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APPLICATION OF PHASE CHANGE MATERIALS AS A SOLUTION FOR BUILDING OVERHEATING: A CASE FOR THE UK

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ABSTRACT

In the UK, there are about 26 million houses and the government's future plan is to build 3 million more by 2020 (BBC, 2008, Jason, 2011). As the demand for housing increases, especially for single occupant homes, the rate of energy consumption and, in effect, the proportion of CO_2 emissions is on the rise. Successful sustainable energy strategies for domestic buildings can thus be an effective tool for mitigating these effects and achieving healthy building conditions.

The main aim of the research are obtaining comfortable building spaces by reducing any overheating and reduce energy demand by using passive method which also will reduce the emission of CO_2. Also this work aims to raise attention on the influence of the domestic sector on the amount of CO_2 emissions by using low thermal mass construction. Thus, the research's objectives are divided into firstly, investigate the opportunity of improving the Micronal Phase Change Material (MPCM) thermal conductivity and secondly, studying the influence of using enhanced MPCM for reducing overheating in lightweight building construction.

This research investigates means of improving the thermal performance of the UKs existing and new domestic buildings stock. In order to increase thermal resistance and hence reduce heat losses, a new panel comprised of outer coating and thin layer or aerogel to increase thermal resistance was developed which could be added to the exterior walls of existing houses.

This research results have shown from the experimental work when MPCM coupled with construction materials that the percentage of MPCM should not be above 50% otherwise it will reduce the potential benefit of the mixture to enhance thermal conductivity of MPCM.. The best thermal conductivity was obtained by mixing 20% PCM, 75% Gypsum and 5% Silica with honeycomb, which gave a value of 0.306

W/mK. On the other hand, the best thermal conductivity was obtained using the clay by mixing 40% MPCM, 20% Clay and 40% cement, which gave a value of 0.253 W/mK. The simulation results shown that natural night ventilation could help reduce the overheating period to about 50% with the use of MPCM. Finally, The results of the new external wall panel that has been developed to improve the thermal performance have shown that through application of these panels a substantial reduction between 3 ºC to 5 ºC in the internal temperature.

Key words: Phase Change Materials (PCMs), microencapsulated PCM, thermal conductivity flat pack buildings, overheating, gypsum board, clay, comfortable spaces.

PREFACE

"Architecture is the masterly, correct, and magnificent play of masses brought together in light. Our eyes are made to see forms in light"[1]

Le Corbusier

As an architect and after I done this research work I hove founded that designing a building is not any more just presenting a pace of art with the function of spaces; it is become more manifold detailed with other building construction fields such as building materials, construction systems, thermal behaviour and other building technologies. Understanding the building thermal performances, effect of ventilation and occupants comfort will help architects to produce more effectiveness and wonderful design that consist of visual and thermal aims.

I believe by all the odds that this work has added more knowledge to my perceptive to see the building design processes in more advanced technique and architecture not just art it is a combination of art and science.

Moataz Ali Khalifa

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[1] http://www.designers-books.com/towards-a-new-architecture-le-corbusier-1927/

PUBLISHED PAPERS AS A RESULTS OF THE PhD PROJECT

Khalifa, M. Siddig, O. and Riffat S.B. (2011), *Experimental Investigations of the Effectiveness of the Phase Change Materials when coupled with pure and mix clay material,* SET2011 -10th International Conference on Sustainable Energy Technologies, Kumburgaz, Turkey

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LIST OF ACRONYMS

BIS	*British Institute Stander*
CBA	*Concrete Block Association*
CIBC	*Chartered Institution of Building Services Engineers*
CSH	*Code for Sustainable Homes*
DABE	*Department of Architecture and Built Environment*
DER	*Dwelling Emission Rate*
UFH	*Under flooring heating system*
LHR	*latent heat ratio*
MMC	*Modern Methods of Construction*
MPCM	*Micronal Phase Change Material*
PCMs	*Phase Change Materials*
PV	*Photovoltaic*
SHR	*sensible heat ratio*
TER	*Target Emission Rate*
TES	*Thermal Energy Storage*
UK	*United Kingdom*
UKCIP	*United Kingdom Climate Impacts Program*

NOMENCLATURE

A	*Area of the wall*	m^2
d	*Distance between the faces*	m
T	*Temperature*	°C or K
Δt	*Temperature difference between the faces*	°C or K
Ta	*Ambient temperature*	°C or K
m	*Mass*	Kg
Q	*Heat flow*	W
q	*Heat flux rate*	W/m^2
K	*Thermal conductivity*	W/mK
U -value	*Rate of heat transfer by all mechanisms*	W/mK
R- value	*Thermal resistance*	Km/W
T1	*Initial temperature*	°C or K
T2	*Final temperature*	°C or K
*Cp	*Specific heat capacity*	KJ/kg K
ϱ	*Density of material*	Kg/m^3

CHAPTER 1: INTRODUCTION

"Architecture is not about designing something from a free, fanciful idea. It is about discovering and establishing one's own principle, some kind of regularity - finding an individual formula to apply to one's buildings."

Shigeru Ban [2]

"*We firmly believe that in order for a building to be sustainable, it must be loved; it must touch the soul. People—not just the current owners, but future generations—must find enough value in a building to continue to occupy and maintain it. Some of this is aesthetic, some performance, some economics. The Roman architect Vitruvius told us that buildings must have "Firmness, Commodity and Delight". True today more than ever."*

David Arkin [3]

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[2] http://www.jacobpringiers.com/index/publications_printed_files/CUBES-VILLAVISTA-JUNE-2011.pdf
3 http://www.treehugger.com/culture/the-th-interview-david-arkin-of-arkin-tilt-architects.html

1. Introduction

The international community is still facing the problem of increasing CO_2 emissions which have increased by 3% in 2011(Kinver, 2012). This is about 54% higher than that of 1990, the year of the Kyoto Protocol, when it was announced it recorded the highest amount in human history. According to Kinver (2012), CO_2 emissions increased by 2.6% in 2012 compared to 2011 . It has been recorded that in 2011, about 43% of the emissions were produced from burning coal and 34% from oil, while gas was responsible for 18% and the cement industry 5% of the emissions (The Global Carbon Project, 2011).

Globally, the average temperature rose by about 0.2ºC during the last century and 0.8 ºC since the end of the nineteenth century (UK Climate, 2009). In the UK, the impact program scenarios of climate change presents that by 2080 the temperature will increase by an annual average of around 4.5°C. This will affect peak summer temperatures, which could reach up to 42°C. Central England, which is on record as the warmest place in 2006, has witnessed a temperature rise of 1 ºC since 1970. In Scotland and Northern Ireland, the temperature rose by 0.8 ºC since around 1980. Nearly 27% of CO_2 emissions come from the housing sector in the UK, where domestic energy consumption was about 30% in 2004 (Druckman, 2008). According to Simon (2008) the energy consumption in domestic buildings is significantly higher, up to four times the energy used by the industrial sector and seven times more than that of public organizations. As a result, the UK government has set a target to cut 20% of the emissions by 2020, 60% CO_2 by 2050, and 80% by 2080. In 2007 the UK government planned to build 240,000 new homes every year until 2016 but in reality only 70,000 homes were built annually up to 2011 (Parliament, 2011, Jason, 2011). The credit crunch affected the target to build 3 million houses in

England by 2020 that the government had previously aimed for (BBC, 2008). It is important to mention that according to the BBC *"buyers of new zero carbon homes now qualify for tax relief on stamp duty."* The UK government is looking to achieve zero carbon emissions for new houses to be built by 2016 and subsequent years (BBC, 2007).

It is important to mention that according to Roberts (2008), most of the houses in the UK were built between the 1930s to 1970s and have very high U-values. The annual replacement rate of new houses in the UK is about 1%. Thus, enormous work needs to be done to increase this value parallel with improving the thermal resistance of existing houses.

The UK government has taken many steps to reduce CO_2 emission by issuing new building regulations, which state that all new houses should attain zero carbon rating by 2016. The government has established a number of construction methods known as Modern Methods of Construction (MMC), which aim to provide high standard construction houses by saving time, materials, thermal and ventilation efficiency. MMC have the ability to meet new building regulations and establish good quality houses with the highest insulation systems that help utilize less energy for heating and cooling spaces. However, houses with efficient insulation systems and low U-values could suffer from overheating under summer weather conditions (Keith, 2006).

Future low carbon buildings are one of the key motivations for reducing CO_2 emissions and obtaining comfortable and healthy living spaces. The straightforward way to reduce carbon emissions is by cutting heating and cooling demands as well as controlling the use of artificial light and heating water through the use of renewable energy or low energy systems.

Thermal comfort is the main aims for designers as well as building regulations. Obtaining comfortable indoor conditions will help people to be more efficient at work and happy living at home (BASF, 2007). Therefore, this research work emphasises the importance of reducing overheating inside building spaces to attain comfortable living environments for the building users.

Part of this work involves improving the thermal conductivity of Micronal Phase Change Material (MPCM) coupled with other construction materials. Thus, it could be used effectively to increase the thermal mass of lightweight construction building. Moreover, increasing the ability of MPCM to absorb and release heat is the way to reduce the heating and cooling demand in a passive way. The results obtained from this research work will lead to the possibility of using MPCM to reduce overheating in building spaces as well as the use of natural ventilation instead of mechanical ventilation.

This project presents a work developing a unique wall panel using flat pack panel for buildings. The new panel has the feature of a lightweight construction with high thermal mass and is achieved by using enhanced MPCM as part of material. In addition, the new wall panel has the ability to reduce any unwanted heat by absorbing and storing it within the wall. A full-scale test was carried out to test the effect of using a unique gypsum board with enhanced MPCM to control the heat inside the building spaces and add extra thermal mass to the envelope.

1.1. The project aims

The aims of this research are dual fold. Firstly, to obtain comfortable healthy building spaces for occupants by reducing any unwanted heat and reduce the energy demand by using passive methods that will help reduce CO_2 emission to the environment and minimise the effects of climate change.

Secondly, this research aims to raise attention on the impact of the housing sector on the proportion of CO_2 emissions by using low thermal mass construction as well as to raise awareness of energy demand in existing domestic buildings.

1.2. Research objectives and scope of work

The main objective of this research is to investigate the possibility of enhancing the Micronal Phase Change Material (MPCM) thermal conductivity by mixing it with construction materials namely clay, cement, gypsum and silica for improving its capability for charging and discharging heat.

The second objective of this investigation is to study the effect of using enhanced Micronal Phase Change Material (MPCM) for reducing overheating in lightweight building construction.

The third objective of this work is to improve the performance of refurbished and existing buildings by enhancing the thermal performances of the walls through increasing their thermal resistances and using MPCM to control the heating and cooling load.

All these objectives were considered alongside the target of meeting the Building Regulations requirements (England and Wales) and the Code for Sustainable Homes. A range of tests through computer modelling, calculations, lab experiments and full-scale experiments under real climatic conditions were employed in this research to achieve project objectives.

1.3. Hypotheses and challenges

The hypothesis posed by this research is that combinations of a novel mixture of Micronal Phase Change Material (MPCM) with gypsum, clay, silica and other construction materials could enhance the thermal performance of the building envelope. This would help to accelerate the ability of MPCM to charge and discharge heat in the building envelope. By accelerating the ability of MPCM to charge and discharge heat passively will help reduce the need of the mechanical ventilation for cooling.

1.4. Methodology

The research commences with a literature review that reflects the Building Regulations 2010 for domestic buildings, as well as clarifies the Code of Sustainable Homes. The review discussed the different types of insulation materials due to their importance in energy conservation and the methods of approaching zero carbon buildings in the UK. Finally, the literature review explained the concept of thermal energy storage in buildings. Thermal energy storage method used in this research is based on Phase Change Materials (PCMs). Thus, a detailed review has been presented to explain the ability of PCMs as energy storage, type of PCMs, their advantages and disadvantages and how other researchers have used this concept in building applications.

Based on conclusions from the literature review outlined above, appropriate research methods have explained and have been divided into three elements.

1.4.1. Experimental method

A number of experiments were carried out in this research, as follows:

The experimental work started with testing two different methods of wall construction, to examine the difference between them in terms of heat transfer and thermal conductivity. These are lightweight and heavyweight constructions. The tests were based on the British Standard (BS) (BS 874-3.2, 1990) explaining the test method known as the Calibrated hotbox method.

As the aim of the research was to develop strategies to reduce overheating, the concept of employing phase change materials was chosen to achieve the goal. Consequently, more tests have carried out. A number of product sample using PCMs and other construction materials such as clay, gypsum, sand and cement was tested in different proportions using Heat Flow Meter (HFM) according to BS874-2.2:1988 to find out the thermal conductivity of the different mixtures (refer to section 5.5). Moreover, a method of adding enhanced materials to avoid cracks known as no-crack concrete to the mixture was used to avoid any serious cracks in the panels (refer to section 5.6). As the aim of these tests was to enhance the thermal conductivity of the PCM, the highest value of the thermal conductivity obtained from the various PCM panels was used for the full-scale test.

The final experiment involved testing of a flat pack modular construction panels provided from Blue Plant Company to investigate the effect of the novel enhanced MPCM panel on reducing overheating to maintain comfortable building spaces and reduce CO_2 emission in order to achieve low carbon houses in the UK. This test was divided into two sections: Firstly, using the Calibrated hotbox method to calculate the U- value of the existing flat pack panel and the new flat pack wall panel with MPCM under British Standards (BSI) (BSI, 1990). Secondly, testing a full-scale building by dividing the building into two identical rooms, using the novel MPCM panel in one room with the other room maintained without any change. Therefore, the purpose of this test was to compare the two rooms by recording the change in temperature in each room (refer to section 7.6).

1.4.2. Calculations method

An analytical method was used to validate the experimental results and to find out the required thickness of aerogel (insulation material) to meet the Building Regulations and the Code for Sustainable Homes (refer to section 4.5.1). The analytical method was also used to calculate the U-values of the walls (refer to section 4.7).

1.4.3. Modelling method

Building modelling was carried out using the computer software TAS which helped to build a virtual model to test the cooling and heating load for the building and also to test the effect of Micronal Phase Change Material (MPCM) on reducing building overheating. The results of the full-scale building test were used to validate the modelling work.

1.5. Thesis Structure

The thesis is structured as follows:

1.5.1. *Chapter 1: Introduction*

The first chapter introduces the research conducted in the project and highlights the aims, the objectives, scope of work, hypotheses and thesis methodology.

1.5.2. *Chapter 2: Literature review*

The chapter reviews literature by summarising the Building Regulation part LA1 2010 regarding the thermal performance of residential buildings. It also highlights the Code of Sustainable Homes as an advanced regulation for buildings. As the insulation materials play an enormous role in controlling heat gain into the building envelope by adding an extra resistance layer of material into the building structure, a detailed review of insulation materials and how they are classified is also discussed in this chapter

1.5.3. *Chapter 3: Phase Change Materials (PCMs) review*

The main point that this report has addressed is the issue of reducing heat overload in buildings. Chapter 3 highlights the effect of the use of the Phase Change Materials (PCMs) as a thermal energy storage method for reducing overheating in buildings. It starts with explanations of the performance of PCMs, illustrates the classification and type of PCMs and highlights the advantages and disadvantages of each group. Moreover, it demonstrates PCMs use for different applications. Finally, the chapter concluded with discussing various studies carried out by other researchers on the use of PCMs in the building envelope.

1.5.4. *Chapter 4: Investigation into the thermal performance analysis of existing and new buildings*

In this chapter two wall panels developed in coordination with Tru-Stone Ltd were tested under the building regulations and the Code for Sustainable Home. British Standard (BS) (BS 874-3.2, 1990) method was used to test the panels. Details of the test procedure are presented in chapter 3. Aerogel (insulation material) was applied to Tru-Stone panel components to improve the thermal resistance of the existing building (refer to section 4.5). Experimental testing and calculations were used to calculate the R and U values of the existing and new panels.

1.5.5. *Chapter 5: Coupled phase change materials (PCMs) with other construction materials*

The fifth chapter presents an investigation into the development of construction panels using MPCMs in different percentages to improve the thermal performance of the construction components. The full explanations of the manufacturing and testing procedures are also presented. The results of the tests and experiments for varying thermal conductivity values have are also presented with complete explanations.

1.5.6. *Chapter 6: Modelling simulation using micronal phase change material (MPCM) as heat storage system*

Building modelling using TAS software program was used to investigate the effect of adding MPCM panels as part of lightweight building construction. Moreover, natural night ventilation was been examined to evaluate the effect of discharging heat from MPCM to be ready for use as a backup passive cooling system the next morning.

1.5.7. *Chapter 7: Full scale test, a case study for Nottingham, UK*

Chapter 7 presents the investigation of adding MPCM panels to the flat pack system after which a full-scale test was carried out to assess the effect of adding enhanced MPCM panels to the existing wall system. Methods and procedure of the test have been presented in the chapter.

1.5.8. *Chapter 8: Conclusions and future work*

This chapter presents the main conclusions of the thesis with suggestions for future work.

1.5.9. *References*

1.5.10. *Appendixes*

CHAPTER 2: LITERATURE REVIEW

First building regulation established by King Herod who stated, "Should a man construct a building which falls down and kills another then this man should be slain"

King Herod (74BC-4AD)[4]

"Homes in the UK have not historically been associated with overheating. This is probably due to a combination of the heavyweight materials from which they were constructed,"

Neil Jefferson
Chief Executive Zero Carbon Hub

[4] http://www.eci.ox.ac.uk/research/energy/downloads/40house/background_doc_f.pdf

2. Literature review

This chapter presents a comprehensive review about the important issues related to this research. The literature review starts with a focus on the effect of energy demand as one of the main impact on the building design, with the continuing rise of energy price every year. Therefore, issues of the impact of Climate Change Scenarios UKCIP02 on lightweight buildings in the UK as a future problem that should be taken into account in future designs and in existing houses have been highlighted. According to BSI (1992) the building durability cases is 60 years, which means the houses built in the last few years and new houses will be affected by the UKCIP02 Scenarios. The latter section of this chapter provides a demonstration of domestic building regulations, which include the Building Regulation 2010 and Code for Sustainable Homes. This research focuses on the regulations in terms of improving the U-value of domestic buildings. Because of the use of lightweight construction method, as will be explained in this research later, and with the low thermal mass of this construction type which known as Modern Method Construction (MMC), and as the insulation materials play a considerable role in (MMC) concept to meet the building regulation, the research focuses on the different type of insulation. As a result of using (MMC) the literature refers to the issue of overheating which appears to be a serious problem for building users' comfort. Finally, the literature also reviews the methods of thermal energy storage that could help to improve the thermal mass of buildings and hence reduce overheating. The diagram on the next page shows the literature review outline.

LITERATURE REVIEW OUTLINE

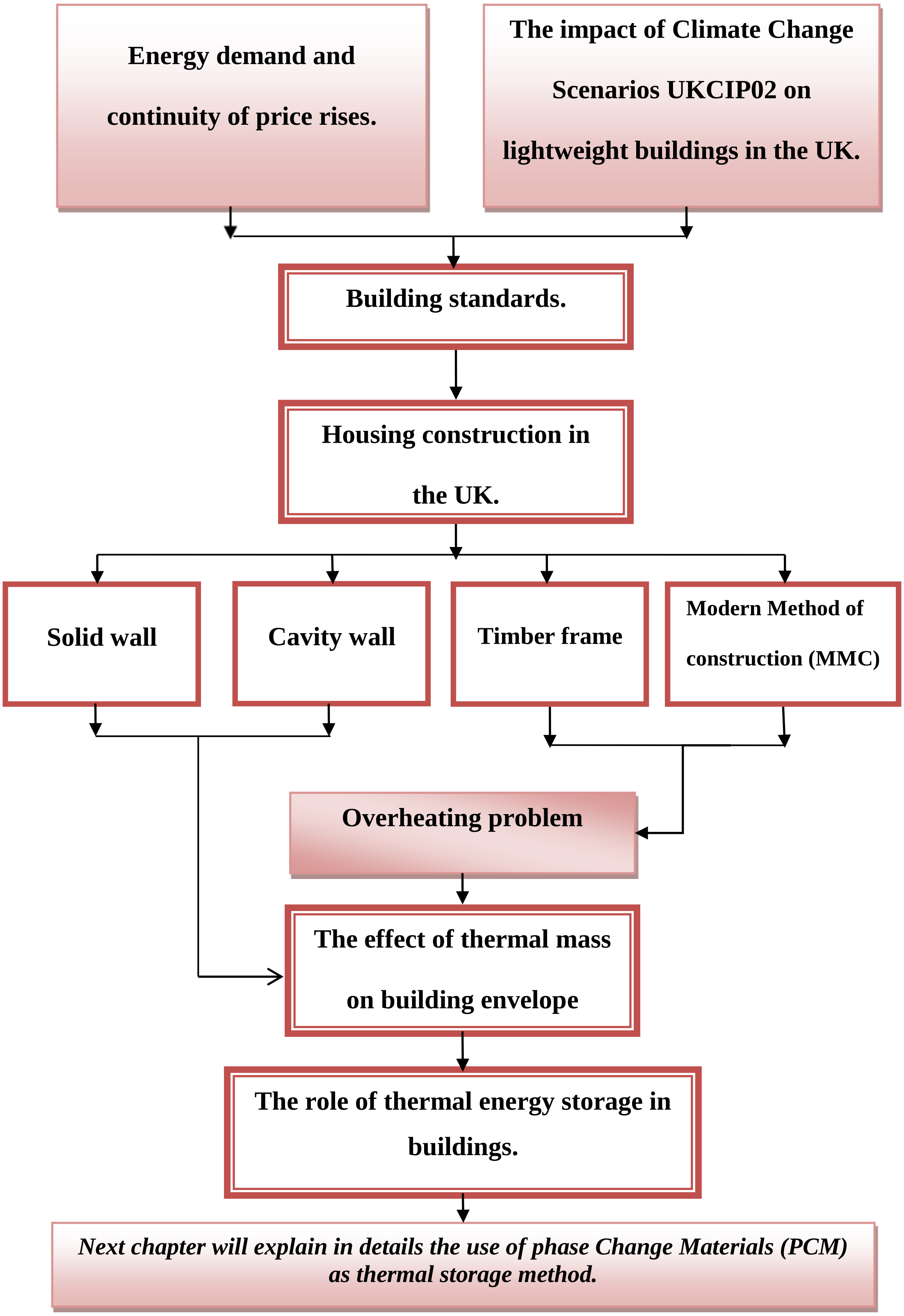


Figure 2-1 Literature review outline.

