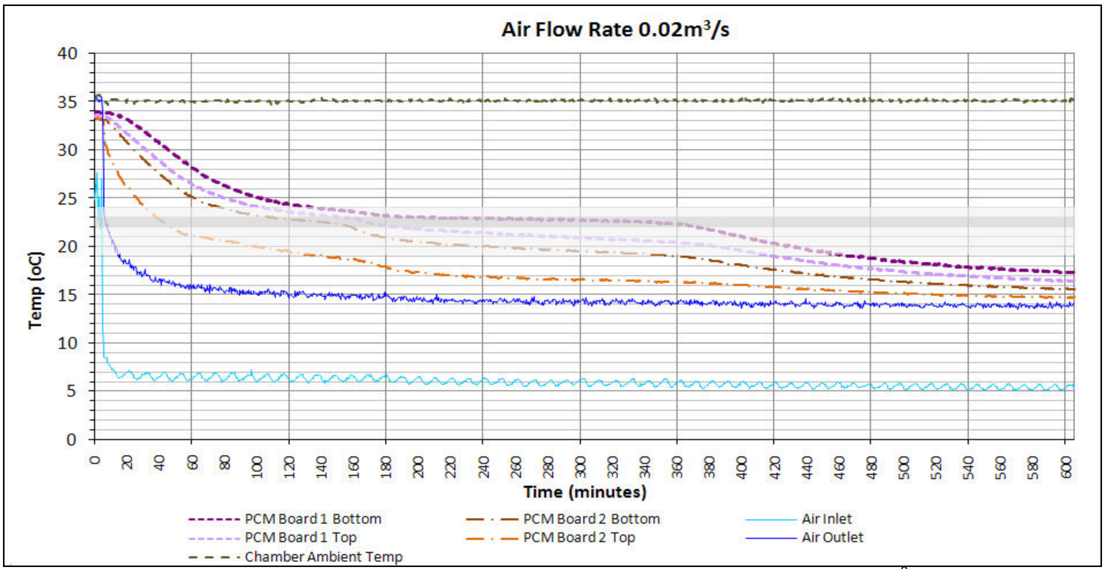


Figure 8.17: Heat removal across 2 PCM boards at air velocity of 2.5m/s (air flow rate $0.02m^3/s$). Board 1 is the bottom board and 2 is the top board exposed to the airflow.

There is a thermal delay across each board and, as expected, the bottom board (numbered 1 in the graph, further away from the air flow) remains at a higher temperature for a much longer period of time but eventually both boards cool down below the phase change level. This shows clearly that it is possible to discharge the heat even from 2 boards together causing it to solidify again just by having a forced air flow on one of the boards' sides.

The results above are a sign that the board's conductivity is relatively high allowing for good heat transfer. However, as may be seen in Figure 8.18 and Figure 8.19, the time taken to discharge the bottom boards (board 1, further away from the air flow) was much longer meaning that a thicker layer (2 boards, 30mm) of the same composition would not work in the same way as the thin layer (1 board, 15mm). Ultimately even the thicker layer gets cooled down by the forced air flow but in this experiment it took 5 hours for the PCM to completely leave the phase change zone.

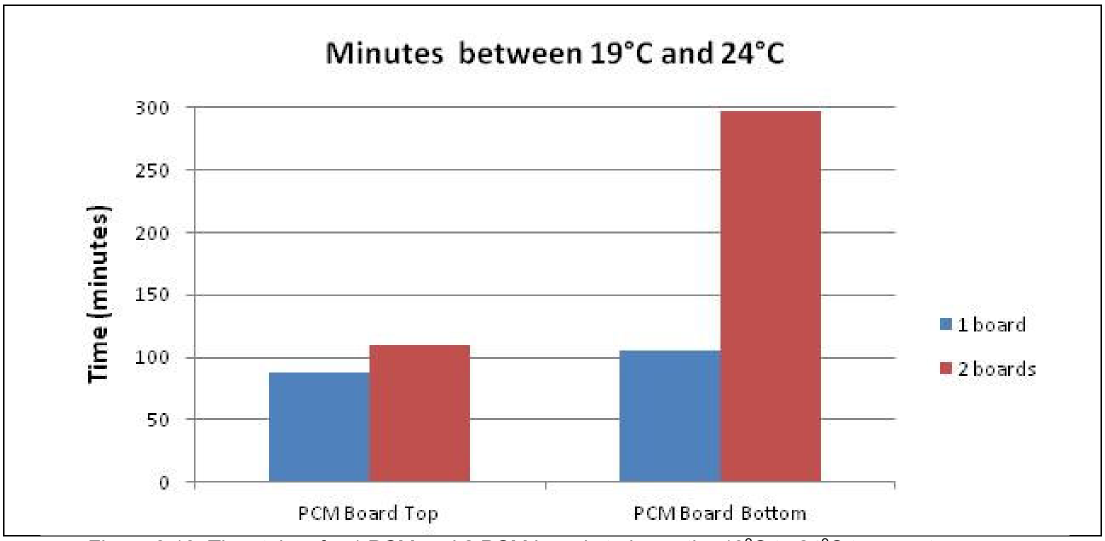


Figure 8.18: Time taken for 1 PCM and 2 PCM boards to leave the 19°C to 24°C temperature zone

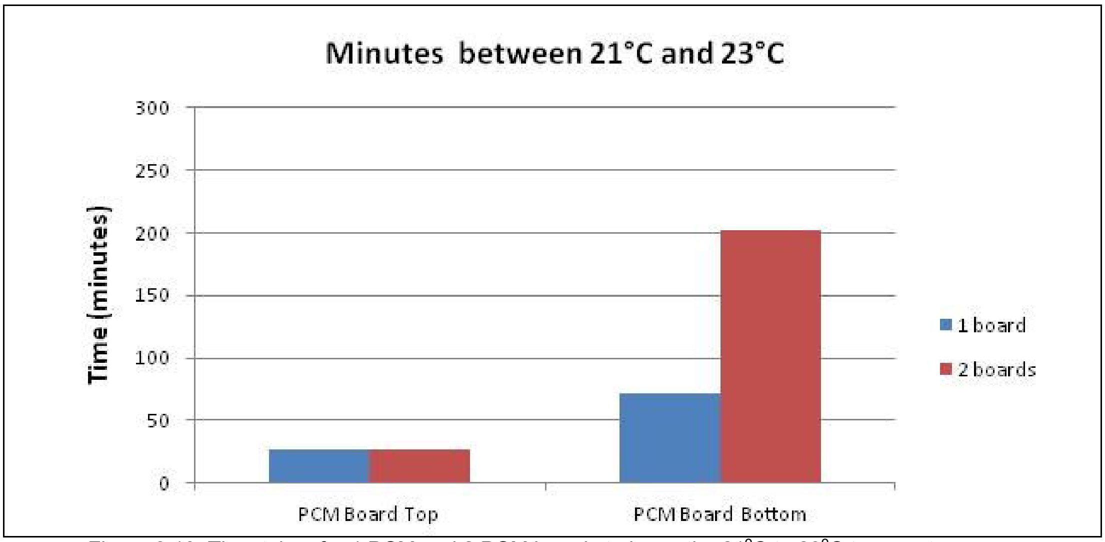


Figure 8.19: Time taken for 1 PCM and 2 PCM boards to leave the 21°C to 23°C temperature zone

8.4.2 Conclusions

The first and the second experiments were basically undertaken to support the set up of the subsequent experiments. Following the second experiment, the set up was found to be satisfactory for the required conditions. The third experiment provided an understanding of the PCM board function and the time that was needed for the melting and solidification processes to take place across 1 board without the aid of the extra air flow.

The fourth experiment allowed for three important conclusions. The first conclusion is that, even though there is a time delay between top and bottom of the board, eventually both get cooled down by the forced air flow. This air flow can be on just one side of the board allowing for the other side to be kept stable for longer but also to be cooled down ultimately. This is the second conclusion and highlights one of the potential benefits of the proposed hybrid system, which is to allow for a subtle temperature change in the space whilst keeping a comfortable wall or ceiling surface temperature. The third conclusion is that the small variation in the air flow, which were based on the air flows commonly used in EAHEs, did not make a lot of difference to the time that the PCM spent in the phase change zone, which varied approximately from 1:40 to 2h. This can be attributed to residence time and possibly to the turbulent nature of the air.

Similarly, in the fifth experiment, the results showed a thermal delay across the 2 layers of PCM board but eventually both PCM boards cooled down below the phase change zone. This shows that it is possible to discharge the heat from 2 layers of board by means of a forced air flow only on one side. The surface that is furthest away from the airflow is just discharged by conduction as air convection does not reach it and so it is maintained at a more stable temperature for much longer. The time for a complete discharge was approximately 5 hours in the last experiment.

8.5 INDOOR RIG IN REAL CLIMATIC CONDITIONS

This experiment combines an EAHE with PCM as proposed making use of the EAHE installed in the BASF House (seen in Chapter 7) combined with the BASF Knauf Micronal PCM Smartboard 23. A rig was designed and constructed by the author and installed in the house's sunspace (where the EAHE outlets are) where it was partially exposed to outdoor conditions. The rig received direct solar radiation and suffered the influence of the 'greenhouse effect' in the sunspace. The aim of this experiment was to investigate the proposed system by comparing with a reference room.

8.5.1 Apparatus

The system was simulated in an insulated wooden box closed by a double glazing unit. The box was divided in the middle defining Room 1 (reference room) and Room 2 (system's room). Each room had a 10cm plenum on the top and supports for the boards. The plenum was closed by vents. Flexible insulated pipes transported the air from the EAHE outlet to the back of the box.

The box was placed inside the BASF house's sunspace in order to make use of solar gains and the EAHE system installed there as shown in Figure 8.20. Room 1 had standard plasterboard whilst Room 2 had PCM board. An anemometer with a recent calibration certificate was used to measure the air flow at the EAHE outlet. The airflow was regulated by the EAHE fan installed in the house. The controls of the fan did not allow for a lot of flexibility so the airflows used were selected from those possible..

The air within the chamber, pipes and plenum was monitored using 14 k-type (chromel–alumel) thermocouples with shielded finish and connected to the analogue inputs of a datalogger (Datataker DT 505 series 2). Thermocouples were positioned inside each room, in each plenum, on the top surface and on the bottom surfaces of each board and in the sunspace. Room 2 also had thermocouples in the inlet and outlet of the plenum. Humidity was not monitored. Solar radiation was also measured in each room using pyranometers. The error in temperature readings through thermocouples were considered to be ±1ºC and they were all tested for their accuracy before the beginning of the experimentation. Data were gathered every 10 minutes.

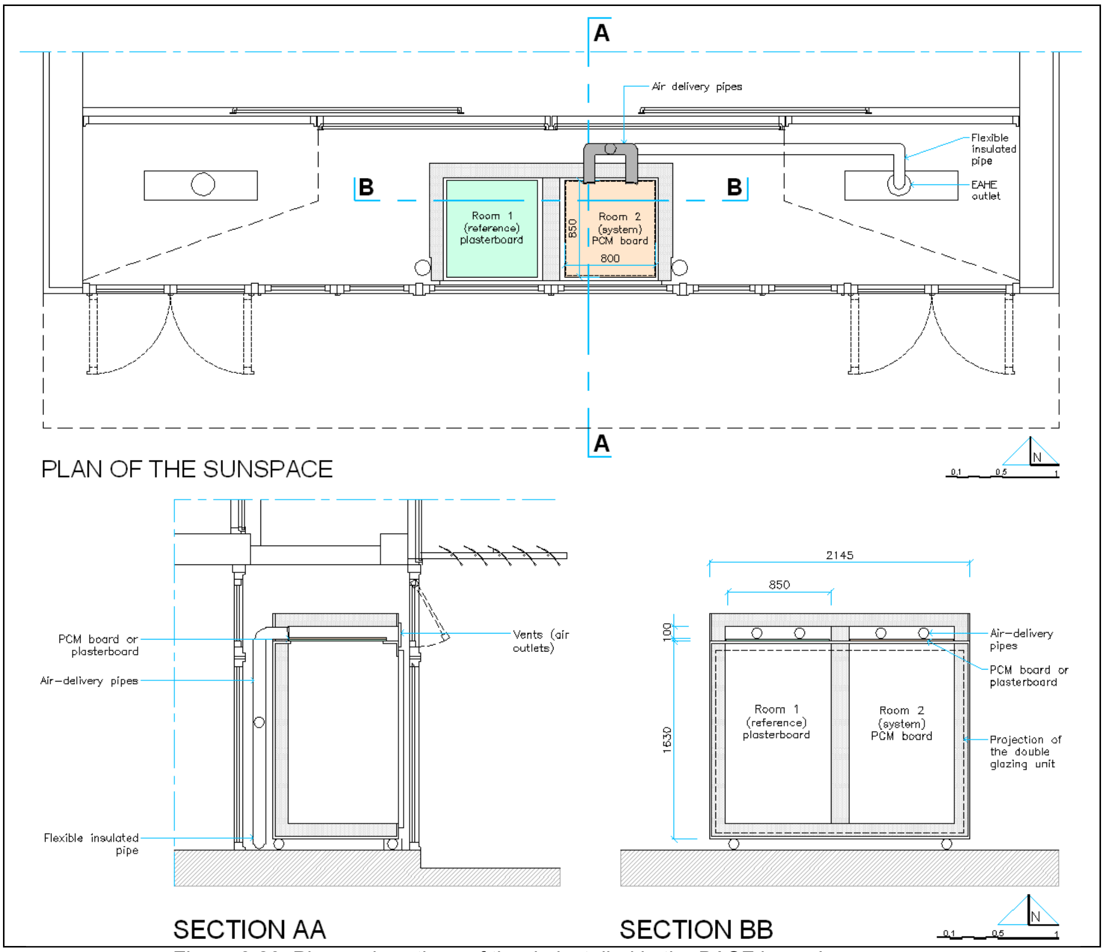


Figure 8.20: Plan and sections of the rig installed in the BASF house's sunspace

8.5.2 Scope and Method

The two experiments were undertaken during the months of May and June of 2008 as described below.

1. First experiment: PCM board VS plasterboard

Firstly this experiment intended to assess the efficiency of the box in simulating a 'warming room'. If required, depending on weather conditions and on the box's performance, an extra heat source could have been added but this was found unnecessary due to the availability of solar radiation. Secondly it allowed a quantification of the PCM benefits against regular plasterboard to maintain a comfortable indoor temperature.

Room 1 (reference room) had 0.68m^2 of regular plasterboard and Room 2 (system room) had 2kg of PCM embodied in 0.68m^2 of BASF Knauf Micronal PCM Smartboard 23. No ventilation was used.

2. Second experiment: Proposed PCM + EAHE system VS plasterboard

This experiment intended to assess the benefits of the proposed system against a room that simulates a common configuration of lightweight buildings (insulated room with suspended plasterboard ceiling). Room 1 and Room 2 had the same configuration as the first experiment. Ventilation was introduced with the EAHE fan on for 24h at different speeds. A range of different airflows were tested, 0.02m^3/s (fan at 20%), 0.04 m^3/s (fan at 40%) and 0.05m^3/s (fan at 60%).

8.5.3 Results

1. First experiment: PCM board VS plasterboard

During this experiment, the days were very sunny. Consequently, due to solar gains alone the temperature in the sunspace went above 32^{o}C and the temperature in the rig reached 46^{o}C in Room 1 (reference room). In Room 2 the PCM board could keep the peak temperature 8^{o}C lower than Room 1.

Over the monitored period, Room 1 and Room 2 average temperatures were very similar, around 24^{o}C (Figure 8.22). As the rooms received the same quantity of solar energy, overall the sum of gains and losses was the same for both. However, the PCM board clearly contributed to the reduction of temperatures swings during the day and night (Figure 8.22). The excess heat absorbed in the day during the phase change of the PCM was released back to the box in the night keeping Room 2's lowest temperature 4^{o}C higher than Room 1. The 2kg of PCM was not able to deal with all the heat in the system, nevertheless its contribution can be clearly appreciated in Figure 8.21 below. The PCM board surface temperature is almost flat during the change of phase of the material.

It is interesting to notice that, despite the initial suggestion from the PCM manufacturers, there is only a slight shift between peak solar radiation and peak temperatures in both rooms and not much difference was observed between Room 1 and Room 2 (i.e. they reach their peak temperatures at the same time). It is difficult to know the reason but it might be because the system was under quite extreme conditions, with large solar gains and relatively large temperature swings. However, new experimentation would be needed to study this hypothesis and find a definite reason.

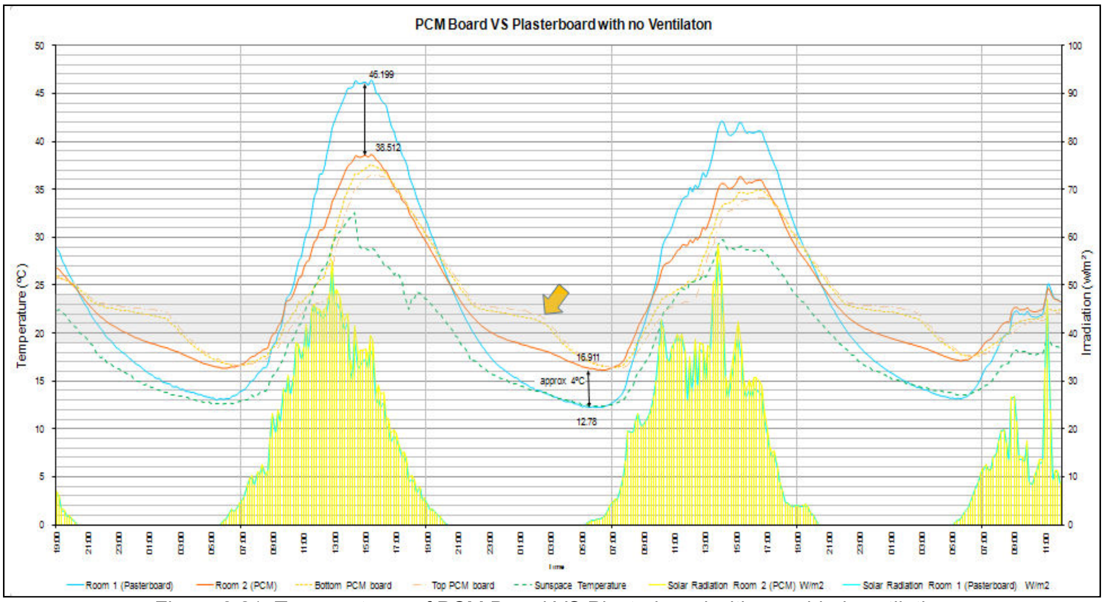


Figure 8.21: Temperatures of PCM Board VS Plasterboard with no added ventilation

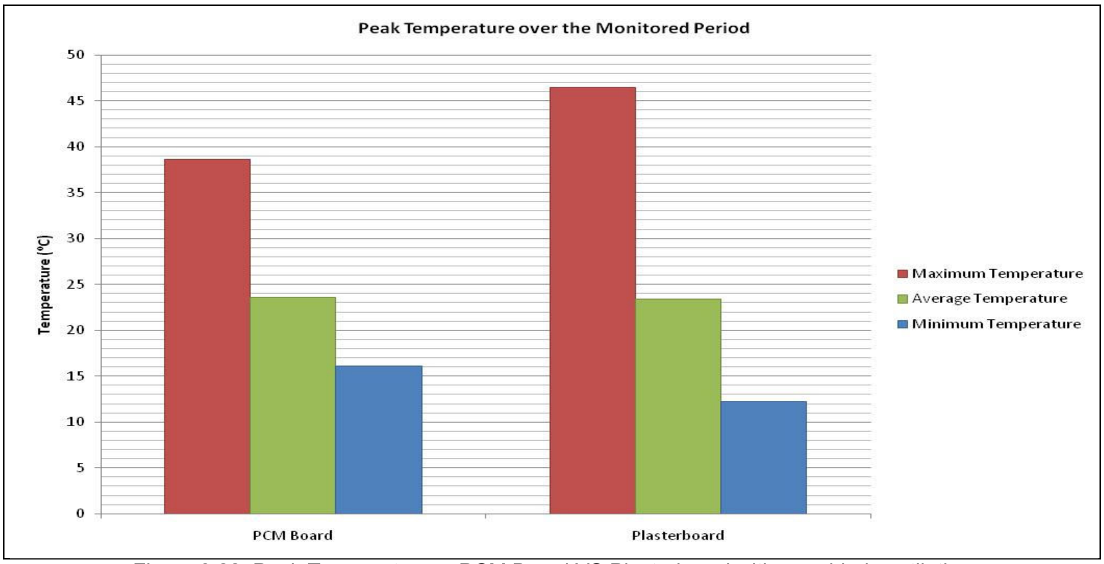


Figure 8.22: Peak Temperatures - PCM Board VS Plasterboard with no added ventilation

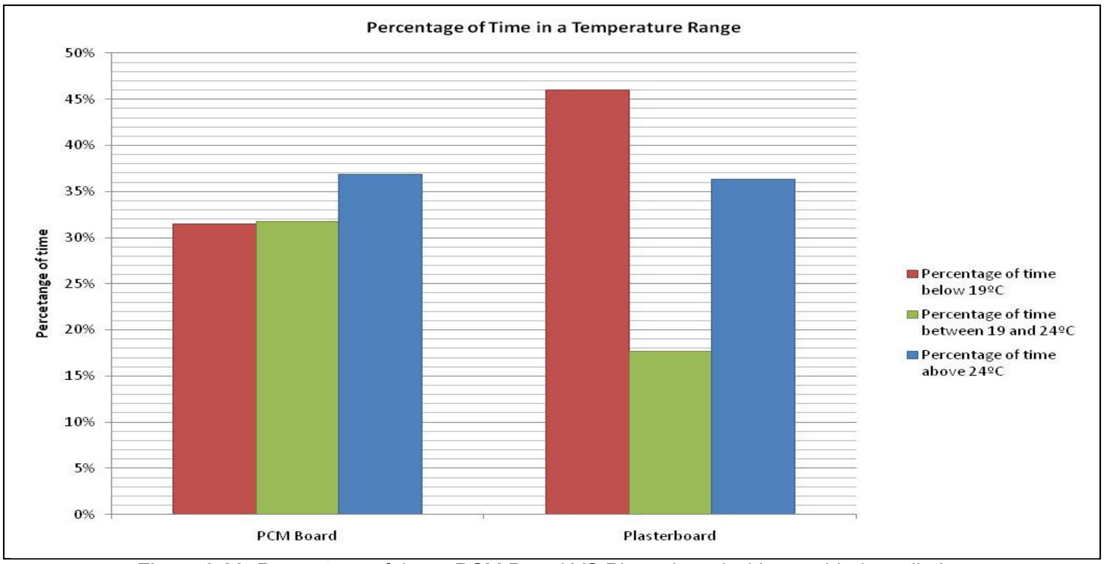


Figure 8.23: Percentage of time - PCM Board VS Plasterboard with no added ventilation

It also interesting to notice in Figure 8.21 is that the temperatures in Room 2 (PCM board) are always around 2°C higher than the 'ambient' (sunspace) temperature while the temperatures in Room 1 (plasterboard) go much higher during the day and are below or similar at night.

Over a 24h period, Room 2 stays within 19 to 24°C around 32% of the time whilst Room 1 just stays within that range around 18% of the monitored period (Figure 8.23). In Room 2, the difference between higher and lower temperature was 22.3°C while in Room 1 was 33.5°C, which means Room 2 temperature swing was 33.3% smaller than Room 1.

Overall the PCM board has produced an average cooling of 8.81W/m^3 of air and an average heating of 5.46W/m^3 air (Figure 8.24). Interestingly, the 2 cooling cycles lasted for the same time, almost 11 hours, the 2 first heating cycles also lasted around the same, just over 13 hours and the last heating cycle lasted around 14.7 hours.