2.1. Energy demand and continuity of price rises

Energy demand and energy price are moving in a parallel manner where both continue to increase and the effect of is significant in two ways. First is the environmental effect by increasing CO_2 emission with a rise in burning fuel and the second level is the increase in energy cost as seen in Figures 2-2 and 2-3 According to OFGEM (2012) the consumer gas and electricity yearly bills rose twice in 2012 compared with 2005. Furthermore, as presented in Figure 2-2 and Figure 2-3 that the electricity bill increased about 10 % in 2012 in contrast with 2010 and gas bills up to 18% in similar years. Economically, consumers are facing an enormous problem with energy prices continuing to rise. This will affect the distribution of users' income, which will reduce spending on other items such as clothes, type of food and entertainment. This is especially true with the announcement from electricity and gas suppliers such as E.On that energy prices are going to be raised again from January 2013 (E.on, 2012)

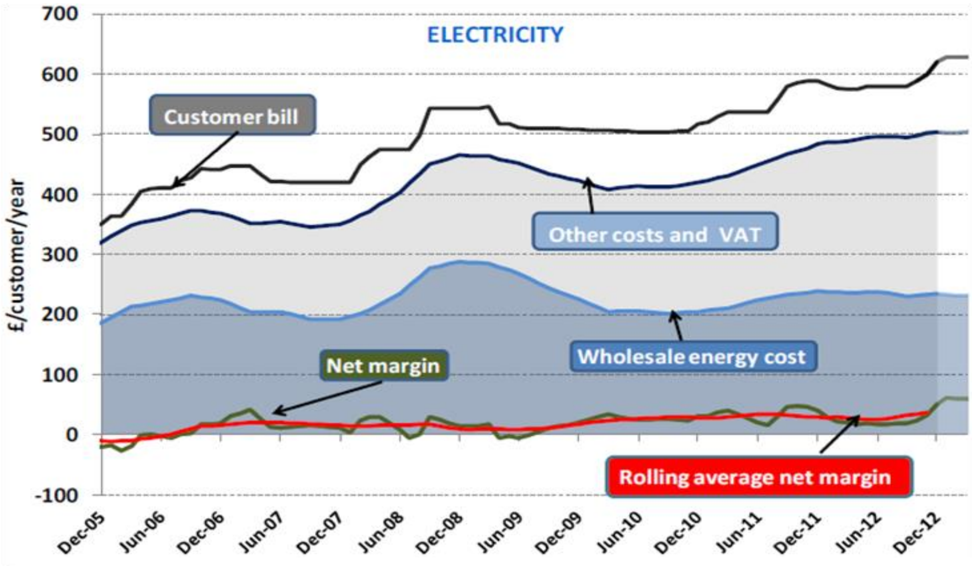


Figure 2-2 Typical electricity customer bill, costs and total indicative net margin for the next 12 months(OFGEM, 2012)

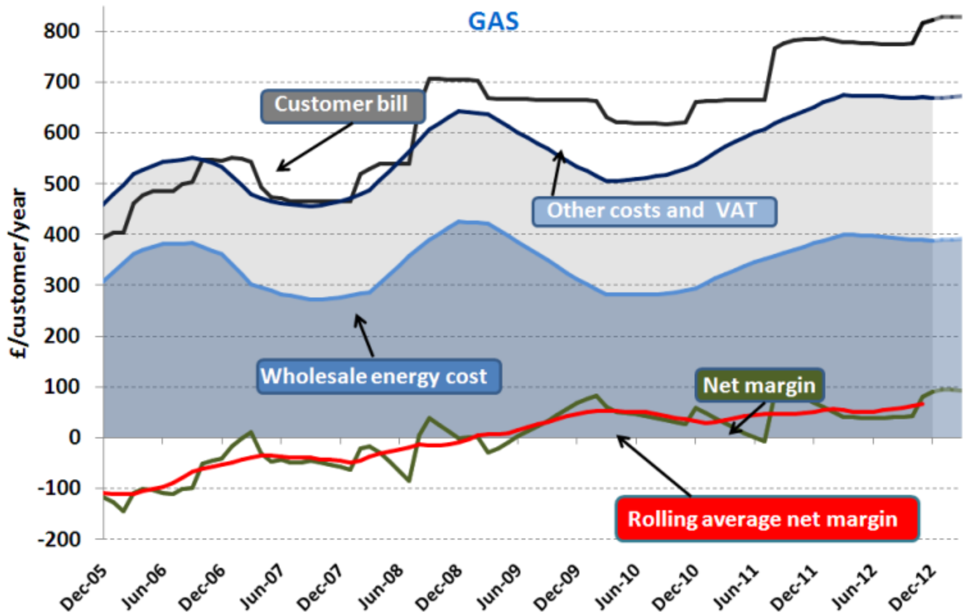


Figure 2-3 Typical gas customer bill, costs and total indicative net margin for the next 12 months(OFGEM, 2012)

2.2. The impact of Climate Change Scenarios UKCIP02 on lightweight buildings in the UK.

These regulations aim to reduce CO_2 emission by reducing the energy consumption of dwellings and increasing the thermal insulation of the structures to be fully insulated to eliminate any thermal bridges. Lightweight construction could easily overheat in summer and even in winter. In summer, temperature increases and as a result the indoor temperature will be over the comfortable temperature. According to the UKCIP (2002) it has been shown that due to the Climate Change Scenarios in 2020, 2050 and 2080 in the United Kingdom, the gradual temperature increase would affect the comfort of building users (Appendix1). These scenarios have been divided into four levels, low emission scenario, medium CO_2 emission scenario, medium high emission scenario and high CO_2 emission scenario. In the worse scenario for summer 2080, the temperature in summer time could rise to over 6 °C and lower emission scenario is from1°C to 2.5°C. Moreover, in autumn the temperature could rise over 4.5 °C around a large area of the country (Appendix1). In conclusion, lightweight construction with low thermal mass will be highly affected by changing temperatures in the UK. According to HUB (2011), the aim to build zero carbon homes by 2016 in some regulations areas is so low, there is an enormous concern whether to achieve this target by 2016 or not.

2.3. Building standards

2.3.1. Building regulations in the UK (England and Wales).

Building regulations are government standards for construction and building design (Directgov, 2009). They ensure the safety of the building structure, secure, healthy and energy conservation. Regulations have been applied to new buildings, existing buildings and refurbished buildings (Eurocell, 2009).

The first issue of regulations in the UK was established in 1936, and was concerned with building construction. It was an option for users to use it or not. However, in 1966 the first enforced building regulation was introduced which was revised in 1972 and later in 1976. 1985 was the year of the first modern building regulations control. Table 2-1 presents the U-value target in 1985 and those regulations were revised in 1991 and in 2000 (Tables 2-2 and 2-3). The last building regulations were issued in 2010 and they were the revised version of the building regulation 2006 as seen in Table 2-4 (Killip, 2005). The regulations have been divided into 14 elements and each element has covered regulations about a specific issue regarding buildings construction.

Table 2-1 Building Regulations 1985 maximum U-values (England and Wales) (Killip, 2005)

Element	U-value (W/m² K)
Exposed walls **Exposed floors** **Ground floors**	0.45
Roofs	0.25
Semi-exposed walls and floors	0.6

Table 2-2 Maximum U-values in 1991 Building Regulations (England and Wales) (Killip, 2005)

Element	U-value (W/m² K)
Roofs	0.25
Exposed walls	0.45
Exposed floors and ground floors	0.45
Semi-exposed walls and floors	0.6
Windows, doors and rooflights	3.3

As this research considers the energy performance of dwelling and how reducing overheating in a passive way can save energy, parts of the regulations relating to the research aims will be presented.

Table 2-3 Maximum U-values in 2000 Building Regulations (England and Wales) (Killip, 2005)

Element	U-value (W/m² K)
Pitched roof with insulation between rafters	0.2
Pitched roof with integral insulation	0.25
Pitched roof with insulation between joists	0.16
Flat roof	0.25
Walls, including basement walls	0.35
Floors, including ground and basement floors	0.25
Windows, doors, and roof lights (area-weighted average), glazing in metal frames	2.2
Windows, doors and roof lights, glazing in wood/PVC frames	2.0

2.3.1.1. Building regulations in dwellings

There are some points that should be taken into account when trying to reduce CO_2 that has been produced from the use of fossil fuel to generate energy for residential buildings. Those points can be presented as follows: building orientation, effect of shading, size of windows, building materials and insulation materials that must be under design control. The right design of the previous points will reduce the need for cooling, heating, and mechanical ventilation for domestic buildings. The new change of building regulation document L1A, has been in use since April 2006 in the UK just for England and Wales and was updated in 2010 (Building Regulation, 2010). These regulations (L1A) aim to meet the energy efficiency and low carbon building for new domestic buildings and L1B for existing domestic buildings (both

L1A, L1B work on the conservation of fuel and power). It is important to understand that, as has been mentioned in document L1A, non-domestic regulations would be applied to some parts of the domestic buildings that are not used as dwellings. In addition, the aim of improving dwelling regulations according to Concrete Block Association (CBA, (2006) is to achieve the target of decreasing carbon emission by 20% compared with dwellings built in 2002. This is expected to reduce the temperature inside buildings by controlling heat gain. However, another change was provided in October 2010 in part L1A 2010 that reveals more reduction in carbon emission CO_2 to be 25%. By increasing the percentage of reduction of CO_2, an extra 5% compared with 20 % in 2006. It is important here to mention that, following the previous state, that according to the Code for Sustainable Homes level 4 (DCLG et al., 2009) in 2013 the target was to reduce the CO_2 emissions by 44% in houses, and that will be followed by a reduction of carbon emissions in new dwellings by 2016, which is an enormous challenge for the UK government (Concrete Block Association, 2010, Kingspan, 2009).

The following points will show significant aspects in the building regulations in new dwellings (Concrete Block Association, 2006, Building Regulation, 2010)

- In regulation 9 the DER (*Dwelling Emission Rate*) should not be higher than the TER (*Target Emission Rate*).
- Conservatory, in new dwelling thermal separation must be constructed in between the conservatory and the dwelling. Moreover, conservatories less than $30m^2$ are exempt from the building regulations.
- Building with multiple dwellings: not in every dwelling DER has to be less TER, or the average DER is greater than the TER.

- Regulations 19, 20 and 21 deal with the Target CO_2 Emission Rate (TER). (The calculations are explained in Appendix 1).
- Multiple domestic buildings have been considered in regulations 23 and 30.
- Air conditioners should have energy efficiency of class C or above (41, L1A).
- The regulation 46 is required to reduce solar gains by design compound of sizing windows, shading, orientation, thermal insulation and ventilation (46, L1A).
- There is no minimum limit of using daylight. However, increasing the amount of daylight will affect the size of windows to be increased and this will increase solar gain. On the other hand, less daylight in the building could mean higher use of artificial lighting (48, L1A).
- According to regulation 51, insulation materials must be continuous over the whole building structure without any thermal bridges on the insulation. High consideration should be taken when installing insulation materials to the joint between elements and in the boundaries of elements (51, L1A).
- The Building regulations (2010) are aimed at reducing the temperature inside the buildings by controlling the heat gain. This should be addressed by more research work to find out more strategies to reduce any extra heating the building could obtain.

2.3.1.2. U value target under new building regulations

Approved document L1 has presented the U- value of all building structure elements walls, roofs, floors, windows and doors as shows in Table 2-4.

Table 2-4 U-value target under the Building Regulation(Concrete Block Association, 2006, Building Regulation, 2010)

Limiting U-value standards (W/m².K) (Approved document L1A		
Element	U value target L1A2006	U value target L1A2010
Wall	0.35 W/m²K	0.30 W/m²K
Floor	0.25 W/m²K	0.25 W/m²K
Roof	0.25 W/m²K	0.20 W/m²K
Windows, roof windows, roof light and doors	2.2 W/m²K	2.00 W/m²K

2.3.2. The Code for Sustainable Home levels 3, 4, 5 and 6

The Code for Sustainable Home is a measure of the environmental sustainability, which ensures a sufficient improvement for those new homes in nine key areas: energy and CO_2, water, materials, surface water run-off, waste, pollution, health, management and ecology. The code consists of six levels, level 1 has been set just after building regulation 2006 and level 6 is a net zero carbon in 2016. The time line in Figure 2-4 shows the timeline between the code levels and the year of starting. Furthermore, the Table 2-5 shows the thermal performance U-value under the code sustainable home and more energy performance of level 6 is presented as follows:

Windows = 0.7 W/m2K (incl. wooden frame), triple glazed, gas filled

Thermal bridging 4.5% of surface area

Energy labelled A++ white goods

4.7kW, 46m² photovoltaic system

10 kW automatic wood pellet boiler– only 2kW needed

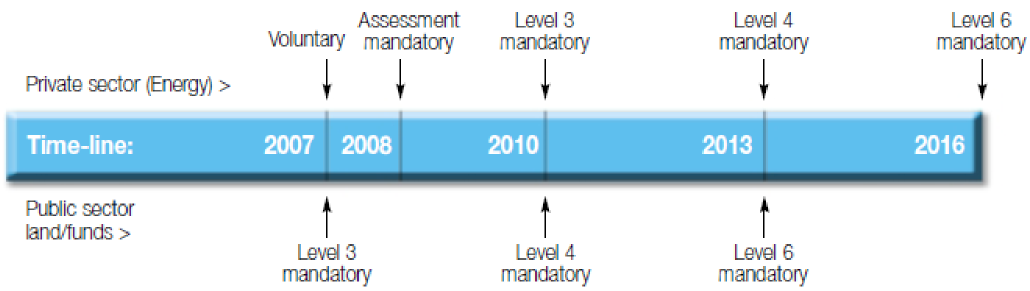


Figure 2-4 The time line of the relation between the code levels and the year of starting(Kingspan, 2009).

Table 2-5 The U value target of the Code for Sustainable Homes(DCLG et al., 2009).

Codes for Sustainable Homes	Level 1&2	Level 3,4&5	Level 6
U-value W/m²K	0.2	0.18	0.11

It is important to understand that the sustainable home code is strongly linked with building regulations and the difference in building regulations presents the minimum required by law (The Code for Sustainable Homes, 2010). Thus, level 1 was better by 10% than L1A 2006, Level 3 is improved by 25% compared to L1A 2006, Level 4 is better by 44% (with some on-site renewable) than L1A 2006, level 5 is 100% better than L1A 2006 and level 6 with super-insulation is the target of zero carbon building.

2.4. Housing construction method in the UK

Housing construction in the UK can be divided into two categories: heavyweight construction and lightweight construction (Hens, 2007).

2.4.1. Solid wall

Houses until 1920 were built using solid wall system as can be seen in Figure 2-5 where no insulation material is used. The benefit of using solid wall is shown on the high thermal mass, which means an effective way to reduce heating or cooling costs, by absorbing and releasing heat. However, the solid wall has low thermal resistances, which means that heat can be easily lost through the wall (Go green, 2013)

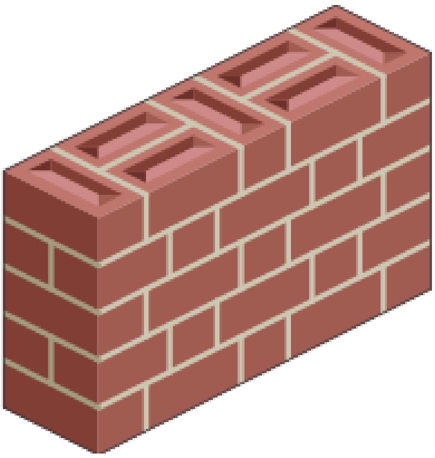


Figure 2-5 Solid wall.

2.4.2. Cavity wall with wooden structure

Since 1920 the construction system has changed by using the cavity wall system as can be seen in Figure 2-6, and since 1973 insulation materials have been applied as part of the cavity wall system to reduce the energy demand. Presently, this system is unable to achieve the annual housing target (about 240,000 house/year till 2016) easily and that is because the need for high skilled labor, the cost of construction and sustainability concern to meet building regulation 2016 (Sahota, 2012).

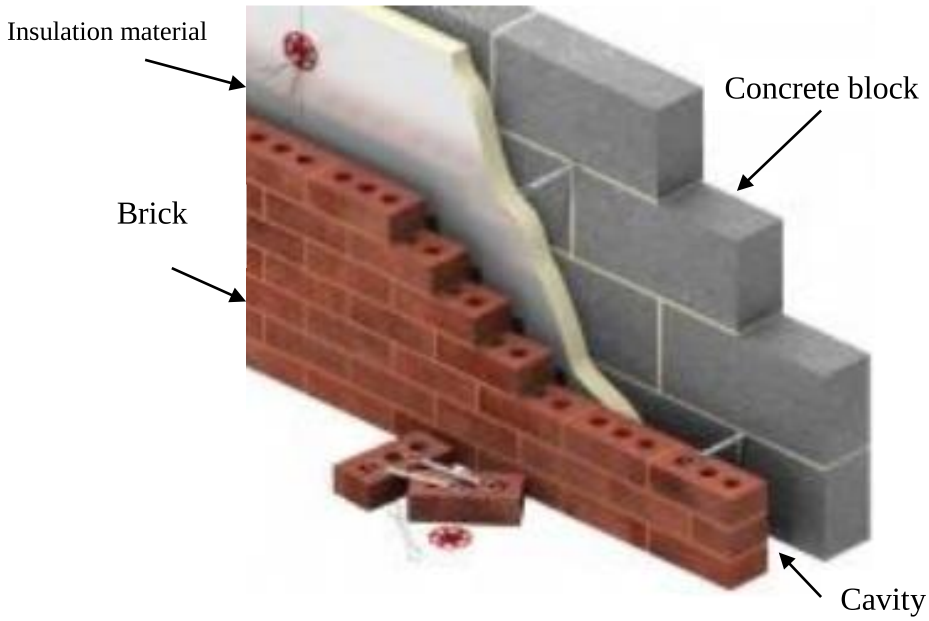


Figure 2-6 Cavity wall system.

Lightweight construction method is the alternative construction method to obtain well-insulated building to meet the new building regulation. Additionally, low or zero carbon buildings can be built within a short period of time.

2.4.3. Timber frame with brick cladding system

The timber frame system, illustrated in Figure 2-7 has the advantage of pre – fabrication that reduces the need for skilled labor. Moreover, this advantage helps to reduce build time, which means houses could be available in the market in a shorter time and this has in additional impact on the economic loop. Timber system can include a massive amount of insulation material that is required to meet low and zero carbon building by 2016.

Figure 2-7 Timber frame with brick cladding (Sahota, 2012)

2.4.4. Modern Methods of Construction (MMC)

The Modern Method Construction (MMC), is based on manufacturing the building elements offsite which known as prefabricated house (Figures 2-8 and 2-9). Monahan and Powell (2011) concluded that using MMC can achieve 34% reduction in embodied energy comparing to an equivalent house that has been built with cavity wall system.

2.4.4.1. Advantage of MMC

- Saving time and cost by constructing most of the building elements offsite.
- Minimum skilled labor needed.
- Energy saving
- Effective finishing and higher quality control.
- Environmental impact by reducing waste materials
- More control of health and safety.

Figure 2-8 Timber frame wall panel manufactured in the Space4 factory (Lovell, 2012)

Figure 2-9 Timber frame wall (Patrick, 2007).

2.4.5. Insulation materials

Recently building designers believe that the high standard insulation of building envelope has been an important method in order to achieve the target of building regulations in the UK (Home and Community/Planning/Building Regulations). However, this is driving building users to face an overheating period during the summer time and even in winter time in future as presented in UKCIP02, that the heat gain inside the buildings will face restrictions from the insulation materials to be released (UKCIP, 2002)

Thermal insulation materials are used to reduce the heat transfer rate, as heat moves by conduction through the building envelope from a hot side to the cold side. It is important here to mention the other mechanisms of heat transfer from one material to another material (solid, liquid or gas) by means of convection and radiation. The R-value -which is the measure of thermal resistance of the materials is the most important factor of insulation materials and it is defined as the temperature difference when the heat flows per unit area. The higher the value of R the better the building is insulated (EnergyGOV, 2012). Table 2-6 presents the thermal conductivity of different insulation materials obtained using the equation 2-1.

Table 2-6 Thermal properties of glass wool.

Thickness(mm)	Thermal conductivity (W/mK)	Thermal resistance (m^2K/W)
140	0.040	3.50
90	0.040	2.25
80	0.044	1.80
60	0.044	1.35

Thermal resistance or R-value

$$R = \frac{d}{k} \qquad \text{Equation 2-1}$$

Where:

R= thermal resistance (m^2K/W).

d= thickness (m).

k= thermal conductivity (W/mK).

It is important to understand the insulation properties including density, thermal conductivity and U-value before considering these for use in the buildings to achieve thermal comfort inside the building, and to obtain higher energy efficiency. In addition, as has been mentioned in the approved document L1A, continuity of insulation is important to improve energy efficiency. Furthermore, an air pressure test is important to improve the efficiency of insulation (Building Regulation, 2010).

2.4.6. Classification of insulation materials

Insulation materials could be divided into their chemical or physical form, and the most popular in use in the EU are organic materials, such as glass wool and inorganic materials, such as polystyrene (Papadopoulos, 2005). In terms of properties, the insulation materials are divided into different categories.

2.4.6.1. Organic insulation materials

Organic insulation includes Glass wool**,** Loose wool and Rockwool. **Glass wool** is one of the organic insulation and consists of quartz lime and ash of soda and in some factories, recycled glass is added. The density of glass wool insulation depends on the amount of insulation targeted and the area where the material will be used. There are many forms of glass wool insulation. Figure 2-10 presents lightweight glass wool rolls and Table 2-6 shows the thermal properties of glass wool (Knauf insulation, 2013a)

Figure 2-10 Lightweight glass wool rolls.

Glass wool, is a lightweight material, is used in pitched roofs in new or existing buildings to achieve thermal insulation as can be seen in Figure 2-11 (Just insulation, 2012).

Figure 2-11 Installing Glass wool in a pitched roof.

Loose wool insulation as shown in Figure 2-12 is a flexible insulation material which is used in irregular shapes of construction elements. Table 2-7 shows the thermal properties of loose wool.

Figure 2-12 Loose wool.

As building regulation have increased the value of thermal insulation in buildings' part L1A, L2A, L1B and L2B and according to Knauf-insulation (Knauf insulation, 2013b) Loose wool insulation is used to improve the thermal resistance of the cavity wall as shown in Figure 2-13.

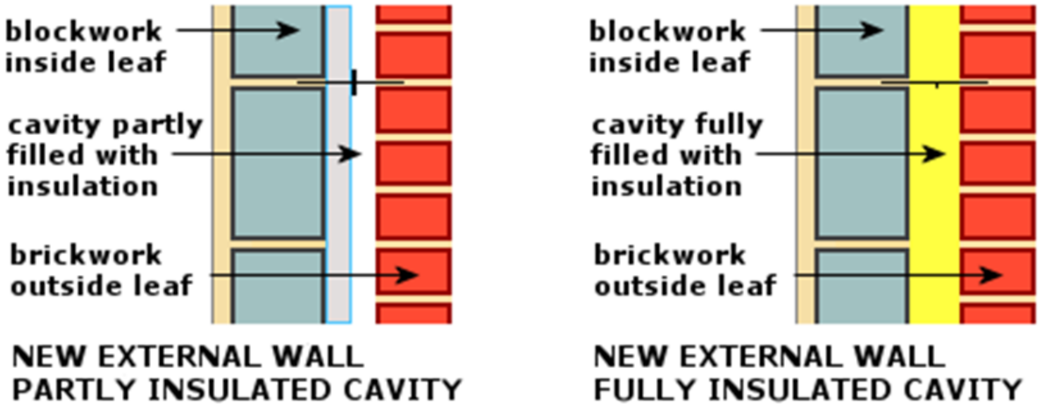


Figure 2-13 The new external wall with A party insulated cavity and B with fully insulated.

Table 2-7 Thermal properties of loose wool.

Density (Kg/m³)	**Thermal conductivity (W/mK)**
100	0.037
100	0.044
100	0.060
150	0.080
150	0.107
150	0.123

Rockwool, illustrated in Figure 2-14 is used as lightweight thermal insulation material, easy to cut to any form with no maintenance needed after installation. Rock wool is one of the most effective insulations that can be used in between wood and metal and it is suitable to be used as thermal insulation of boiler room, walls, roofs and floors. Also, it is easy to handle and install without gaps and it will not sag under moisture conditions. Table

2-8 shows the thermal properties of Rockwool insulation (Just insulation, 2012).

Figure 2-14 Rockwool as insulation material (Just insulation, 2012)

Table 2-8 Thermal properties of Rockwool insulation.

Thickness(mm)	Thermal conductivity (W/mK)	Thermal resistance (m^2K/W)	U-value ($W/\ m^2K$)
20	0.022	0.90	1.11
30	0.022	1.35	0.74
40	0.022	1.80	0.56
45	0.022	2.00	0.50

Aerogel

Aerogel insulation is an extremely lightweight material, has a density equivalent to 3 times the density of the air; only a small fraction of a volume of Aerogel is the material itself as the rest is air. It provides nearly 40 times the insulation of conventional fiberglass insulation where thermal conductivity is 0.0135 W/m K. Aerogel has the potential for very high moisture resistance. It is available for some high performance application including building facades and as insulation material for buildings Figure 2-15 (Paksoy, 2007).

The main disadvantage of aerogel is the cost as it is still expensive compared with other organic and inorganic insulation materials, for example blanket aerogel 600mm × 600mm × 10mm costs about 60£ and thermal wrap from aerogel 300mm × 300mm × 6mm costs about 16£. On the other hand, Rockwool can be obtained from different supplier and the prices vary. For example from Insulation Express 1200mm × 600mm × 100mm costs about 8.5£ and from BSO 1000mm × 600mm × 30mm costs about 8£.

Figure 2-15 Aspen Aerogel(Paksoy, 2007).

Aerogel has many advantages including:

- High thermal resistances.
- Equal thermal resistance with less thickness.
- High moisture resistance.
- Saving space when shipping, storing and when installed in building elements or any other applications.
- Easy to apply and store.