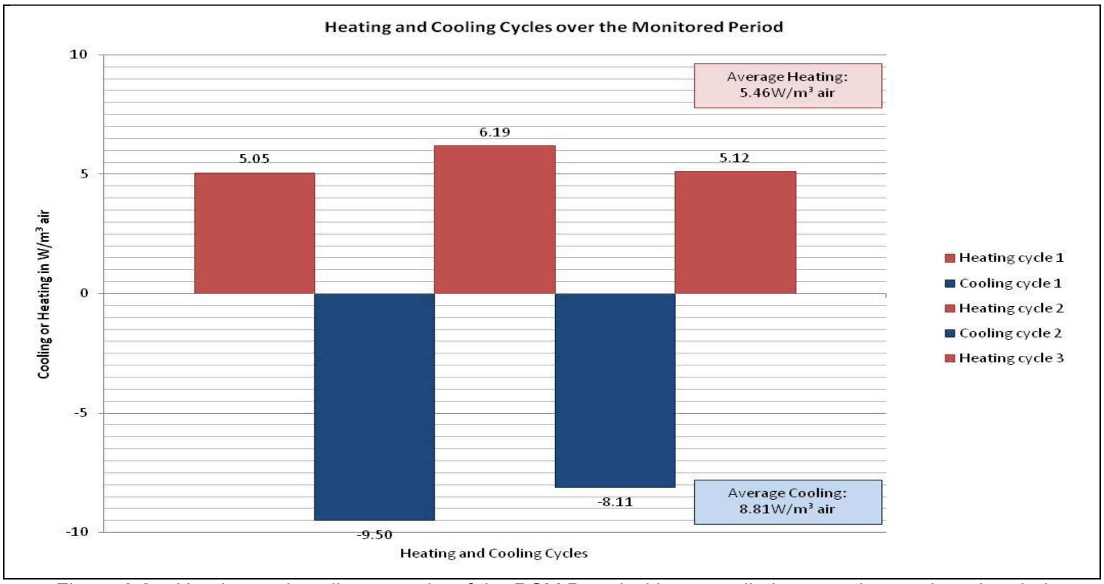


Figure 8.24: Heating and cooling capacity of the PCM Board without ventilation over the monitored period

2. Second experiment: Proposed PCM + EAHE system VS plasterboard

The experiments with different air flows were undertaken over a couple of weeks with different weather conditions and different usage of the sunspace (when there were visitors the sunspace doors were opened for short periods of time). For those reasons it was not possible to compare the results directly. Firstly the full monitored periods were analysed then the most significant day of each experiment was selected for analysis. In addition, each time the results were compared with the reference room with plasterboard.

Using Equation 2.9 (Chapter 2) the quantity of energy (either cooling or heating) that the system produced when compared to the room with regular plasterboard was calculated for each case. Figure 8.25, Figure 8.26 and Figure 8.27 represent 3 cycles of heating and 2 of cooling for each air flow rate (with the exception of $0.05m^3/s$ as the house occupants complained about the noise and the fan had to be turned off). As the quantity of heat energy produced depends on the temperature difference, whenever there was little availability of solar radiation and/or the temperature was cold, the result was less important (i.e. first cooling cycle with the fan at $0.02m^3/s$). Nevertheless, for each case the system performed better than the regular plasterboard.

On average the 3 cases produced a cooling of $5.52W/m^3$air in 10.5 hours and $3.55W/m^3$air of heating in a little over 12.5 hours. Whenever there was large availability of solar radiation (Figure 8.28, Figure 8.29 and Figure 8.30) the system produced cooling of around $7W/m^3$air regardless of the air flow rate.

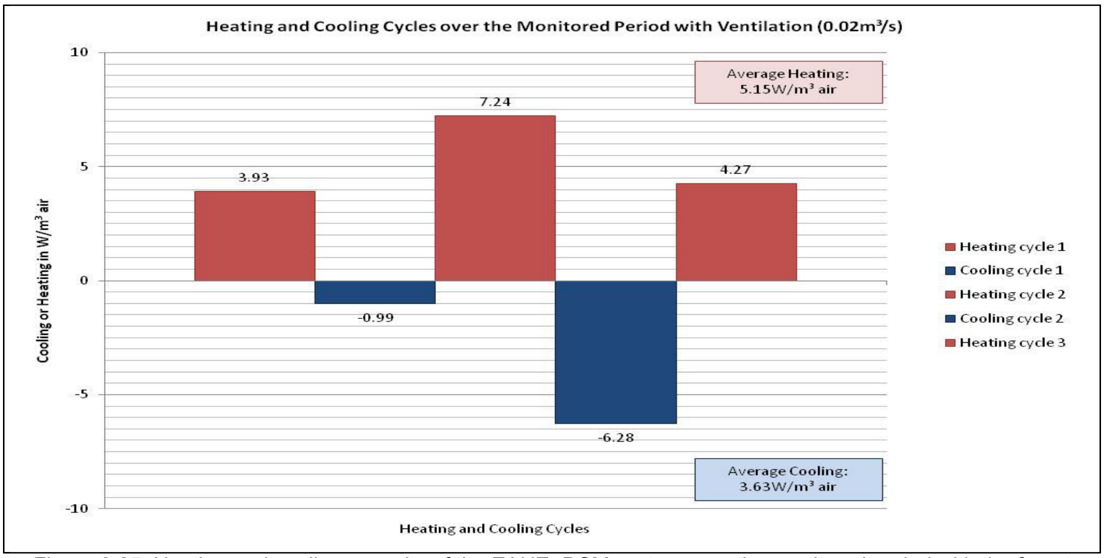


Figure 8.25: Heating and cooling capacity of the EAHE+PCM system over the monitored period with the fan at $0.02m^3/s$

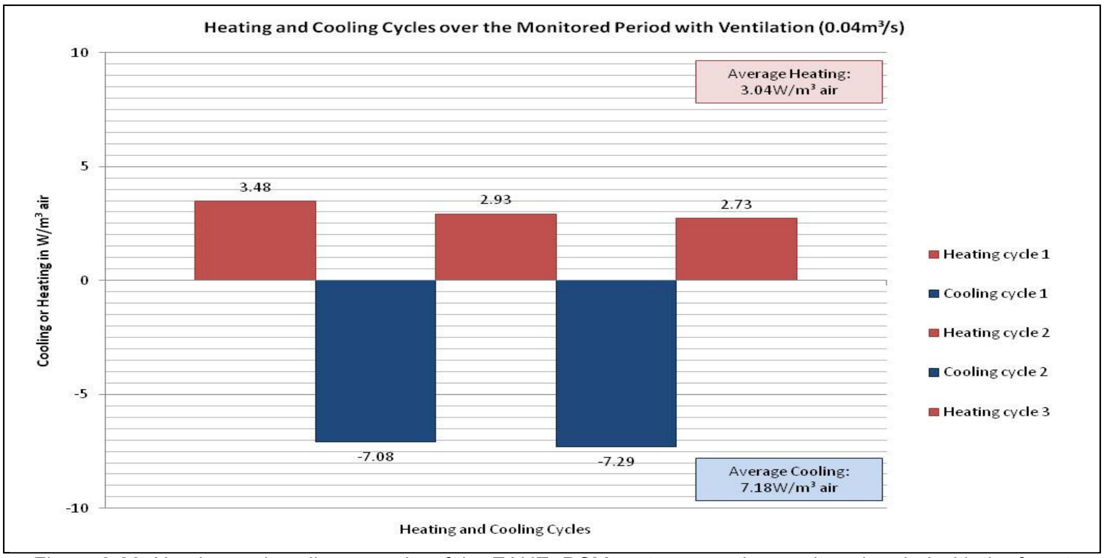


Figure 8.26: Heating and cooling capacity of the EAHE+PCM system over the monitored period with the fan at $0.04m^3/s$

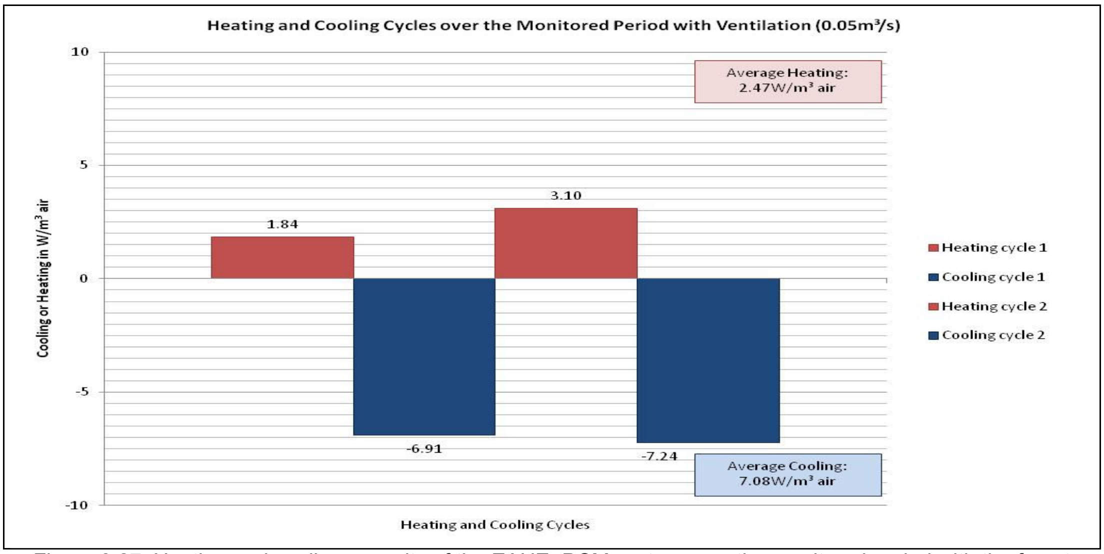


Figure 8.27: Heating and cooling capacity of the EAHE+PCM system over the monitored period with the fan at $0.05m^3/s$

For the $0.02m^3/s$ air flow, the most significant day is illustrated in Figure 8.28. Again the average temperatures of both rooms are very similar, Room 2 is 19.9°C and Room 1 is 20.1°C. However, over a 24h period, Room 2 stays within 19 to 24°C for 11.1% of the time whilst Room 1 just stays within that range for 6.3% of the time, around 44% less than Room 2. Room 2 difference between higher and lower temperature was 17.0°C while Room 1 was 28.1°C, which means almost a 40% decrease on temperature swings.

For the $0.04m^3/s$ air flow, the most significant day is illustrated in Figure 8.29. Once more the average temperatures are very similar, Room 2 is 23.1°C and Room 1 is 24.0°C. Over the period, Room 2 stays within 19 to 24°C for 31.9% of the time whilst Room 1 just stays within that range for 16.0% of the time, around 50% less than Room 2. For Room 2 the difference between higher and lower temperature was 13.3°C while Room 1 was 25.2°C, which means more than a 47% decrease on temperature swings.

Finally, at $0.05m^3/s$ air flow, Room 2 average temperature was 23.3°C and Room 1 was 25.5°C. Room 2 stays within 19 to 24°C for 39.6% of the time against 20.1% of Room 1, around 51% better. Room 2 peak temperature difference was 10.5°C whilst Room 1 was 19.4°C, which means a 46% decrease on temperature swings. There was less availability of solar radiation during the week this experiment took place as it can be seen in Figure 8.30. In addition, the noise of the fan at this speed was bothering the house occupiers so the system was turned off.

In all cases the peak temperature of both rooms happened at similar times.

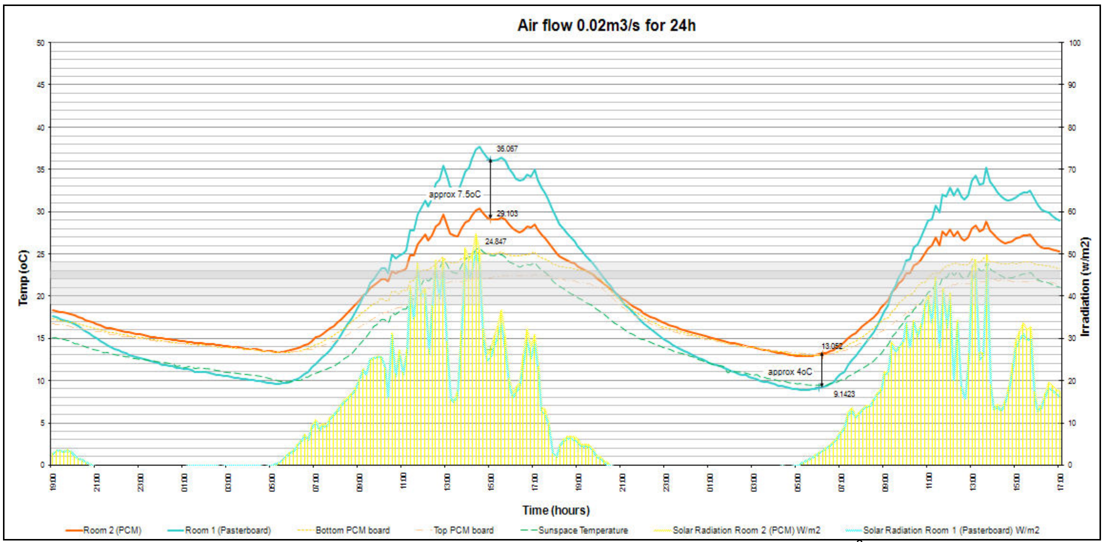


Figure 8.28: PCM board VS Plasterboard with 24h airflow of $0.02m^3/s$

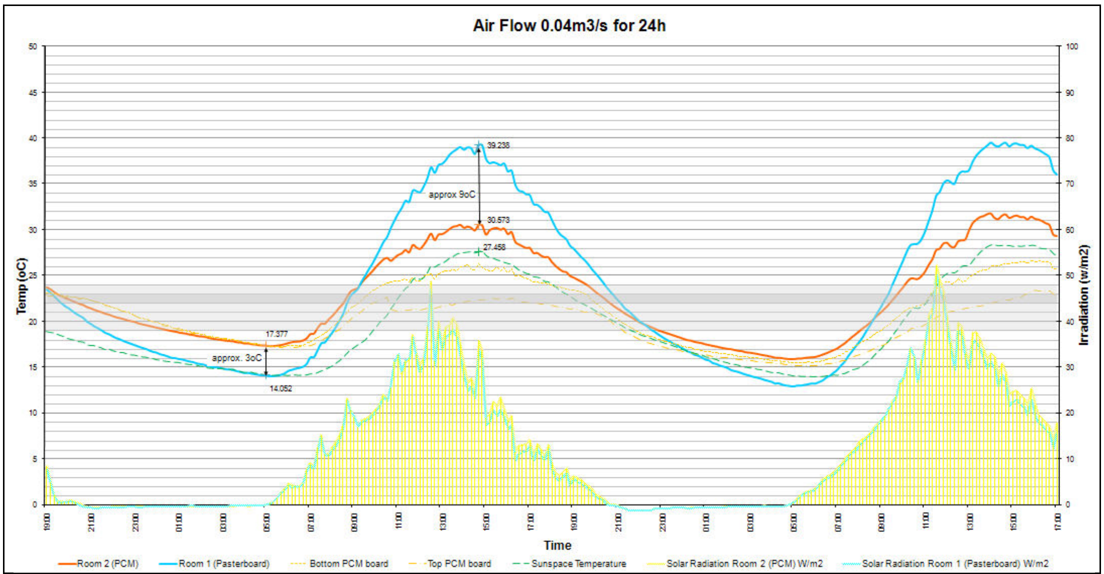


Figure 8.29: PCM board VS Plasterboard with 24h airflow of $0.04m^3/s$

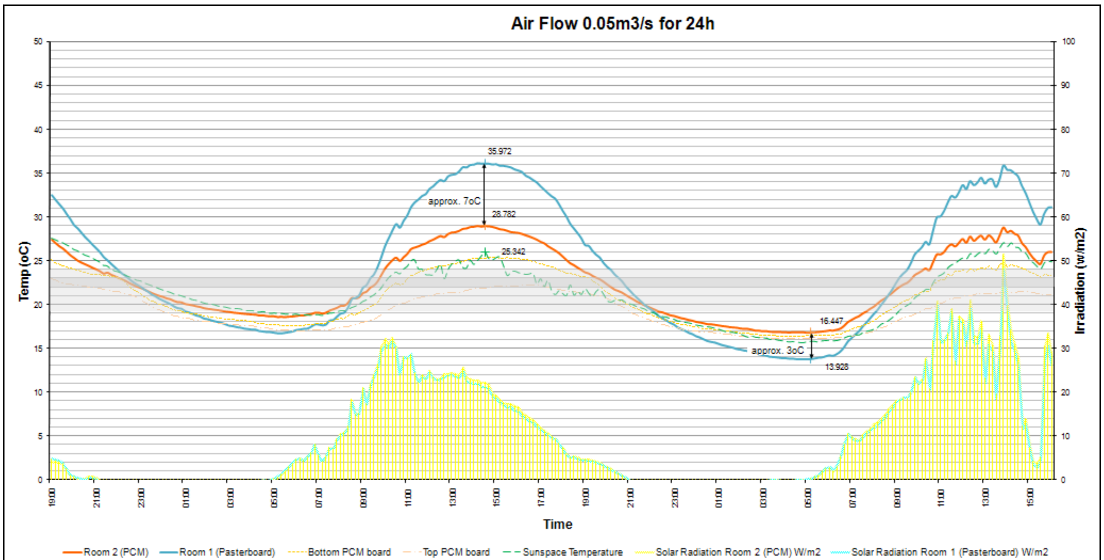


Figure 8.30: PCM board VS Plasterboard with 24h air flow of $0.05m^3/s$

Figure 8.31 shows that the average temperatures in each room were always similar to each other and always above the sunspace temperature. The difference between them increases slightly with higher airflows but the difference is still quite small and can thus be neglected.

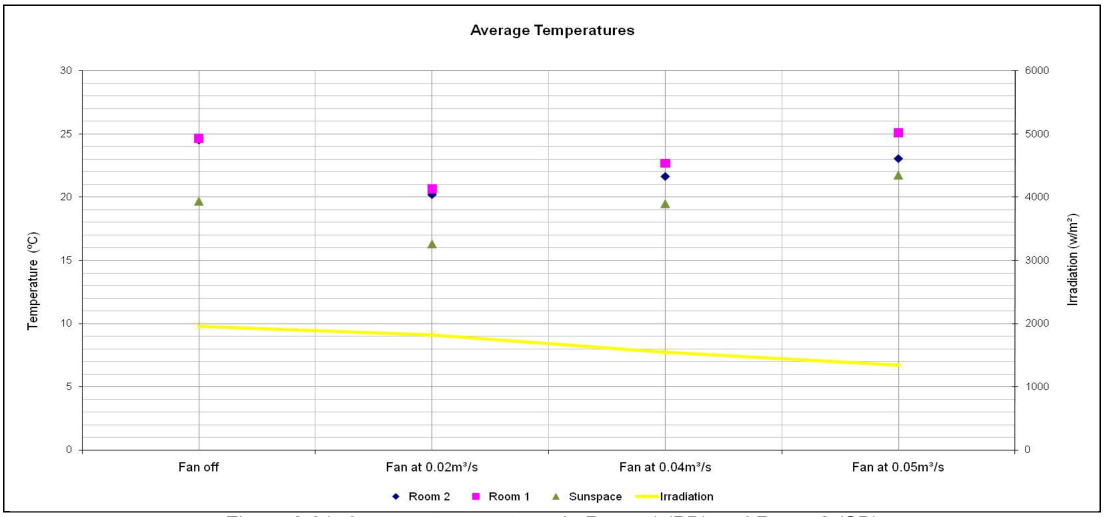


Figure 8.31: Average temperatures in Room 1 (PB) and Room 2 (SB)

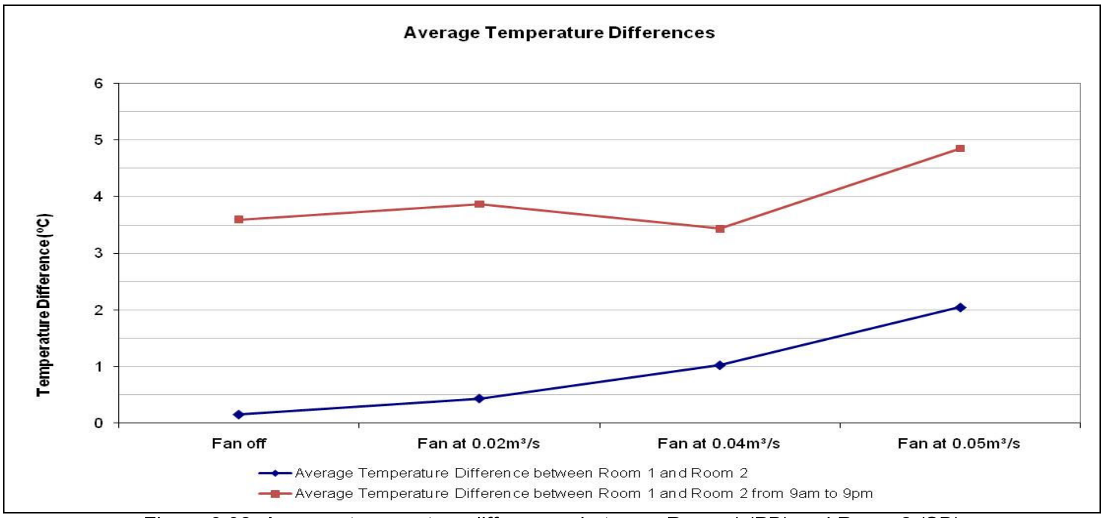


Figure 8.32: Average temperature differences between Room 1 (PB) and Room 2 (SB)

As may be seen in Figure 8.32, the average temperature difference between Room 1 and Room 2 rises with the higher airflow. However, if only daytime is considered (from 9am to 9pm) then very little variation can be seen for all the airflows. The higher speed shows a greater variation but that is just around 1^{o}C above the others.

Figure 8.33 and Figure 8.34 were created in an attempt to find a relationship between the variables of the system. The pattern of cooling was found to be a reflection of the pattern of ambient temperatures as they are related as demonstrated in Equation 2.9 (Chapter 2). On the other hand, the quantity of heating energy was found to inversely related to the airflow rate: the more heat the ventilation extracts from the PCM the less heat is left for the next heating cycle.

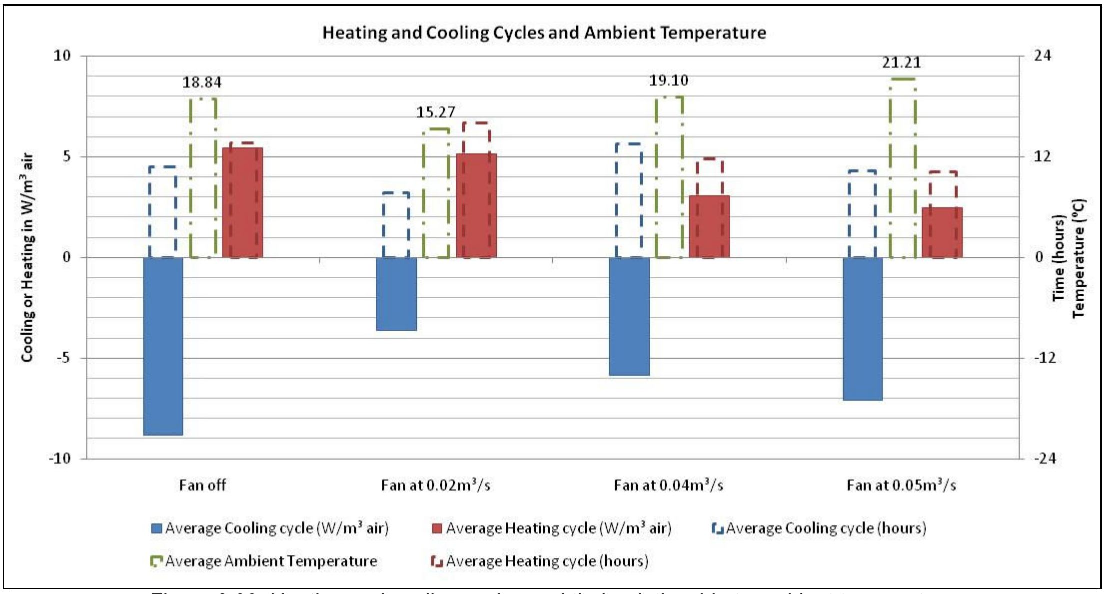


Figure 8.33: Heating and cooling cycles and their relationship to ambient temperature

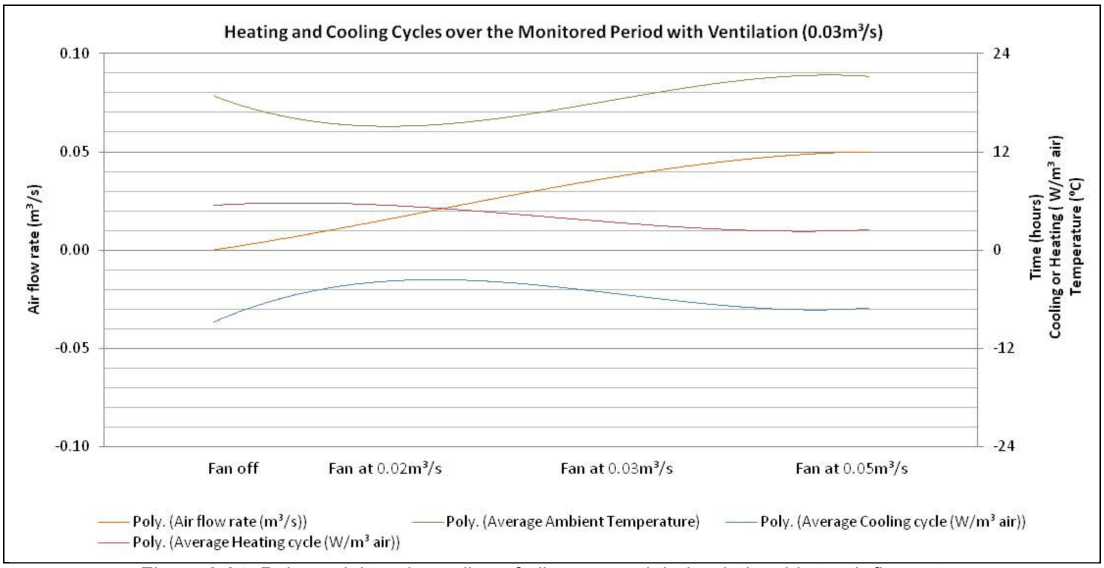


Figure 8.34: Polynomial tendency line of all cases and their relationship to air flow rates

8.5.4 Conclusions

Experiment 1 has shown that there are benefits of using the PCM board rather than regular plasterboard as it diminished the temperature swing by 33%. The average temperature in each room was similar, proving that average temperature is not a good measure of the benefits of PCMs.