2.4.6.2. Location of insulation

Insulation materials can be added into existing building by using two different methods. It can be added as internal surface or as an external surface (English Heritage, 2010). However, adding the insulation material in the internal layer or in the middle of the construction element will help the other layer to conduct heat and use it later at night.

2.4.6.3. Inorganic insulation materials

Polystyrene is one of the common inorganic insulation material and as shown in Figure 2-16 is used as a thermal insulation material for floors, cavity walls, flat roofs and pitched roofs. It is a rigid and strong material. Polystyrene could be provided in different thicknesses: 10mm, 20mm and 30mm. It is important to highlight that the density can be different for similar thickness of polystyrene sheet. Table 2-9 shows density and thermal conductivity of the polystyrene (Insulation-Express, 2013)

Different thicknesses >10mm

Figure 2-16 The rigid Extruded Polystyrene (Insulation-Express, 2013).

Table 2-9 Density and thermal conductivity of the polystyrene.

Density (Kg/m³)	Thermal conductivity (W/mK)
15	0.038
20	0.036
23	0.035
30	0.034

There are some facts that should be taken into account when choosing thermal insulation materials such as the thickness of the insulation. The thickness of insulation materials that should be used to insulate buildings is dependent on the location of the building, building construction materials, environmental impact and the level of thermal saving required. Moreover, Papadopoulos (2005) notes that "*Insulation materials are not independent energy production or conservation systems, but part of the complex structural elements which form a building's shell".* Additionally, the best insulation material is the material that has the lowest thermal conductivity and the highest R-value. The advantage of a well-insulated building is saving energy, which will help to reduce CO_2 emissions and reduce global warming. In addition, controlling the transfer of heat by means of insulation materials will lead occupants of buildings to achieve thermal comfort. On the other hand, the disadvantage of a well-insulated building is the cause of overheating in some zones, especially in summer time. Thus, as new buildings in the UK are built with lightweight material, with high- standard insulation systems due to the new building regulations this may lead to overheating in summer. In addition, temperatures have been rising over the last century; in 2003 the temperature reached 37.7 °C in the UK (Betting betfair, 2009). Tables 2-10 and 2-11 shows the thermal conductivity of diffrent types of insulation materials and shown the thecknesses of those materilas when the U-value is $0.25W/m^2K$, those tables provided from Energy saving trust (2010).

Table 2-10 Shows the thermal conductivity of diffrent type of insulation materials (Energy savin trust, 2010)

Insulation Materials Chart		**Insulation thickness (mm) to achieve U-value= 0.25W/m²K**	**Range of Thermal Conductivity (W/mK)**						
			0.00	0.01	0.02	0.03	0.04	0.05	0.06
Highest performance	Vacuum Insulated Panels	30	0.008						
	Aerogel	50-55		0.013 0.014					
Polyurethane (PU)	Polyurethane with pentane up to 32kg/m^3	105-115			0.027	0.03			
	Polyurethane soy-based	100-145			0.026	0.038			
	Foil-faced Polyurethane with pentane up to 32kg/m^3	75			0.02				
	Polyurethane with co_2	130				0.035			
	In-situ applied Polyurethane (sprayed or injected)	80-100			0.023 0.028				
Polyisocyanurate (PIR)	Polyisocyanurate up to 32kg/m^3	95-105			0.025 0.028				
	Foil –faced polyisocanurate up to 32kg/m^3	80-85			0.022 0.023				
	In-situ applied polyisocyanurate (sprayed)	80-100			0.023 0.029				
Phenolic foam (PF)	Phenolic foam	80-95			0.020 0.025				
	Foil –faced Phenolic foam	75-85			0.020 0.023				
Expanded Polystyrene (EPS)	Expanded Polystyrene up to 30kg/m^3	115-165				0.03	0.045		
	Expanded Polystyrene with graphite (grey)	115-120				0.03 0.032			
Extruded Polystyrene (XPS)	Extruded Polystyrene withCO_2	95-140			0.025	0.037			
	Extruded Polystyrene with HFC 35kg/m^3	110-120			0.029	0.031			

Table 2-11 Shows the thermal conductivity of different type of insulation materials

Insulation Materials Chart		Insulation thickness (mm) to achieve U-value= 0.25W/m²K	Range of Thermal Conductivity (W/mK)						
Wool and fiber	Glass wool (up to 48kg/m³)	135-180				0.03	0.044		
	Galss wool (equal/greatar than 48kg/m³)	155				0.036			
	Stone wool (less than 160kg/m³)	150-160				0.034 0.038			
			0.00	0.01	0.02	0.03	0.04	0.05	0.06
	Stone wool (160kg/m³)	160-170				0.037	0.040		
	Sheeps wool (25kg/m³)	150-215				0.034			
	Cellulose fibre (dry btawn 24kg/m³)	150-190				0.035	0.046		
	Hemp fibre	165				0.039			
	Polyester fibre	150-180				0.035	0.046		
	Wood fibre (WF)	145-225				0.039			
Alternative	Hemp time (monolithic)	260				0.039			
	Cotton	165-170							
	Cork (120kg/m³)	155-200				0.039			
	Vermiculite	235							
	Perlite (expanded)board	190						0.051	
	Celular galss (CG)	140-185				0.038		0.05	
	Flexible thermal linings						0.04		0.06 3

2.5. Overheating problem

Overheating is the accumulation of heat in building spaces, which lead to users' discomfort and to health problems that could affect respiratory and cardiovascular disease. According to CIBC, 25°C is the warm temperature for most people and 28°C is the hot temperature in cold regions. According to BRE, well insulated homes and doubled or trebled glazing windows can lead to overheating, as illustrated in Figure 2-17.

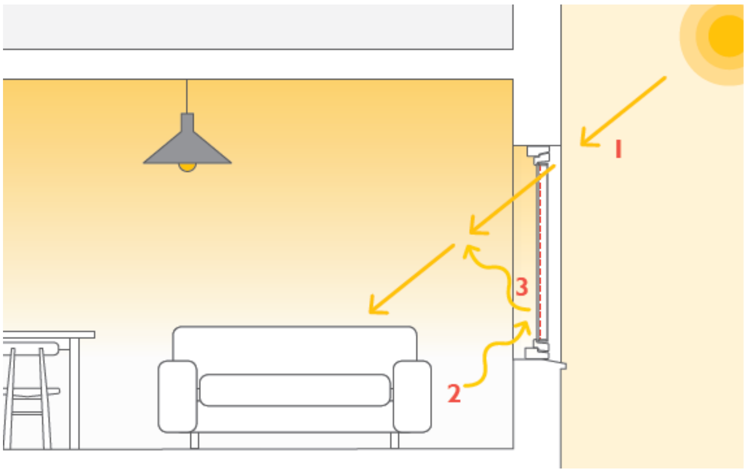


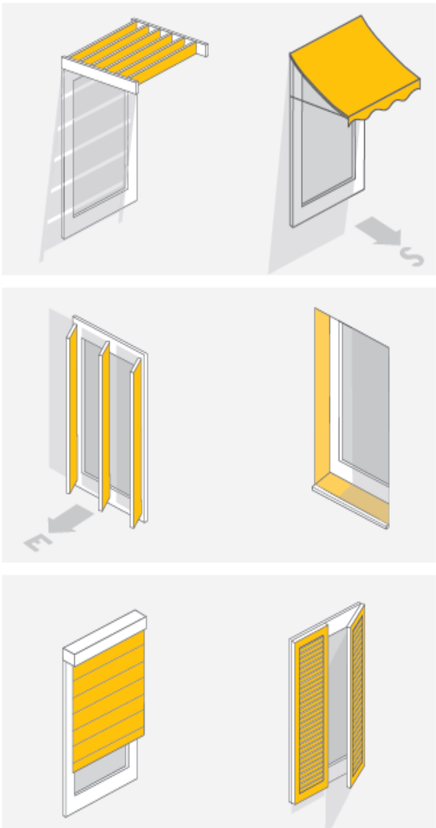
Figure 2-17 Double or trebled glazing windows lead to overheating issue (NHBC Foundation, 2012).

There are many factors that lead to increase the risk of overheating including the following:

- Building orientation.
- Building design.
- Absence of shading elements for the buildingThermal mass.
- Service design.
- Restricted ventilation.

On the other hand, the following factors may help to reduce the risk of overheating:

- User behaviour.
- Solar shading and shading devices (Figure 2-18).
- Ventilation (Figure 2-19).
- Increasing thermal mass (Figure 2- 20) (NHBC Foundation, 2012).



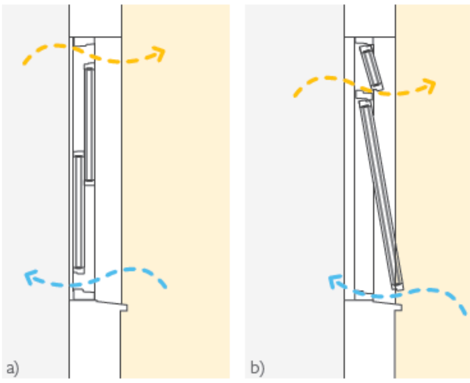
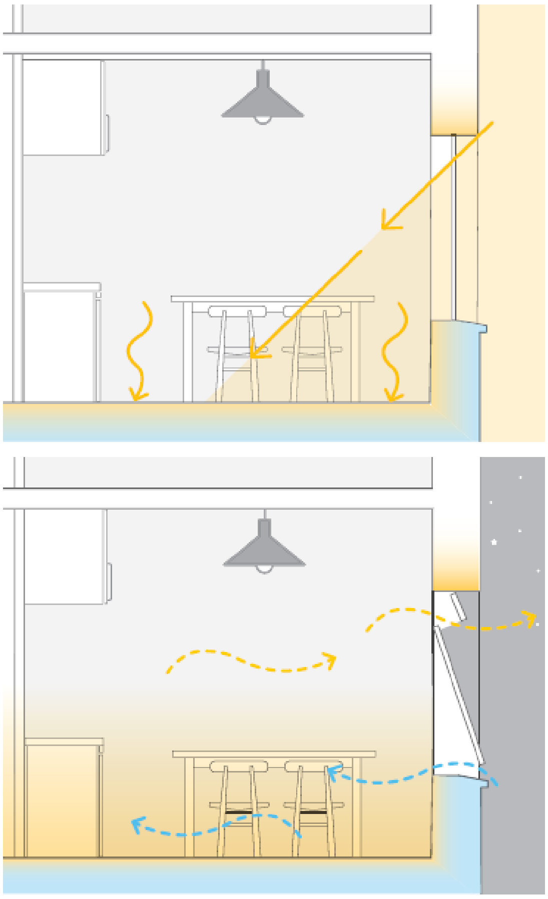


Figure 2-19 Ventilation(NHBC Foundation, 2012)

Figure 2-18 Solar shading(NHBC Foundation,



Thermal mass during the daytime

Figure 2-20 Thermal mass at night (NHBC Foundation, 2012)

2.6. The effect of thermal mass on building envelop

Thermal mass is the ability of the building materials to absorb (store) and release heat. Figure 2-21 illustrates how high thermal mass affects the internal temperature in comparison to low thermal mass. Concrete, brick and stone are used as high thermal mass structure materials. However, the building could be structured using heavyweight materials but still has low thermal mass and that is because the modern use of the false ceiling, carpets and any element that could isolate the heavy thermal mass element from direct contact with building spaces. As a result, this will usually require mechanical cooling for heat recovery in summer (Braham et al., Balaras, 1996). Thus, building elements thermal mass can provide benefits to the building spaces in the following manner:

- Stable daily temperature during the year.
- Reduce cooling and heating load in summer and winter.

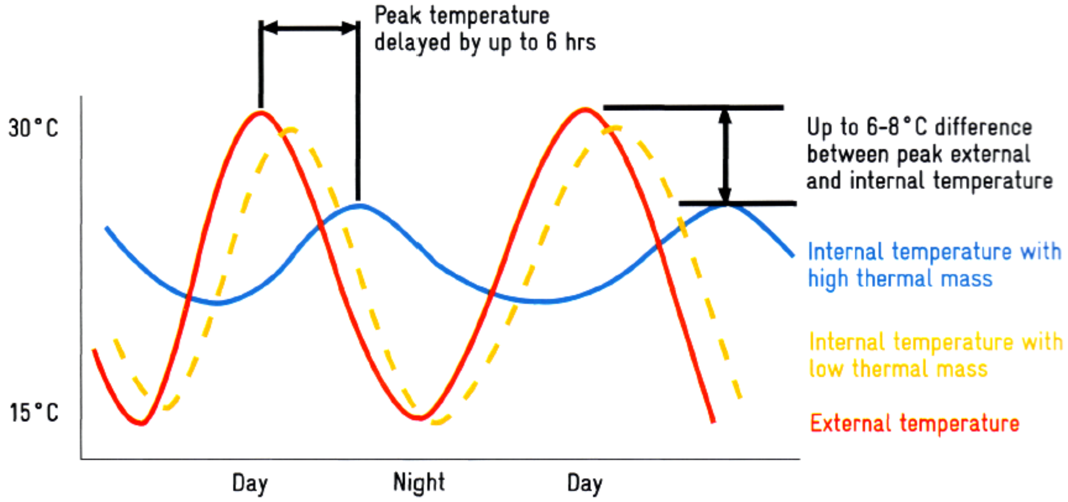


Figure 2-21 The impact of increasing building thermal mass (Energy Saving Trust, 2010)

Thermal mass and insulation material are very important for the thermal performance of buildings. However, insulation material affects the role of other thermal mass materials, by isolating the released heat to enter building's spaces. Ventilation plays an enormous role in the processing, absorption and release of heat continuously during the day and night.

2.7. The concept of thermal energy storage in buildings

The term thermal storage according to Roaf et al. (2003) means saving the energy to be used at another time. Thermal energy storage applications are used to store energy for 24 hours, a week or even a season. Thus, the concept simply is to store energy at peak times to be used at off peak times (Hasnain, 1998, Zafer UREM.Sc., 2011). Therefore, with the widespread use of lightweight construction methods, increasing the cost of fossil fuel and awareness about the environment, thermal energy storage systems have become one of the strategies of heating and cooling for the building (Zhang et al., 2007). Hasnain (1998) stated that both sensible and latent heat storage are the two main factors responsible for thermal energy storage.

2.8. Conclusions

As chapter two present comprehensive reviews about the important subjects related to this research. Thus, it can be concluded that energy demand and protection the environment are the mine points that all other issues work to obtain them. The first issue that has been addressed was the building regulation in the UK and hoe it is impotent to control the energy demand and reduce the use of energy and supporting the clean environment. The UK start working on establishing regulation to control every aspect in building construction late to 1936, however the first forced regulation has been issued in 1966. In October 2010 the building regulation for domestic buildings has present in L1A that 25% of CO_2 should be reduced which 5% extra is cut comparing with regulation 2006. On other hand, the Code for sustainable home has been issued late 2007 and has 6 levels target to improve the privet and public buildings in terms of reducing CO_2 gradually till 2016 where is the target to obtain zero emission of CO_2.

This review also addresses the housing construction in the UK and presents that there are different construction methods have been used:

- Solid wall.
- Cavity wall.
- Tamper frame with brick cladding system.
- Modern Method of Construction known as MMC.

As the energy demand has been raised and with new target of U-value presented in building regulation and the Code of Sustainable Home the use of insulation materials has been increased. Insulation materials can be classification as flow:

- Organic insulation materials.
    - Loose wool.
    - Rockwool.
    - Aerogel.
- Inorganic insulation materials.
    - Polystyrene.
    - Phenolic foam.
    - Foil –faced polyisocanurate.

As a result of well insulated building the problem of overheating has been raised even in cold regains such as the UK. According to CIBC, 25^{o}C is the warmer temperature for most people and 28^{o}C is the hot temperature in cold regions. Also, according to BRE, well insulated homes and doubled or trebled glazing windows can lead to overheating. Moreover, other factors also leading to overheating such as:

- Building orientation.
- Building design
- absence of shading elements for the buildingThermal mass
- Service design
- Restricted ventilation

Also the review presents key points that could help to reduce the risk of overheating:

- User behaviour
- Solar shading and shading devices
- Ventilation
- Increasing thermal mass.

Thermal mass is the ability of the building materials to absorb (store) and release heat. Thus, as the new building construction MMC using more insulation which has low thermal mass the next chapter addressing the use phase change materials (PCMs) as a solution to increase the buildings thermal mass and decrease the risk of overheating.

CHAPTER3: PHASE CHANGE MATERIALS (PCMs) REVIEW

"*Thermal energy storage (TES) appears to be the most appropriate method for correcting the mismatch that sometimes occurs between the supply and demand of energy. It is therefore a very attractive technology for meeting society's needs and desires for more efficient and environmentally benign energy use.*"

Ibrahim Dincer
Marc A. Rosen
(Dincer and Rosen, 2011)

3. Phase Change Materials (PCMs) review

In brief, Phase Change Materials (PCMs) can be defined as unique materials that store and release heat by means of latent heat. PCMs are used as thermal energy storage (TES) for buildings to control temperature over a cycle period of 24 hours to charge and discharge the heat (pcmproducts, 2011). PCMs are one of the best management methods used to control building temperature within the daily cycle. According to Diaconu (2011), the thermal mass of the building envelope could be improved without significant change in building structure by using PCMs to compensate the thermal value of the building envelop.

The basic mechanism of Phase Change Materials (PCMs) application is for reduction of overheating inside buildings, as PCMs have enormous thermal capacity to absorb large amounts of heat and large ranges of melting temperatures (Darkwa, 2009, Huang et al., 2006). As such, the use of PCMs will help to reduce the need for regular heating and cooling and will work as an alternative to air-conditioning to control the temperature inside the space (Baetens et al., 2010). Furthermore, using PCMs for energy storage will help reduce the demand on fossil fuels. This will have a positive impact on the energy consumption, energy cost and the environment (Shilei et al., 2006, Darkwa et al., 2006). In building construction, PCMs form part of the building envelope, thus the position of the PCM is important in relation to the thermal behaviour of the wall materials (Huang et al., 2006).

PCMs have the ability to change from solid to fluid or from fluid to gas at a certain temperature (Pasupathy et al., 2008b). According to Peeters (2009) and Pasupathy (2008b) during the day for instance when the temperature rises above a human comfortable temperature (between 18 ^{o}C to 23 ^{o}C in cold regions), the chosen PCM melting temperature should be equal or just below the comfortable temperature

(Ahlstrom, 2005, BASF, 2011). The PCM will decrease overheating at daytime by changing from solid to liquid. This drops the temperature inside the building volume. Therefore, the aim is increasing the thermal mass of the building envelope for existing and new buildings by using PCMs (Diaconu, 2011, Pasupathy et al., 2008b).

There are however some points which need to be highlighted. Firstly, if the temperature at night in summer time is not low enough, the PCM will not be triggered to move into a normal phase change cycle to reduce the building overheating during the daytime. Secondly, if the building is well insulated, the heat transfer into the building would have a minimal effect (Ahlstrom, 2005). Thirdly, there is the effect of condensation on the PCMs containers if the building is not well designed in terms of ventilation and humidity.

Pure PCM materials have to be tested as performance differs initially depending on material conductivity and heat capacity from different manufacturers (Zalba et al., 2003). Thus more experiments need to be conducted in order to evaluate different effects of PCMs under different conditions. PCMs are available for a wide range of temperatures even for a commercial use between -114 to +164 (PCM Products, 2009). It should be taken into account that the PCMs' behaviour depends on the quantity of the material and the temperatures during the day and night (Zalba 2003).

According to Zalba et al (2003) there is a limitation of using PCMs because of "*poor stability of the materials properties due to thermal cycling, and/or corrosion between the PCM and the container"*. Ahlstrom 2005) highlighted that although PCMs appear as a great technique of controlling heat and saving energy, users and manufacturers have to recognize that they cannot use PCMs for all needs. A simple example of PCM is water, but it cannot be used to decrease temperature because the freezing point of water is 0°C. Below this temperature, it will change from liquid to solid (ice). This is not helpful in most applications (PCM Products, 2009). However, many researchers have investigated the potential of increasing the stability of PCMs thermal cycling by using different methods and strategies as highlighted in section 3.14.

3.1. Operation of PCMs:

As mentioned earlier, PCMs operate in the following modes:

- Solid /Liquid (most practicable), during the cooling process.
- Liquid/ Gas (not practicable because of the enormous changes in volume and pressure).
- Solid / Solid (known as a change in crystalline structure), heating mode.

Figure 3-1 explains the behaviour of the PCMs as latent heat storage. As illustrated, A is the solid state. As the temperature rises there is no change in material structure between A_B, and the substance remains solid as at the starting point A. During B_C period, the crystalline structure of the solid material starts to change. This is known as the solid-solid phase change. As a consequence of extra heat, there is no change in the solid structure where sensible heat is applied in C_D. During the solid-liquid phase change D_E, the material absorbs heat as latent heat and changes from solid to liquid. The duration of this process depends on the heat capacity of the materials, melting temperature, latent heat of fusion and the thermal conductivity. As illustrated, within E_F no phase change of the liquid occurs as sensible heat is obtained. Liquid-gas phase change takes place between F_G where the material stores energy as latent heat. In the G_H period, no more heat will be stored as latent heat and any further heat will appear as sensible heat (Regin et al., 2008, Zhou et al., 2012).

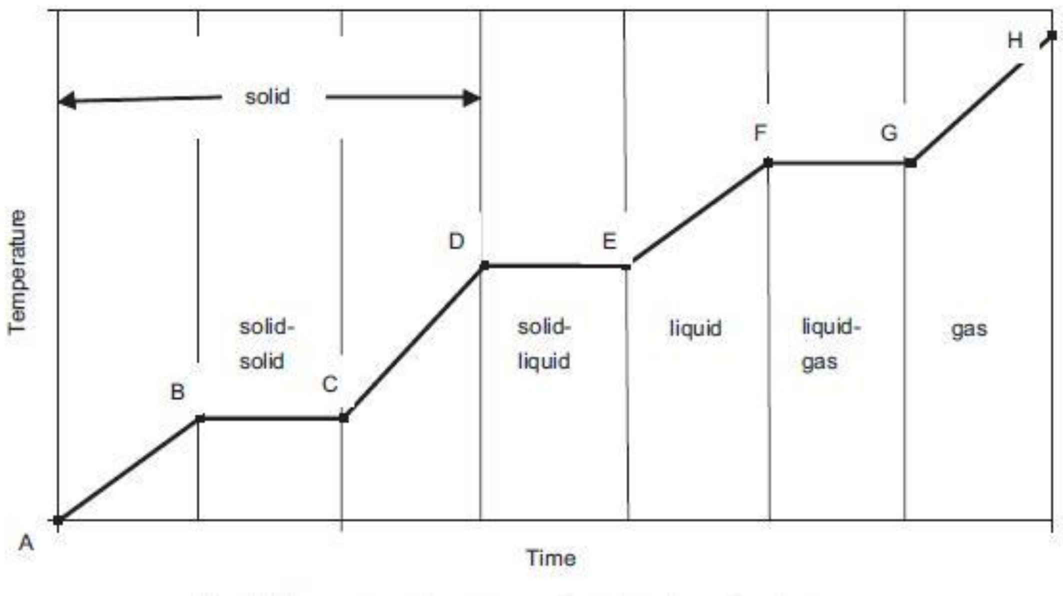


Figure 3-1 Diagram illustrating the Phase change of the materials related to the temperature and time(Regin et al., 2008).

3.2. Advantage and disadvantage of PCMs

The advantage of using PCMs include:

- Green solution.
- Reduction of energy cost (Shilei et al., 2006).
- No moving parts, thus presents low maintenance cost.
- Works for a long time without any start or stop operations.
- PCM containers can be made from different materials and in any form.

The disadvantage of using PCM include:

- Not effective for a large spaces or volumes unless it is designed to be placed in different places to absorb and release the heat with enormous consideration for the thermal conductivity of the PCM material used.
- Change in size when the material change phase from solid to liquid or from liquid to gas.
- The effect of moisture and leaks on the building structure, especially if the PCM used is not encapsulated (Huang, 2002), (refer to section 3.5).
- PCMs cannot be stimulated in summer time with night cooling if the temperature outside is not lower than the melting point of the PCM.