Experiment 2 has shown that PCM benefits can be enhanced by the addition of ventilation. Airflows of $0.02m^3/s$, $0.04m^3/s$ and $0.05m^3/s$ brought the temperature swing down by 40, 47 and 46% respectively. Similarly to experiment 1, the average temperature in each room is alike in each case. The average temperature difference was not very different for each case showing that there are not a lot of benefits in improving the airflow greatly when this air is not being delivered directly to the space as in the proposed system. In all cases the system performed better than the room with regular plasterboard,

Unexpectedly, there was no shift in the time that the peak temperatures happened in Room 2 (PCM board) when compared with Room 1 (plasterboard). There was a time lag between the peak availability of solar radiation and the peak temperature but the system did not help to shift the time of peak demand. The experiment did not help to clarify the reason.

In all cases the temperature still rose above the comfort zone in the day and below it at night. As the only gains come from sun, this implies that the proportion of glazing for the size of the space is too large. It is also due to the sunspace temperatures. However, these variables could not be changed in this experiment. The quantity of PCM could be doubled since it would be ok to have 2 layers of PCM boards as shown before. Nevertheless the rig had to be removed from the house and it was thought that a trial outdoors would be more appropriate. No condensation was observed at any point due to the fact that the air from the EAHE is always at a colder temperature than the experimental box.

A limitation of the system with ventilation was that as the air from the EAHE extracted heat from the PCM on a 24 hour basis, there was less heat stored in the board at night, diminishing its heating capacity. If peak temperatures are considered, then the system with ventilation performed better. If quantity of cooling and heating are considered then the PCM alone seems to have performed better. However, the set of experiments without ventilation profited from much higher outside temperatures and solar radiation availability, which resulted in higher heat quantities.

Overall the system has shown interesting results but also the need for a control system to avoid the waste of energy. If the ventilation can be turned on just when the temperature is higher than desirable, better conditions might be achieved, not just because the system would use less energy to run the fan, but also because more heat could be stored in the PCM boards as desired. Night time ventilation, a more traditional technique, was not desirable as the temperature at night in the rooms always went below the comfort zone. As a consequence, another experiment was undertaken with the rig exposed to real climatic conditions and with a fan control system connected to the temperature sensors.

8.6 OUTDOOR RIG IN REAL CLIMATIC CONDITIONS

This experiment combines EAHEs with PCM as proposed in a situation as close as possible to reality. The rig was designed to use the EAHE installed by the author for the Stoneguard House as seen in Chapter 6 combined with the BASF Knauf Micronal PCM Smartboard 23 and to be exposed to outdoor conditions. This set of experiments was undertaken in August 2008.

8.6.1 Apparatus

The system was simulated in the same insulated wooden box closed by a double glazing unit used in the last experiment (please refer to Figure 8.20). However, this time the box received cladding and it was sealed and treated to be exposed to the weather. The box was divided in the middle defining Room 1 (reference room) and Room 2 (cooling system room). Each room had a 10cm plenum on the top and supports for the boards. The plenum was closed by vents. Flexible insulated pipes transported the air from the EAHE outlet to the back of the box.

The box was positioned on campus, in a place exposed to the sun at the School of the Built Environment. Soon it was found that the rooms were getting too hot and reached their peak temperature at different times (morning or afternoon) due to receiving Eastern or Western sun. In order to overcome this problem, the glazing was fully shaded so just indirect solar radiation was received.

This time, both rooms had PCM board so only the benefit of the combined system could be assessed. An anemometer with a recent calibration certificate was used to measure the air flow at the EAHE outlet, just above a fan, which had a controller.

The air within the chamber, pipes and plenum was monitored using 14 k-type (chromel–alumel) thermocouples with shielded finish and connected to the analogue inputs of a datalogger (Datataker DT 505 series 2). Thermocouples were positioned inside each room, in each plenum, on the top surface and on the bottom surfaces of each board and outside. Room 2 also had thermocouples in the inlet and outlet of the plenum. Humidity and temperature in the EAHE outlet were also monitored. Solar radiation was also measured using a pyranometer, which was installed vertically and inside the glazing (Figure 8.35). The glazing was totally shaded. The error in temperature readings from the thermocouples was considered to be ±1ºC and they were all tested for their accuracy and calibrated against each other before the beginning of the experimentation. A weatherproof metal box housed all the data monitoring equipment. Data were gathered every 5 minutes.

Figure 8.35: Picture of the outdoor rig at the School of the Built Environment, University of Nottingham

8.6.2 Scope and Method

It was found that 1m/s (0.01m^3/s) was not enough to pull enough air through the EAHE of the Stoneguard House (its configuration is illustrated in Chapter 6) and the rig due to pressure losses so the experiments used only 2m/s (0.02 m^3/s) and 3m/s (0.03 m^3/s). Two temperatures were chosen for investigation, 24^{o}C (only just slight above the melting temperature of the BASF Knauf Micronal PCM Smartboard 23) and 26^{o}C (in order to allow for more heat to be stored).

1. First experiment: Room 1 (PCM board) VS Room 2 (EAHE + PCM hybrid system), fan at 2m/s (0.02 m^3/s) switched on just when temperature in Room 2 went above 24^{o}C
2. Second experiment: Room 1 (PCM board) VS Room 2 (EAHE + PCM hybrid system), fan at 2m/s (0.02 m^3/s) switched on just when temperature in Room 2 went above 26^{o}C
3. Third experiment: Room 1 (PCM board) VS Room 2 (EAHE + PCM hybrid system), fan at 3m/s (0.03 m^3/s) switched on just when temperature in Room 2 went above 24^{o}C
4. Fourth experiment: Room 1 (PCM board) VS Room 2 (EAHE + PCM hybrid system), fan at 3m/s (0.03 m^3/s) switched on just when temperature in Room 2 went above 26^{o}C

8.6.3 Results

In each experiment the system was monitored over a period of 4 days. The temperatures in the rooms were generally much lower than in the previous experiment as the rig was outside and thus not ‘protected’ by the sunspace. In addition, the rig was receiving diffuse solar radiation only. An overview of each monitored period is given by Figure 8.36, Figure 8.37, Figure 8.38 and Figure 8.39.

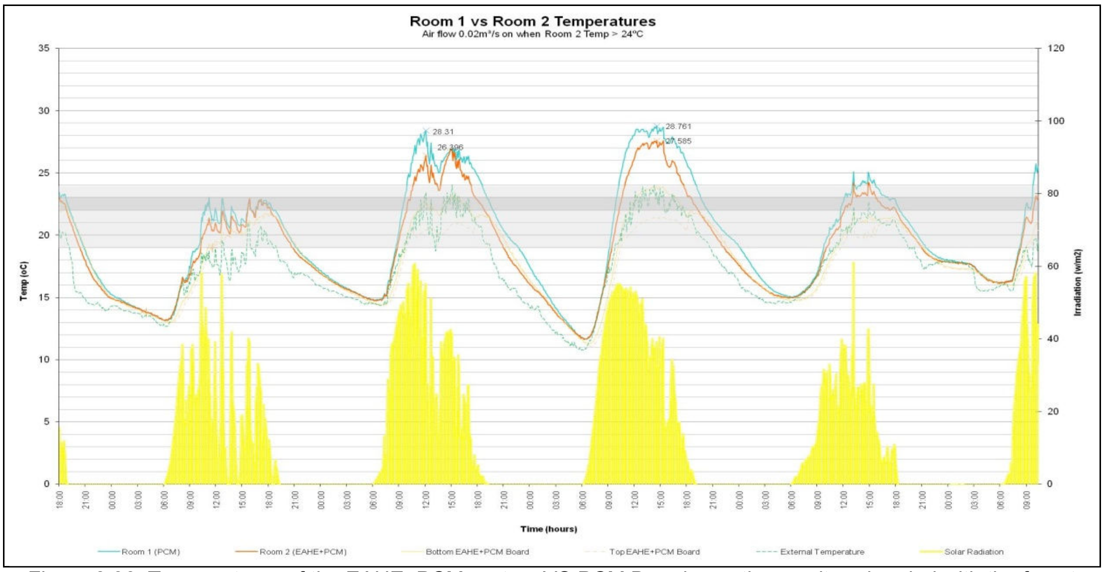


Figure 8.36: Temperatures of the EAHE+PCM system VS PCM Board over the monitored period with the fan at $0.02m^3$/s when temperatures were above 24^{o}C

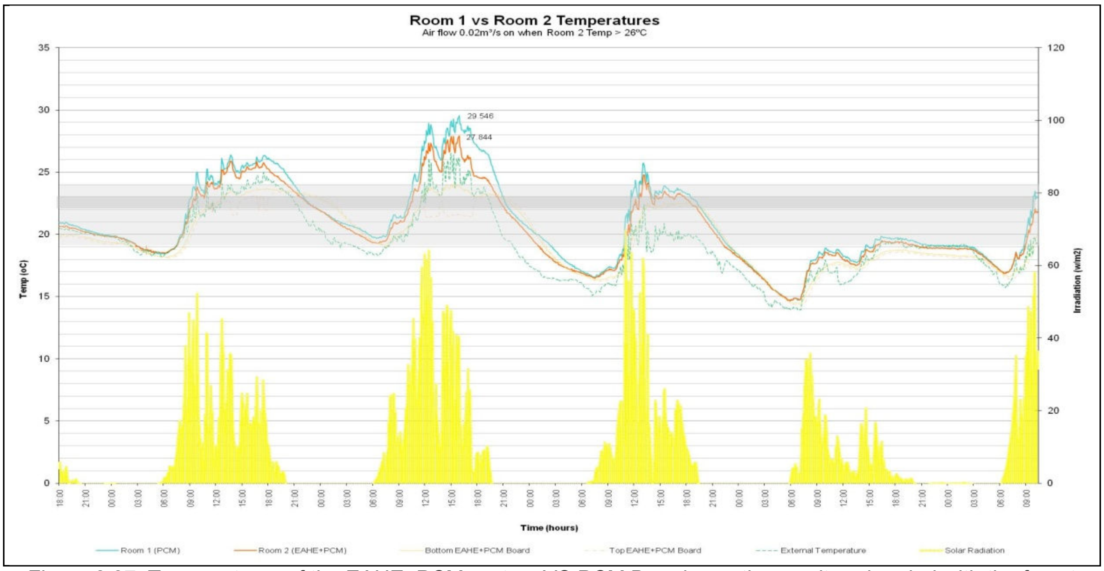


Figure 8.37: Temperatures of the EAHE+PCM system VS PCM Board over the monitored period with the fan at $0.02m^3$/s when temperatures were above 26^{o}C

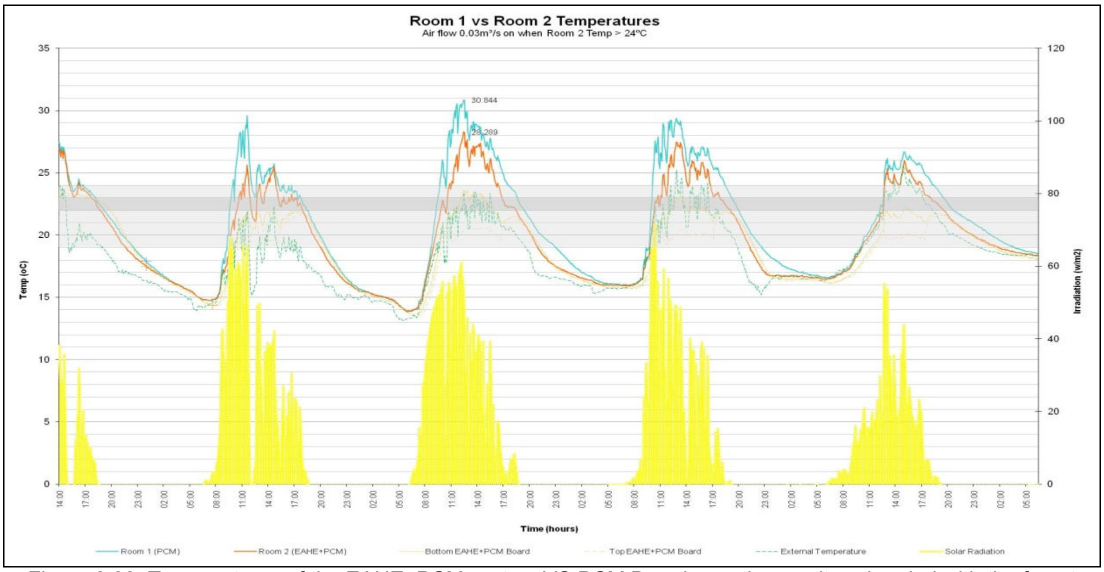


Figure 8.38: Temperatures of the EAHE+PCM system VS PCM Board over the monitored period with the fan at $0.02m^3/s$ when temperatures were above 24°C

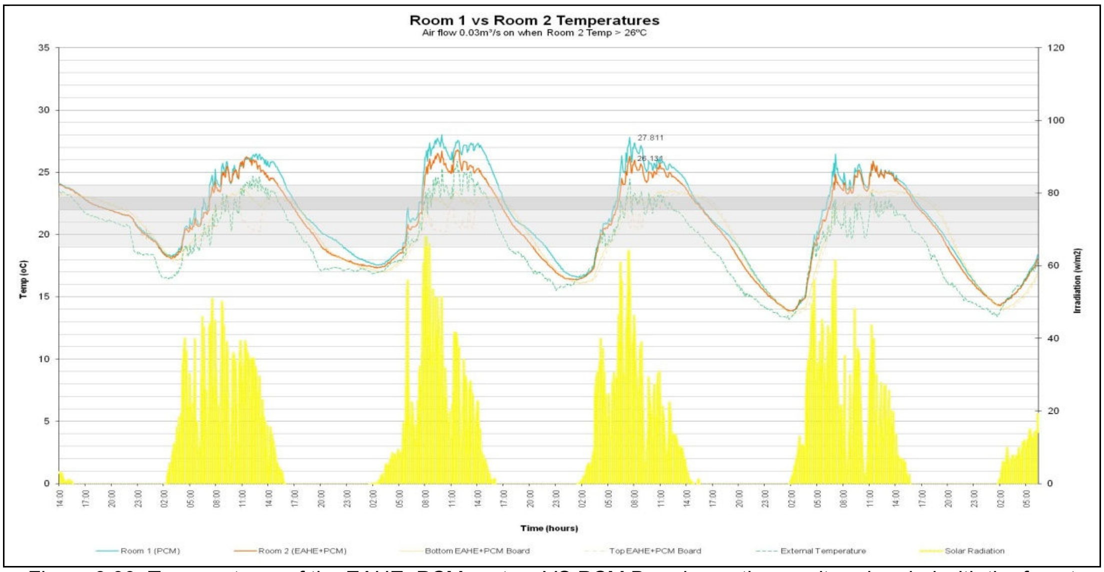


Figure 8.39: Temperatures of the EAHE+PCM system VS PCM Board over the monitored period with the fan at $0.02m^3/s$ when temperatures were above 26°C

There is a shift in the peak temperature time when compared with the maximum solar radiation received as expected based on previous experiments. The EAHE+PCM system (Room 2) was able to reduce the peak temperature on all days when temperatures in the box went higher than 25°C. There is virtually no difference between the lowest temperatures in each room, although there is a small delay in the time that value is reached (Room 1 keeps warmer for longer). The difference in heating energy between Room 1 (PCM) and Room 2 (PCM+EAHE) became negligible, which was a positive result showing that just excessive energy is being extracted by the system once the fan was programmed to work just when the temperatures went above 24 or 26°C. This is illustrated in Figure 8.40.

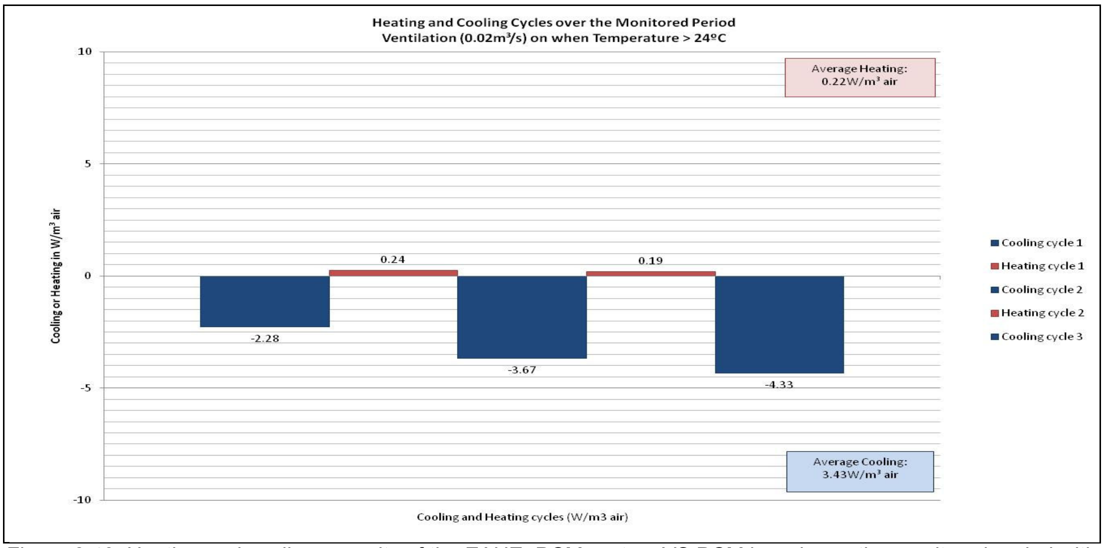


Figure 8.40: Heating and cooling capacity of the EAHE+PCM system VS PCM board over the monitored period with the fan at $0.02m^3/s$ when temperatures were above 24^oC

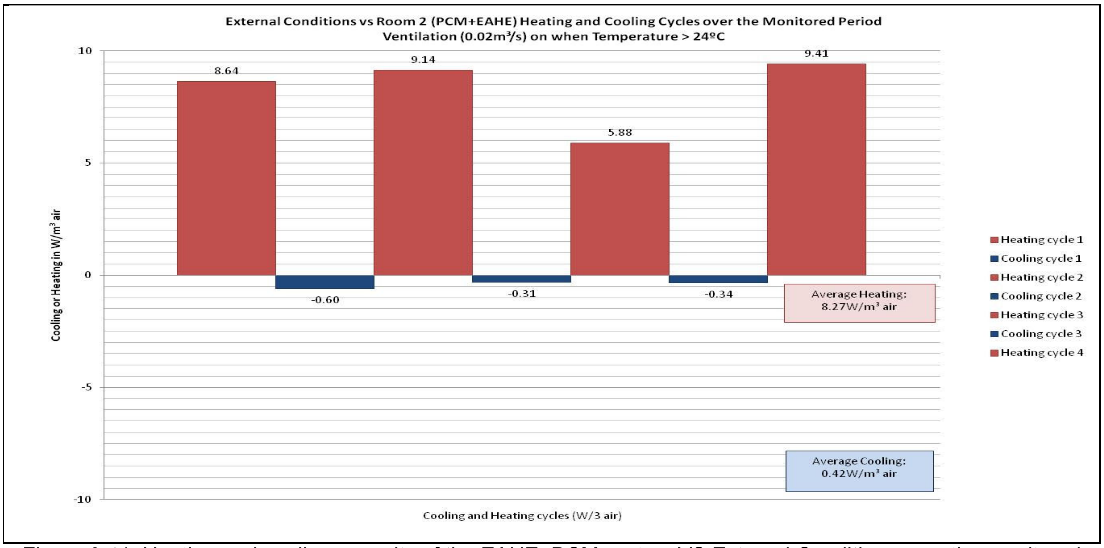


Figure 8.41: Heating and cooling capacity of the EAHE+PCM system VS External Conditions over the monitored period with the fan at $0.02m^3/s$ when temperatures were above 24^oC

In order to show that the system is still providing heating for the room at nights, Room 2 was compared with outside conditions (Figure 8.41). Most of the time the room is warmer than external temperatures and the combination of large glazing and PCM meant an average of $8.27W/m^3$ air of heating was being generated when compared to the outside. This excess heat was necessary in order to test the hybrid PCM+EAHE cooling system. The rest of the results will concentrate on cooling.

Figure 8.42, Figure 8.43, Figure 8.44 and Figure 8.45 demonstrate that the outside condition varied greatly during the monitoring periods making a direct comparison of the impact of the variables difficult. In the first case temperatures were much colder and did not go above 24^oC for significant amounts of time. The 3rd case was similar although less extreme and the 2nd and 4th cases has similar temperature conditions. In all cases, the system reduced the percentage of time that the temperatures went above 24^oC if compared with the PCM Board alone. However, it also increased the percentage of time below 19°C showing that the system might be better suited for a warmer climate. The temperatures within 19 and 24°C were similar in all cases.

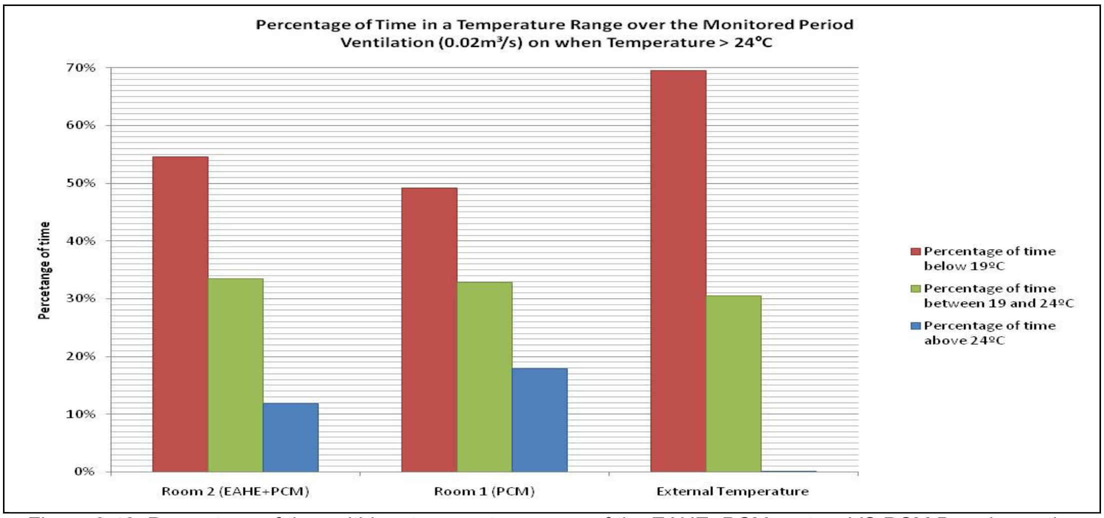


Figure 8.42: Percentage of time within a temperature range of the EAHE+PCM system VS PCM Board over the monitored period with the fan at 0.02m^3/s when temperatures were above 24°C

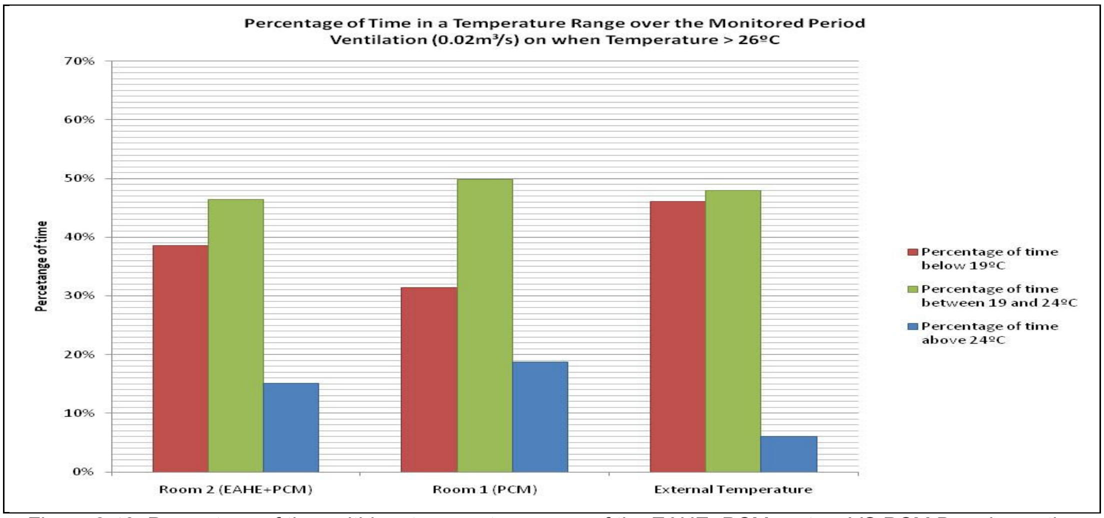


Figure 8.43: Percentage of time within a temperature range of the EAHE+PCM system VS PCM Board over the monitored period with the fan at 0.02m^3/s when temperatures were above 26°C

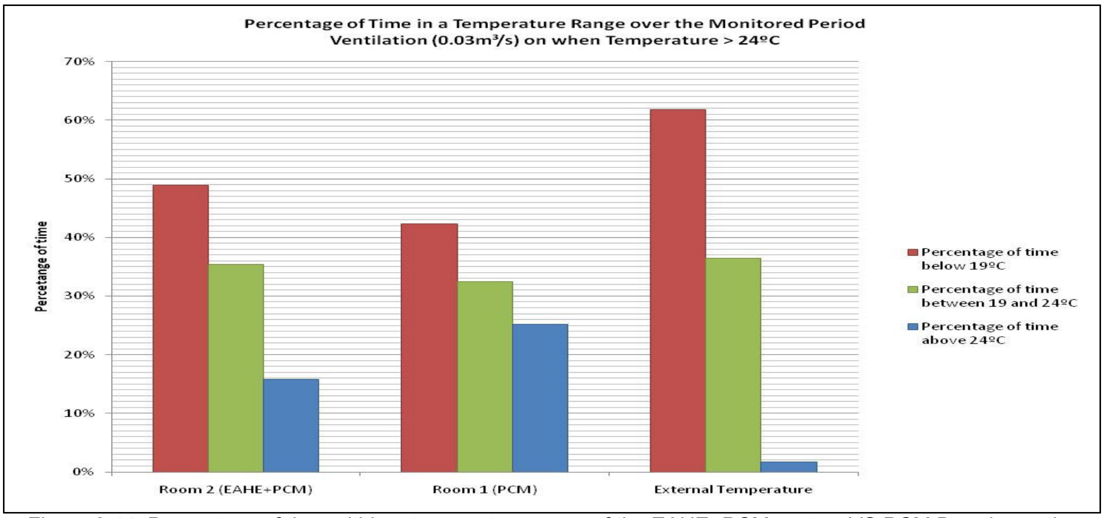


Figure 8.44: Percentage of time within a temperature range of the EAHE+PCM system VS PCM Board over the monitored period with the fan at 0.03m^3/s when temperatures were above 24°C

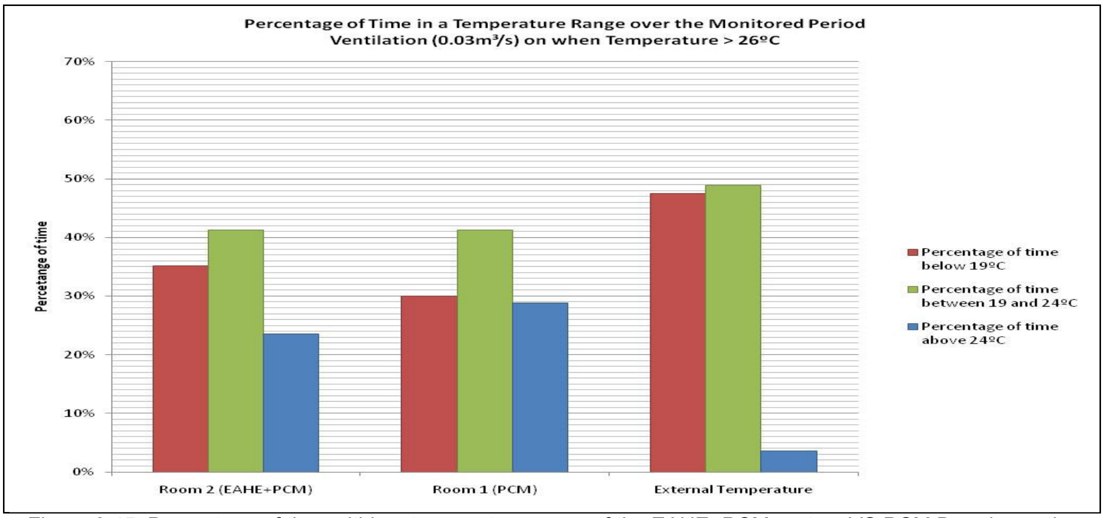


Figure 8.45: Percentage of time within a temperature range of the EAHE+PCM system VS PCM Board over the monitored period with the fan at $0.03m^3/s$ when temperatures were above 26^oC

Temperatures in the EAHE+PCM system plenum (at inlet and outlet) were measured but were discarded because they show a large influence from outside temperature as they were located on uninsulated vents in the external envelope of the box.

Figure 8.46 shows a comparison of all cases. Setting the fan to turn on above 26^oC rather than 24^oC meant an approximate reduction of 60% in the time the fan was in use but an improvement of around 35% in the quantity of cooling energy delivered.

Improving the air flow rate by a third (from 0.02 to $0.03m^3/s$) and activating the fan just when temperatures were above 24^oC, generated an improvement of 31% in the cooling energy delivered per cubic meter of air. Improving the air flow rate by a third but activating the fan just when temperatures were above 26^oC generated an improvement of 27% in the cooling energy delivered per cubic meter of air when compared with activating the fan at 24^oC.

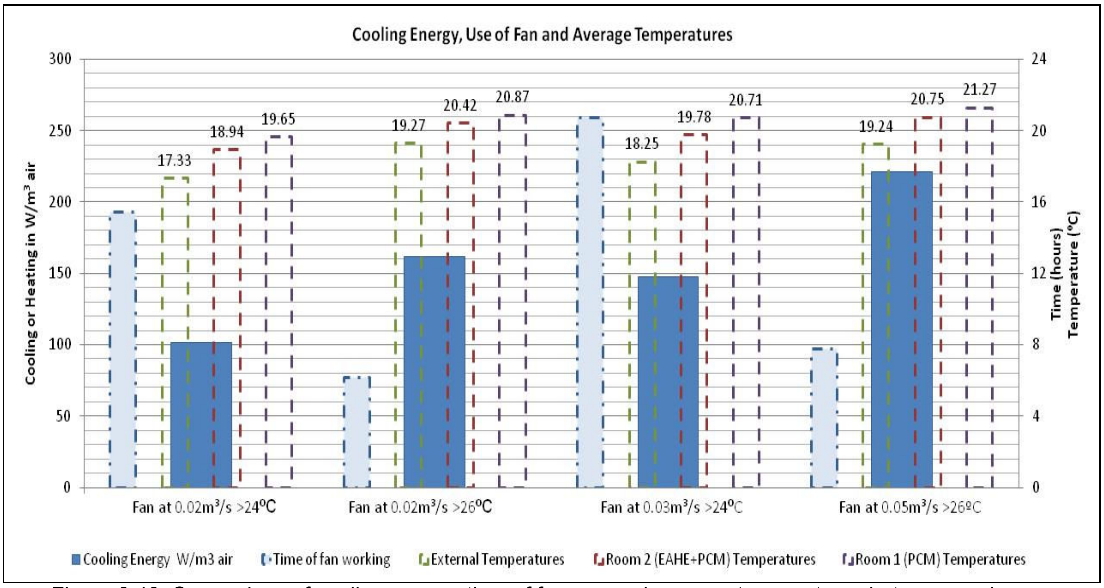


Figure 8.46: Comparison of cooling energy, time of fan use and average temperatures between each case

8.6.4 Conclusions

In all the experiments of this section, the box presented higher temperatures than outside for most of the time. Lower temperatures tended to follow more closely the outside conditions in both rooms.

When compared with the use of a PCM board alone, the combined system presented improvements especially regarding the reduction of peak temperatures. However, it also presents a rise of temperatures below 19^{o}C suggesting that it may be more appropriate for a warmer climate. Nevertheless the quantity of heating stored in the PCM to be used when outside temperatures were colder was similar in both rooms, which is an indication that effective fan management might allow for control of the quantity of heat kept in the PCM for later use, discharging excessive heat only.

Although a direct comparison is not entirely accurate due to different weather conditions and length of monitored period, having the fan set to work at 0.03m^3/s just when temperatures in Room 2 were above 26^{o}C showed the best results, producing more instantaneous cooling energy (200W/m^3 air) and fewer hours of fan usage. It exhibited the same hours between 19 and 24^{o}C as Room 1, fewer hours above 24^{o}C but more hours below 19^{o}C.

8.7 CONCLUSIONS AND FURTHER WORK

This chapter proposed a new kind of air conditioning system that uses surfaces as sources of heating or cooling and which may provide better temperature distribution across a space and delight to thermal senses. The system combines EAHEs with PCMs to support thermal comfort maintenance with a low energy use. It does not aim to provide a flat temperature pattern but rather to allow for an acceptable level of fluctuation. The idea is to use an EAHE and a fan to provide cold air to discharge the PCM enhancing the heat transfer between the air and the PCM.

The system aims to overcome certain limitations of EAHEs, such as difficulty in controlling air quality, complicated distribution of conditioned air and cold draughts, and limited performance due to quantity of required conditioned air. In addition, it aims to overcome limitations of PCMs such as the need for lower indoor temperatures to enable heat discharge from the PCM and need for enhanced heat transfer, which might be limited if it relies on natural ventilation only. If the heat discharge cannot be done by natural means (i.e. night time ventilation) then mechanical cooling sources such as EAHE should be used and that may allow for the heat to be released outside rather than back into the conditioned space.

EAHE are expensive to install and have limited use in winter and in intermediate seasons due to the limited quantity of fresh air required inside the spaces. The hybrid system can extend the benefits of the EAHE throughout the year as the air is not delivered directly to the space but used to keep surface temperatures fairly stable. Moreover, the installed system could allow for both, delivery of fresh air directly inside the space when required and discharge of heat from PCM when necessary. The system could extend the use of PCMs to warmer climates or locations where there is no great fluctuation of temperature between day and night time limiting the use of natural ventilation and/or night time ventilation.

A series of experiments was undertaken to test the proposed system starting from testing the board containing Micronal PCM with a phase change temperature of 23^{o}C. Firstly, the PCM was tested in relation to its position in a space and it was found that thermally, the ceiling was the most effective way of installing it.

The second set of experiments tested the effectiveness of the heat transfer across the PCM board and the time taken for a full charge and a full discharge of the PCM under controlled conditions. It was found that, even though there was a time delay between the bottom and the top of the board, it was possible to fully charge or discharge the PCM board by applying heat and/or ventilation with cold air to one surface only. Higher air flows did not show much advantage due to air turbulence or air resident time in contact with the board.

A box was built and installed in the BASF House sunspace to make use of the EAHE installed there for the next set of experiments. The box was divided into Room 1 (plasterboard) and Room 2 (PCM board + EAHE). The EAHE+PCM system was tested and compared against a regular room with no PCM or ventilation. The PCM board alone (without the aid of the EAHE) could reduce temperature swing by 33%. The complete hybrid system with air flow rates of 0.02, 0.04 and 0.05m^3/s for 24 hours caused decreases of 40%, 47% and 46% respectively in temperature swings. Average temperatures were proven to be a poor measure of the benefits of using PCMs.

The final set of experiments placed the box outside exposed to weather conditions. Room 1 received PCM board this time and Room 2 the complete hybrid system. The rig was positioned to make use of 60 meters of the EAHE built for the Stoneguard House (the full 80 meters-long pipe was unfortunately not finished). This time the fan was arranged to start when the temperatures went above a set level (24 and 26^{o}C) regardless of time and 2 air flow rates were tested (0.02 and 0.03m^3/s)

The most noticeable improvement between the PCM board alone and the full hybrid system was on reduction of the highest temperatures. There was virtually no alteration of the lowest temperatures but there was a rise in the time Room 2 (EAHE+PCM) stayed below 19^{o}C. Nevertheless, the quantity of heating energy stored in the PCM in both rooms was similar showing that fan management might allow for optimisation of the quantity of heat energy kept in the PCM for later use. The best results were produced by the fan delivering an air flow rate of 0.03m^3/s just when temperatures in Room 2 were above 26^{o}C meaning an instantaneous cooling of 200W/m^3 air.

There was a shift between the highest availability of solar radiation and the maximum temperature in the rooms. However, in all experiments, no significant shift in the time that the peak temperatures happened in Room 2 when compared with Room 1 was observed. The PCM board and the hybrid system did not present a time delay with regards to higher and lower temperatures signifying that although it might reduce energy consumption by flattering the sinusoidal curve of temperatures, it might not be able to shift the use of energy from peak times to off peak times as suggested previously.

Overall it can be said that the EAHE+PCM hybrid system is promising and should be researched further. However, there are limitations to the system and it might be better suited to a warmer climate than the UK or possibly to the UK in the future as temperatures are expected to rise. This could not be proved due to the lack of opportunity to try these possibilities. An important further development would be the possibility of simulating the system in computer software to assess more variables in less time enabling an informed decision when selecting new experimental settings. As mentioned, at the moment both EAHEs and PCMs suffer from a lack of simulators that are accessible to designers, which is one of the restrictions stopping a wider use of the techniques. This proposed hybrid system could suffer from the same problem if no easily obtained and user friendly software is available.

One of the main limitations of the experiments was time. Even though this work could benefit from a real EAHE installed on site, this was not available to be used until the 3rd year of this doctorate. Other limitations such as unavailability of power on site and health and safety issues also delayed the testing. In addition, the system had to be tested in summer and not only are summers in the UK short but also, unluckily, this work experienced 2 of the coldest summers of the last 10 years. Consequently, the system was tested over a few months of the summer of 2008 only and more tests are recommended for an effective and definite conclusion. These new tests should consider more variables such as quantity of PCM and varying air flow rates and also occur over longer periods of time to allow for a pattern and a relationship between parameters to be found.

Other aspects left to be investigated are the system against PCM with night time ventilation in a more controlled environment and different proportion of glazing per floor area and of PCM per glazing and floor area. Another possibility is to try the system against a room with EAHE and PCM working separately.

9 CONCLUSIONS AND FURTHER WORK

9 CONCLUSIONS AND FURTHER WORK

> *"My glass is always half empty."*
>
> Max Fordham, referring to a "thirst for knowledge" when giving a seminar at the University of Nottingham, January 2009

The UK Government has set ambitious targets for reducing the carbon dioxide emissions associated with energy use in buildings, including the target for all new homes to be zero-carbon by 2016. In addition, the government is also committed to promote Modern Methods of Construction (MMC) as they can supply better quality homes faster and may be a solution for the shortage in housing that the country has been experiencing. Clearly these targets will require significant step changes in the design process and construction practice.

The use of MMC is in rapid expansion due to not just to the housing shortage but also to a lack of skilled labour. Using MMC could mean more dependence on well-thought-through and highly detailed projects placing more responsibility on the architect. The market still needs to adapt to this reality where projects take longer in the hands of a designer but are much quicker to be built on site. There are many advantages in this change, such as a shorter supply chain meaning less risk of error. Much work has been done on the financial and social sides of MMC but little had been published on its thermal performance.

Previous works have suggested that air-tight super-insulated houses built using MMC may suffer from summer overheating problems, a fact that will become increasingly important as UK temperatures rise due to manmade climate change. This work has shown by both, computer simulations and analysis of monitored data, that overheating can be an issue in British houses.

It is therefore essential that robust solutions are used that may alleviate these problems whilst at the same time facilitate the successful use of MMC solutions for housing. In addition to confirming the importance of conventional thermal mass, good ventilation and solar shading strategies this work has outlined two other strategies that may be useful for preventing summer overheating: Phase Change Materials (PCM) and Earth Air Heat Exchangers (EAHE). These two technologies are being trialled as part of the Creative Energy Homes Project at the University of Nottingham.

EAHEs make use of the soil's temperature to condition outside air before delivering it to a space. These systems should be treated as a ventilation system for the purpose of both, costing and control of air quality. Installation cost is in fact one of the most significant drawbacks of the technique but it is able to run using very little energy. EAHEs have the potential to provide all of a home's needs for cooling, but they have limited performance in winter due to the quantity of fresh air required in the space and the temperature it is able to deliver. Installed systems are generally not well documented and long term monitored data is very rare. The two systems analysed in this work have shown good results and may become of greater importance as the climate warms up.

Small quantities of PCMs can potentially substitute large amounts of conventional thermal mass by making use of latent heat storage. Most of published works focus on tests in the laboratory and data from building applications are difficult to find. Nevertheless all the published results are positive. However, there are obstacles to a wider use of PCMs such as the difficulty to simulate their performance, which restricts specification by designers. Cost is also an issue, especially when its potential benefits cannot be shown. The BASF Micronal PCM board tested in this work was proven to work effectively in experimental work where comparison was possible. In a real life situation (i.e. the BASF House) it was not possible to quantify the benefits of the PCM but it was possible to observe that the board stayed within its phase change temperature range for almost 90% of the summer period.

Eight different wall construction types, with different quantities of thermal mass but same low U-Values, were analysed and simulated. The parameters admittance, decrement factor and time constant did not reflect the results found in the dynamic simulations meaning that these are not necessarily good values to quantify thermal mass as it is often suggested in literature. Thermal mass was found to benefit the space but to a limited extent. As the walls are highly insulated, most of the heat gains occur internally or through fenestration, which means that the size and position of the glazing and openings and the control of internal gains are of larger importance than the availability of thermal mass. Nevertheless there was always around 2^{o}C of difference between the top performer (the wall type with the highest thermal mass) and the bottom performers (the ones with the lowest thermal mass).

The simulations have shown overheating even in today's weather if mitigation strategies are not in place and overheating in future weather scenarios was shown to occur even with all mitigation strategies in place. Therefore, in the future new strategies such as EAHE and PCM will gain more importance with the advent of climate change. It should be kept in mind that a building should be constructed to be in use for many decades so these strategies should be considered now in order to avoid the use of energy expensive cooling equipment in the future. This chapter also discussed the need to re-educate people to accept larger (though still comfortable) temperature swings and to understand the functioning of their homes. In the UK, the Code for Sustainable Homes is attempting to address the issue of 'knowing your house' by giving points if the construction comes with a manual.

It was found that computer simulations should not be used to try to simulate reality but rather to simulate the impact of each variable on the overall performance. This is not because of their accuracy only but more importantly because of the user and how the inputs and assumptions are built. In fact, the accuracy of the software becomes of smaller importance when the influence that each parameter input by the one doing the modelling is taken into account. Suggestions for further work to be undertaken as a development of this part of the thesis is to experiment with different room configurations (changing dimensions, window size, etc) and to create a guide that may inform designers of decisions in the early stages of their projects without necessarily having to do dynamic simulations.

With that in mind, the Stoneguard House was simulated and each parameter changed in turn. The house presents a small degree of overheating in today's weather but a more severe problem is presented in the future when the house is likely to need an active cooling device to remain comfortable. The large sunspace of the house, which was designed to be used as an entrance and sitting area, presents great overheating despite being simulated with all mitigation strategies in place including an EAHE. It is likely that this space will be uncomfortable for large periods of the year. Part of the EAHE installed for the house was monitored over a summer period and has presented good results. Unfortunately there was no monitored data as the house is not finished.

The approach taken for the BASF House was slightly different as there was data available for the summer period of 2009. The data analysis has shown overheating in the bedrooms of the house. Interestingly, the occupiers seem to feel comfortable due to the large volume of the bedrooms. Part of the problem could be occurring because the users do not often use the high level windows due to noise issues. However, in the simulations, overheating was always present in these areas. It was identified that the causes are design related issues: the sizes of the effective openings are not appropriate and the sunspace relies largely on the bedroom windows for extraction of warm air. The only way to alleviate this overheating is to use all the mitigation strategies in addition to the EAHE. Nowadays the occupants are not using the EAHE very often but, as temperatures get warmer, it is likely that the strategy will become essential for maintaining the home's thermal comfort. Further investigation of the house's ventilation system was also suggested by CFD simulation and a more comprehensive monitoring campaign.

In both houses the effectiveness of the PCM could not be proved except by a computer simulator designed by BASF, the supplier of the selected PCM. As a result, this was the first thing done when the experimentation presented in Chapter 8 started. Based on the laboratory tests and on the purposely built chamber, which was exposed to the weather, the Micronal PCM used in this work was shown to be effective in diminishing higher peak temperatures by up to 8^{o}C and augmenting the lower temperature by up to 4^{o}C.

The proposed hybrid system aims to overcome some of the limitations of both EAHEs and PCMs. A series of experiments was undertaken to assess its potential, testing it against regular plasterboard and against PCM board alone. The system was found to be especially effective at reducing the peak temperatures but did not greatly influence lower temperatures.

The system was found to be promising but probably more effective in a warmer climate. Further work involves the development of a way to simulate it so more variables can be tested in less time before a new set of experiments is designed.

Another suggestion of further work is to try water in the EAHEs pipes linked to a heat exchanger. This way, water could be used to discharge heat from the PCM but also to condition air to be delivered to the space.

One of the main limitations of this work was time. The use and dependency on real life experiments (such as the houses and their systems) were both, exciting and limiting. Many things that caused delays were out of the author's control but still represented a large amount of learning and experience.

In summary, there is overheating in the UK today, especially in MMC houses but that is totally dependent on the design and use of the house. Thermal mass is desirable and can assist the mitigation of overheating and the improvement of overall conditions but it is not essential in the UK today. However, it will become crucial in the future (short and long term) that thermal mass is included in the construction of dwellings, either in the envelope (by traditional means of PCM elements) or by other strategies such as EAHEs in addition to the traditional passive means of environmental control.

The promotion of MMC has put more pressure on designers not just because the projects are almost totally controlled by them but also because it has never been more vital to understand and implement the principles of environmental design.

> *"The important thing is not to stop questioning."*
>
> Albert Einstein

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APPENDIX 1

This section details the thermal properties of each layer of the construction types used in Chapter 5. The top layer is always inside the building and the description, from left to right, includes the layer number, the layer code, the width used (in millimetres), the conductivity of the material (in W/m^{2}K), the density of the material (in kg/m^3), the specific heat capacity of the material (J/kgK) and a short description.

It can also be appreciated that internal and external solar Absorptance, internal and external Emissivity, and Conductance (U-Value) were left similar for all construction types.