3.3. Required characteristics of PCMs

Choosing a suitable PCM is a critical decision. Many aspects have to be considered, such as the economy of use, environmental issues as well as the PCM properties such as its melting point, thermal conductivity and heat capacity (Abhat, 1981). The following factors have to be considered when choosing PCM for building use.

- An appropriate range of melting temperatures required for the applications (Regin et al., 2008) .
- The shape of the PCM container, which suits required applications.
- PCMs should have lower super cooling degree with slight expansion in volume during the phase change period.
- Heat fusion, heat capacity and thermal conductivity should be in high rate (Kenisarin and Mahkamov, 2007)

3.4. Classification of PCMs:

Phase Change Materials (PCMs) can be divided into three groups namely organic, inorganic and eutectic as illustrated in Figure 3-2 (Paksoy, 2007, Pasupathy et al., 2008b, Sharma et al., 2009, Baetens et al., 2010, Zhou et al., 2012). There is a large number of PCMs under each category. However, not every PCM has the required target properties for sufficient thermal storage (Pasupathy et al., 2008b, Sharma et al., 2009). In many cases the thermal properties of the PCMs have to be improved. For instance, this can be done by using metal to increase the thermal conductivity of the PCMs or by coupling them with other materials to increase the ability to conduct heat (Sharma et al., 2009).

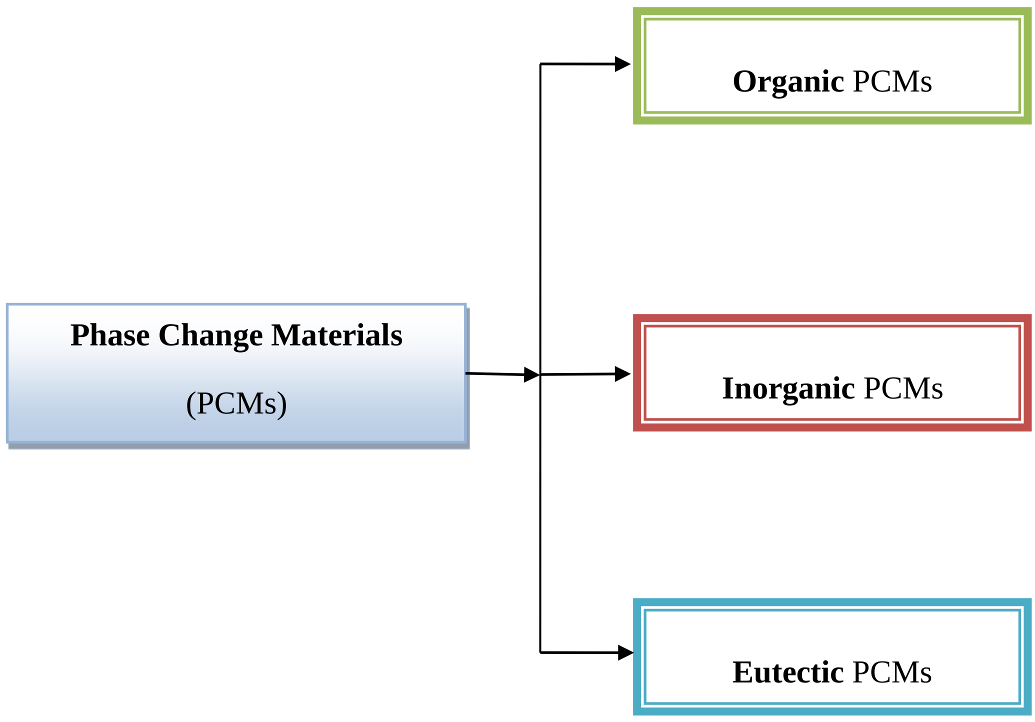


Figure 3-2 Classification of PCMs.

3.4.1. Organic PCMs

Organic materials can be defined as materials that are built from carbon and hydrogen (C and H). They can also be divided into paraffin and non-paraffin such as Caprilic acid, Phenol and Methyl palmitate as shown in Table 3-1 (Oró et al., 2012, Zivkovic and Fujii, 2001, Sharma et al., 2009).

Table 3-1 Organic PCM substances (Zalba et al., 2003)

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m3)	
Dimethyl-sulfoxide (DMS	16.5	85.7	-	1009	(Farid et al., 1998)
Paraffin C16–C18	20	152	-	-	(Zalba,2002)
Polyglycol E600	22	127.2	0.189	1126	(Dincer and Rosen, 2011)
Paraffin C13–C24	24	189	0.21	760	(Abhat, 1983)
1-Dodecanol	26	200	n.a.	n.a.	(Hawes et al., 1993a)
Paraffin C18.	28	244	0.148	774	(Abhat, 1983)
1-Tetradecanol	38	205	-	-	(Hawes et al., 1993a)

Paraffins have been used as an organic PCMs to store heat for many reasons such as low vapour pressure when the PCM changes from liquid to gas or for negligible super-cooling. The organic PCMs have low thermal conductivity and there are two methods to improve it. The first is by using intermediary mass to transfer heat while the second involves mixing PCM with other materials which have higher thermal conductivities. The advantages and disadvantages of organic PCMs are presented in Table 3-2.

Table 3-2 Advantage and disadvantage of Organic PCMs (Zalba et al., 2003, Pasupathy et al., 2008b, Sharma et al., 2009, Zhou et al., 2012)

Organic Phase Change Materials	
Advantages	**Disadvantages**
• High temperature range • Paraffin is safe to be used. • Non corrosive • Slight volume change when melting. • Long freeze and melt cycle. • No need for supper cooling to freeze. • Non paraffin has a high heat of fusion. • Compatible with other materials such as cement and aluminium. • Recyclable.	• Paraffin high cost • Low thermal conductivity • Non- compatible with plastic container • Costly. But some types of paraffin mixture are low cost. • Low capacity of latent heat storage. • Low enthalpy. • Flammable

3.4.2. Inorganic PCMs

Inorganic materials such as Polyethylene glycol 600, Acetic acid and Palmatic acid have been divided into salt hydrate and metallic. Salt hydrates can be defined as a combination of salts and water while metallics are defined as low melting metals illustrated in Table 3-3 (Sharma et al., 2009). The advantages and disadvantages of inorganic PCMs are presented in table 3-4. However it is important to highlight that inorganic PCMs have higher thermal storage capacity compared to organic PCMs (Farid, 2004, Sharma et al., 2009).

Table 3-3 Inorganic PCM s substances (Zalba et al., 2003).

Compound	**Melting temperature (°C)**	**Heat of fusion (kJ/kg)**	**Thermal conductivity (W/m K)**	**Density (kg/m3)**
Na2CrO4 . 10H2O 18	18	n.a.	n.a.	n.a.
KF. 4H2O 18.5	18.5	231	n.a.	1447
Mn(NO3)2 . 6H2O	25.8	125.9	n.a.	1728
CaCl2 . 6H2O	29	190.8	0.540	1496
LiNO3 . 3H2O	30	296	n.a.	n.a.
Na2SO4 . 10H2O	32.4	254	0.544	1485
Na2CO3 . 10H2O	32	246.5	n.a.	1442

Table 3-4 Advantage and disadvantage of inorganic PCMs(Zalba et al., 2003, Farid, 2004, Pasupathy et al., 2008b, Sharma et al., 2009, Zhou et al., 2012)

Inorganic Phase Change Materials	
Advantages	**Disadvantages**
• Low cost. • High thermal conductivity (about 0.5 W/mk) • High enthalpy. • Great heat fusion. • Higher thermal storage. • Non-flammable. • Compatible with plastic containers.	• Susceptible to corrosion. • Low thermal stability. • High volume change. • Super cooling problem. • Slightly toxic.

3.4.3. Eutectics PCMs

Eutectic PCMs are defined as compounds that consist of two or more PCMs that melt and freeze compatibly without segregation (Sharma et al., 2009, Oró et al., 2012, PCM Products, 2009). An example is the compound mixture Triethylolethane + water + urea by weight % as 38.5 + 31.5 + 30 where the melting point is 13.4 ^{o}C and latent heat 160 KJ/Kg. More examples of eutectic PCMs are given in Table 3-5 (Sharma et al., 2009). According to Baetens et al. (2010) eutectic PCM compounds can be classified into three: 1) organic-organic 2) inorganic-inorganic 3) inorganic- organic. The advantages and disadvantages of eutectic PCM are listed in Table 3-6.

Table 3-5 Eutectic PCM (Zalba et al., 2003)

Compound of PCMs	**Melting temperature (°C)**	**Heat of fusion (kJ/kg)**	**Thermal conductivity (W/m K)**	**Density (kg/m3)**
66.6% CaCl2 _ 6H2O+ 33:3% MgCl2 _ 6H2O	25	127	n.a.	1590
48% CaCl2 + 4:3% NaCl+ 0:4% KCl 47:3% H2O	26.8	188.0	n.a.	1640
47% Ca(NO3)2 _ 4H2O+ 33% Mg(NO3)2 _ 6H2O	30	136	n.a.	n.a.
60% Na(CH3COO) . 3H2O+ 40% CO(NH2)2	31.5	226	n.a.	n.a.
61.5% Mg(NO3)2 .6H2O+ 38:5% NH4NO3	52	125.5	0.494	1515
58.7% Mg(NO3) _ 6H2O+ 41:3% MgCl2 _ 6H2O	59	132.2	0.510	1550
53% Mg(NO3)2 _6H2O+ 47% Al(NO3)2 _9H2O	61	148	n.a.	n.a.
14% LiNO3 + 86% Mg(NO3)2 _ 6H2O	72	>180	n.a.	1590

Table 3-6 Advantage and disadvantage of eutectic PCMs (Pasupathy et al., 2008b, Baetens et al., 2010, Zhou et al., 2012)

Eutectics Phase Change Materials	
Advantages	**Disadvantages**
• Storage capacity is slightly better than organic PCMs. • Sharp melting point (Sharma et al., 2009).	• Corrodes if in contact with metal container for long time.

3.5. Encapsulation of Phase Change Materials (PCMs)

It is important that PCMs melt and solidify within the target period to absorb and release heat according to the needs of building load. Thus, one of the most key points to improve the melting and solidifying lag time is providing great attention into the containers design, where the PCMs can be encapsulated (Zivkovic and Fujii (2001). The size and the shape of the container should suit the place where it will be used. On the other hand, this improves heat transfer rate (Oró et al., 2012). According to Salunkhe and Shembekar (2012) investigations into different geometries such as cylinder, plate, tube and sphere were carried out to encapsulate PCMs. The results concluded that the spherical shape is perfect to improve the heat transfer rate, also and in terms of the material container to avoid any corrosion. The shape of the container should allow maximum contact of surfaces with the heat source. This helps the PCMs to conduct heat within a short period of time.

Tube ICE can be designed in any volume depending on the requirements of heat storage. It is a possible to construct the tube from a variety of materials such as plastic, concrete and steel as illustrated in Figure 3-3 (Kenisarin and Mahkamov, 2007, Plus-ICE, 2011). Moreover, tube containers, could be installed underground for instance as a tank; or above ground for instance under the roof (Figure 3-4).

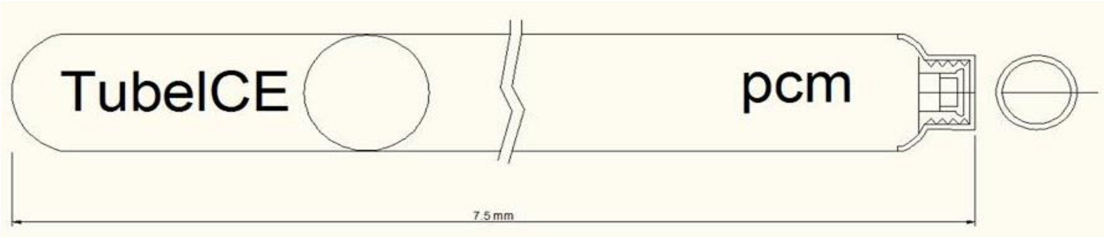


Figure 3-3 Tube- ICE PCM container(Plus-ICE, 2011).

Figure 3-4 Places set Tube- ICE PCM container (PCM products, 2011).

3.5.1. Ball ICE

Ball ICE has been designed by PCM product Ltd, with the balls made of plastic or metal as illustrated in Figure 3-5. This type of encapsulated method is used in small-scale applications for TES. The size of the ball is between 20 mm to 40 mm, however it could be produced in any other size larger than 40 mm (PCM Products, 2009).

Figure 3-5 Plastic and steel PCM container (Kenisarin and Mahkamov, 2007)

3.5.2. PLATES

Plate containers are plastic containers constructed to contain PCMs. The internal support has been added inside the containers to ensure its ability to be stacked on top of each other as can be seen in Figure 3-6. The concept of these container designs is to obtain large amounts of heat exchange surfaces where gaps between them will help to increase the air moving around the surfaces of each container. This helps to increase the heat exchange rate (Figure 3-7). The weight of the plates is between 0.37 kg for the small container, and up to 5.57 for larger containers of Flat ICE (PlusICE, 2011).

Figure 3-6 Flat ICE plastic containers (Plus-ICE, 2011, PlusICE, 2011).

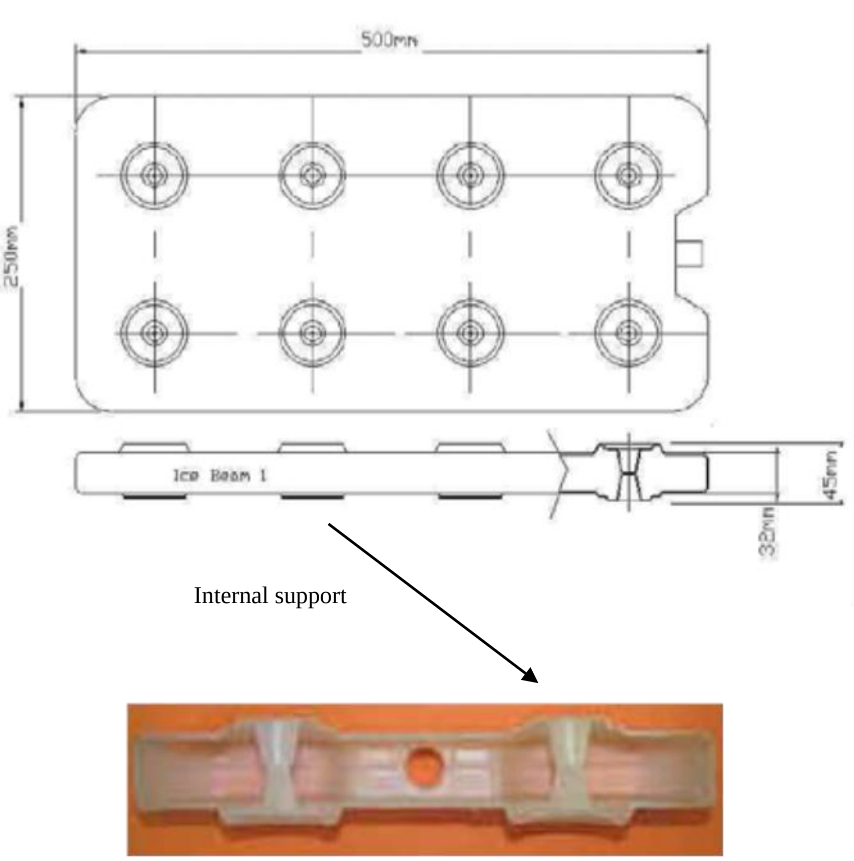


Figure 3-7 The design of the Flat ICE container, showing the internal support (Plus-ICE, 2011).

3.5.3. Pouches for PCMs

Pouches are made of plastic or metal materials. The main advantages of this type of container is the thickness as it can be few millimetres, which gives a higher ability of charging and discharging to ensure the cycles of melting and freezing. This will guarantee the effective use of the PCMs. This category of containers is mainly used to transport medical products and food which can be set in a smaller package as seen in Figure 3-8 (Plus-ICE, 2011).

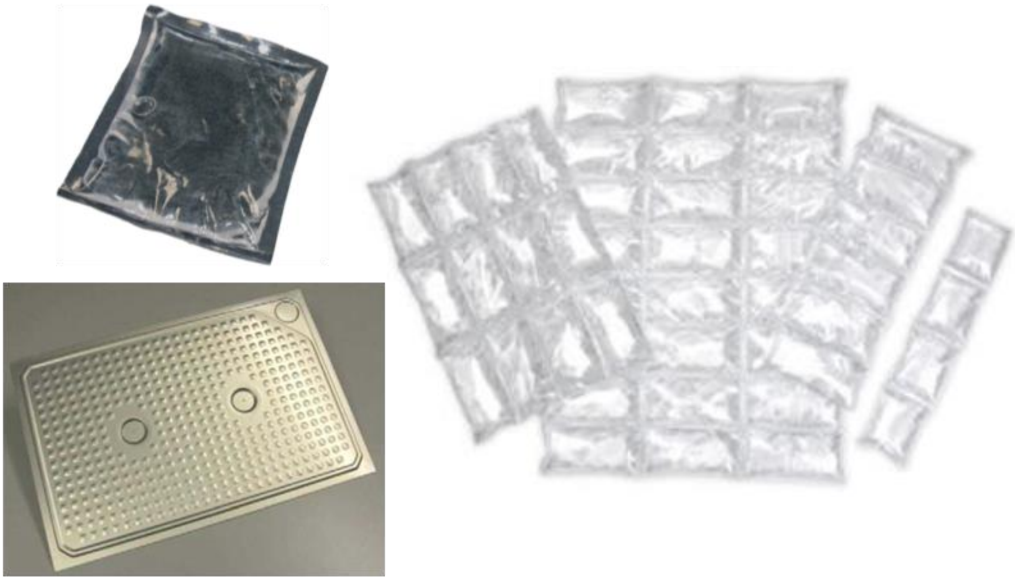


Figure 3-8 Pouches carrying PCMs (Cryopayk, 2010, Zhou et al., 2012)

3.6. Micronal PCM high tech in microcapsules (MPCM)

MPCM is paraffin phase change materials stored in the 5μm core of the microcapsule as illustrated in Figure 3-9. The melting temperature range is from 21 °C, 23 °C and 26 °C as shown in Table 3-7. The advantage of MPCM is that it can be used with different building materials as will be mentioned in chapter 5, as no leak take place when the PCM change from solid phase to liquid phase

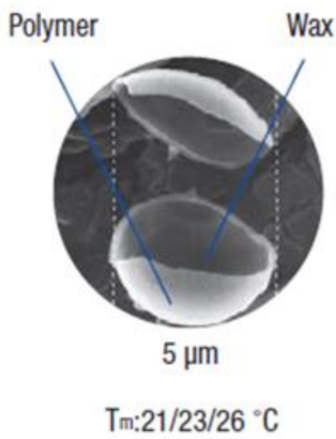


Figure 3-9 Core of the microcapsule (BASF, 2011)

Table 3-7 Micronal PCM properties (BASF, 2007).

Product designation	**Melting point approx.**	**Application**	**Overall storage capacity approx.**	**Latent heat capacity approx.**
DS 5000	26°C	Summertime excessive heating protection	59 kJ/kg	45 kJ/kg
DS 5007	23°C	Stabilisation of the indoor temperature in the comfort zone Passive and active application	55 kJ/k	41 kJ/kg
DS 5030	21°C	Surface cooling systems	51 kJ/kg	37 kJ/kg
DS 5001	26°C	Summertime excessive heating protection	145 kJ/kg	110 kJ/kg
DS 5008	**23°C**	**Stabilisation of the indoor temperature in the comfort zone Passive and active application**	**135 kJ/kg**	**100 kJ/kg**

3.7. Measuring the thermal properties of PCMs

There are two main techniques for measuring the thermo-physical properties of PCMs (Zalba et al., 2003, Huang, 2002):

- Differential Thermal Analysis (DTA).

  DTA can provide data about melting and freezing temperature point range, degree of sup-cooling, and homogeneity of original substance. The substance weight from 1g to 10 g.

- Different Scanning Calorimetric (DSC).

  DSC can provide data about melting and freezing temperature, degree of super-cooling and specific heat. The substance weight from ≥10 g.

Measuring thermal conductivity

- Hot-wire method (Frusteri et al., 2005)

  The method uses a constantan wire connected with two electric connectors. The thermocouple is set in between two samples of material (Figure 3-10). This method is used to measure the thermal conductivity for solid materials. Constant voltage is used as input for 10 second and the temperature recorded by using a thermocouple. The test procedure will be replicated many times to minimize error. A high attention should be paid when connecting the hot-wire with the surface of the substance.

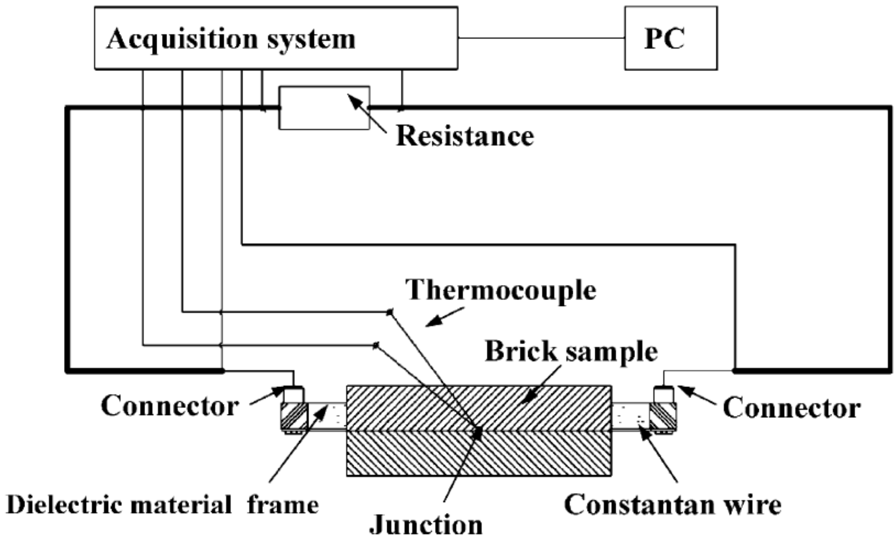


Figure 3-10: Thermal conductivity measure using Hot-wire method (Frusteri et al., 2005).

- Heat Flow meter (HFM) method

  The HFM consists of a cold and a hot plates. The cold plate temperature was controlled using a refrigerator and a heater was used to heat the hot plate. Additionally, the sample is located in a high efficiency insulated box and adjusted to control the thickness between plates. The HFM is designed for one dimension heat transfer with an accuracy level of ±1 (please refer to section 5.3 for more details about HFM) (Darkwa and Kim, 2005).

3.8. The applications of PCMs

Phase Change Materials (PCMs) can be used to control the temperature and to store energy for when it is needed. PCMs have been used in different applications and a wide range of benefits can be obtained, such as for medical transportation where vaccine carriers need to be protected from freezing as illustrated in Figure 3-11 (Donnelly, 2012); food transportation (Stritih, 2004, Zalba et al., 2003), domestic hot water, and telecom shelters to keep the system under 45°C. According to Zalba (2003), PCMs have been used in thermal storage of solar energy, heating water, ice storage, and building applications for heating and cooling spaces. It is important at this stage to highlight that Jurinak and Abdel-Khalik (1979) conclude that using the melting temperature as the basis for selection of PCMs for any application is more effective than selection by means of heat capacity, as the heat capacity can be controlled by the amount of PCMs.

Figure 3-11 Transporting vaccinations using PCMs (Donnelly, 2012).

3.9. Problems of Phase Change Materials

In order to improve the use of PCMs, a number of problems must be resolved. These problems affect the use of PCMs, thus a large number of researchers have been involved in studies to find solutions to these problems.

- Super cooling (Farid, 2004).

  PCMs solidify and melt at the same temperature. However, in some cases the temperature of PCM to solidify is below the melting temperature. In that case the PCM will change from liquid to solid in temperature below the melting temperature. This process known as sub or super cooling.

- Low thermal conductivity (Paksoy, 2007).

  One of the disadvantages of the PCMs is low thermal conductivity. As the PCM stores a large amount of heat in a small volume, heat should be transferred through the materials from outside or vice versa in short time to get the maximum benefit.

- Encapsulation and composite of the materials (Zalba et al., 2003).