Opaque Construction | Name: 1_BrickBlock (BB) | Description: Plaster, Aerated concrete block, Rockwool, Brick Outer L

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.725	0.400	0.930	0.900	0.121	2.825

Layer	M-Code	Width...	Cond...	Density...	Spec...	Description
Inside	Plaster Lightweight	10.0	0.079	400.0	837.0	LIGHTWEIGHT PLASTER 1 *4
2	Concrete Block Aerated	100.0	0.85	400.0	1100.0	AERATED, AIR CURED CONCRETE BLOCK *1
3	Phenolic Kingspan Kooltherm	190.0	0.024	35.0	1470.0	Phenolic Insulation
4	Brick Outer Leaf (CIBSE)	110.0	0.96	2000.0	650.0	BRICKWORK *4

Figure 9-1: Brick and Block full fill cavity wall (BB) – thermal properties of each layer

Opaque Construction | Name: !_TimberFrame (TF) | Description: Plasterboard, Rockwool, CPB, Rockwool, Air, Brick Outer

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.725	0.400	0.930	0.900	0.119	4.791

Layer	M-Code	Width ...	Cond...	Density ...	Spec...	Description
Inside	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4
2	Rockwool	140.0	0.034	23.0	710.0	MINERAL WOOL, FILL TYPE *3
3	Plywood (CIBSE)	10.0	0.13	544.0	1214.0	PLYWOOD 3 *3
4	Rockwool	130.0	0.034	23.0	710.0	MINERAL WOOL, FILL TYPE *3
5	AirCavity 50mm	50.0	0.0	0.0	0.0	50MM AIR (HORIZONTAL FLOW)
6	Brick Outer Leaf (CIBSE)	110.0	0.96	2000.0	650.0	BRICKWORK *4

Figure 9-2: Timber frame part fill cavity wall (TF) – thermal properties of each layer

Opaque Construction | Name: :oncFormwork (ICF) | Description: Plasterboard, EPS, Concrete, EPS, EPS

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.700	0.400	0.900	0.900	0.122	116.499

Layer	M-Code	Width...	Cond...	Density ...	Spec...	Description
Inside	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4
2	EPS (Polystyrene)(CIBSE)	70.0	0.035	23.0	1470.0	POLYSTRENE EXPANDED SHEET CLOSED CELL
3	Concrete Heavyweight (CIBSE)	158.0	1.3	2000.0	840.0	CONCRETE 3% m.c. 3 *3
4	EPS (Polystyrene)(CIBSE)	70.0	0.035	23.0	1470.0	POLYSTRENE EXPANDED SHEET CLOSED CELL
5	EPS (Polystyrene)(CIBSE)	140.0	0.035	23.0	1470.0	POLYSTRENE EXPANDED SHEET CLOSED CELL
6	Surface Finish 0.7 Absorp	5.0	0.79	1330.0	1000.0	Absorptance 0.7, similar brick

Figure 9-3: Insulated concrete formwork wall (ICF) – thermal properties of each layer

Opaque Construction | Name: 4_SteelFrame (SF) | Description: Plasterboard, CPB, Rockwool, CPB, EPS

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.700	0.400	0.900	0.900	0.121	4.871

Layer	M-Code	Width...	Cond...	Density ...	Spec...	Description
Inside	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4
2	Rockwool	90.0	0.034	23.0	710.0	MINERAL WOOL, FILL TYPE *3
3	Plywood (CIBSE)	10.0	0.13	544.0	1214.0	PLYWOOD 3 *3
4	EPS (Polystyrene)(CIBSE)	190.0	0.035	23.0	1470.0	POLYSTRENE EXPANDED SHEET CLOSED CELL *2
5	Surface Finish 0.7 Absorp	5.0	0.79	1330.0	1000.0	Absorptance 0.7, similar brick

Figure 9-4: Steel frame wall (SF) – thermal properties of each layer

Opaque Construction | Name: ucInsPanels (SIPs) | Description: Plasterboard, Air, Softwood, PUR, Softwood, Plaster

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.700	0.400	0.900	0.900	0.121	2.237

Layer	M-Code	Width...	Cond...	Density ...	Spec...	Description
Inside	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4
2	AirCavity 50mm	50.0	0.0	0.0	0.0	50MM AIR (HORIZONTAL FLOW)
3	Softwood Board (CIBSE)	15.0	0.17	550.0	1880.0	SOFTWOOD 2 *2
4	PUR (Polyurethane)	195.0	0.025	30.0	1400.0	POLYURETHANE BOARD *3
5	Softwood Board (CIBSE)	15.0	0.17	550.0	1880.0	SOFTWOOD 2 *2
6	Surface Finish 0.7 Absorp	5.0	0.79	1330.0	1000.0	Absorptance 0.7, similar brick

Figure 9-5: Structural insulated panel wall (SIPs) – thermal properties of each layer

Opaque Construction | Name: 6_CrossLamTimber | Description: Plasterboard, Air, Timber, Rockwool, Air, Brick Outer Leaf

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.700	0.400	0.900	0.900	0.12	10.073

Layer	M-Code	Width...	Cond...	Density ...	Spec...	Description
Inside	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4
2	AirCavity 50mm	50.0	0.0	0.0	0.0	50MM AIR (HORIZONTAL FLOW)
3	Cross L Timber Spruce (CLT)	100.0	0.105	420.0	1420.0	SPRUCE, 12% m.c. *2
4	Phenolic Kingspan Kooltherm	170.0	0.024	35.0	1470.0	Phenolic Insulation
5	Surface Finish 0.7 Absorp	5.0	0.79	1330.0	1000.0	Absorptance 0.7, similar brick

Figure 9-6: Cross laminated timber wall (CLT) – thermal properties of each layer

Opaque Construction | Name: 7_SolidBlock (SB) | Description: Plaster, Aerated concrete block, Rockwool, Brick Outer L

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.700	0.400	0.900	0.900	0.12	7.253

Layer	M-Code	Width ...	Cond...	Density ...	Spec...	Description
Inside	Plaster Lightweight	10.0	0.079	400.0	837.0	LIGHTWEIGHT PLASTER 1 *4
2	Concrete Block Aerated	250.0	0.85	400.0	1100.0	AERATED, AIR CURED CONCRETE BLOCK *1
3	Phenolic Kingspan Kooltherm	190.0	0.024	35.0	1470.0	Phenolic Insulation
4	Surface Finish 0.7 Absorp	5.0	0.79	1330.0	1000.0	Absorptance 0.7, similar brick

Figure 9-7: Solid Concrete Block wall (MT) – thermal properties of each layer

Opaque Construction	Name	tConcPanels (PCP)	Description	Plaster, Concrete, PUR, Concrete

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.700	0.400	0.900	0.900	0.122	5.014

Layer	M-Code	Width ...	Cond...	Density ...	Spec...	Description
Inside	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4
2	Concrete Heavyweight (CIBSE)	100.0	1.3	2000.0	840.0	CONCRETE 3% m.c. 3 *3
3	PUR (Polyurethane)	200.0	0.025	30.0	1400.0	POLYURETHANE BOARD *3
4	Concrete Heavyweight (CIBSE)	80.0	1.3	2000.0	840.0	CONCRETE 3% m.c. 3 *3
5	Surface Finish 0.7 Absorp	5.0	0.79	1330.0	1000.0	Absorptance 0.7, similar brick

Figure 9-8: Precast concrete panel wall (PCP) – thermal properties of each layer

Opaque Construction	Name	Ground Floor	Description	0.150 Wooden Floor, Concrete Screed, Concrete slab, Po

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.650	0.600	0.900	0.900	0.102	215.720

Layer	M-Code	Width...	Cond...	Density ...	Spec...	Description
Inside	am1wood\28	12.0	0.112	500.0	2805.0	PINE, WHITE *2
2	am1concd\9	40.0	1.28	2100.0	1000.0	CONCRETE SCREED *3
3	am1ins\15	150.0	0.03	140.0	1380.0	POLYSTRENE, EXPANDED *2
4	am1concd\3	125.0	1.45	2200.0	920.0	CONCRETE 3% m.c. 10 *3
5	am1ins\15	100.0	0.03	140.0	1380.0	POLYSTRENE, EXPANDED *2
6	am1soil\7	50.0	0.329	1515.0	796.0	SAND, DRY *2
7	am1aggr\4	600.0	0.55	1580.0	1057.0	CRUSHED BRICK AGGREGATE *1

Figure 9-9: Ground floor – thermal properties of each layer

Opaque Construction	Name	Roof	Description	0.148 Mineral wool insulation 300mm

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.700	0.400	0.900	0.550	0.103	31.901

Layer	M-Code	Width...	Cond...	Density ...	Spec...	Description
Inside	am1plast\22	25.0	0.18	960.0	837.0	PLASTERBOARD, FOIL BACKED *2
2	am1ins\7	450.0	0.048	240.0	1050.0	MINERAL WOOL BOARD *4
3	am1cav\12	20.0	0.0	0.0	0.0	20MM AIR (UPWARD FLOW)
4	am1asph\9	2.0	0.41	960.0	1000.0	ROOFING FELT 1 *2
5	am1tile\2	5.0	0.85	1900.0	837.0	CLAY,RED/BROWN *4

Figure 9-10: Roof – thermal properties of each layer

APPENDIX 2

This appendix presents more results of section 5.4 (Chapter 5) which includes Case 0, Case 1, Case 2 and Case 3.

1. Case 0

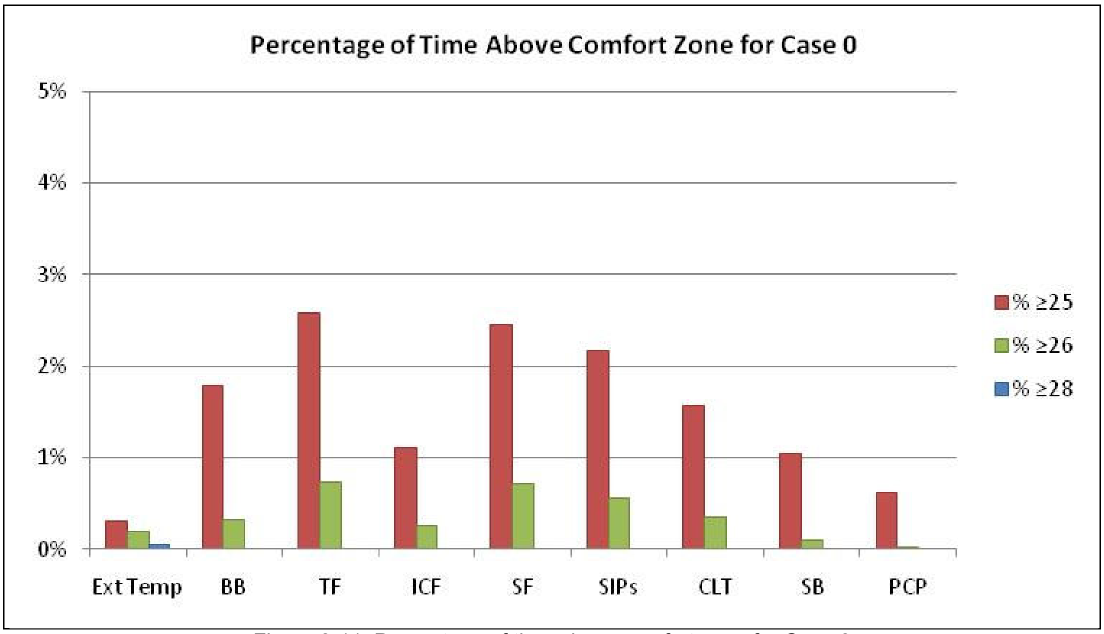

Figure 9-11: Percentage of time above comfort zone for Case 0

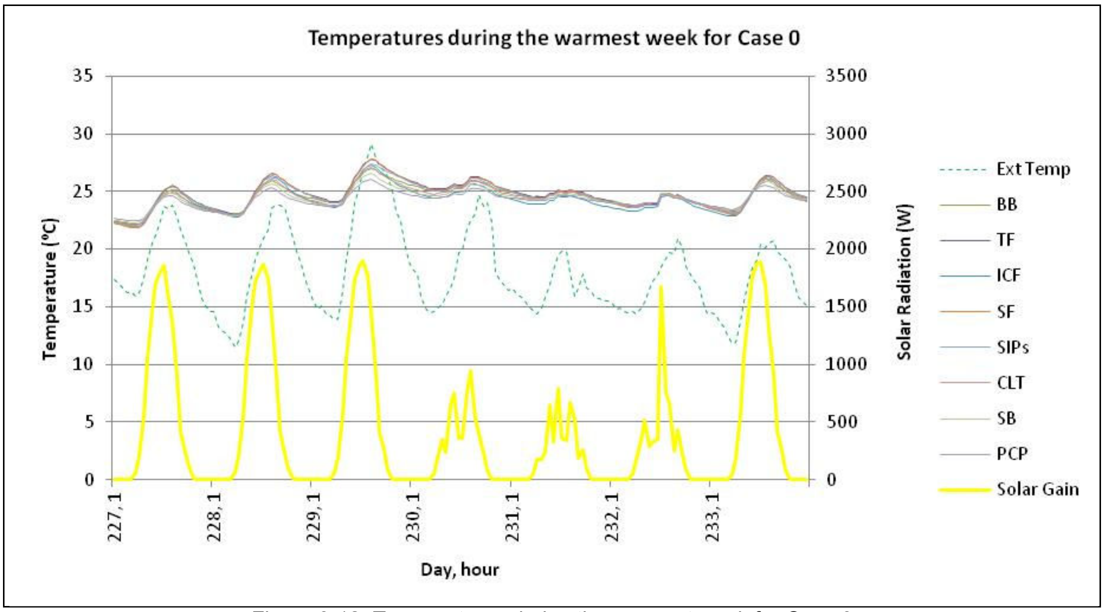

Figure 9-12: Temperatures during the warmest week for Case 0

2. Case 1

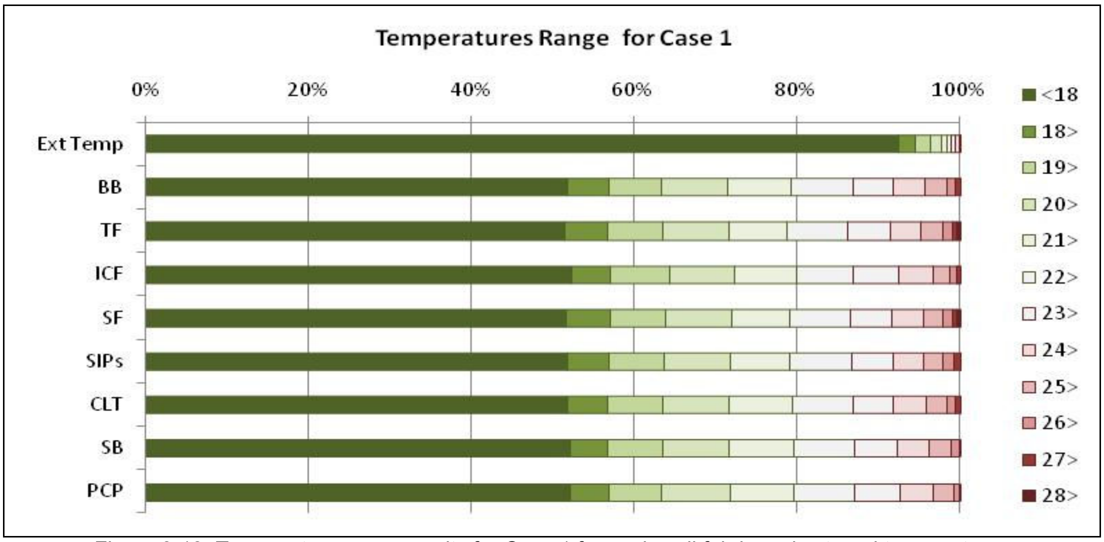

Figure 9-13: Temperature range results for Case 1 for each wall fabric and external temperatures