As the PCMs in most used cases change phase to liquid in order to absorb heat and to avoid any problem of leakage, PCMs should be encapsulated (please refer into section 3-5).

- Compatibility with other materials (Paksoy, 2007).

  PCM should be compatible with any other materials that have direct contact with it such as the PCM container. It is important to consider this issue to maintain the lifetime of PCMs.

3.10. Overview of PCMs investigated in literature for building applications

Table 3-8 presents some PCMs that have been mentioned in the literature and whose influences have been investigated on buildings. Tables 3-9and 3-10 show commercial PCM products used in building comfort applications.

Table 3-8 PCMs used for building applications.

PCM	Melting Temperature °C	Heat of fusion KJ/Kg	Reference
CaCl2.6H2O+Nucleator	23	-	(Zhang et al., 2007)
Heptadecane	22	214	(Koschenz and Lehmann, 2004)
Capric-lauric 45/55	21	-	(Hawes et al., 1993b)
Capric-myrstic 73.5/26.5	21.4	-	(Peippo et al., 1991)
Capric-palmitate 75.2/24.8	22.1	-	(Peippo et al., 1991)
Peg1000+Peg600	23-26	-	(Kauranen et al., 1991)
RT25	25	-	(Ismail and Castro, 1997)
65–90% methyl palmitate + 35–10% Methyl stearate	22-25.5	120	(Cabeza et al., 2011)

Table 3-9 Commercial PCMs available in the market (Zalba et al., 2003).

PCM name	**Melting temperature (°C)**	**Heat of fusion (kJ/kg)**	**Density (kg/m³)**	Source
STL-21	-21	240	1.12	Chemical
SN18	-18	268	1.21	Cristopia
STL-16	-16	n.a.	n.a.	Mitsubishi Chemical
SN15	-15	311	1.02	Cristopia
SN12	-12	306	1.06	Cristopia
SN10	-11	310	1.11	Cristopia
TH-10	-10	283	n.a.	TEAP
STL-6	-6	284	1.07	Mitsubishi Chemical
TH-4	-4	286	n.a.	TEAP
SN03	-3	328	1.01	Cristopia
ClimSel C 7	7	130	n.a.	Climator
RT5	9	205	n.a.	Rubitherm GmbH
ClimSel C 15	15	130	n.a.	Climator
ClimSel C 23	23	148	1.48	Climator
RT25	26	232		Rubitherm GmbH
STL27	27	213	1.09	Mitsubishi Chemical
RT30	28	206	n.a.	Rubitherm GmbH
TH29	29	188	n.a.	TEAP
ClimSel C 32	32	212	1.45	Climator
RT40	43	181	n.a.	Rubitherm GmbH

Table 3-10 Commercial PCM for building comfort applications(Cabeza et al., 2011).

PCM	**Melting Temperature °C**	**Heat of fusion KJ/Kg**	**Thermal conductivity W/mK**	**Source**	**Reference**
RT 20	22	172	0.88	Rubitherm GmbH	(Cabeza et al., 2011)
Climsel C 23	23	148	-	Climator	
E23				EPS Ltd.	
Climsel C 24	24	108	1.48	Climator	
TH 24	24	45.5	0.8	TEAP	
RT 26	25	232	-	Rubitherm GmbH	

3.11. Overview of using PCM applications in the building envelope.

It is well known that using energy storage materials as part of building elements such as walls, floors and roofs helps to obtain passively designed buildings as well as in reducing energy consumption and achieving more comfortable internal spaces (Darkwa and O'Callaghan, 2006). Telkes and Lane carried out the first study on the use of PCMs for heating and cooling spaces in buildings in 1975 (Zalba et al (2003). In 1986 however, Barkmann and Wessling studied the use of building structure as thermal storage.

In 2004 (Darkwa and Kim) tested randomly mixed PCM of laminated PCM with wallboard to understand the factors that may affect the processes of melting and solidifying of PCMs (Figure 3-12 and Table 3-11). Results show that laminated

PCM latent heat occurred while the temperature was constant. On the other hand, randomly mixed PCM latent heat demonstrates some gradient in temperature. Moreover, changing factors by increasing PCM mass or heat transfer coefficient from 5 W/m^{2}K to 15 W/m^{2}K raised heat flux enhancement from 20 to 50%.

Table 3-11 The component of the drywall(Darkwa and Kim, 2004)

	PCM-gypsum board (randomly distributed)	**PCM-gypsum board (laminated)**
Composition	PCM+ gypsum powder	PCM+ gypsum powder + + water+ sodium silicate
Dimension (mm)	60×60×12.5	60×60×12.5

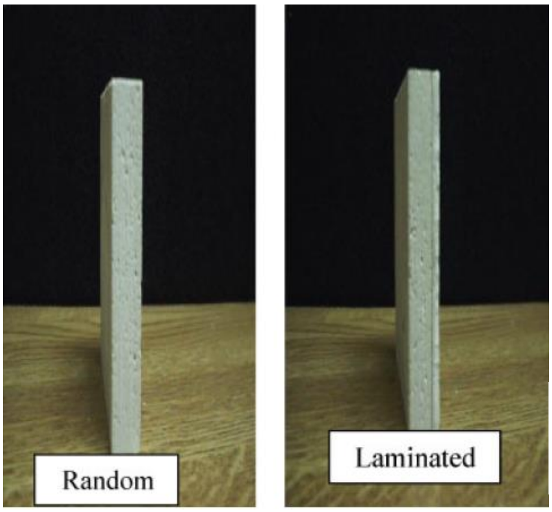


Figure 3-12 The panel of the drywall (Darkwa and Kim, 2004).

Evers et al (2010) and Darkwa and O'Callaghan (2006) investigated the use of integration of PCMs as latent heat storage materials with building materials for decreasing the energy consumption and CO_2 emissions of buildings. Darkwa and Kim (2004) investigated the insufficient heat transfer problem of PCMs during energy recovery. Low thermal conductivities have the most effect on the PCM integration. BASF (2007) concluded that 1.5cm of the PCM smart board is equivalent to 14 cm of concrete wall or 36.5 cm of brick wall in terms of latent heat storage.

Furthermore, Darkwa and O'Callaghan (2006) investigated the use of phase change drywalls in a passive solar building by modelling a room of width 3m, length 4m and height 2.5m. The window was located in the south facade (1m*1.5m). Darkwa and O'Callaghan used two samples, 12mm PCM wallboard and drywall, where 16.7% of the mass was PCM. The laminated plated sample consists of a 2mm layer of PCM with 10mm gypsum. The randomly mixed sample was a 12mm layer of PCM mixed with gypsum. The total heat gain was assumed to be 200W, which is equivalent to the heat obtained from one person with one source of light and one small office equipment running from 8am to 6pm. This was disregarding the effect of radiant heat on the outer wall surfaces. Following the 120 hours of simulation. it was concluded that laminated PCM wallboard 2mm was more efficient in obtaining reasonable temperatures during the night as the laminated PCM increased the temperature at night by 17% more than the randomly mixed PCM with gypsum. Therefore, by using PCMs temperature could be reduced by 4°C during the daytime (Athienitis et al., 1997, Cabeza (2007). In addition Darkwa and O'Callaghan (2006) emphasized that the majority of PCMs research about energy storage materials discuss the effect of coupling PCMs with gypsum wallboard and concrete blocks as construction materials. (Athienitis et al., 1997) concluded that the experiment regarding the use of PCMs to absorb heat -where the aim was reducing ambient temperature- that PCMs has been effectively used as a heat storage materials to achieve thermal comfort if the material applied on large surface area.

Stritih (2004) studied the improvement of heat transfer in a rectangular container containing a PCM thermal storage by using water as the medium to transfer heat into the Phase Change Material (paraffin). The aim was to investigate the effect of different surface types of PCM storage on the melting and solidification process through analysing the process of heat transfer. It also involved investigating the property of PCMs in terms of charging and discharging as heat storage materials. The study concluded that the best way to investigate PCMs is through experiments. The second method of studying PCMs is numerical. However, Xu et al (2005) stated that it is not possible to test the effect of using PCMs in different locations, weather and type of construction only by experiment as it is difficult to understand the influences of different factors without modelling. It has also been stated that it was possible to transfer the heat through water as transfer media to the PCM as heat storage. Finally, the result has shown that there were no issues within the melting process period of PCM but the solidification process could be enhanced by using a mechanical system (Stritih, 2004)

Xu et al (2005) opines that experiments are not enough to test the influence of using PCMs. As a result, modelling is used and validated by experiments to investigate the effect of the following factors:

I. Rate of heat fusion.
II. Thermal conductivity.
III. Melting temperature of PCMs.
IV. Thickness of shape stabilized PCM layer.
V. The air gap between the PCM and the floor.
VI. The floor covering materials.

Xu (2005) concluded that the melting temperature of PCM used should be around the average temperature of a winter sunny day, where the heat fusion should be higher than120 kJ/kg. The thermal conductivity also has to be enhanced to be above 0.5W/m.K, which increases the PCM's ability to absorb and release heat. The maximum thickness of the PCM layer should be 20mm. Finally, the air gap between the PCM panels and the floor surface should be minimal (Xu et al., 2005).

Many researches examine a combination of PCMs and different building materials. Shilei et al (2006) investigated a combination made of Capric acid 82% and Lauric acid 18% as a PCM material. The new mixture of the PCM was tested by using Differential Scanning Calorimetry (DSC) to determine the thermal properties of the materials. The PCM was added to the gypsum by soaking where PCM accounted for 26% by weight of the wallboard. As a result of using DSC to test the wallboard with PCM, the value of the enthalpy was found to vary with the temperature non-linearly. The PCM wallboards were attached to the internal surface of the experimental room. The experimental results of the full test concluded that by using PCM the temperature dropped about 2 ºC. Also defined was the heat flow through an ordinary wall, which was estimated to be a maximum of about 60 W/m². However, this was 52 W/m² only where the PCM wallboards were used, indicating that the PCM was able to absorb the extra heat and acted as a barrier to minimize the heat flow, which reduced overheating.

A number of researches have addressed the issue of adding PCMs into building materials, including the addition of PCMs with cement, which is one of the ways to raise the thermal mass of the building and maintain the heat in the internal spaces to suit the convenience of the users. As concrete is widely used in building construction around the world, Bentz and Turpin (2007) have looked into the use of the advantages of the massive thermal mass of the concrete. By combining PCMs with lightweight aggregates, the panels absorbed the unwanted heat released from the concrete mass, which is beneficial in maintaining comfort zones.

Pasupathy et al (2008a) discussed the effect of integrating PCM in the building's roof numerically and experimentally. They used a stainless steel container filled with a PCM (salt hydrate), and placed it between two layers of the roof slab. The simulated results do not match the results obtained through experiments. This is due to several reasons namely: i) an incomplete process of melting and solidification during the experiment, the fluctuating influence of solar radiation and the effect of the thermal conductivity of the PCM on the distribution of heat transfer of the stainless steel container. It was concluded that PCM could be used to improve the building thermal mass and obtain comfortable spaces, but attention must be taken with the type of PCM, the orientation of the building and the building construction method.

Alawadhi (2008) studied the potential of using bricks containing cylinders filled with PCM placed in the building façade. The concept of the study was the absorption of heat by PCMs to reduce heat transfer through the bricks. Parameters of PCM located in the brick, PCM quantity and PCM types were tested. The studies concluded that a central position was the most effective place to reduce heat flux. Furthermore, different types of PCMs could affect the amount of heat flux. Finally, results of the effect of the quantity of PCM on heat flow show that increasing the amount of PCM three times reduced the amount of heat flux by 11.5% to 24.2%.

Voelker et al (2008) divided the test room into two identical rooms and attached PCM gypsum boards in room 1 and room 2, with room 2 devoid of any modifications. The parameter of air change rate was examined. The experiment concluded that the use of PCM (paraffin mixed with salt) increased the building thermal mass and decreased the temperature in the summer time. However, the conclusion stated that changing the air change rate could solve the problem of PCM discharge if it appears.

Evers et al (2010) highlight the use of PCMs to enhance wall performance by spraying the PCM onto cellulose insulation. Two types of PCMs were used, paraffin and hydrated salt. The result showed using paraffin as PCM dropped the heat flux by 5.7% up to 9.2%. Thus, the amount of reduction depends on the quantity of used paraffin. On the other hand, using hydrated salt did not decrease the heat flux. Instead it gave negative results that increased the amount of heat flux.

Diaconu (2011) investigated the influence of occupancy and ventilation on using PCMs as thermal energy saving in buildings. Numerical modelling under specific assumptions was carried out. The results establish that the energy saving potential for heating had decreased by ventilating the building. Also, the result showed that different occupancy patterns affect the energy saving probability.

3.12. Conclusions

It can be concluded that Phase Change materials PCMs should have the cycle period of 24 hours in building to control temperature for charge and discharge used to control temperature in buildings. PCMs are divided into three categories a) Organic PCMs b) Inorganic PCMs c) Eutectic PCMs. PCMs are used in many applications such as transportation of vaccines and food, domestic hot water, telecom shelters and building construction.

PCMs are one of the keys approaches to passive building designs. So, using PCMs could increase the thermal mass of existing buildings. The thermal mass of new buildings with lightweight construction method could be improved by using PCMs. Thus, PCMs have been used widely to reduce overheating spicily with lightweight construction buildings. Furthermore, It is important to choose where the PCMs will be placed in the building envelope to maximise the benefit of PCMs as TES. Thus, PCMs have the ability to store energy as latent heat and use it when required. Also, it is important to be aware that comfortable temperature varies from one region to another, so choosing the right PCM is important.

There is an economic benefit of using PCM by reducing the need of active systems of heating or cooling. In addition, the use of distinct environmental PCM systems helps to reduce CO_2 emission. It is important to understand the properties of PCMs for different applications.

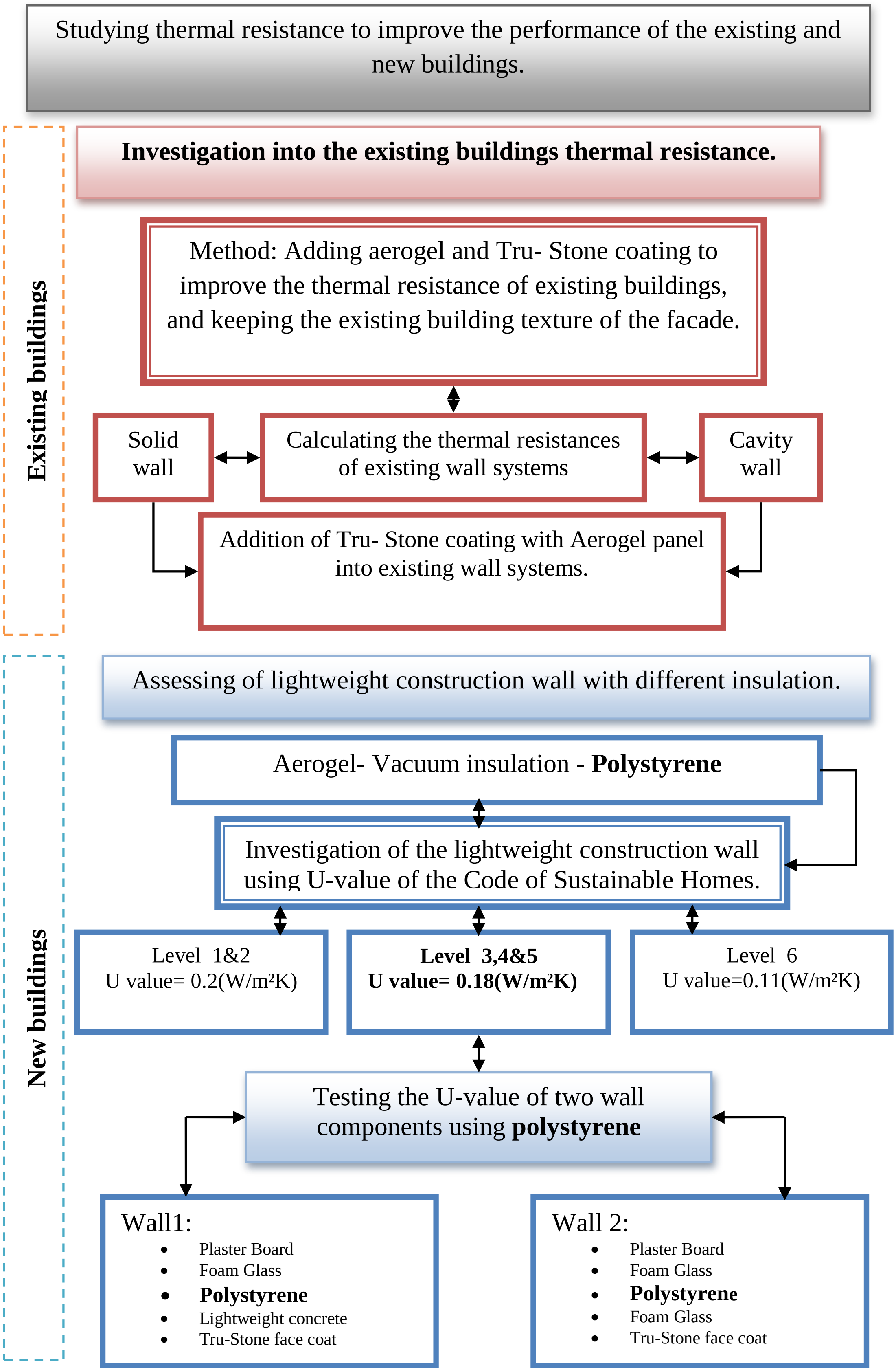
PCMs have low thermal conductivities. As a result many researchers such as Darkwa and Kim have investigated the ways to enhance the thermal conductivity of PCMs. One of the methods to improve the thermal conductivity is by mixing PCMs with different materials to enhance heat transfer. Also, other key point to improve the melting and solidification time of PCMs is by providing the right container. Thus, Different researchers have addressed the effects of natural and mechanical ventilation. Therefore, this aspect still needs more research to raise the PCMs ability to conduct heat.

CHAPTER 4: INVESTIGATION INTO THE THERMAL PERFORMANCE ANALYSIS OF EXISTING AND NEW BUILDINGS

"What I want to show in my work is the idea which hides itself behind so-called *reality. I am seeking for the bridge, which leans from the visible to the invisible through reality. It may sound paradoxical, but it is in fact reality which forms the mystery of our" existence.*

Max Beckmann [5]

[5] http://www.gurdjieff-legacy.org/40articles/beckmann.htm



Procedure for thermal performance analysis of buildings.

4. INVESTIGATION INTO THE THERMAL PERFORMANCE ANALYSIS OF EXISTING AND NEW BUILDINGS

4.1. Introduction

This chapter is divided into two main sections. The first section presents studies regarding the improvement of thermal resistances of existing buildings constructed with solid and cavity wall systems. Panels constructed from Tru-Stone coating with aerogel insulation material were used to increase the thermal resistance of the existing building. The idea of using Tru-Stone with aerogel panels was valuable for two reasons. Firstly, using aerogel insulation material minimises the thickness and weight of the panels. Secondly, Tru-Stone coating system emulates the building's original details in texture and colour.

The second section pertains the pre-investigation of lightweight construction system using three different types of insulations as well as the investigation of walls based on the Code of Sustainable Homes at different level and keeping the lightweight construction method. Polystyrene insulation material was chosen because of the cost if it be compared with aerogel and lifetime if it be compared with vacuum insulation. Two types of lightweight construction methods were employed to meet the Code of Sustainable Homes for the study. These include the experimental and calculation methods.

4.1.1. Objective of the study

- Understanding the need of enhancing the thermal resistance of existing buildings to meet future climate change and provide comfort for the users as well as strategies for reduce energy use.

- To design investigations of lightweight construction systems for new buildings by examining different insulation materials on the wall system to meet the Code of Sustainable Homes.

4.2. Improving the thermal resistance of existing buildings

4.2.1. Tru-Stone coating

Tru-Stone is a product made from 100% natural environmental resources. The product is manufactured without any chemical based polymers. It is a unique material which has obtained patented approval. Tru-Stone coating is a powder product, that when mixed with water can be applied to many surfaces by trowel or spray as illustrated in Figure 4-1. It is suitable for both internal and external surfaces to produce an outstanding quality finish, whether smooth or brick like as can be seen in Figure 4-2, and can be applied as wet or dry appropriation (Tru Stone, 2010b).

Figure 4-1Tru-Stone coating applied by spray or trowel(Tru Stone, 2010c).

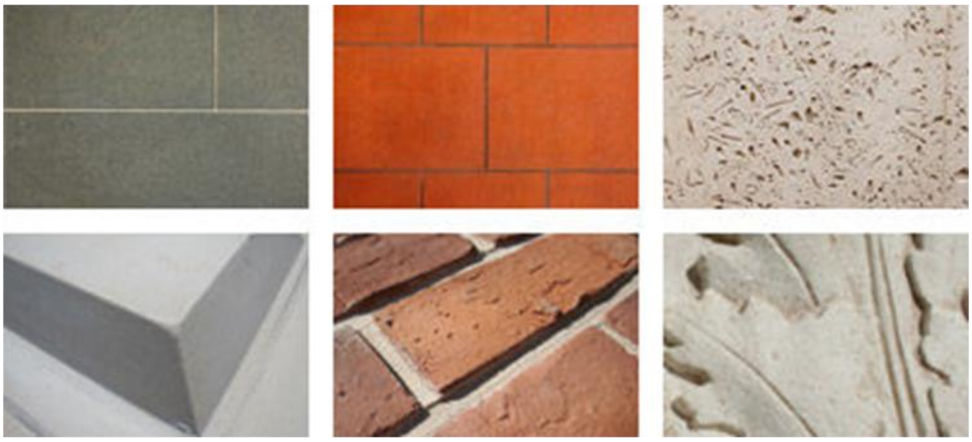


Figure 4-2 Tru-stone coating materials (Tru Stone, 2010b)

4.2.2. The advantage of Tru-Stone:

- *Natural*

  The main material is ground natural stone mixed with other natural materials.

- Environmentally safe

  As the material is made from recycled stone without any chemical additive, it makes the product a green material.

- *Flexible*

  Tru-Stone can be used for internal or external surfaces, and can be applied by trowel or spraying the product on the site; or in the factory and delivered as panels. The surfaces can be dyed to any colour. Moreover, it is important here to mention that joints can be formed to fully integrate all irregular shapes of the building.

- *Durable*

  Simply, Tru-Stone can be used as per usual use of stone, and in any weather condition.

- *Economical*

  True-Stone is a light weight product compared with brick and stone. It could be applied on surfaces on the site which means reduction in transportation and labor costs (Tru Stone, 2010a).

  The principle of adding True-Stone to aerogel is to produce a panel that can be used to improve the thermal performance of existing building walls as well as matching the exterior of the building in all its details. It is important to clarify that aerogel is still an expensive material. On the other hand, it has two main advantages; firstly, high moisture resistance and secondly, high thermal resistance with less thicknesses compared with any other insulation material.

4.2.3. Tru- Stone coating with Aerogel

The new panel as illustrated in Figure 4-3 is constructed of two layers. The first layer is Tru-Stone coating which, is according to the Tru-Stone Ltd., comprises by weight Mica 20%, Portland cement 20%, and ground Portland Limestone 60%. The thermal conductivity of the Tru-stone compound is 0.75 W/mK (a test was conducted to find the thermal conductivity of Tru-stone compound at the Materials Lab in the Faculty of Engineering, University of Nottingham). The second layer is an aerogel layer (refer to chapter 2 for more information about aerogel insulation materials). In addition, the thicknesses of the two layers are presented in Table 4-1. However, the thickness of Tru-Stone was reduced from 18m to be 4mm in order to decrease the weight of the panels (more details are given in Chapter 7).

Table 4-1 The Aerogel with Tru-Stone coating panel.

Material	R-value W/mK	Thickness (mm)
Tru-Stone face coat	0.75	d1 = 18
Aerogel	0.0135	d2 = 35

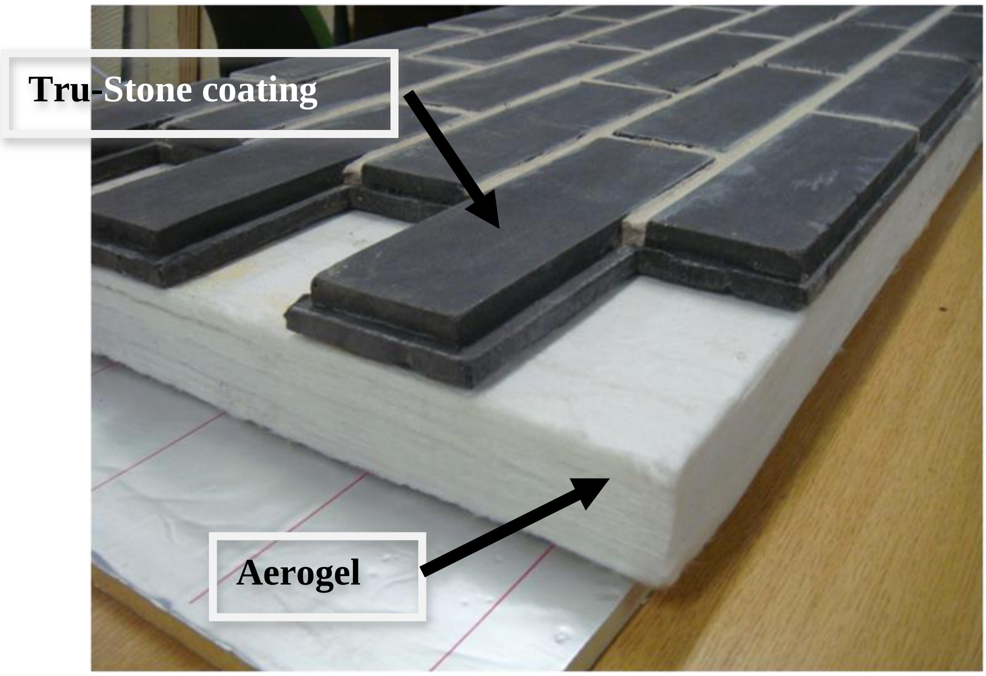


Figure 4-3 Aerogel with Tru-Stone coating panel.

4.3. Investigating of the thermal resistance of the combined of Tru-Stone aerogel

This section of the investigation is divided into two parts. The first part assesses the ability of the Tru-Stone coated with aerogel panel for thermal resistance. The second part describes the experimental arrangement to obtain the U-value of the panel.

4.3.1. Methodology of the test

The panel was evaluated as follows: the panel from Tru-Stone Ltd was tested under a controlled environment to assess heat transfer rates through the panel section as detailed later. The test was based on British Standard (BS 874-3.2, 1990) and the method of the test is known as the Calibrated hot-box method (BSI, 1990) .

4.3.2. Design and construction of the test room

The chamber was divided into two sections with the first section known as the hot side and the second section known as the cold side. The test room was built from 8mm thick timber. Dimensions of the room were 160cm length, 110cm width and 210cm height. Insulation material was attached along the walls, floor and roof. The experimental box was fully insulated using insulation of U value <0.21 W/m²K (BS requires the minimum U value of the box walls (test room) = 0.4 W/m²K (BSI, 1990) (Figure 4-4)

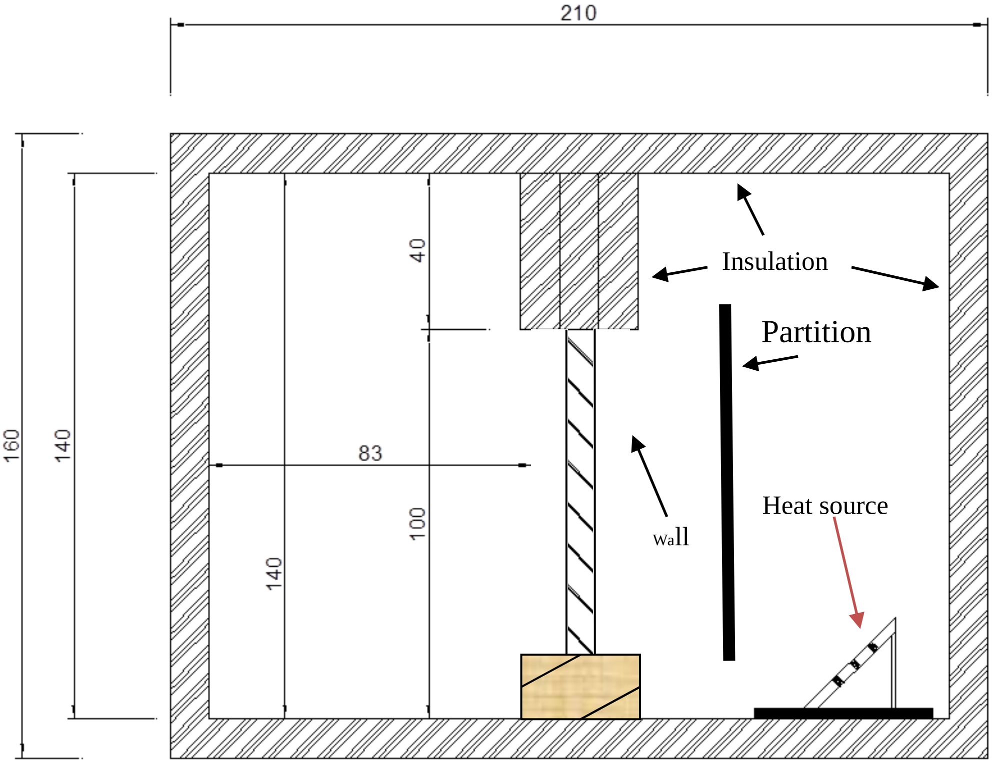


Figure 4-4 Section A-A showing the position of the wall in the test room.

4.3.3. Description of the test procedure

- The panel was located as shown in Figure 4-5 in the wooden insulated room.
- The U value of the test room is 0.21 W/m²K.
- The U value of the Tru-Stone with aerogel panel (will be obtained from the test) W/m²K.
- The room was divided into two sections by the wall.
- One side of the test room was heated using heater of three set 700W, 1400W and 2100 W to simulate heat flow through the test wall (Figure 4-5).

Figure 4-5 Tru-Stone with aerogel panel in the middle of the test room.

- The other side of the room was maintained at room temperature with a temperature controller (refrigerator used).
- K type thermocouples were attached in both sides of the wall and in the two sections of the test room. The accuracy of the thermocouples is ±0.4 °C according to the calibration test.

- Heat flux plate HF01 which is made of ceramics and plastic combined as flat plate. HF01 is been used to measure the heat flow through the wall surfaces by measuring the temperature in both side of the plate. The device produce a small amount of voltage which will be monitor using data collector and by divided it by the sensitivity of the HF01 heat flux could be calculated. HF01 has been proved by ISO 9869 and ASTM C1046 to be used to calculate R-value and U- value of buildings envelop.
    - Temperature range -30 to +70.
    - Sensor thermal resistances < 6.25 10^{-3} Km^2/W.
    - Calibration traceability: NPL, ISO 8302 / ASTM C177

  HF01 was attached on the cold side of the wall to measure the heat flow from the hot side of the wall. Heat flux is a sensor that measures the heat flow through walls and building envelopes. Thus, it was used to measure the heat flow from the hot side of the wall to the cold side of the wall.
- After fixing the panel in the middle of the test room, all the thermocouples were connected and the heat flux is attached to the panel and the door is closed and sealed.
- Figure 4-6 shows the thermocouples attached to the side of the panel.

Figure 4-6 The thermocouples K type attached into the Tru-Stone panel.

- The heater was switched on using the maximum power of 2400W. The test period lasted for about 12 hours. Figure 4-7 shows the period when the temperature on the cold side reached 20 ^{o}C.
- The wall started to absorb heat by convection. When it reached the maximum, the heat started to move to the cold side by conduction.
- When the heat attained a steady state condition, the reading on both sides of the wall was taken to obtain a temperature difference.

4.3.4. Experiment results

Figure 4-7 shows that after about 6 hours the panel kept the difference between the hot side- where the heat source was 2400W- and the cold side of the room at a temperature difference of about 32 °C (the experiment was in a controlled chamber. Figure 4-7 shows the steady state condition). While the difference between the temperature in hot side (H1,H4 and H5) and the cold side (C1, C4 and C5) reached the steady state was about 32°C. Heat flux sensor was attached to the cold side of the wall surface, and it was calculated using the data obtained from the data logger through the heat flux sensors at the steady state period. As the heat flux sensitivity was 64.6 µV/ W. m², the heat flux was calculated by dividing the voltage (or result from the data logger) by the sensitivity of the sensor (Heatse flux, 2011).

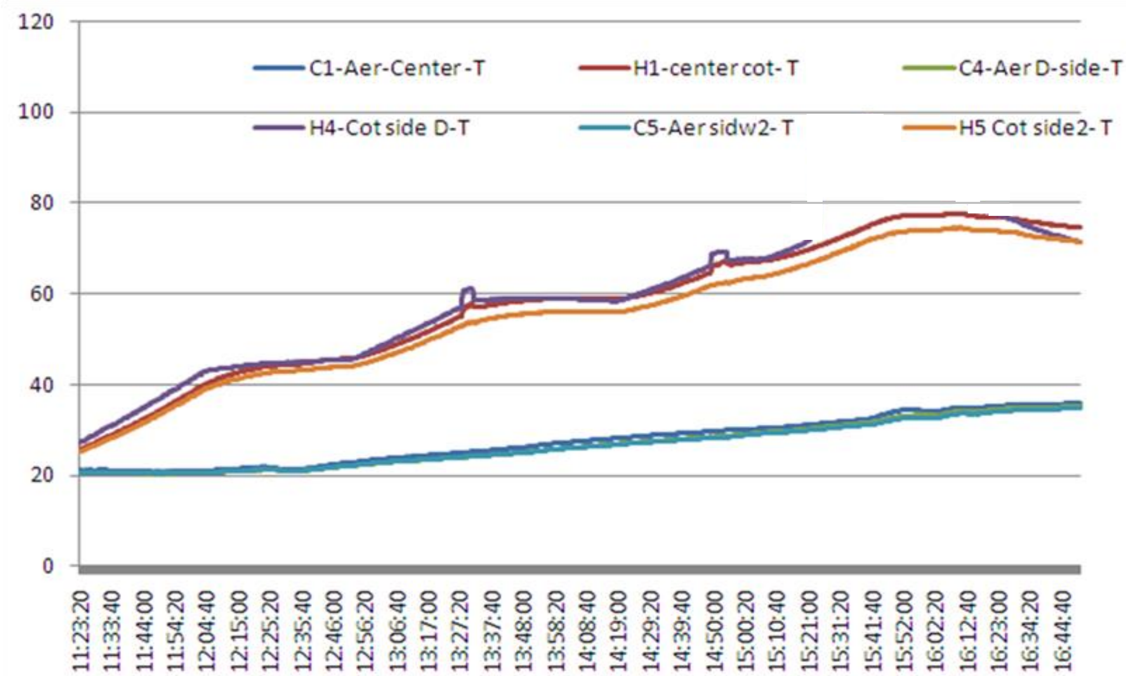


Figure 4-7 The ability of the Tru-Stone system to resist heat.

4.3.5. Results from the experiment

Taking the average difference in temperature as 32.03°C

Heat flux $q(W/m^2) = \dfrac{0.75194 \times 1000}{64.6} = 11.6399(W/m^2)$ *By using the equation*

Heat flux through the wall $\dot{Q}$

$$\dot{Q} = \frac{K \times A \times \Delta t}{d}, \qquad \text{Equation 4-1}$$

Where:

K = thermal conductivity (W/mK).

A = area of the wall (m^2).

Δt = temperature difference between the faces (°C).

d = distance between the faces (m).

In addition:

Heat energy by unit area $\dot{Q} = q \times A$, Equation 4-2

Where:

$\dot{Q}$ =heat flow (W).

q =heat flux (W/m^2).

A = Area (m^2).

<u>*As a result:*</u>

Using equation 4-2 $\dot{Q}$ =11.6399 × 0.54 =6.28 W

Thermal conductivity is given by $K = \dfrac{Q \times d}{A \times \Delta t}$, Equation 4-3

<u>*As a result:*</u>

$$K = \frac{0.053 \times 6.28}{0.54 \times 32},$$

K=0.0192 W/m K

Using equation 2-1

$$R = \frac{0.053}{0.0192} = 2.76 \text{ m}^2\text{K/W}$$

Thermal conductance, U-value $U = \frac{1}{R}$ (W/m²K) Equation 4-4

or to obtain the whole U value of the whole wall layers)

$$U = \frac{1}{R_{si} + \sum_{i=1}^{\infty} R_i + R_{so}} \quad (\text{W/m}^2\text{K})$$

<u>*As a result:*</u>

$$U = \frac{1}{2.76} \text{ W/m}^2\text{K}$$

***U*= 0.362 W/m²K**

4.4. Calculating the U value of Aerogel with the Tru-Stone coating model

Using equation 2-1and the thermal resistances of multilayer element

$$R = R_{si} + \sum_{i=1}^{2} R_i + R_{so} (m^2 K / W)$$

Equation 4-5

Where:

$R_{si} = R$- value of the inside surface = 0.123 $m^2 K / W$ (McMullan, 1992).

$R_{so} = R$-value of the outside surface = 0.55 $m^2 K / W$ (McMullan, 1992).

$$R = 0.123 + \frac{0.04}{0.75} + \frac{0.035}{0.0135} + 0.055$$

R= 0.123+0.053 + 2.59 +0.055

R= 2.821 m^2K/W

Using equation 4-4

$$U = \frac{1}{2.821}$$

***U* = 0.354 W/m²K**

4.5. Adding layers of Tru-Stone Face coating and Aerogel into the existing building

To increase the wall resistance, a layer of Tru-Stone Face coating and a layer of aerogel were been added to the existing building facade. This section provides a calculation model of the thickness of Aerogel with 4mm of Tru-stone coating that can improve the wall thermal performance, for which two types of walls have been chosen a) solid wall and b) cavity wall.

4.5.1. Calculation method

Calculations were carried out to obtain the required thickness of aerogel (insulation material), which meets the Building regulation and the Codes for Sustainable Homes using to equations 2-1, 4-4 and 4-5. The thermal conductivity K-value of materials used are presented in Table 4-2 and the required U-value are listed in Table 4-3.

Table 4-2 The conductivity of building materials.

Material	Conductivity (W/m K)
Air	2.5
Brick	0.98
Concrete Block Heavy weight	1.63
Concrete Block medium weight	0.51
Concrete Block light weight	0.19
Tru- Stone Coat	0.354
Aerogel	0.0135

Table 4-3 The U-value for the Code of Sustainable Homes (DCLG et al., 2009).

Code for Sustainable Homes	Level 1&2	**Level 3,4&5**	Level 6
U-value W/m²K	0.2	**0.18**	0.11

4.5.2. Improving solid wall resistances

This process was conducted to verify whether adding a layer of 4mm Tru-Stone coating with aerogel onto an existing solid structure wall helps to increase the wall resistance. Figure 4-8 shows one of the construction types of solid wall built by using brick or stone in single layer or in two layers (English Heritage, 2010). Although, the solid wall obtained has a high thermal mass, the resistance of the wall to heat flow is not enough to meet the current efficiency target for building regulations. Table 4-4 illustrates the thicknesses of the solid wall and Figure 4-9 shows the solid wall with the external extra layer of Tru-Stone and Aerogel.

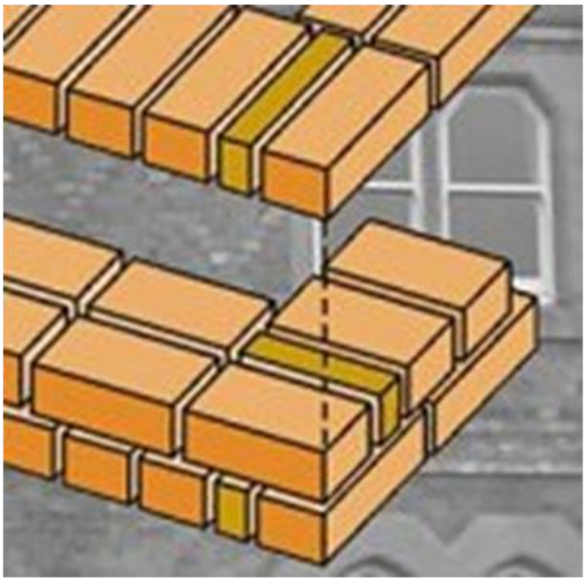


Figure 4-8 Solid wall construction of 1920 to 1930 (TheBuiltEnvironment, 2006).

Table 4-4 Solid wall layer thicknesses with Tru-Stone Face coat and Aerogel.

Material	**Thickness (mm)**
Brick	216
Tru-Stone Face coat	4
Aerogel	X

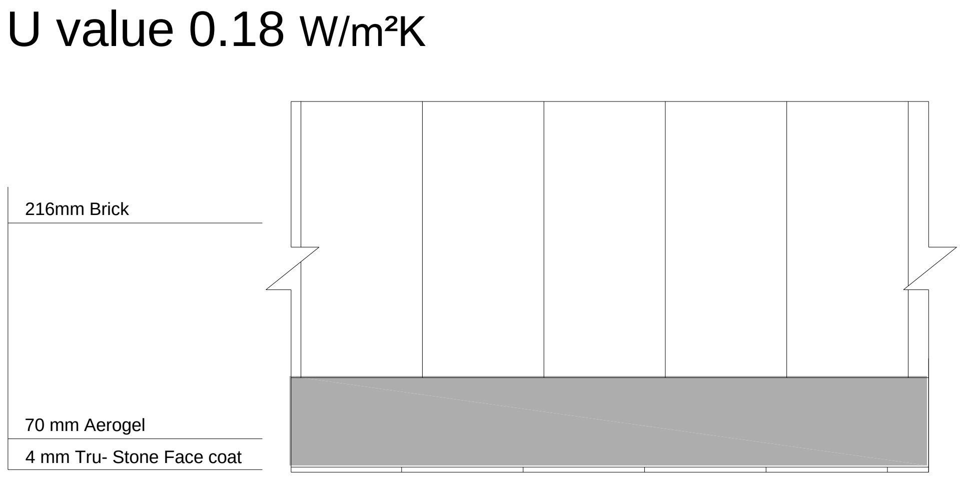


Figure 4-9 Solid wall layers with Tru-Stone face coating and Aerogel

To estimate the necessary thickens of Aerogel (insulation material) to improve the thermal resistance of the solid wall, the first step was to calculate the thermal resistance of the existing solid wall with Tru-Stone coating and in the second step, calculate the resistance needed to achieve the target U-value target as follows:

Using equation 4-5:

$$R = 0.123 + 0.005 + \frac{0.216}{0.98} + 0.055$$

R without Aerogel= 0.898 m²K/W

Using equation 4-4

In addition, as the U-value (target) = 0.18 (according to *Codes for Sustainable Homes level 3,4 and 5).*

$$R \text{ (target)} = \frac{1}{0.18}$$

R = 5.55 m²K/W (according to *Codes for Sustainable Homes level 3,4and 5).*

R (for Aerogel) = 5.55 – 0.409

R= 4.602 (m²K/W)

Using equation 2-1 to calculate the necessary thickness of aerogel

and as $d = R \times k$

$d(aerogel) = 4.602$ a $\times 0.0135$ =0.069m= 6.9cm

This means that it is possible for the existing solid wall to meet the building regulation 2010 and Code for Sustainable Homes in terms of U value by adding 70mm of aerogel and 4mm of Tru-Stone.

4.5.3. Improving the cavity wall resistance

A layer of Tru-Stone coating with aerogel was added to a cavity wall to improve the resistance. The cavity wall, illustrated in Figure 4-10 and Table 4-5 consists of three layers: a Brick, Air and Concrete block.

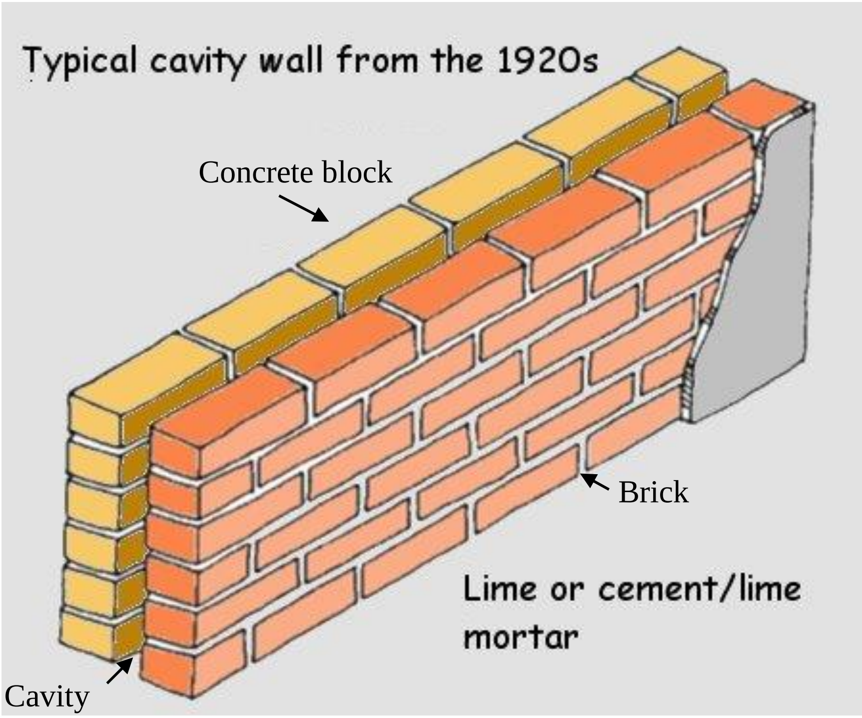


Figure 4-10 Two examples of early cavity walls(UWE, 2006)

Figure 4-11 Injecting the insulation into the cavity wall (Lgloo insulation, 2011).

It is important to mention that there is another method to increase the resistances of the cavity wall by injecting insulation in between the brick and the concrete blocks as illustrated in Figure 4-11.

Table 4-5 The thickness of the layers of the cavity wall with Tru-Stone Face coating and aerogel.

Material	**Thickness (mm)**
Brick	76
Cavity air	50
Concrete Block	100
Tru-Stone coat	4
Aerogel	X

To calculate the necessary thickness of aerogel (insulation material) to improve the thermal resistance of the cavity wall, the following steps were followed 1-calculate the existing thermal resistance of the cavity wall with Tru-Stone coating 2- calculate the resistance needed to achieve the target of U-value as follows:

Using equation 4-4

$$R = 0.123 + 0.11 + \frac{0.076}{0.98} + \frac{0.05}{0.02} + \frac{0.10}{0.51} + 0.055$$

R (cavity wall with Tru-Stone coating) = 2.96 m²K/W

Using equation 4-4

In addition, as the U (target) = 0.18 (according to *Codes for Sustainable Homes level 3,4and 5).*

$$R\text{ (target)} = \frac{1}{0.18}$$

R = 5.55 m²K/W (according to *Codes for Sustainable Homes level 3,4and 5).*

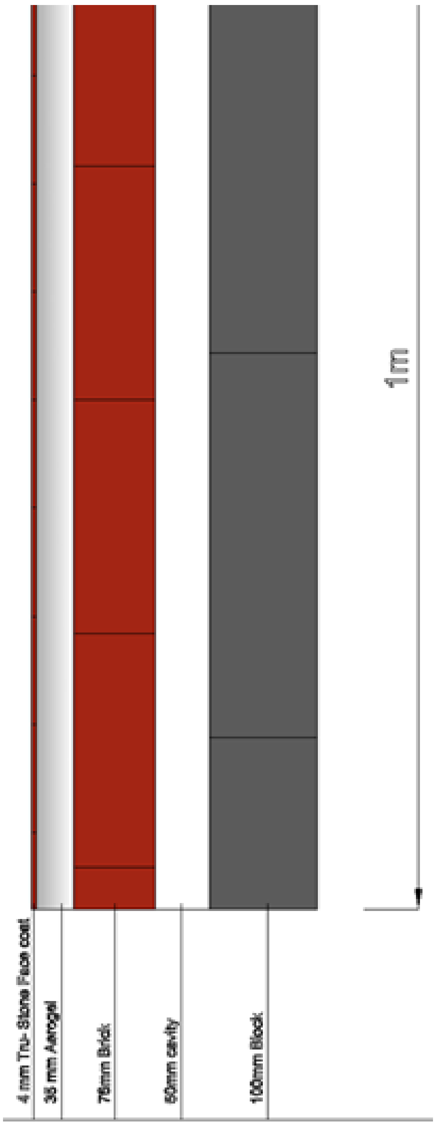
R (for Aerogel) = 5.55 – 2.96 (m²K/W)

R= 2.59 (m²K/W)

Using equation 2-1 to calculate the necessary thickness of aerogel and as $d = R \times k$

$$d(aerogel) = 2.59 \times 0.0135 = 0.035\text{m}.$$

$$d\ (\text{aerogel}) = 3.5\text{cm}.$$



As a result, adding 3.5cm of aerogel panel with 4 mm of Tru-Stone coating as illustrated in Figure 4-12 will increase the R-value of the existing cavity wall. This means that the existing cavity wall could meet the Building Regulation 2010 and the Codes for Sustainable Homes in terms of U values.