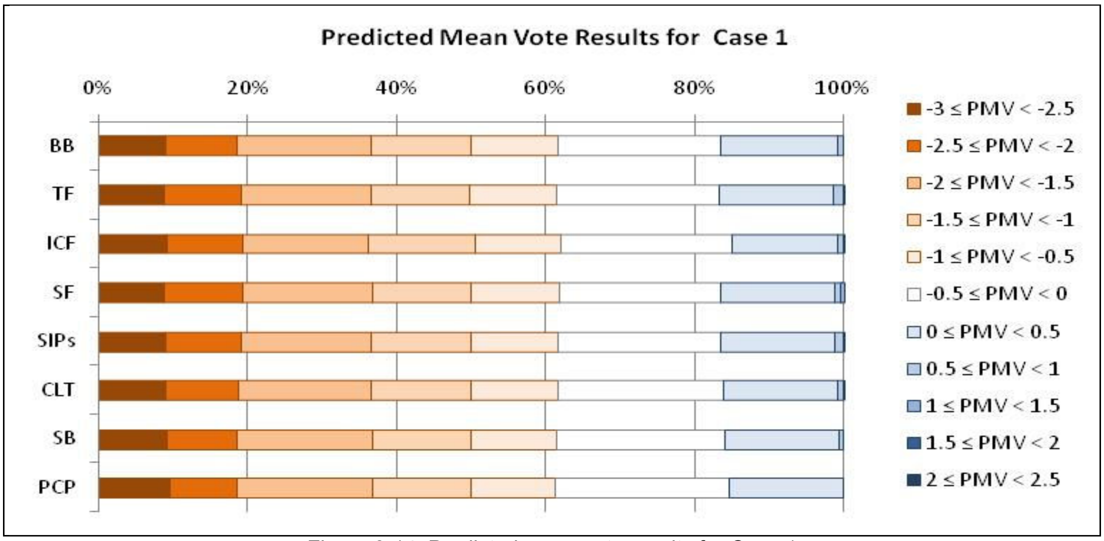

Figure 9-14: Predicted mean vote results for Case 1

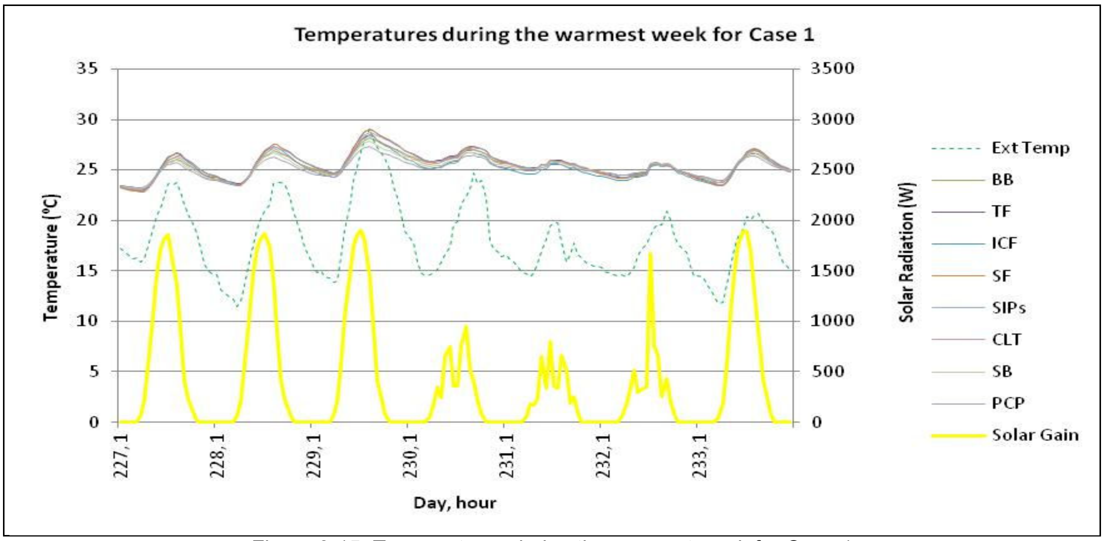

Figure 9-15: Temperatures during the warmest week for Case 1

3. Case 2

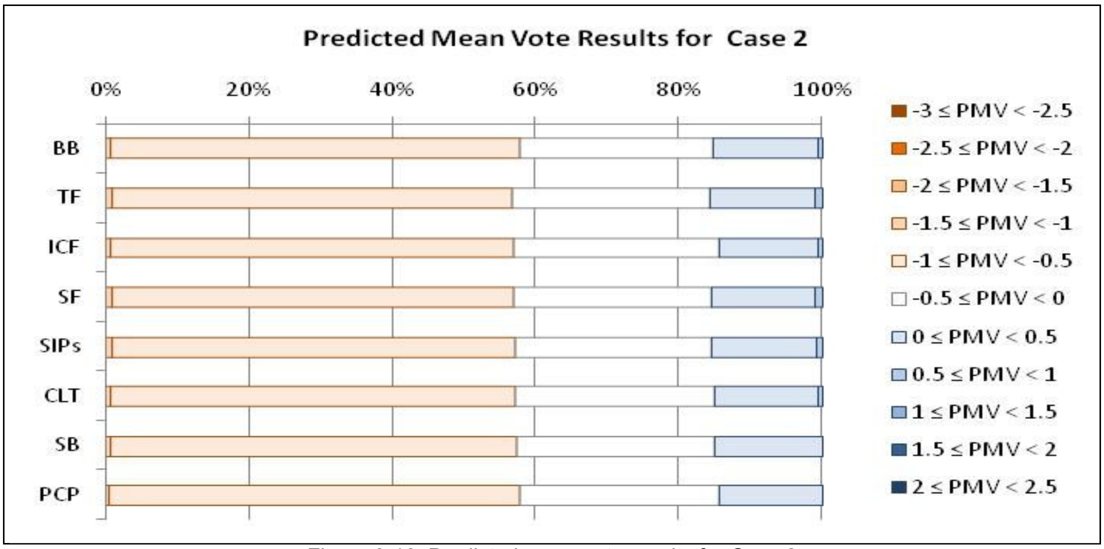

Figure 9-16: Predicted mean vote results for Case 2

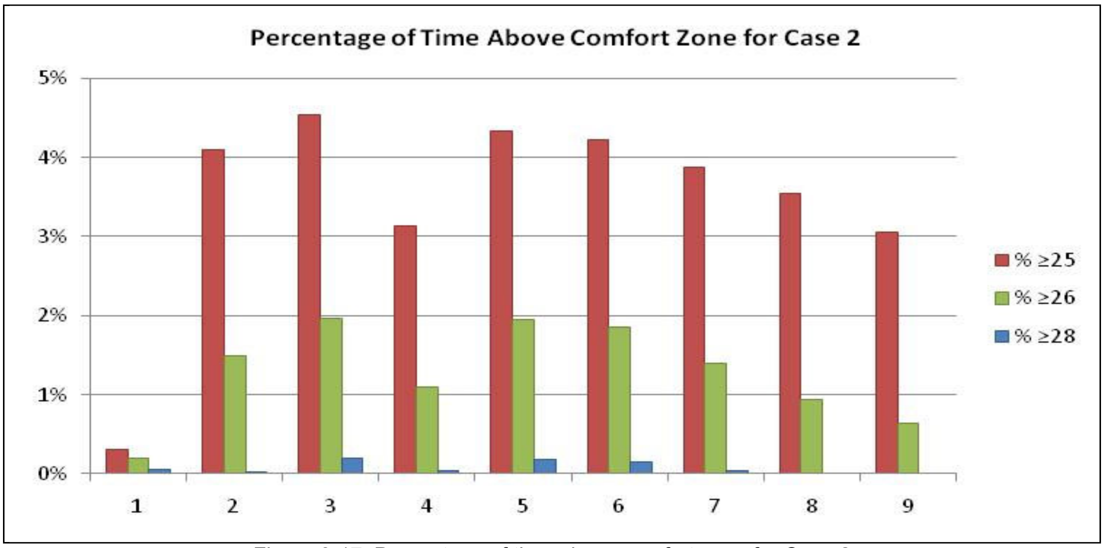

Figure 9-17: Percentage of time above comfort zone for Case 2

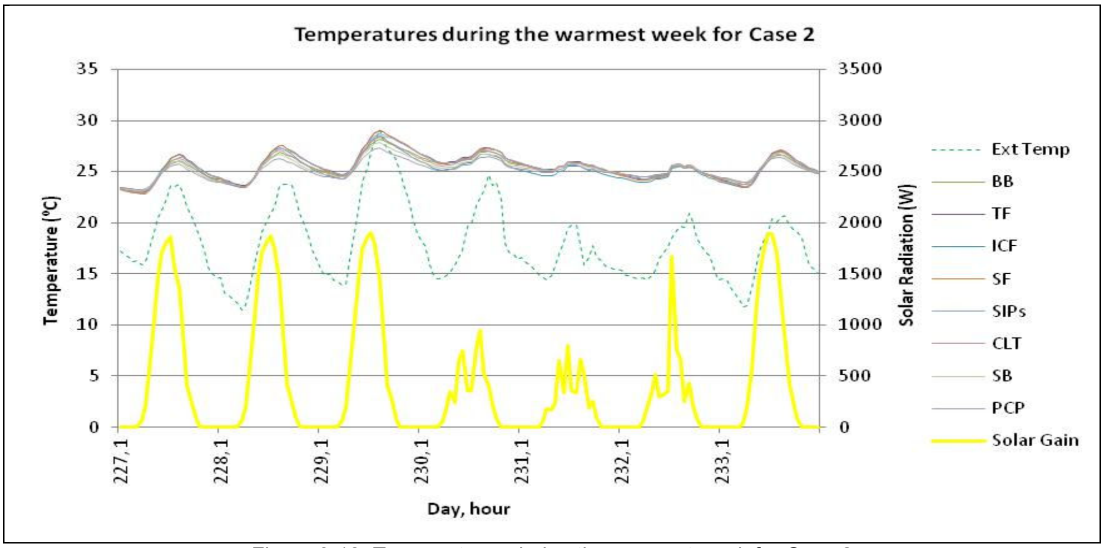

Figure 9-18: Temperatures during the warmest week for Case 2

4. Case 3

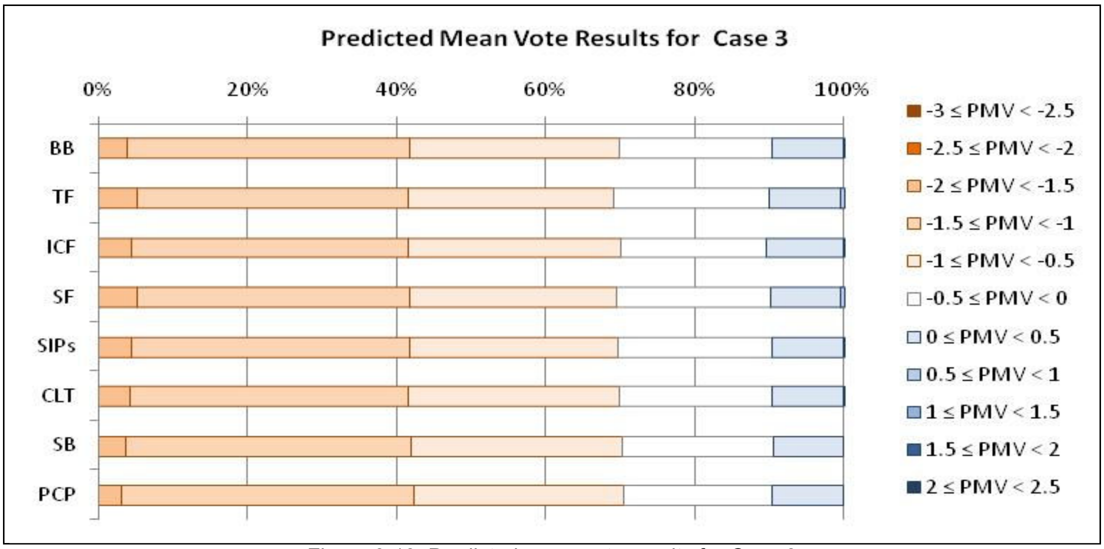

Figure 9-19: Predicted mean vote results for Case 3

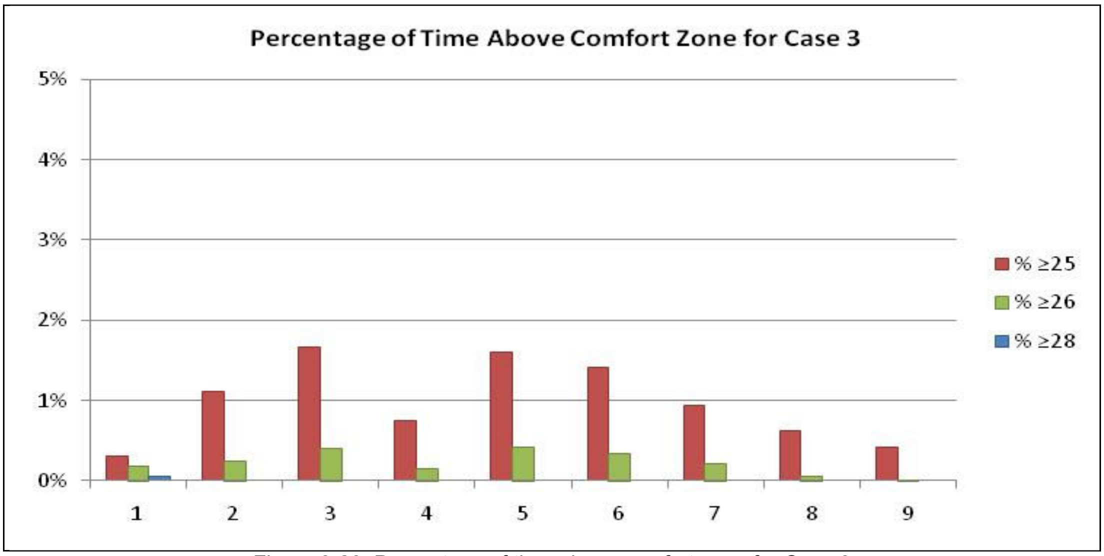

Figure 9-20: Percentage of time above comfort zone for Case 3

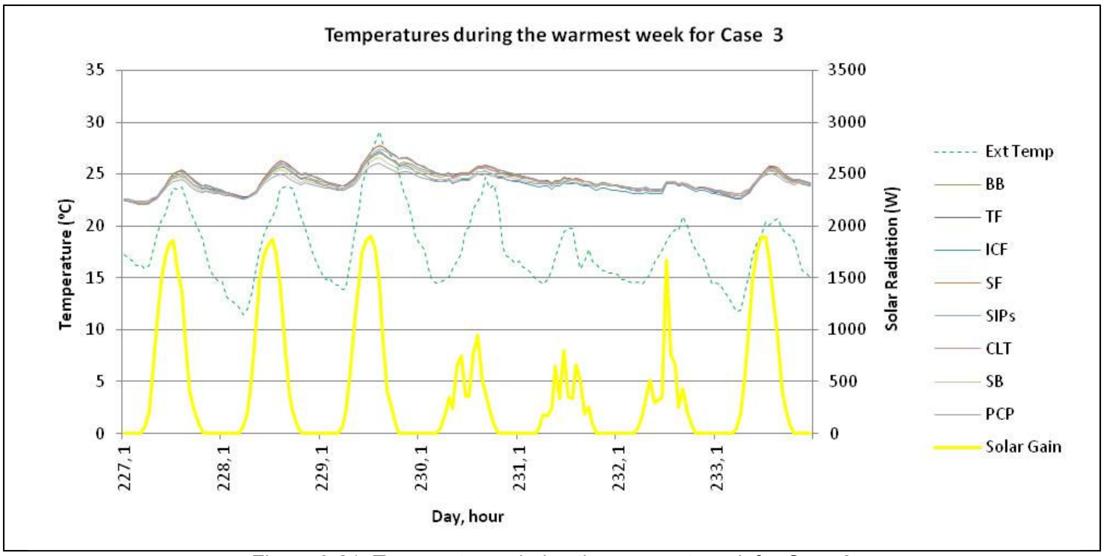

Figure 9-21: Temperatures during the warmest week for Case 3

APPENDIX 3

This appendix presents more results of section 5.5 (Chapter 5) which includes Case 4, Case 5, Case 6 and Case 7.

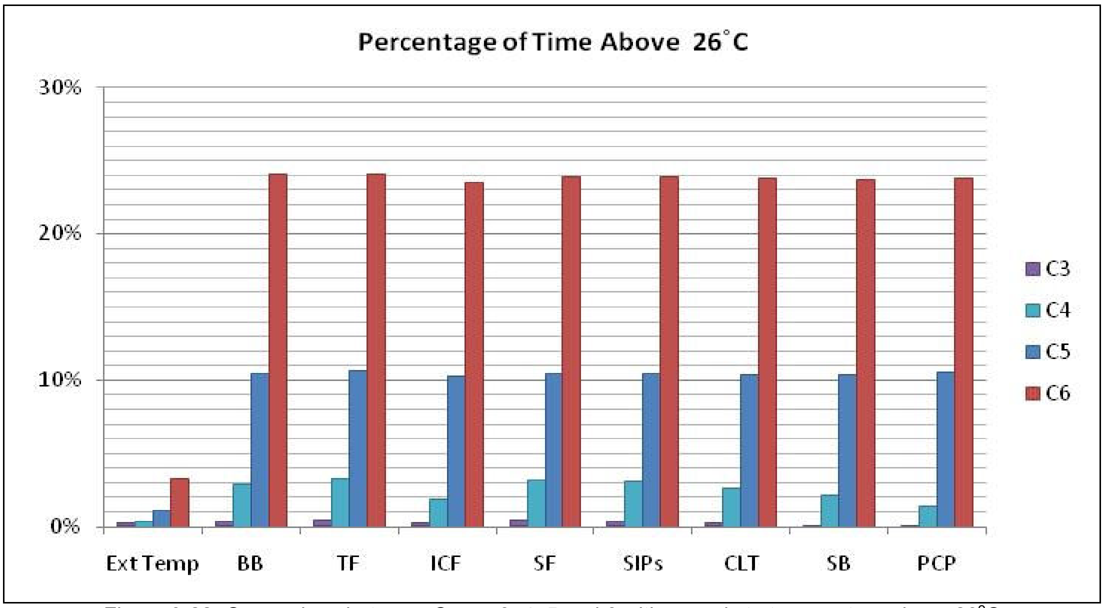

Figure 9-22: Comparison between Cases 3, 4, 5 and 6 with regards to temperature above 26°C

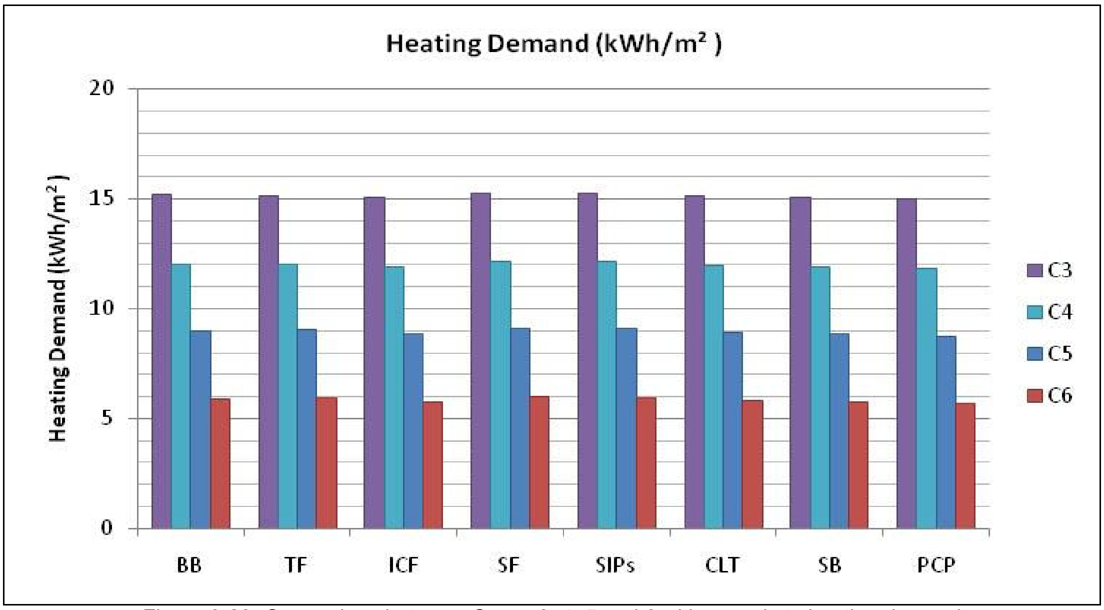

Figure 9-23: Comparison between Cases 3, 4, 5 and 6 with regards to heating demand

APPENDIX 4

Stoneguard House (Chapter 6) plans with dimensions.

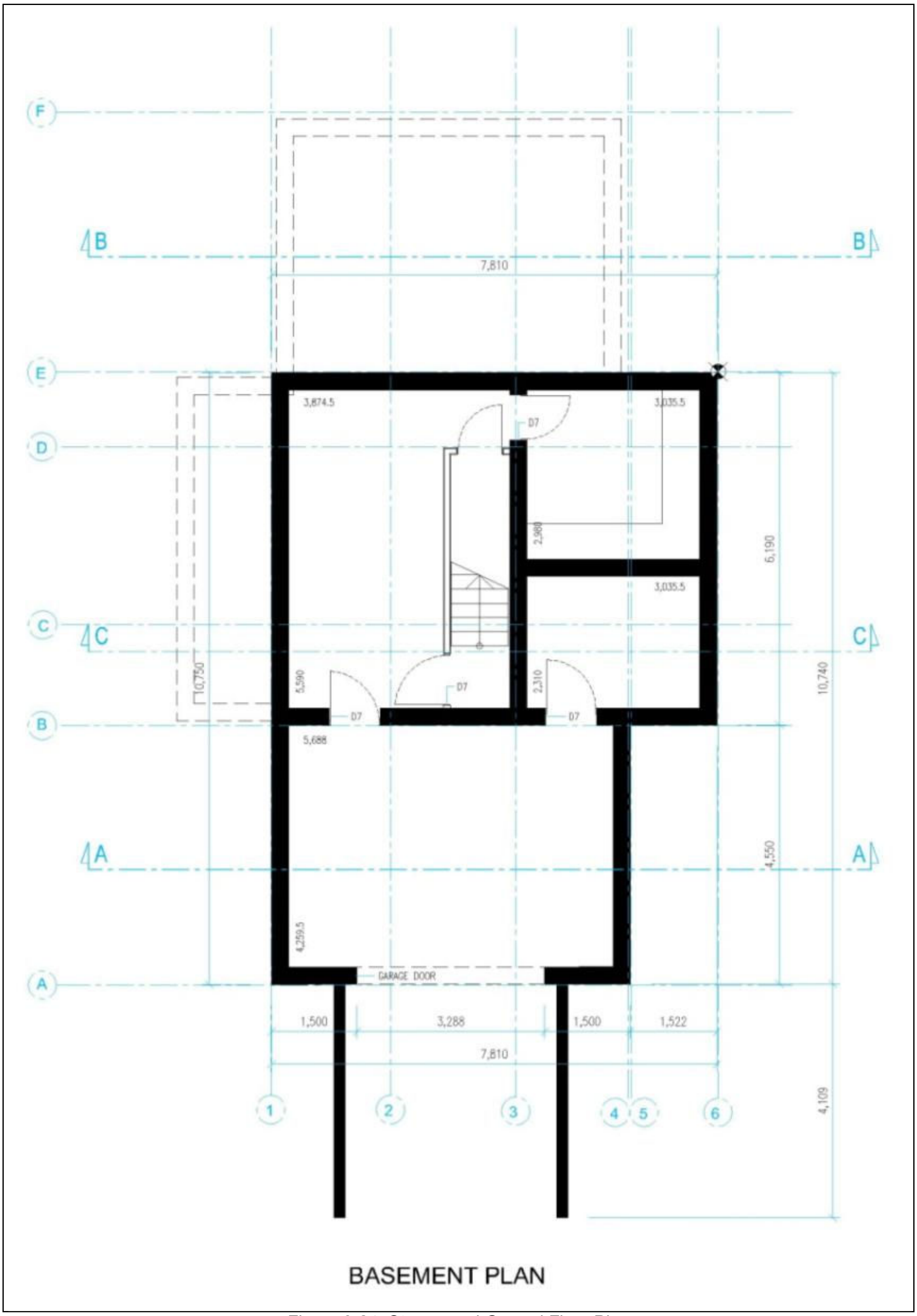

Figure 9-24: Stoneguard Ground Floor Plan

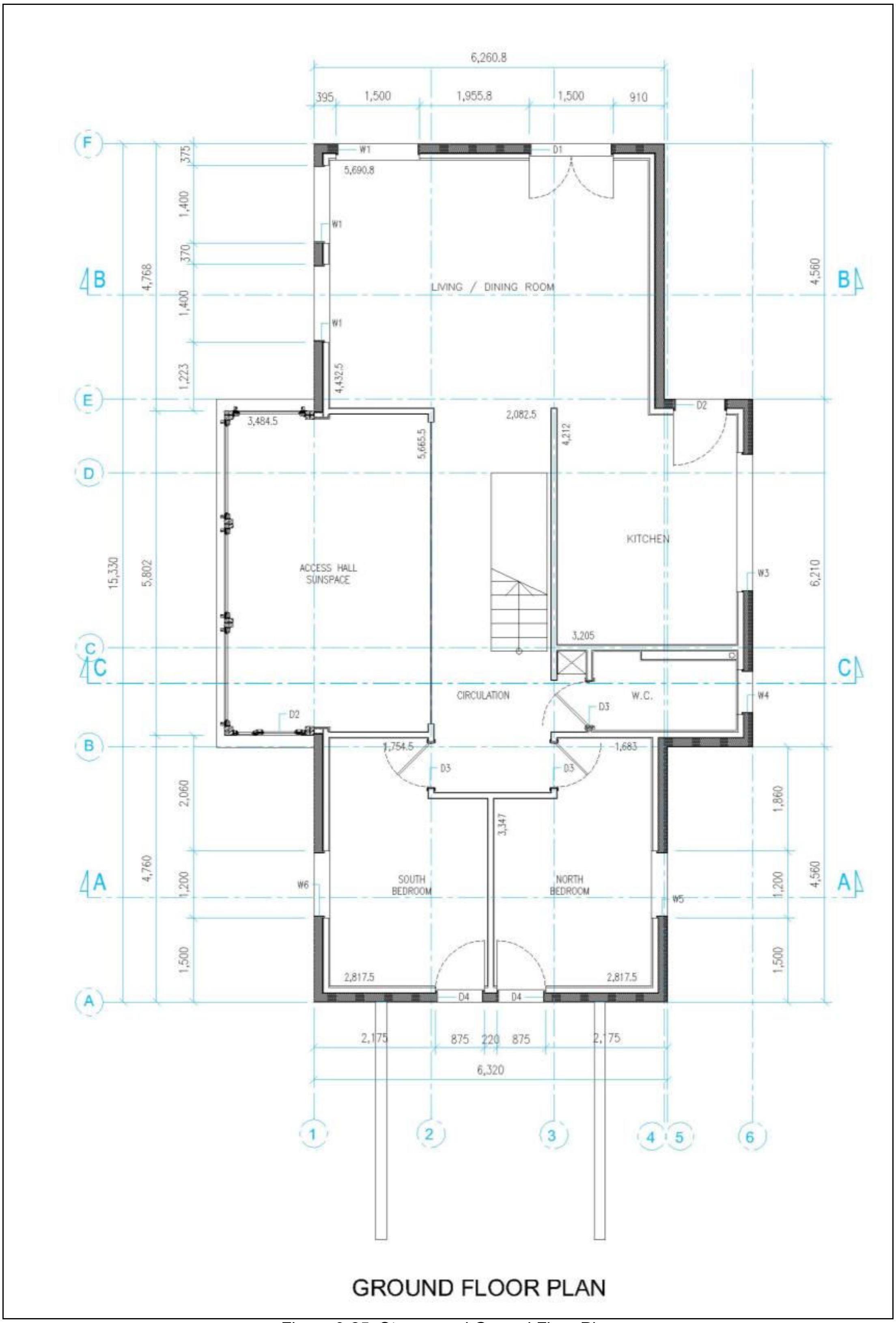

Figure 9-25: Stoneguard Ground Floor Plan

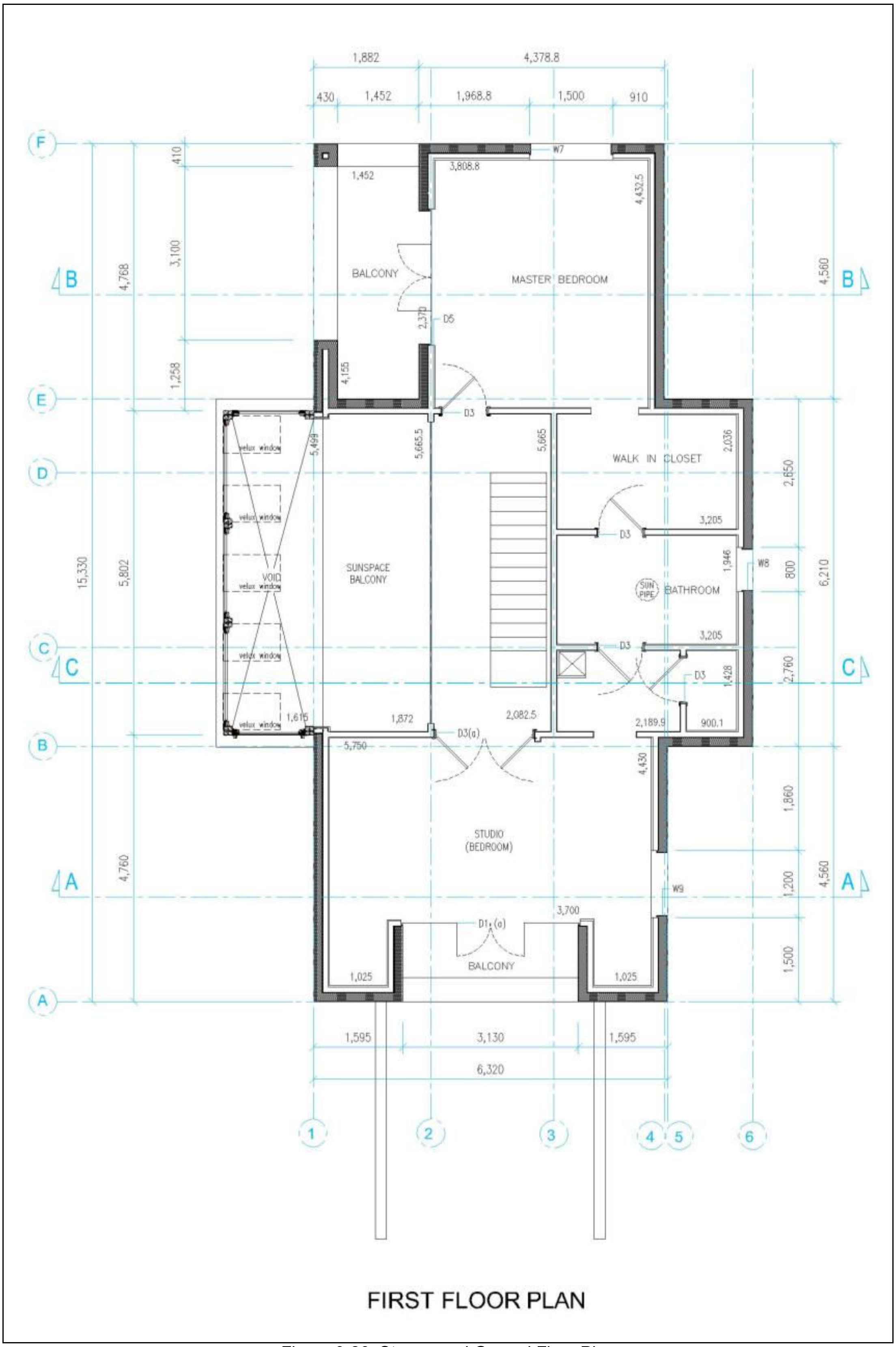

Figure 9-26: Stoneguard Ground Floor Plan

APPENDIX 5

Images of the Stoneguard House Tas model geometry and material properties (Chapter 6).