Figure 4-12 The cavity wall layers with Tru-Stone Face coating and an aerogel.

4.6. Pre-investigations of lightweight construction wall systems performance by using different insulation materials

This study is based on Tru-Stone coating as an external layer with the proposal of the lightweight construction wall system as presented in Table 4-6. The primary purpose of this test was to show and compare the differences in thicknesses of various insulation materials to give the required U-value. Different insulation materials were used in the system of lightweight constructions. Thus, the thicknesses required for each type of insulation to meet the building regulation 2010 and Codes for Sustainable Homes in different levels as shown in Table 4-2 were calculated using to the equations 2-1 and 4-4.

4.6.1. Details of the lightweight construction system

As shown in Figures 4-13, 4-14 and 4-15, each case of the walls consists of five layers as illustrated in Table 4-6, which shows the thicknesses and the thermal conductivity of materials used.

Table 4-6 Description of the first type of wall panels.

Material	Thickness (mm)		Conductivity (W/m K)	
Plaster Board	d1	12	K1	0.16
Foam Glass	d2	50	K2	0.04
Aerogel , Vacuum insulation, or Polystyrene	d3	X	K3	0.0135 0.0025 0.03
Light Weight concrete	d4	50	K4	0.38
Tru- stone	d5	4	K5	0.75

To find out the thicknesses of Aerogel, Vacuum insulation, and Polystyrene, equations 3 and 4 were used and the target U-value that is shown in Table 4-2 was used to find the thickness (d) for each insulation material.

4.6.2. Results

The Table 4-7 and Figures 4-13, 4-14, 4-15 show the results of thicknesses of each type of insulation for the first light weight construction system under the same target U-value.

Table 4-7 Calculated thicknesses of insulation materials under different level of U value for first light weight construction system.

Material	U=0.2 W/m²K	U=0.18 W/m²K	U=0.11 W/m²K
Aerogel	48mm	55mm	103mm
Vacuum insulation	9mm	10mm	19mm
Polystyrene	106mm	**123mm**	229mm

Thus, using vacuum insulation reduced the wall thickness to 10mm, which is more than twelve times less thick than equivalent walls using Polystyrene and more than five times less contrasted with Aerogel. However, Vacuum insulation can easily be damaged. Therefore, using Aerogel reduces the wall thickness and improves the thermal resistances to meet the building regulation and Codes for Sustainable Homes. Nevertheless, the cost of Aerogel should be considered. Figures 4-13, 4-14 and 4-15 compares the thicknesses of combining materials required to provide the U-value of 0.2 W/m²K, 0.18 W/m²K and 0.11 W/m²K.

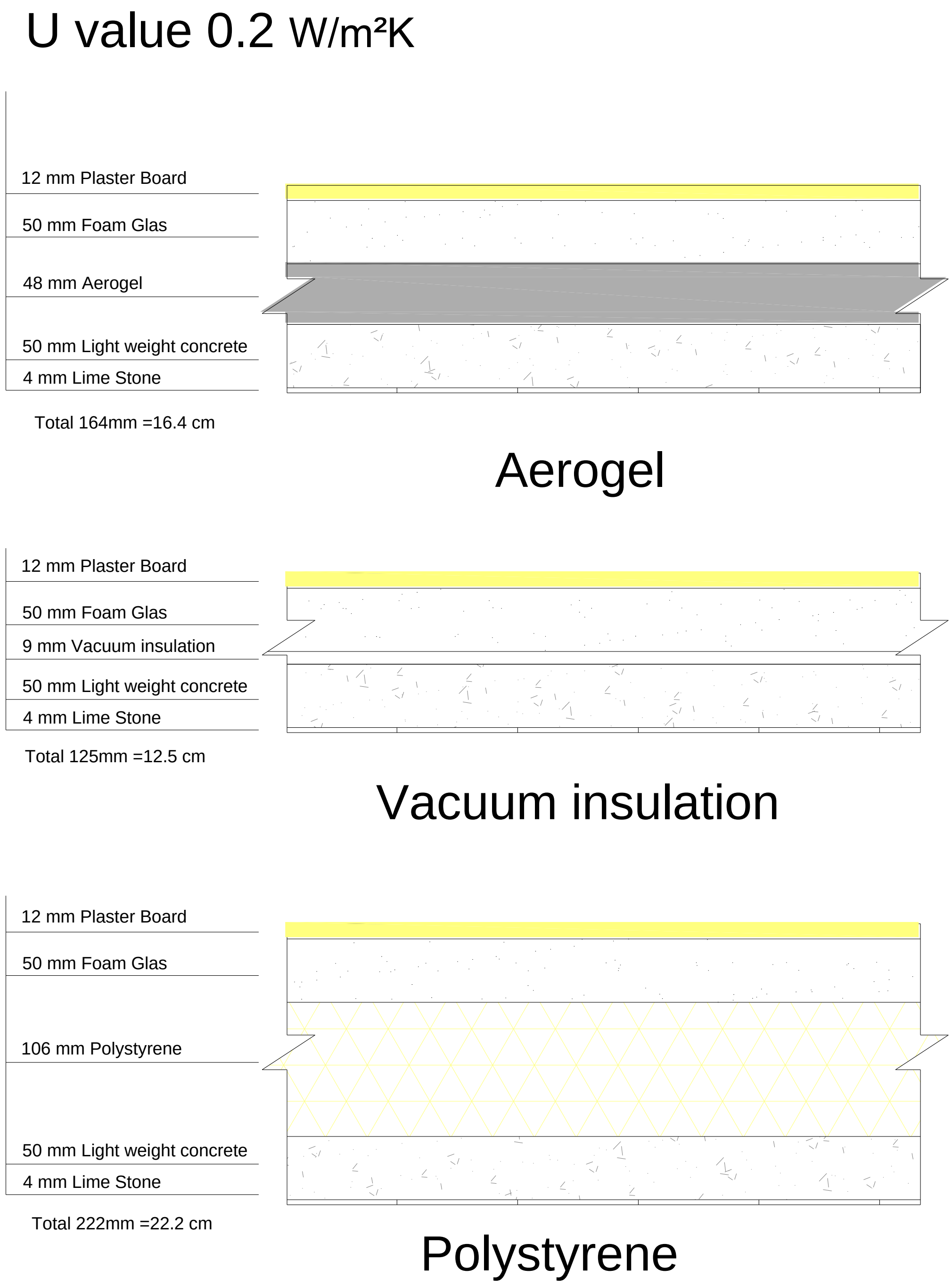


Figure 4-13 Comparison of three type of walls where U value=0.20 (W/m²K).

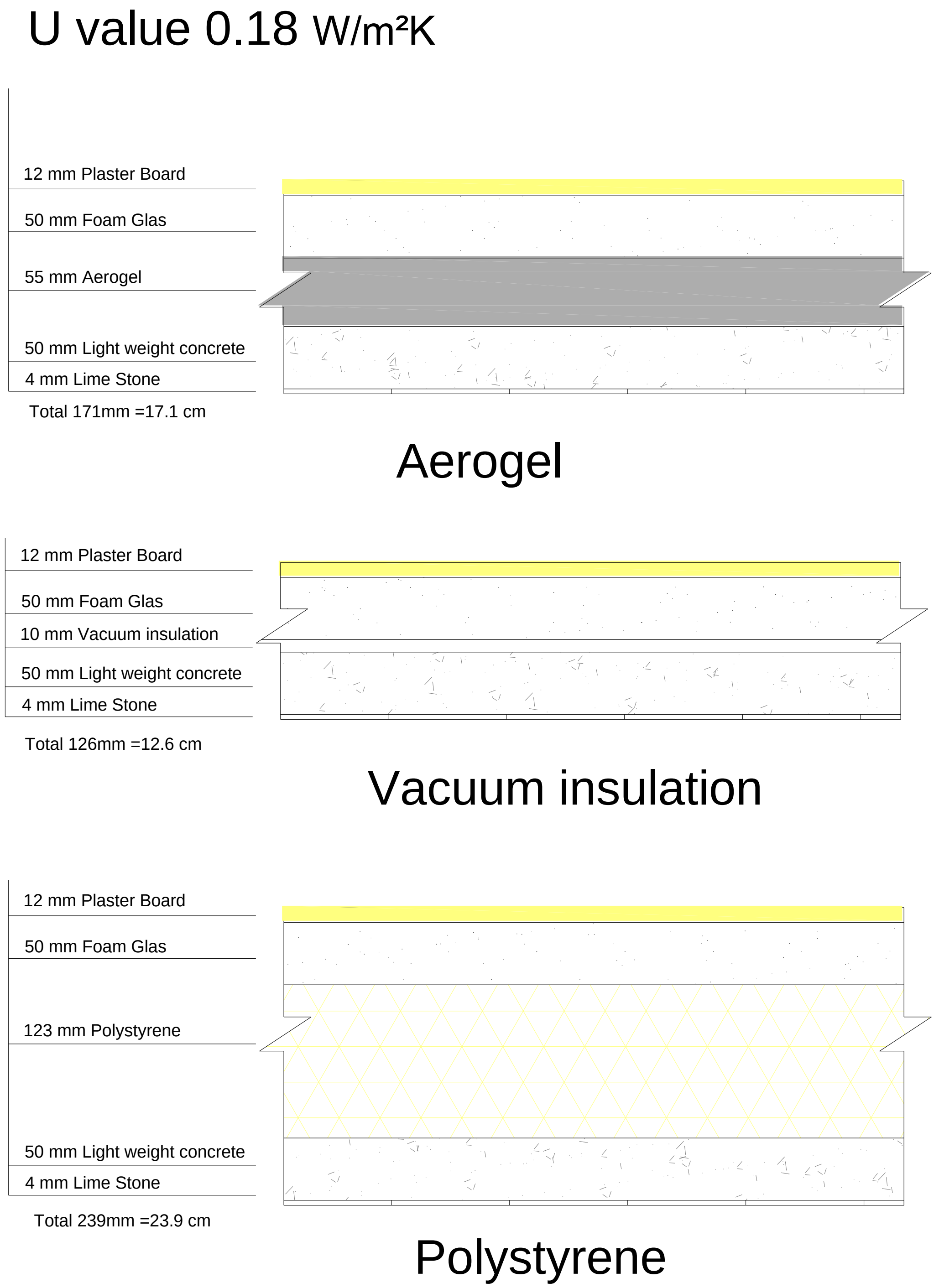


Figure 4-14 Comparison three type of walls where U value=0.18 (W/m²K).

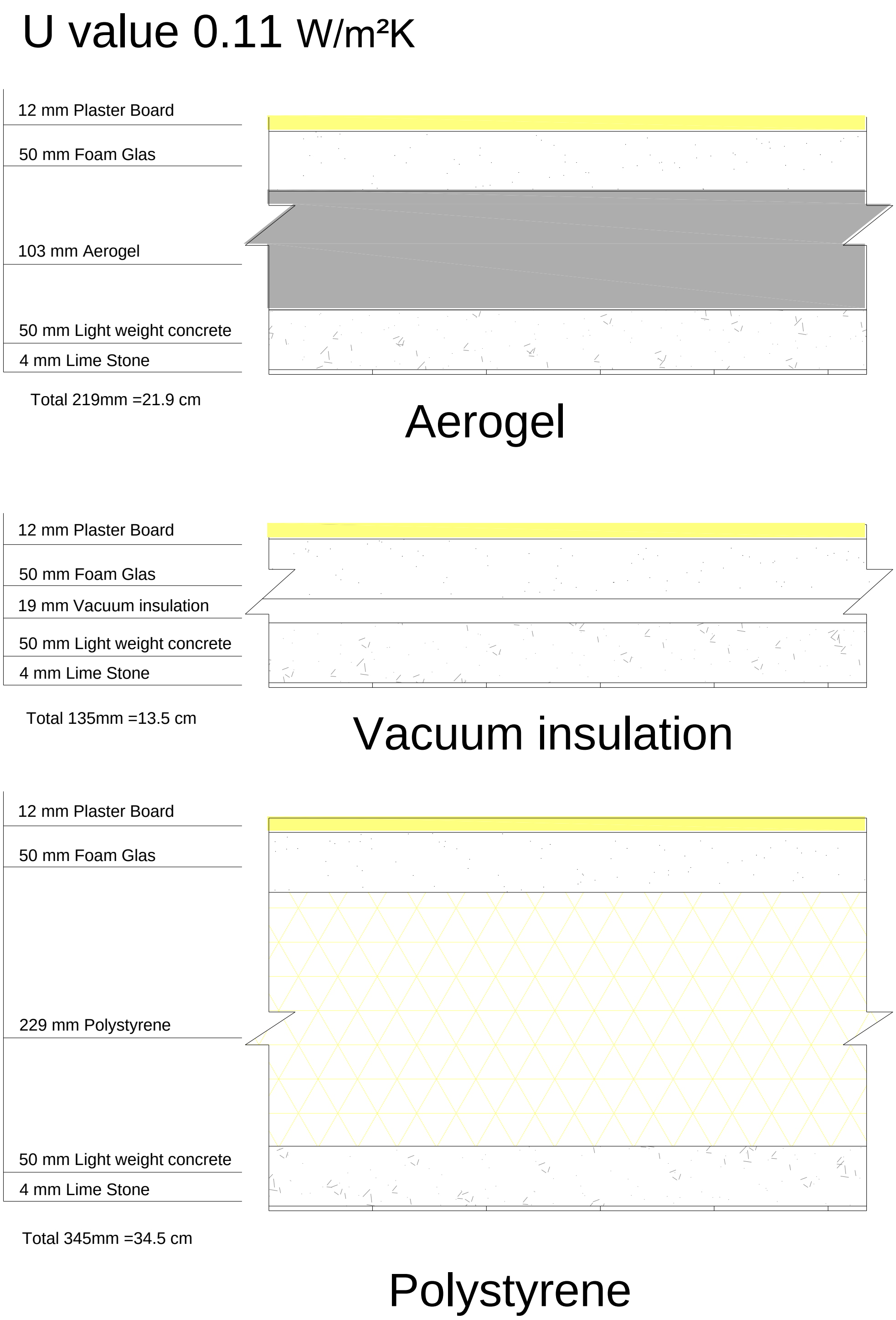


Figure 4-15 Comparison three types of walls where U value=0. 11 (W/m²K).

4.7. Testing the U-value of two wall components

4.7.1. Introduction

This work presents the experiment, which was conducted to test the thermal conductivity and performance of two wall panels manufactured at Tru-Stone Ltd. They present two construction methods, which are lightweight and heavyweight construction, and both of which consist of five different layers of materials. These experiments were carried out at the Department of Architecture and Built Environment, Faculty of Engineering, University of Nottingham.

4.7.2. Aim of the experiment

The aim of the experiment is to examine the ability of the panels (from Tru-stone Ltd) which will help existing buildings to meet the new building regulations 2010 and the Code for Sustainable Homes in the UK in terms of U value by determining the thermal conductivity and the performance of these panels.

4.7.3. Methodology of the test

The walls were evaluated in two steps. For the first step, a 1m × 1m panel was tested under a controlled environment to assess heat transfer rates through the panels as detailed later. The test was based on British Standard (BS) (BS 874-3.2, 1990) known as the Calibrated hot-box method. In the second step the panels were tested using a calculation method to calculate the U-value (this is described in a subsequent section).

As a result, while the aim was to find the U value of the walls, the methodology according to BS was used to find the thermal conductivity of the walls. The method is described in Figure 4-16 and the purpose is to create a temperature differential between the two surfaces of the wall by placing a heat source on one side allowing heat to be transferred to the other side through the wall layers. The temperatures of both surfaces of the wall were measured under a steady state condition. The k-value was determined by knowing the temperature difference between both sides of the wall (Δt), wall surface area (A), the thickness of the wall (d) and the heat flow across the wall (Q). By identifying the k-value, the U value calculated will be explained subsequently.

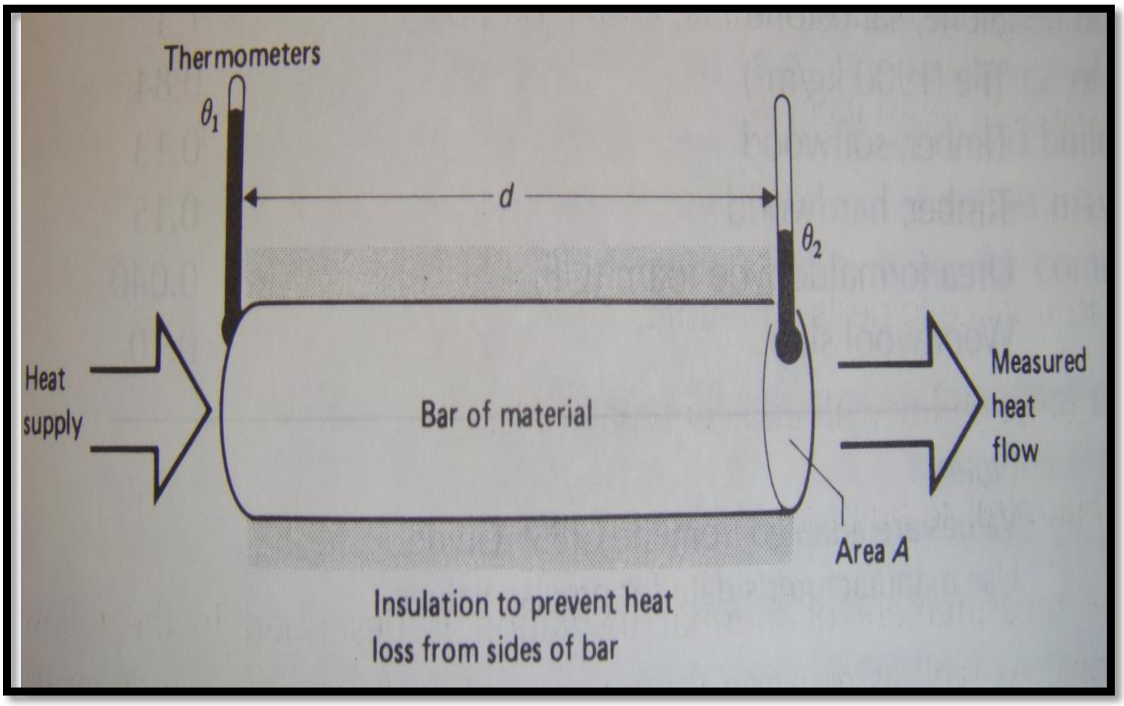


Figure 4-16 The method of measurement of thermal conductivity (McMullan.1992).

4.7.4. Experiment

This section is divided into two parts; the first part discusses the design of the test room where the wall panels were tested and the second part, describes the test procedure and the equipments used.

4.7.5. Design and construction of the test room

As shown in Figures 4-17, 4-18 and 4-19 the test room was built from 8mm thick timber. The dimensions of the room are length 160cm, width 110cm and height 210cm.

Insulation material was attached along the walls, floor and roof. The experimental box was fully insulated using an insulation of a U-value <0.21 W/m²k (BS requires the minimum U value of the box walls (test room) = 0.4 W/m²K (BSI, 1990).

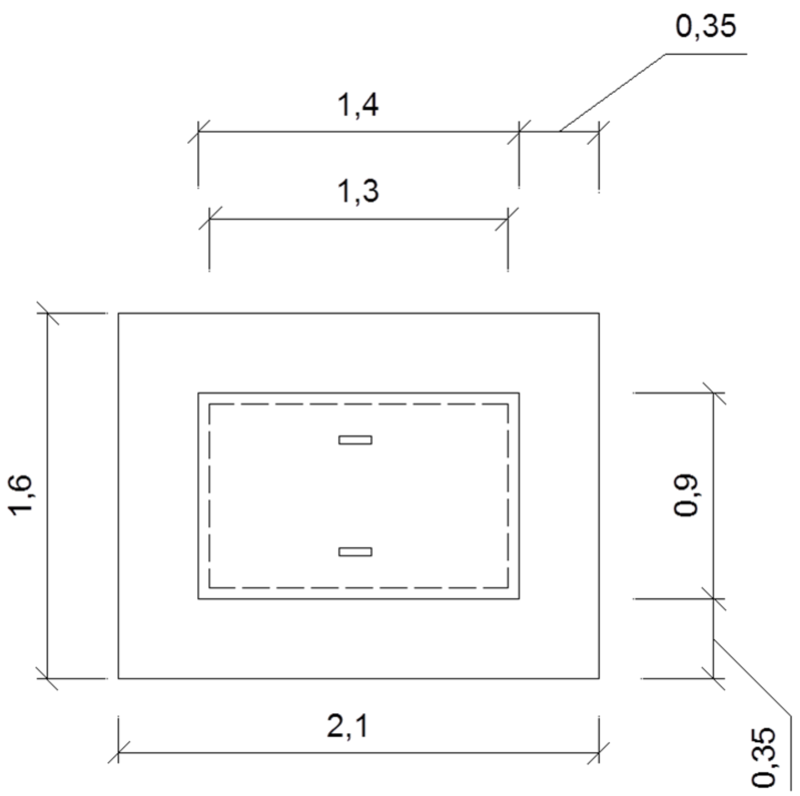


Figure 4-17 The front view of the test room.

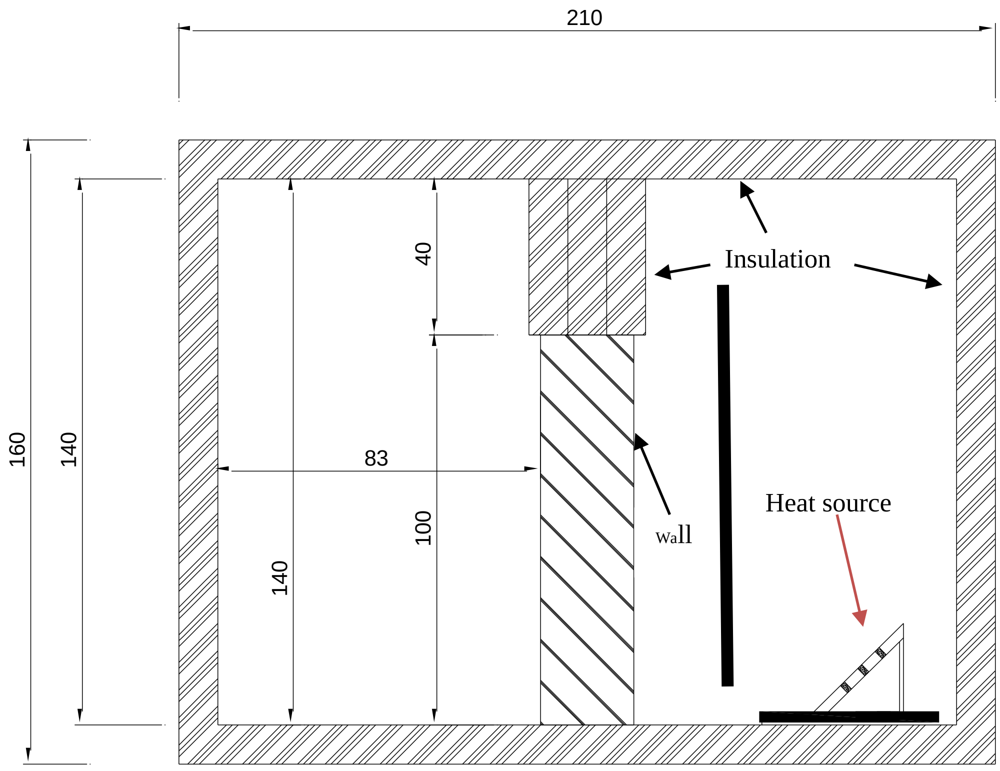


Figure 4-18 Section A-A is showing the position of the wall in the test room.