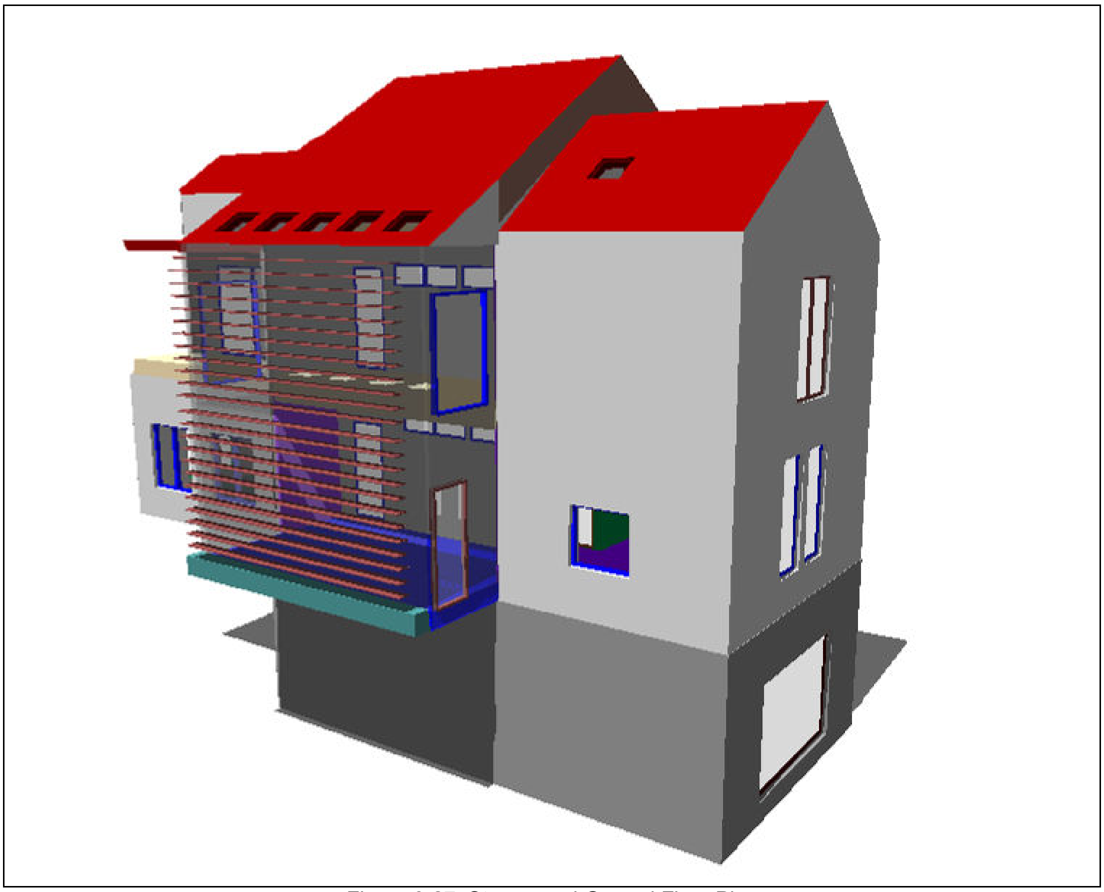

Figure 9-27: Stoneguard Ground Floor Plan

Opaque Construction | Name: W ext 1 (ICF) | Description: Plasterboard, EPS, Concrete, EPS, EPS

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.700	0.400	0.900	0.900	0.238	76.470

Layer	M-Code	Width (...	Cond...	Density ...	Spec...	Description
Inside	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4
2	EPS (Polystyrene)(CIBSE)	70.0	0.035	23.0	1470.0	POLYSTRENE EXPANDED SHEET CLOSED CE
3	Concrete Heavyweight (CIBSE)	158.0	1.3	2000.0	840.0	CONCRETE 3% m.c. 3 *3
4	EPS (Polystyrene)(CIBSE)	70.0	0.035	23.0	1470.0	POLYSTRENE EXPANDED SHEET CLOSED CE
5	Surface Finish 0.7 Absorp	5.0	0.79	1330.0	1000.0	Absorptance 0.7, similar brick

Figure 9-28: Basement external wall to underground

Opaque Construction | Name: W ext 2 (ICF) | Description: Plasterboard, EPS, Concrete, EPS, EPS

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.700	0.400	0.900	0.900	0.131	113.286

Layer	M-Code	Width...	Cond...	Conv...	Densit...	Spec...	Description
Inside	Plasterboard (CIBSE)	12.5	0.16	0.0	800.0	840.0	PLASTERBOARD *4
2	EPS (Polystyrene)(CIBSE)	70.0	0.035	0.0	23.0	1470.0	POLYSTRENE EXPANDED SHEET CLO...
3	Concrete Heavyweight (CIBSE)	158.0	1.3	0.0	2000.0	840.0	CONCRETE 3% m.c. 3 *3
4	EPS (Polystyrene)(CIBSE)	70.0	0.035	0.0	23.0	1470.0	POLYSTRENE EXPANDED SHEET CLO...
5	EPS (Polystyrene)(CIBSE)	120.0	0.035	0.0	23.0	1470.0	POLYSTRENE EXPANDED SHEET CLO...
6	Surface Finish 0.7 Absorp	5.0	0.79	0.0	1330.0	1000.0	Absorptance 0.7, similar brick

Figure 9-29: Basement external wall, exposed

Opaque Construction | Name: W ext 3 (SF) | Description: Plasterboard, CPB, Rockwool, CPB, EPS

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.700	0.400	0.900	0.900	0.141	5.617

Layer	M-Code	Width...	Cond...	Density ...	Spec...	Description
Inside	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4
2	Rockwool	90.0	0.034	23.0	710.0	MINERAL WOOL, FILL TYPE *3
3	WoodChip Cement board (CIBSE)	12.5	0.15	530.0	1470.0	Wood chip board cement bonded
4	EPS (Polystyrene)(CIBSE)	150.0	0.035	23.0	1470.0	POLYSTRENE EXPANDED SHEET CLOSED CEI
5	Surface Finish 0.7 Absorp	5.0	0.79	1330.0	1000.0	Absorptance 0.7, similar brick

Figure 9-30: Ground and first floors external walls

Opaque Construction | Name: W int 1 (ICF) | Description: Plasterboard, EPS, Concrete, EPS, EPS

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.400	0.400	0.900	0.900	0.234	77.833

Layer	M-Code	Width...	Cond...	Density ...	Spec...	Description
Inside	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4
2	EPS (Polystyrene)(CIBSE)	70.0	0.035	23.0	1470.0	POLYSTRENE EXPANDED SHEET CLOSED CEL...
3	Concrete Heavyweight (CIBSE)	158.0	1.3	2000.0	840.0	CONCRETE 3% m.c. 3 *3
4	EPS (Polystyrene)(CIBSE)	70.0	0.035	23.0	1470.0	POLYSTRENE EXPANDED SHEET CLOSED CEL...
5	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4

Figure 9-31: Basement internal wall

Opaque Construction | Name: W int 2 (SF) | Description: Plasterboard, CPB, Rockwool, CPB, EPS

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.400	0.400	0.900	0.900	0.337	0.000

Layer	M-Code	Width...	Conduc...	Density ...	Spec...	Description
Inside	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4
2	WoodChip Cement board (CIBSE)	12.5	0.15	530.0	1470.0	Wood chip board cement bonded
3	Rockwool	90.0	0.034	23.0	710.0	MINERAL WOOL, FILL TYPE *3
4	WoodChip Cement board (CIBSE)	12.5	0.15	530.0	1470.0	Wood chip board cement bonded
5	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4

Figure 9-32: Ground and first floors internal walls

Opaque Construction | Name: nheated Basement | Description: 0.150 Wooden Floor, Concrete Screed, Concrete slab, Pc

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.650	0.600	0.900	0.900	0.612	78.751

Layer	M-Code	Width...	Cond...	Density ...	Specific...	Description
Inside	am1wood\28	12.0	0.112	500.0	2805.0	PINE, WHITE *2
2	am1concd\9	100.0	1.28	2100.0	1000.0	CONCRETE SCREED *3
3	am1concd\3	300.0	1.45	2200.0	920.0	CONCRETE 3% m.c. 10 *3
4	am1soil\7	50.0	0.329	1515.0	796.0	SAND, DRY *2
5	am1aggr\4	600.0	0.55	1580.0	1057.0	CRUSHED BRICK AGGREGATE *1

Figure 9-33: Unheated basement floor

Opaque Construction | Name: ? Heated Basement | Description: 0.150 Wooden Floor, Concrete Screed, Concrete slab, Pc

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.650	0.600	0.900	0.900	0.298	205.560

Layer	M-Code	Width ...	Cond...	Density ...	Spec...	Description
Inside	am1wood\28	12.0	0.112	500.0	2805.0	PINE, WHITE *2
2	am1concd\9	38.0	1.28	2100.0	1000.0	CONCRETE SCREED *3
3	EPS (Polystyrene)(CIBSE)	62.0	0.035	23.0	1470.0	POLYSTRENE EXPANDED SHEET CLOSED CELL *2
4	am1concd\3	300.0	1.45	2200.0	920.0	CONCRETE 3% m.c. 10 *3
5	am1soil\7	50.0	0.329	1515.0	796.0	SAND, DRY *2
6	am1aggr\4	600.0	0.55	1580.0	1057.0	CRUSHED BRICK AGGREGATE *1

Figure 9-34: Heated basement floor

Opaque Construction	Name	nheated Sunspace	Description	0.150 Wooden Floor, Concrete Screed, Concrete slab, Pc

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.650	0.600	0.900	0.900	0.27	104.525

Layer	M-Code	Width ...	Cond...	Density ...	Specific...	Description
Inside	am1wood\28	12.0	0.112	500.0	2805.0	PINE, WHITE *2
2	am1concd\9	100.0	1.28	2100.0	1000.0	CONCRETE SCREED *3
3	am1concd\3	200.0	1.45	2200.0	920.0	CONCRETE 3% m.c. 10 *3
4	EPS (Polystyrene)(CIBSE)	75.0	0.035	23.0	1470.0	POLYSTRENE EXPANDED SHEET CLOSED CELL *
5	am1soil\7	50.0	0.329	1515.0	796.0	SAND, DRY *2
6	am1aggr\4	600.0	0.55	1580.0	1057.0	CRUSHED BRICK AGGREGATE *1

Figure 9-35: Unheated sunspace floor

Opaque Construction	Name	ext 4 Heated Living	Description	0.150 Wooden Floor, Concrete Screed, Concrete slab, Pc

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.650	0.600	0.900	0.900	0.184	173.243

Layer	M-Code	Width...	Cond...	Density ...	Spec...	Description
Inside	am1wood\28	12.0	0.112	500.0	2805.0	PINE, WHITE *2
2	am1concd\9	38.0	1.28	2100.0	1000.0	CONCRETE SCREED *3
3	EPS (Polystyrene)(CIBSE)	62.0	0.035	23.0	1470.0	POLYSTRENE EXPANDED SHEET CLOSED CELL *2
4	am1concd\3	200.0	1.45	2200.0	920.0	CONCRETE 3% m.c. 10 *3
5	EPS (Polystyrene)(CIBSE)	75.0	0.035	23.0	1470.0	POLYSTRENE EXPANDED SHEET CLOSED CELL *2
6	am1soil\7	50.0	0.329	1515.0	796.0	SAND, DRY *2
7	am1aggr\4	600.0	0.55	1580.0	1057.0	CRUSHED BRICK AGGREGATE *1

Figure 9-36: Heated living room floor

Opaque Construction	Name	int 1 Heated Living	Description	0.150 Wooden Floor, Concrete Screed, Concrete slab, Pc

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.400	0.600	0.900	0.900	0.234	117.289

Layer	M-Code	Width...	Cond...	Density ...	Specific...	Description
Inside	am1wood\28	12.0	0.112	500.0	2805.0	PINE, WHITE *2
2	am1concd\9	38.0	1.28	2100.0	1000.0	CONCRETE SCREED *3
3	EPS (Polystyrene)(CIBSE)	62.0	0.035	23.0	1470.0	POLYSTRENE EXPANDED SHEET CLOSED CELL *
4	am1concd\3	200.0	1.45	2200.0	920.0	CONCRETE 3% m.c. 10 *3
5	EPS (Polystyrene)(CIBSE)	75.0	0.035	23.0	1470.0	POLYSTRENE EXPANDED SHEET CLOSED CELL *
6	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4

Figure 9-37: Heated ground floor/ basement ceiling

Opaque Construction | Name: or Ceiling/First Floor | Description: Plasterboard, CPB, Rockwool, CPB, EPS

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.400	0.600	0.900	0.900	0.211	0.822

Layer	M-Code	Width...	Cond...	Density ...	Specific...	Description
Inside	am1wood\28	12.0	0.112	500.0	2805.0	PINE, WHITE *2
2	Plywood (CIBSE)	22.0	0.13	544.0	1214.0	PLYWOOD 3 *3
3	AirCavity 50mm	50.0	0.0	0.0	0.0	50MM AIR (HORIZONTAL FLOW)
4	Rockwool	140.0	0.034	23.0	710.0	MINERAL WOOL, FILL TYPE *3
5	WoodChip Cement board (CIBSE)	12.5	0.15	530.0	1470.0	Wood chip board cement bonded
6	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4

Figure 9-38: First floor/ ground floor ceiling

Opaque Construction | Name: Roof (Ceiling) | Description: Sloping tiled roof

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.700	0.400	0.900	0.900	0.117	7.030

Layer	M-Code	Width...	Cond...	Density ...	Specific...	Description
Inside	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4
2	Rockwool	120.0	0.034	23.0	710.0	MINERAL WOOL, FILL TYPE *3
3	WoodChip Cement board (CIBSE)	12.5	0.15	530.0	1470.0	Wood chip board cement bonded
4	PUR (Polyurethane)	120.0	0.025	30.0	1400.0	POLYURETHANE BOARD *3
5	am1asph\9	5.0	0.41	960.0	1000.0	ROOFING FELT 1 *2
6	am1tile\2	10.0	0.85	1900.0	837.0	CLAY,RED/BROWN *4

Figure 9-39: Roof

APPENDIX 6

BASF House (Chapter 7) plans with dimensions.

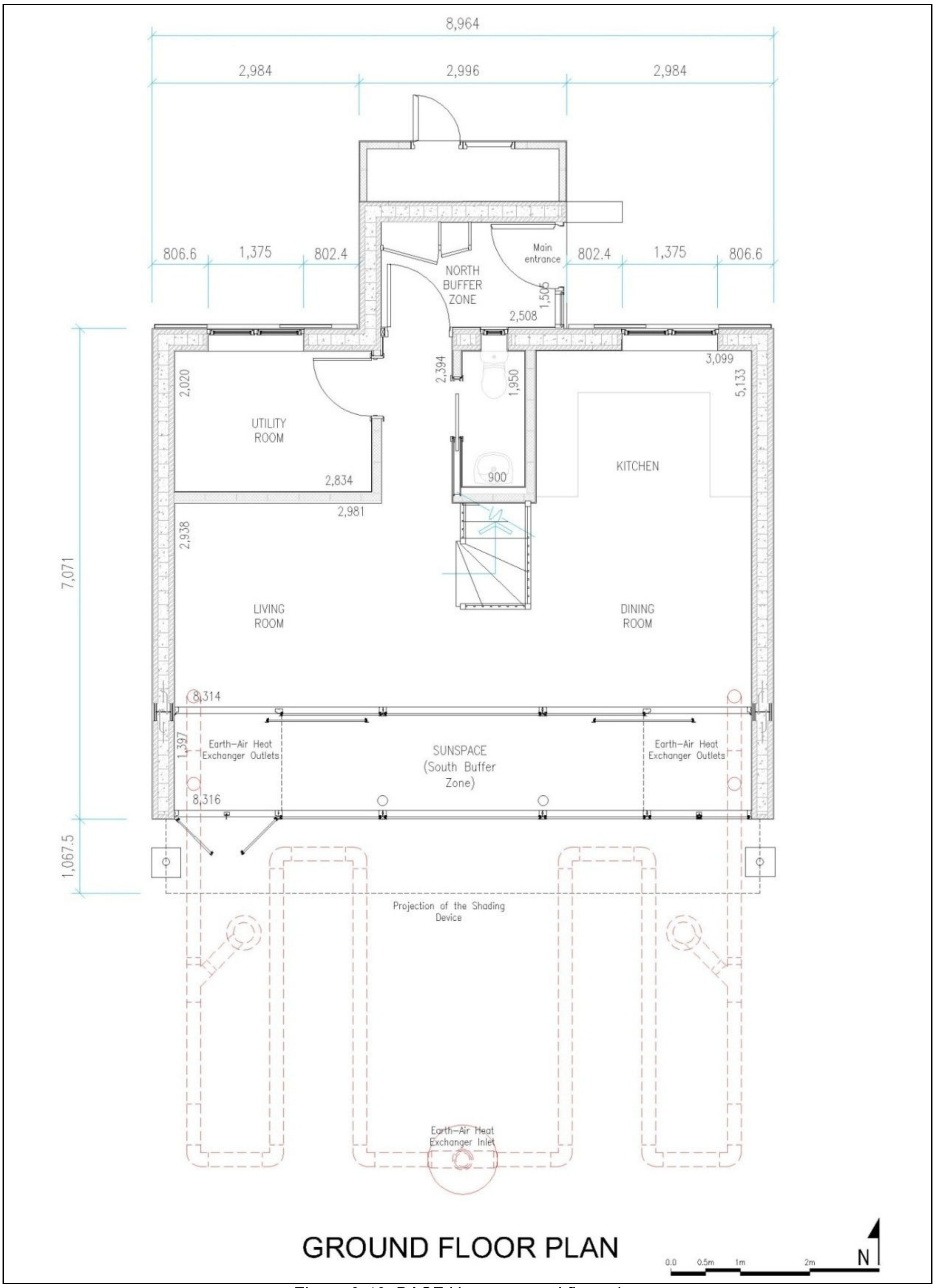

Figure 9-40: BASF House ground floor plan

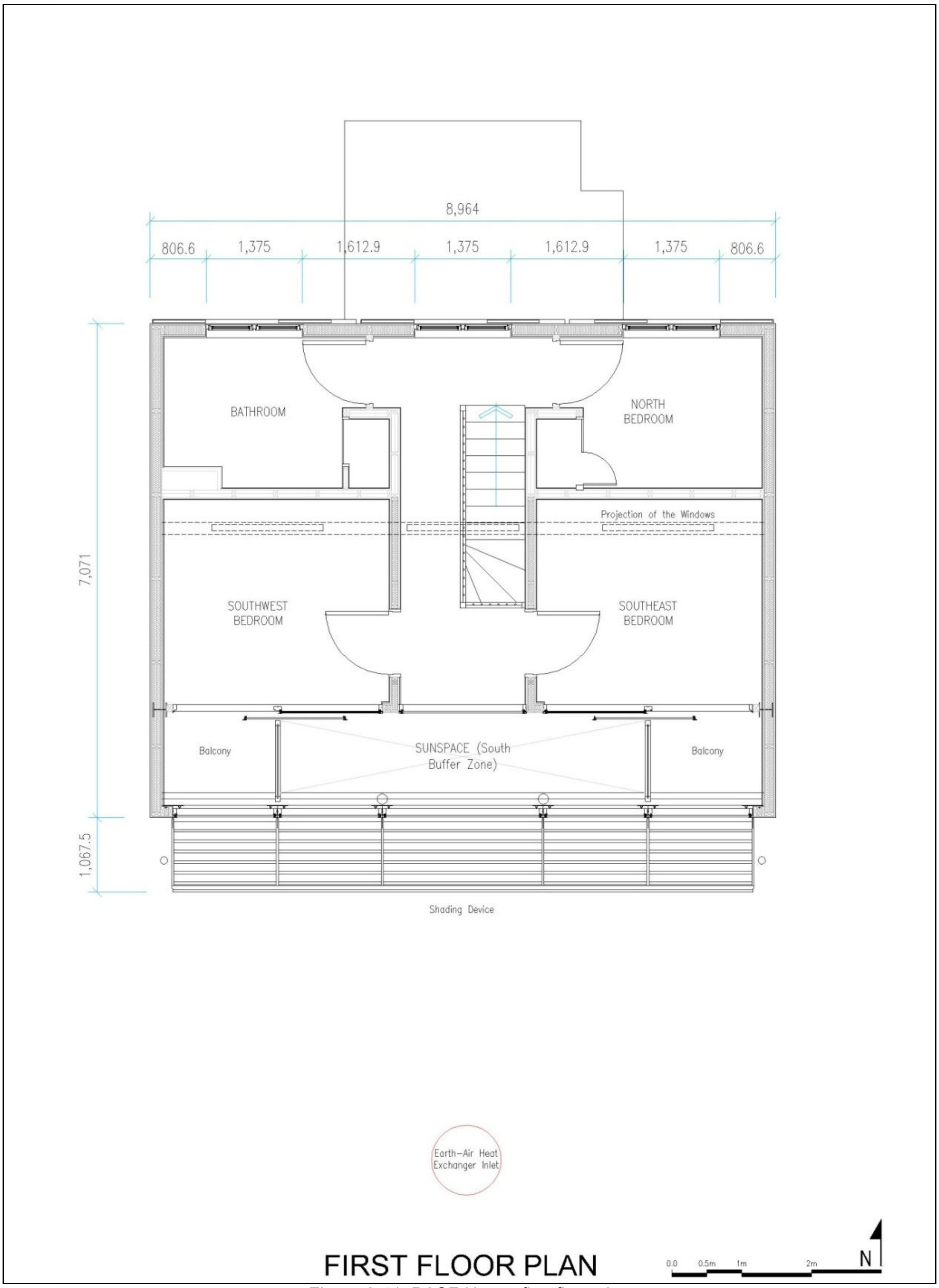

Figure 9-41: BASF House first floor plan

APPENDIX 7

Data collected in summer 2009 at the BASF House (Chapter 7).

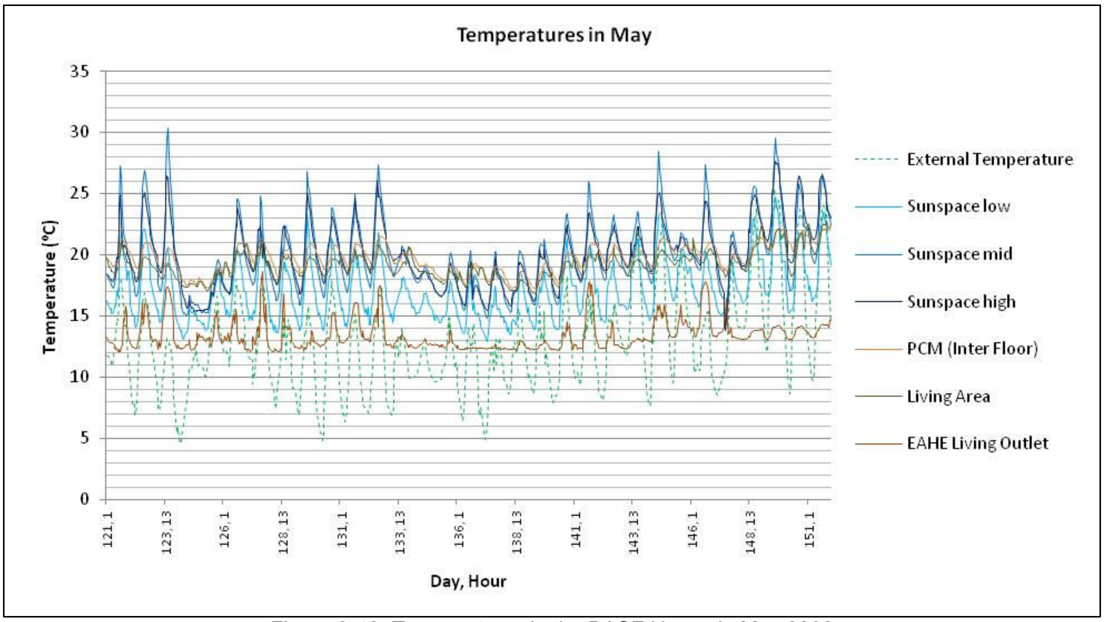

Figure 9-42: Temperatures in the BASF House in May 2009

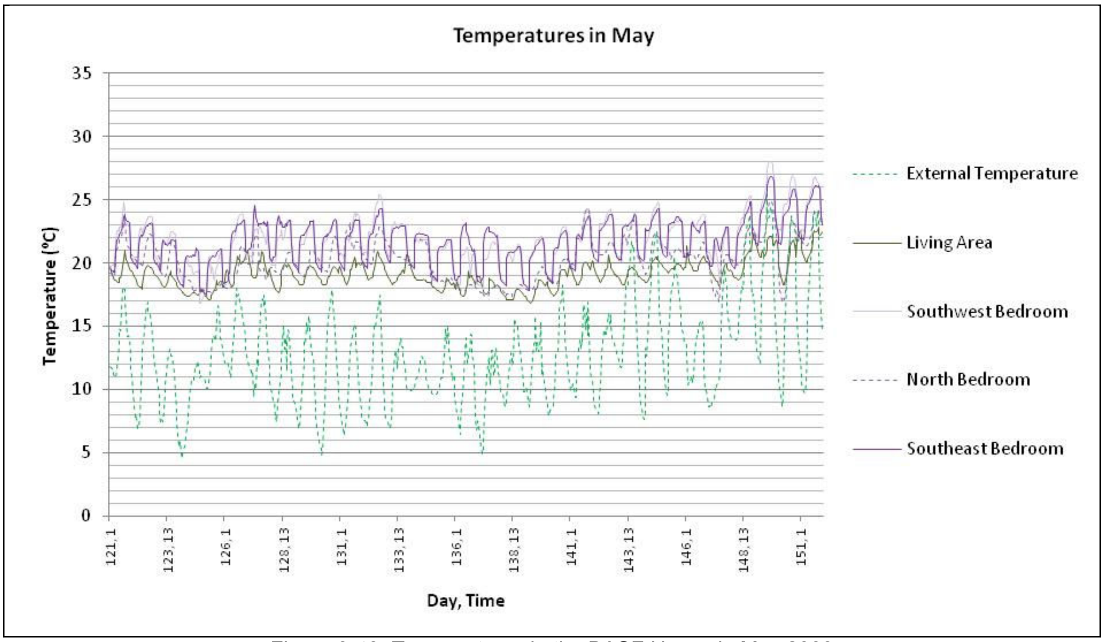

Figure 9-43: Temperatures in the BASF House in May 2009

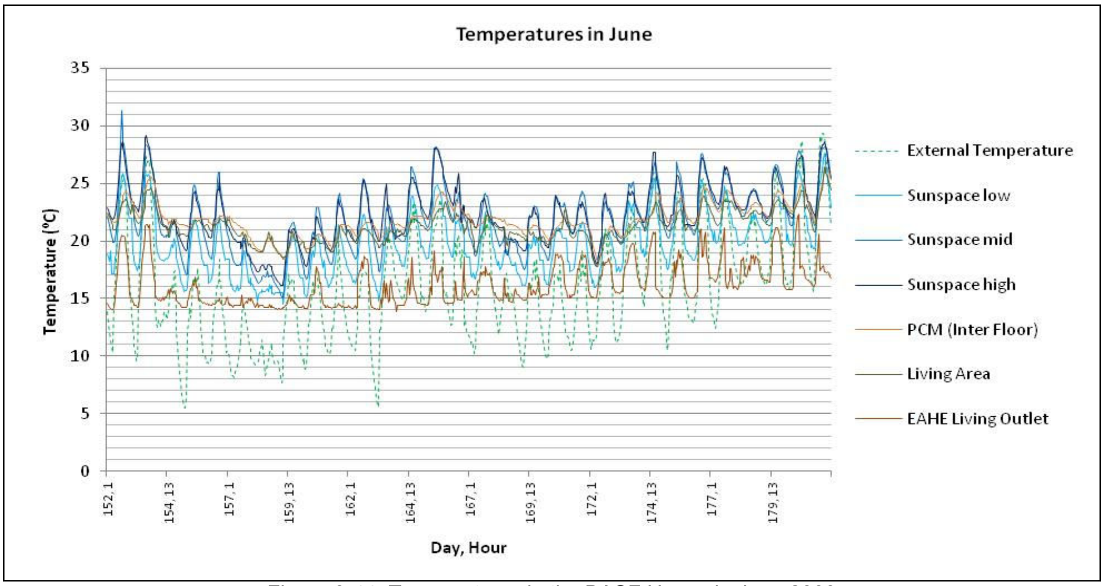

Figure 9-44: Temperatures in the BASF House in June 2009

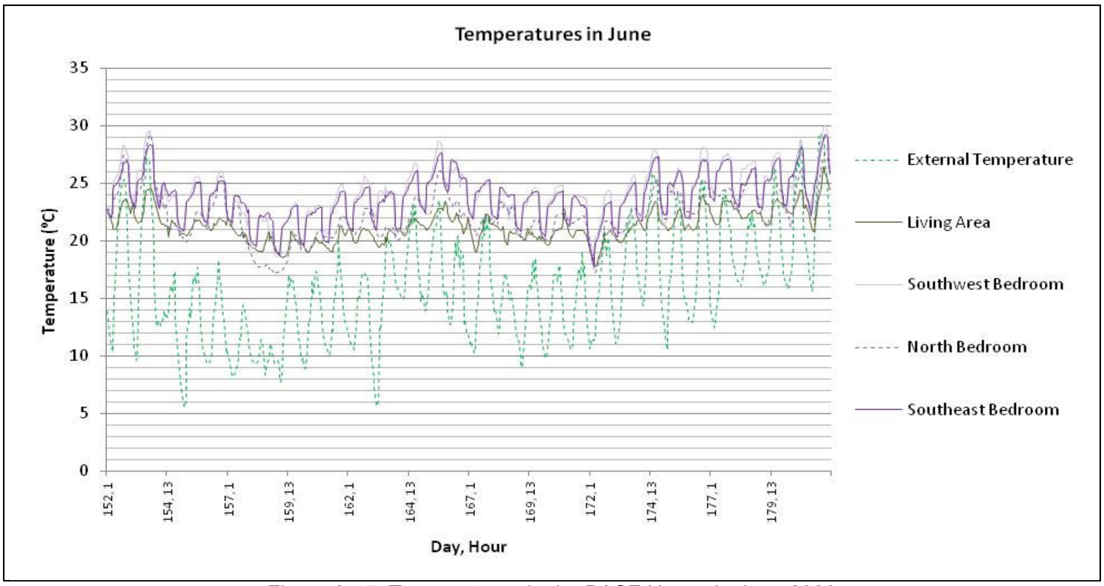

Figure 9-45: Temperatures in the BASF House in June 2009

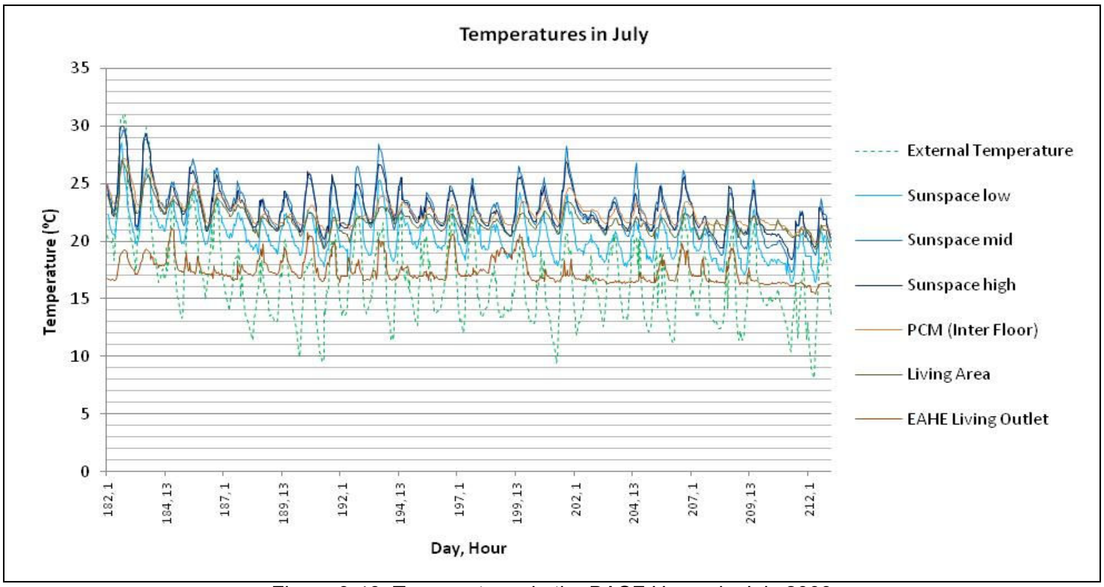

Figure 9-46: Temperatures in the BASF House in July 2009

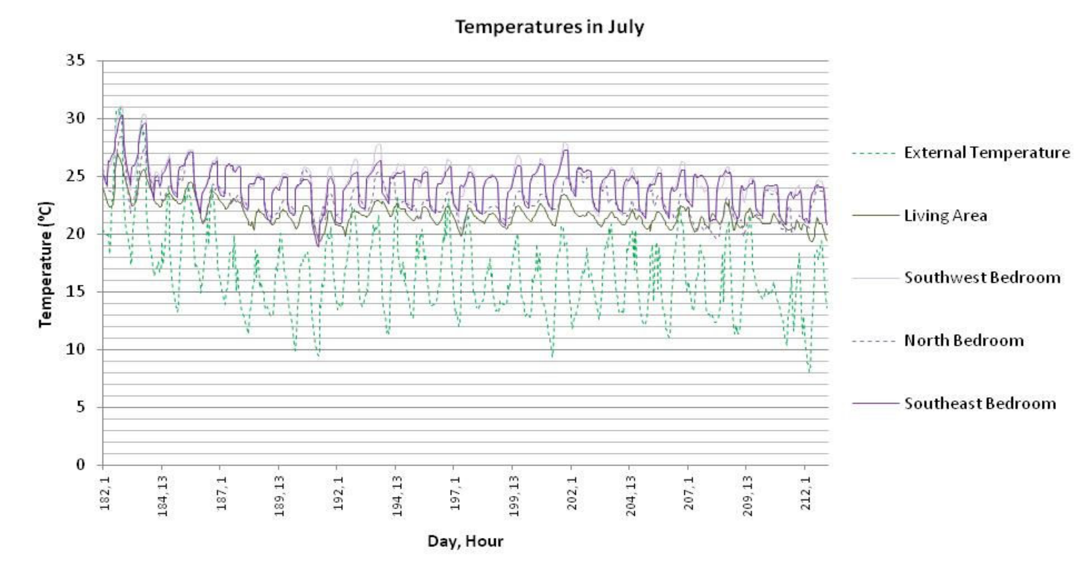

Figure 9-47: Temperatures in the BASF House in July 2009

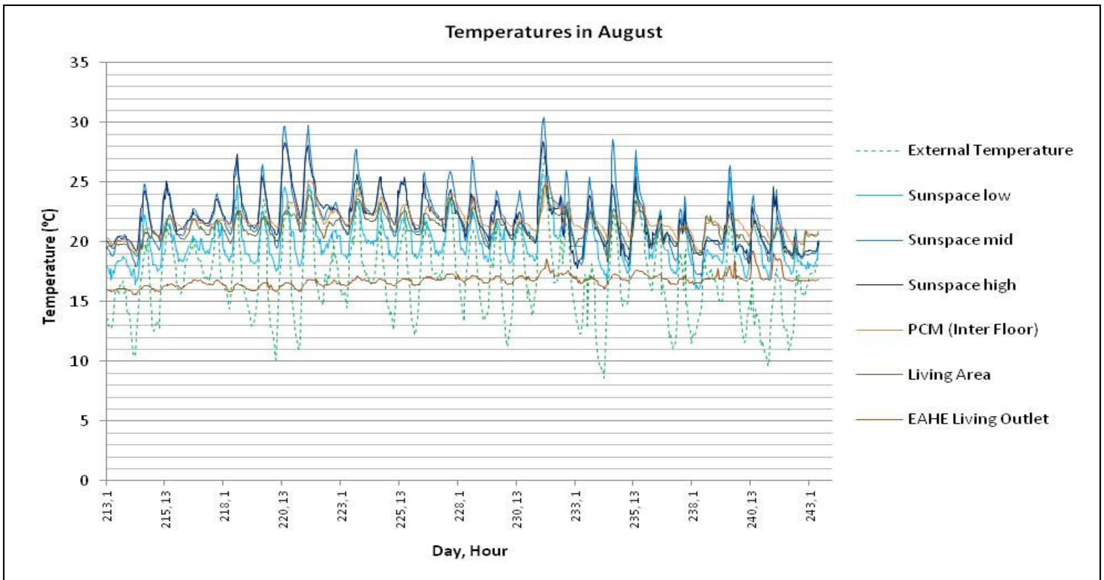

Figure 9-48: Temperatures in the BASF House in August 2009

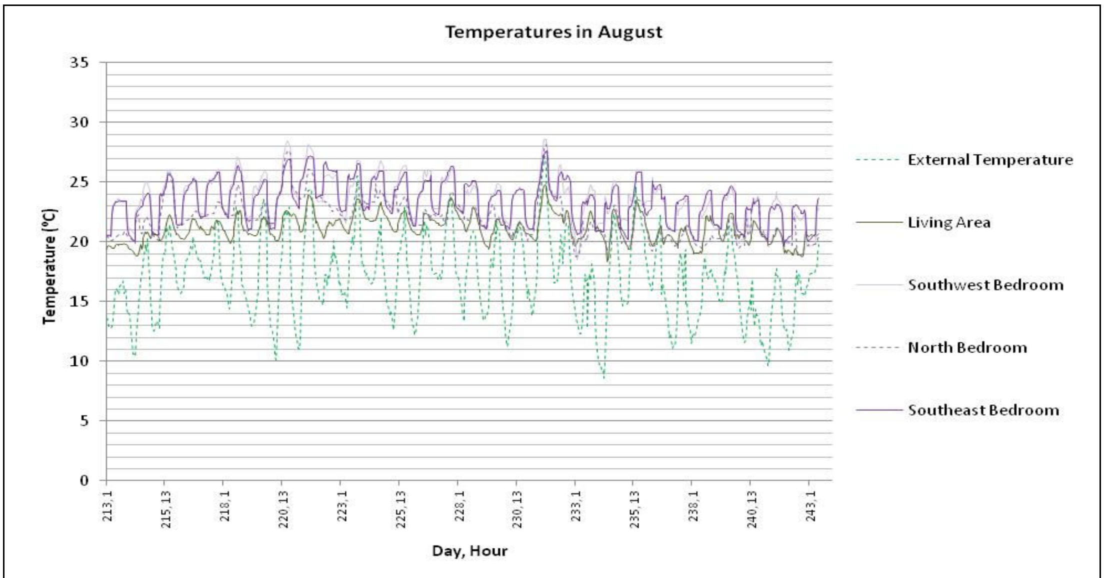

Figure 9-49: Temperatures in the BASF House in August 2009

APPENDIX 8

Images of the BASF House Tas model geometry and material properties (Chapter 7).

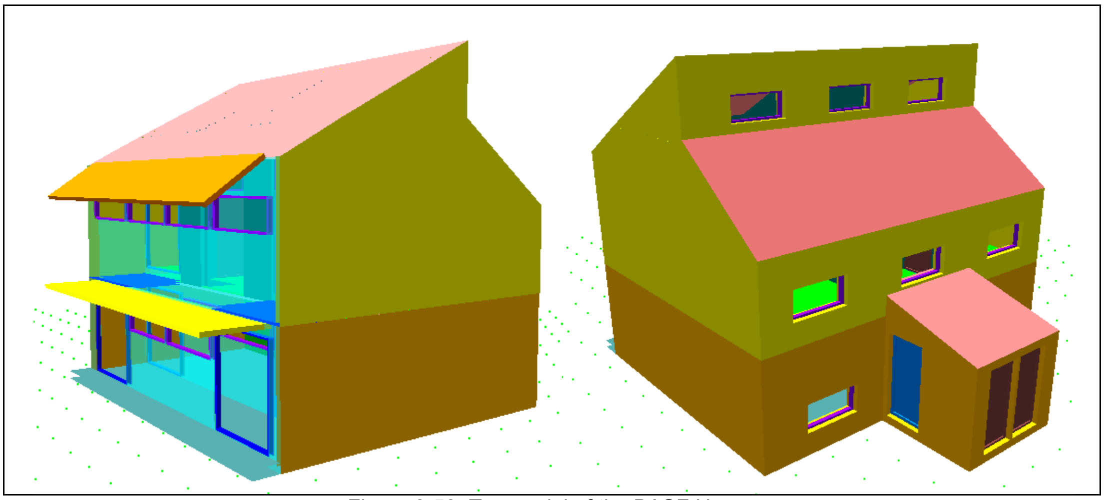

Figure 9-50: Tas model of the BASF House

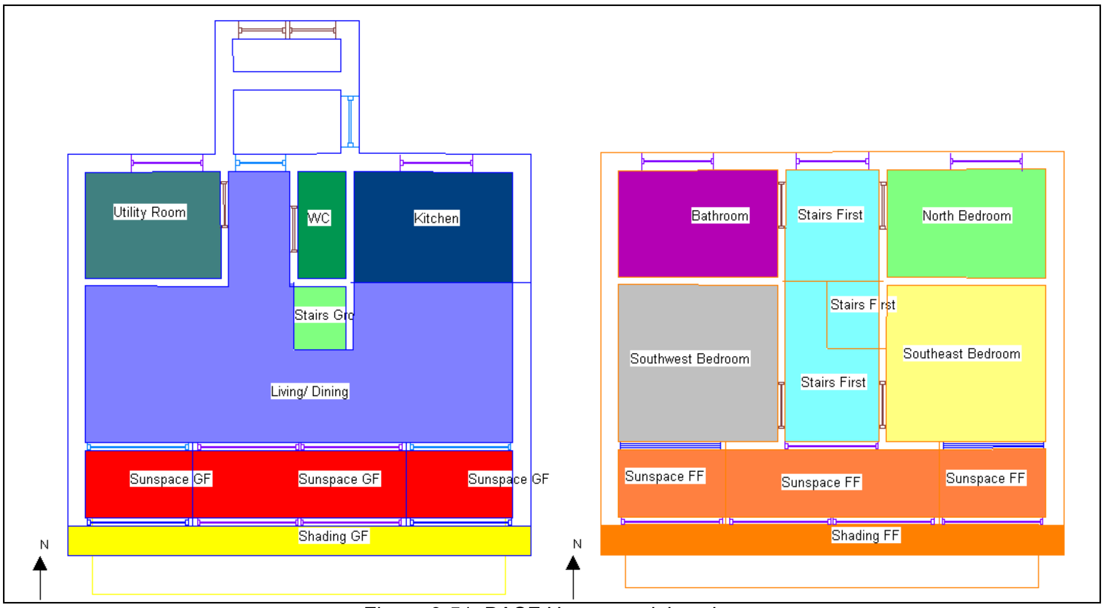

Figure 9-51: BASF House model zoning

Opaque Construction | Name: GF GroundFloor | Description:

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.650	0.700	0.900	0.900	0.143	164.302

Layer	M-Code	Width ...	Cond...	Density ...	Spec...	Description
In...	Carpet	12.0	0.06	186.0	1360.0	CARPET *2
2	am1concd\9	40.0	1.28	2100.0	1000.0	CONCRETE SCREED *3
3	EPS Styrodur (Polystyrene)	100.0	0.035	45.0	1470.0	EXTRUDED POLYSTRENE Rigid Board
4	Concrete Heavyweight (CIBSE)	150.0	1.3	2000.0	840.0	CONCRETE 3% m.c. 3 *3
5	Neopor 27kg/m3	75.0	0.032	27.0	1210.0	POLYSTRENE EXPANDED SHEET CLOSED CELL
6	AirCavity 200mm	200.0	0.0	0.0	0.0	200MM AIR (UPWARD FLOW)
7	am1soil\7	50.0	0.329	1515.0	796.0	SAND, DRY *2
8	am1aggr\4	600.0	0.55	1580.0	1057.0	CRUSHED BRICK AGGREGATE *1

Figure 9-52: Ground floor

Opaque Construction | Name: FF FirstFloor | Description:

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.400	0.700	0.900	0.900	1.334	1.237

Layer	M-Code	Width ...	Cond...	Density ...	Spec...	Description
In...	Carpet	12.0	0.06	186.0	1360.0	CARPET *2
2	Softwood Board (CIBSE)	18.0	0.17	550.0	1880.0	SOFTWOOD 2 *2
3	AirCavity 200mm	200.0	0.0	0.0	0.0	200MM AIR (UPWARD FLOW)
4	Softwood Board (CIBSE)	18.0	0.17	550.0	1880.0	SOFTWOOD 2 *2
5	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4
6	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4

Figure 9-53: First floor/ ground floor ceiling

Opaque Construction | Name: Roof SIPs | Description:

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.530	0.400	0.250	0.900	0.162	3.073

Layer	M-Code	Width...	Cond...	Density ...	Spec...	Description
In...	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4
2	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4
3	EPS Styrodur (Polystyrene)	25.0	0.035	45.0	1470.0	EXTRUDED POLYSTRENE Rigid Board
4	Softwood Board (CIBSE)	11.0	0.17	550.0	1880.0	SOFTWOOD 2 *2
5	PUR (Polyurethane)	128.0	0.025	30.0	1400.0	POLYURETHANE BOARD *3
6	Softwood Board (CIBSE)	23.0	0.17	550.0	1880.0	SOFTWOOD 2 *2
7	am1metal\4	0.5	43.0	7800.0	500.0	STEEL *3

Figure 9-54: Roof

Opaque Construction | Name: orExternalWall_ICF | Description: GFW ext GroundFloorExternalWall_ICF

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.700	0.400	0.900	0.900	0.162	104.960

Layer	M-Code	Width ...	Cond...	Density ...	Spec...	Description
In...	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4
2	EPS Styrodur (Polystyrene)	55.0	0.035	45.0	1470.0	EXTRUDED POLYSTRENE Rigid Board
3	Neopor 27kg/m3	70.0	0.032	27.0	1210.0	POLYSTRENE EXPANDED SHEET CLOSED CELL *
4	Concrete Heavyweight (CIBSE)	158.0	1.3	2000.0	840.0	CONCRETE 3% m.c. 3 *3
5	Neopor 27kg/m3	70.0	0.032	27.0	1210.0	POLYSTRENE EXPANDED SHEET CLOSED CELL *
6	Surface Finish 0.7 Absorp	12.0	0.79	1330.0	1000.0	Absorptance 0.7, similar brick

Figure 9-55: Ground floor external wall

Opaque Construction | Name: rExternalWall_SIPs | Description: FFW ext FirstFloorExternalWall_SIPs

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.530	0.400	0.250	0.900	0.154	3.425

Layer	M-Code	Width...	Cond...	Density ...	Spec...	Description
In...	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4
2	EPS Styrodur (Polystyrene)	25.0	0.035	45.0	1470.0	EXTRUDED POLYSTRENE Rigid Board
3	Softwood Board (CIBSE)	11.0	0.17	550.0	1880.0	SOFTWOOD 2 *2
4	PUR (Polyurethane)	128.0	0.025	30.0	1400.0	POLYURETHANE BOARD *3
5	Softwood Board (CIBSE)	23.0	0.17	550.0	1880.0	SOFTWOOD 2 *2
6	AirCavity 20mm	20.0	0.0	0.0	0.0	20MM AIR (HORIZONTAL FLOW)
7	am1metal\4	0.5	43.0	7800.0	500.0	STEEL *3

Figure 9-56: First floor external wall

Opaque Construction | Name: InternalWall_Block | Description: GFW int GroundFloorInternalWall_Block

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.400	0.400	0.900	0.900	1.565	1.732

Layer	M-Code	Width...	Cond...	Density ...	Spec...	Description
In...	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4
2	am1cav\4	20.0	0.0	0.0	0.0	20MM AIR (HORIZONTAL FLOW)
3	Concrete Block Aerated	100.0	0.85	400.0	1100.0	AERATED, AIR CURED CONCRETE BLOCK *1
4	am1cav\4	20.0	0.0	0.0	0.0	20MM AIR (HORIZONTAL FLOW)
5	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4

Figure 9-57: Ground floor internal wall

Opaque Construction | Name: orInternalWall_SIPs | Description: FFW int FirstFloorInternalWall_SIPs

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.400	0.400	0.900	0.900	0.173	1.385

Layer	M-Code	Width...	Cond...	Density ...	Spec...	Description
In...	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4
2	AirCavity 20mm	20.0	0.0	0.0	0.0	20MM AIR (HORIZONTAL FLOW)
3	Softwood Board (CIBSE)	11.0	0.17	550.0	1880.0	SOFTWOOD 2 *2
4	PUR (Polyurethane)	128.0	0.025	30.0	1400.0	POLYURETHANE BOARD *3
5	Softwood Board (CIBSE)	11.0	0.17	550.0	1880.0	SOFTWOOD 2 *2
6	AirCavity 20mm	20.0	0.0	0.0	0.0	20MM AIR (HORIZONTAL FLOW)
7	Plasterboard (CIBSE)	12.5	0.16	800.0	840.0	PLASTERBOARD *4

Figure 9-58: First floor internal wall

APPENDIX 9

Comparison of CIBSE weather data and real data collected on site in the period of May, June, July and August 2009 (Chapter 7).

Real data:

- maximum temperature 31°C
- average temperature 15.6°C
- minimum temperature 4.5°C

CIBSE weather data:

- maximum temperature 29.1°C
- average temperature 14.5°C
- minimum temperature 3.7°C

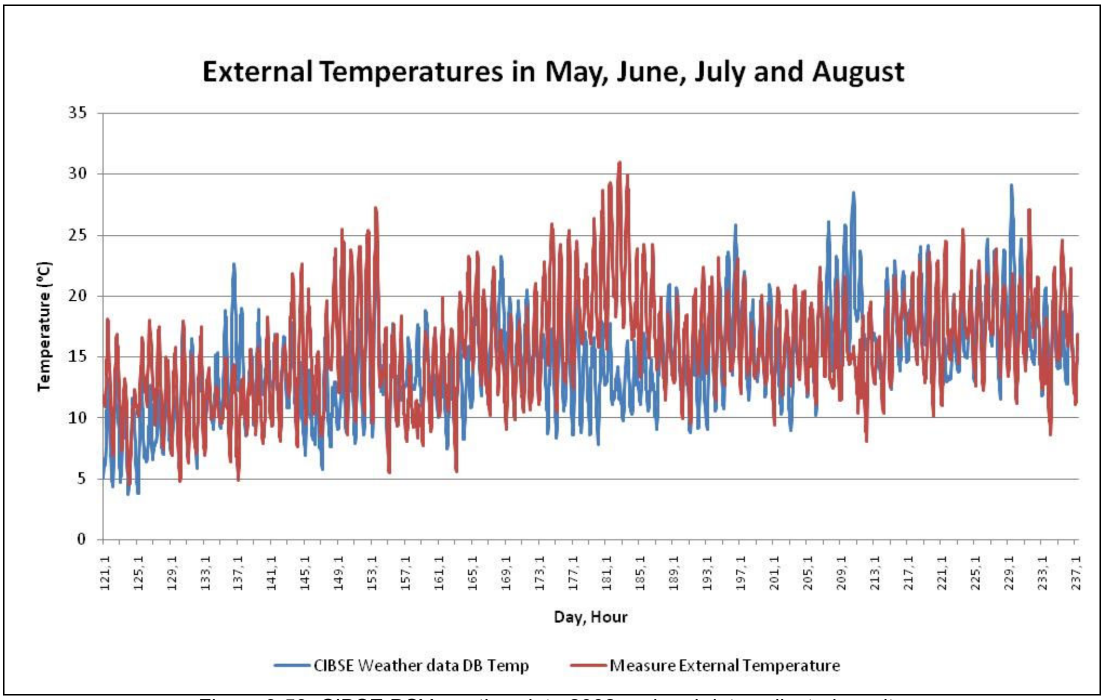

Figure 9-59: CIBSE DSY weather data 2002 and real data collected on site