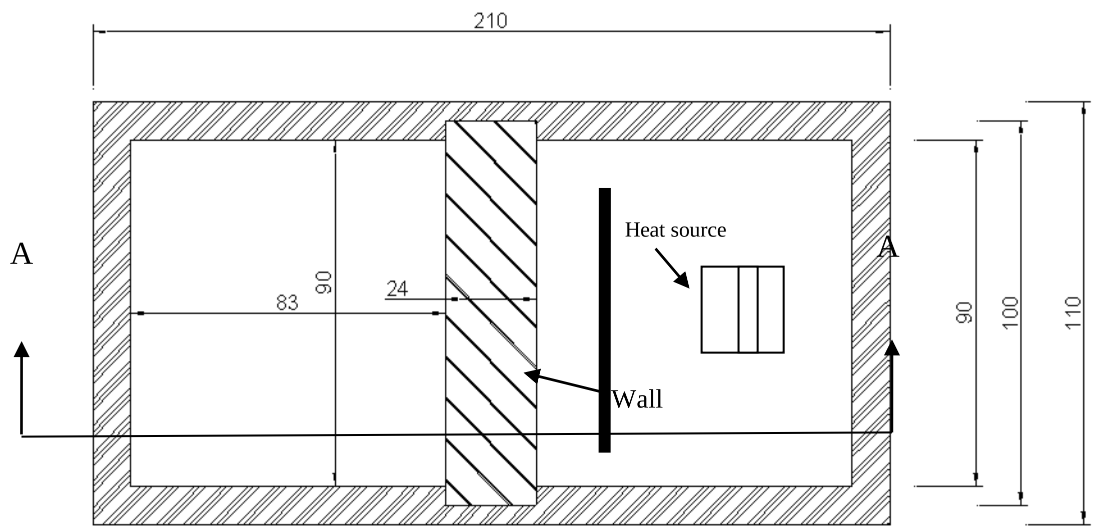


Figure 4-19 Plan of the test room showing the wall between the test rooms. Note: All measurements in the drawing in Figures 4-18 and 4-19 are in centimeters (cm).

4.7.6. Description of the test procedure and equipment used

- The panel was located as shown in Figure 4-20 in the fully insulated wooden room.
- The U-value of the test room was 0.21 W/m²K.
- The U value of the wall panel =X (to be obtained from the test) W/m²K.
- The wall was used to divide the room into two sections.
- One side of the wall was heated to increase the temperature.
- A heater with three levels 700W, 1400W and 2100W was used to simulate heat flow through the test wall (Figure 4-21).

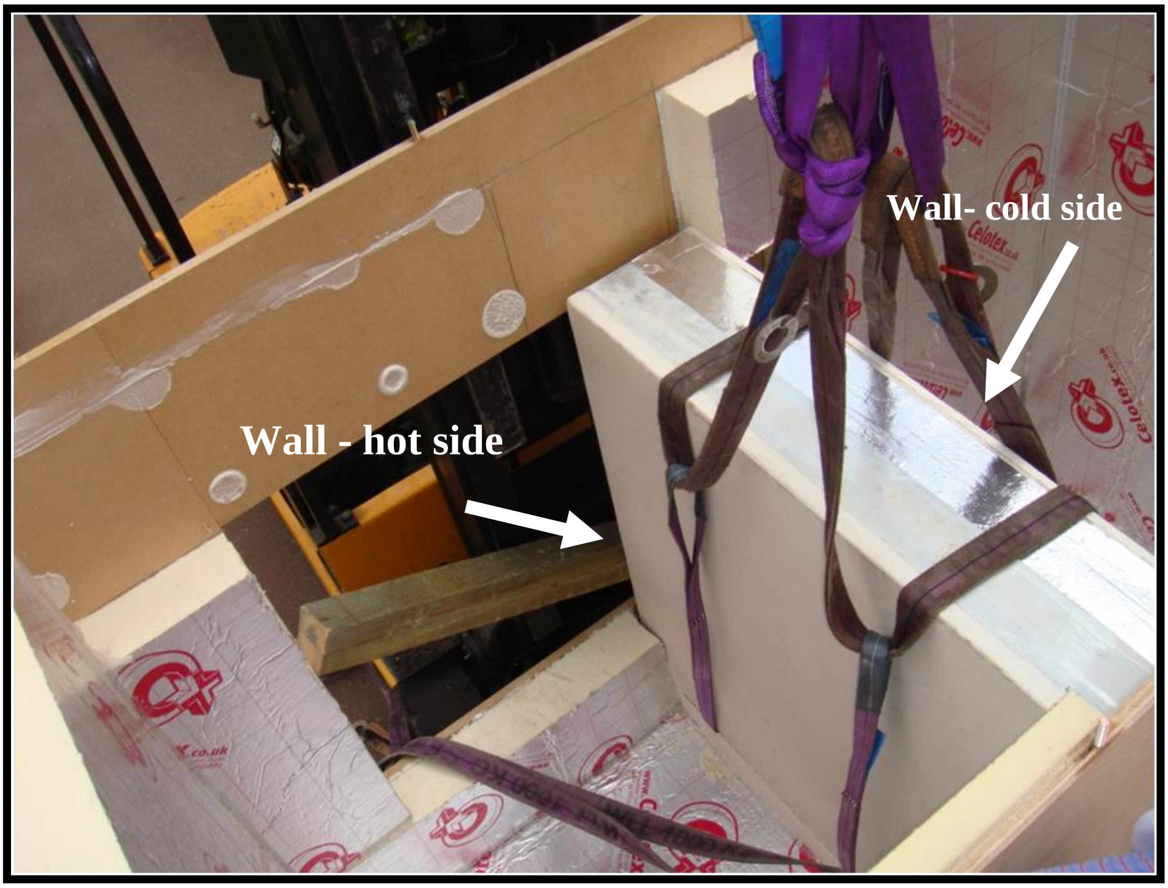


Figure 4-20 The position of the panel in the middle of the test room.

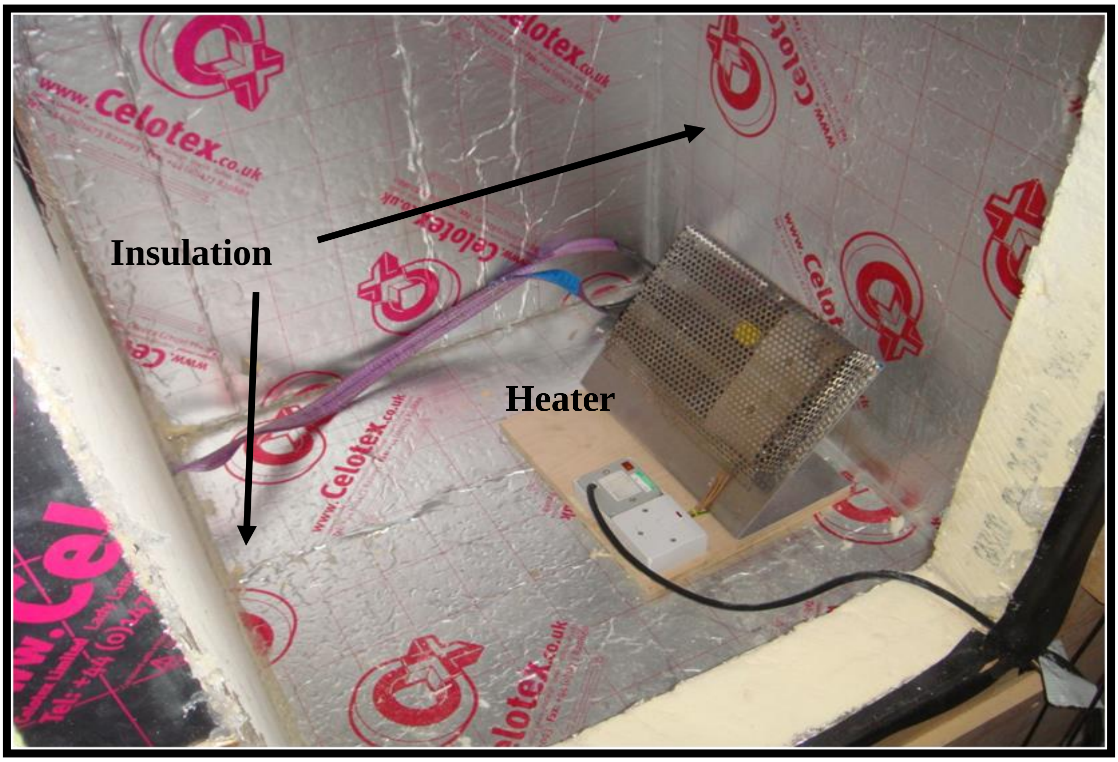


Figure 4-21 The heater and insulation material.

- The other side of the room was maintained at room temperature, with a temperature controller.
- T-type thermocouples were used on both sides of the wall and in the two parts of the test room. The accuracy is ±0.4 °C according to the calibration test Table 4-8.
- (Figure 4-22). However, a calibration has been made in the laboratory for the all thermocouples that have been used as can be seen in Table 4-8, which is shown that the accuracy for them ± 0.41 °C.

Table 4-8 The laboratory calibration for the thermocouples.

Thermocouple	0 °C	100 °C
1	0.01	99.8
2	0.01	100.10
3	0.02	100.14
4	0.01	100.05
5	0.11	100.34
6	0.02	99.60
7	-0.01	99.59
8	0.19	100.25
9	0.08	100.28
10	0.02	100.10
11	-0.03	100.15
12	0.14	100.05
13	0.21	100.24
14	0.02	100.28
15	0.12	100.16
16	0.21	99.09
17	0.09	100.11
18	0.19	99.86
19	-0.13	99.94
20	0.01	99.89

- Two heat fluxes were attached on the cold side of the wall to measure the heat flow from the hot side of the wall (Figures 4-23 and 4-24). Thus, they were used to measure the heat flow from the hot side of the wall to the cold side of the other side of the wall.

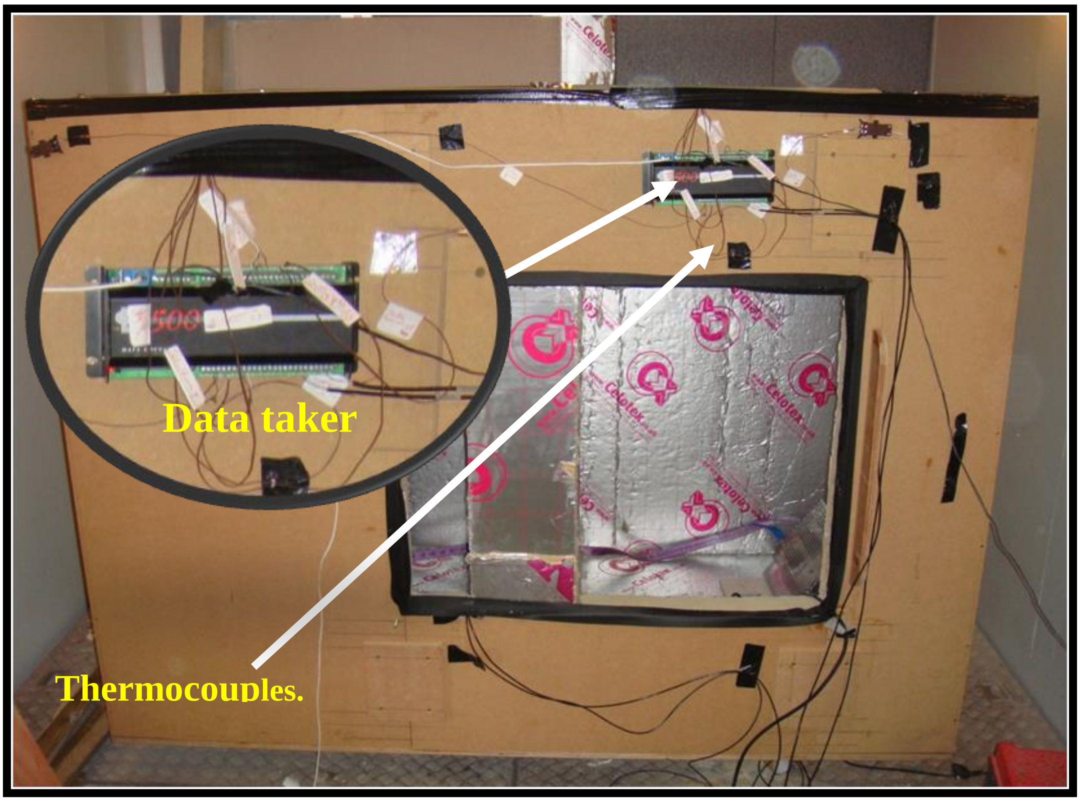


Figure 4-22 The location of data taker, and how thermocouples are connected.

Figure 4-23 Heat flux sensor(Heatse flux, 2011)

- After fixing the panel in the middle of test room, all the thermocouples were connected and the heat fluxes attached to the panel. The door was closed and sealed.
- Door was sealed to avoid heat loss (see Figure 4-25).

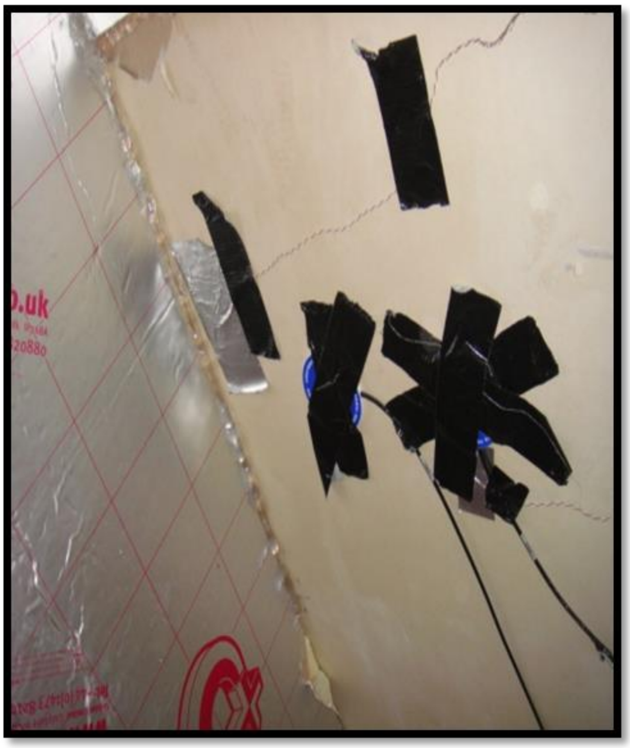


Figure 4-24 Heat flux sensor attached on the wall.

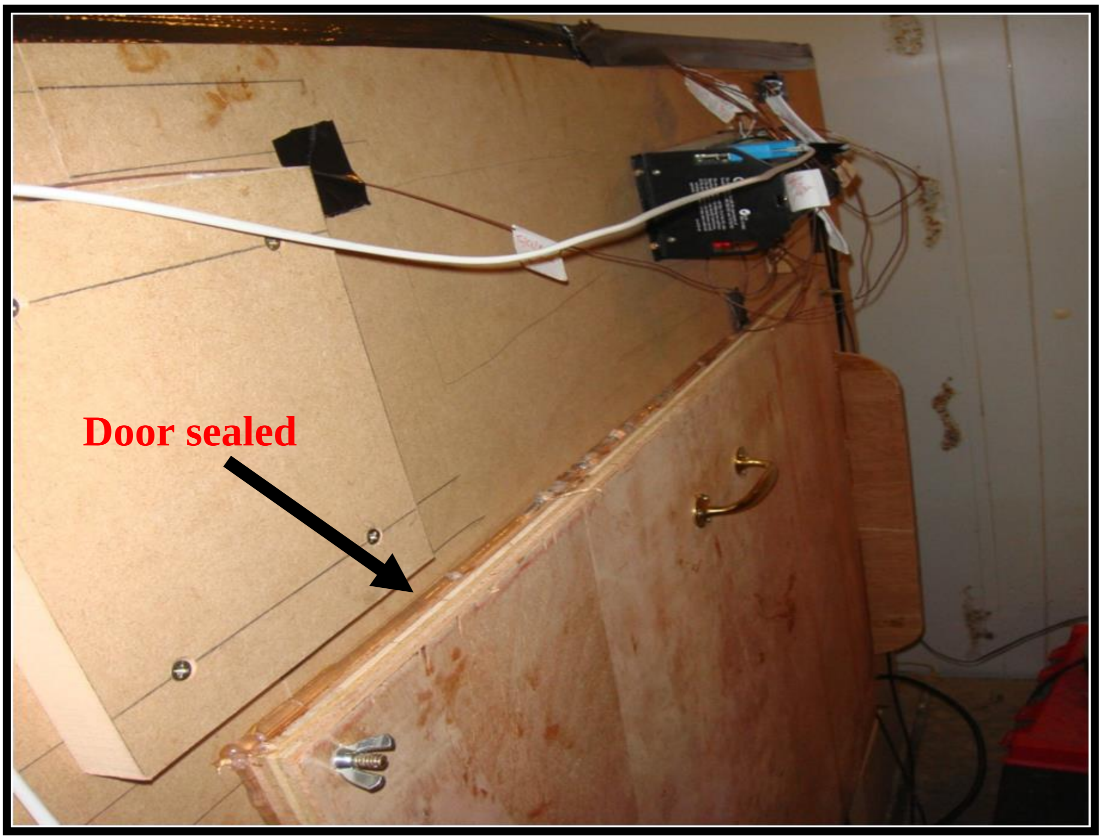


Figure 4-25 The sealed door.

Using the equations, the following procedure are followed

- The heat flux was calculated using equations 4-1 and 4-2

  The K thermal conductivity was calculated using equation 4-3

- The U-value was calculated using equation 4-4

(U value is a measure of the overall rate of heat transfer by all mechanisms under standard conditions through a particular section of the construction).

> - The U value under the new building regulation is U value: Walls less U= 0.28 W/m²K.
> - The U value under the Code of Sustainable Homes is
> - Level 1&2 U value= 0.2 W/ m²K.
> - Level 3, 4&5 U value= 0.18 W/ m²K.
> - Level 6 U value= 0.11 W/ m²K.

4.7.7. Description of the wall (panel 1)

Wall Panel 1 was constructed of five layers: Plaster Board, Foam Glass, Polystyrene beads, lightweight concrete with 8mm pumice and Tru-Stone face coating (see Figure 4-26). The thicknesses of the five layers are presented in Table 4-8. The Tru - Stone face coat according to the Tru-Stone Ltd comprises by volume 20% Mica, 20% Portland cement and 60% ground Portland Limestone. The thermal conductivity of the materials used for panel 1 layers are presented in Table 4-9 (Szokolay, 2008, Engineering-toolbox)

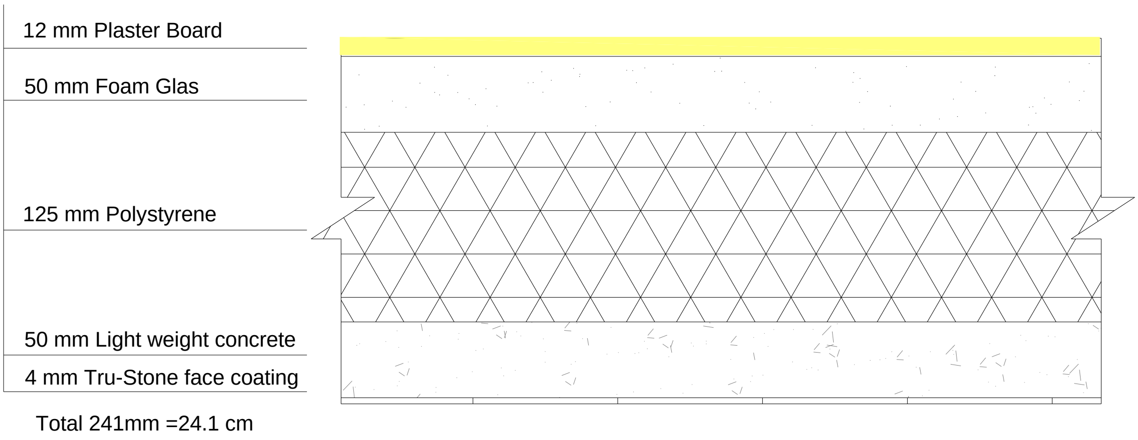


Figure 4-26 Panel 1 layers.

Table 4-9 The materials and thicknesses of panel 1 layers.

Material	**Thickness (mm)**
Plaster Board	d1 = 12
Foam Glass	d2 = 50
Polystyrene	**d3 = 125**
Lightweight concrete with Pumice 8mm	d4 = 50
Tru-Stone face coat	d5 = 4

Table 4-10 The thermal conductivity of panl1 layers.

Material	**Conductivity (W/m K)**
Plaster Board	K1 = 0.16
Foam Glass	K2 = 0.045
Polystyrene	**K3 = 0.034**
Lightweight concrete with Pumice 8mm	K4 = 0.38
Tru-Stone face coat	K5 = 0.75

4.7.8. Description of the wall (panel 2)

As illustrated in Figure 4-27, the wall panel consists of five layers of Plaster Board, Foam Glass, Polystyrene beads, Foam Glass and Tru-Stone face coat. Table 4-10 demonstrates the thicknesses and material layers of panel 2. Table 4-11 presents the thermal conductivity of the panel's material layers.

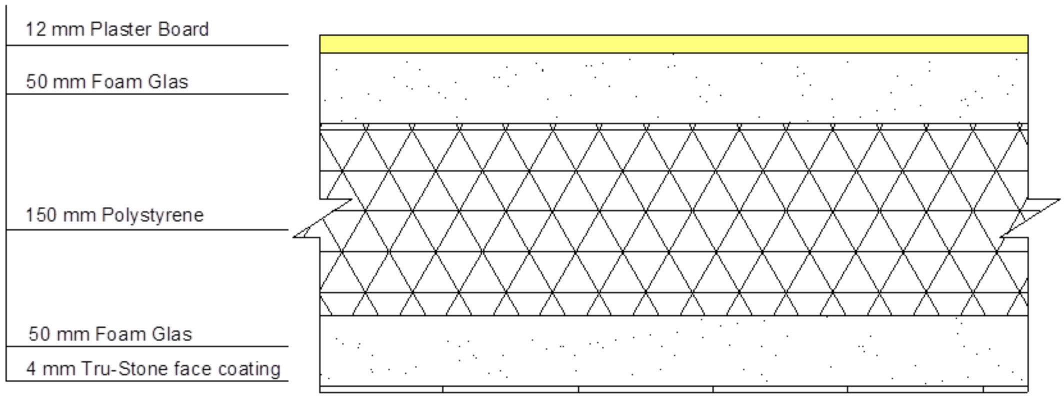


Figure 4-27 Panel 2 layers.

Table 4-11 Thicknesses of the panel 2 layers.

Material	Thickness (mm)
Plaster Board	d1 = 12
Foam Glas	d2 = 50
Polystyrene	**d3 = 150**
Foam Glas	d4 = 50
Tru-Stone face coat	d5 = 4

Table 4-12 Thermal conductivity of Panel 2 layers.

Material	Conductivity (W/m K)		
Plaster Board	K1	=	0.16
Foam Glas	K2	=	0.045
Polystyrene bead	**K3**	**=**	**0.034**
Foam Glas	K4	=	0.045
Tru-Stone face coat	K5	=	0.75

4.7.9. Experimental results

4.7.9.1. Wall panel 1

The Figure 4-28 presents the steady state condition-"*In steady state condition, the amount of heat entering a section is equal to the amount of heat coming out"* (Papadopoulos, 2005), where the difference between the temperature Δt at H1p1 hot side of the wall and C1p1 cold side of the wall is about 15.5°C. Heat flux was calculated using the data obtained from the data logger through the heat flux sensors at the steady state period. As the heat flux sensitivity is 64.6 µV/ W.m², the heat flux will be the result coming out from the divided voltage (result from the data logger) by the sensitivity of the sensor (Hukseflux thermal sensors).

Heat flux Q (W/m²) = 0.181×1000/64.6= 2.80 (W/m²)

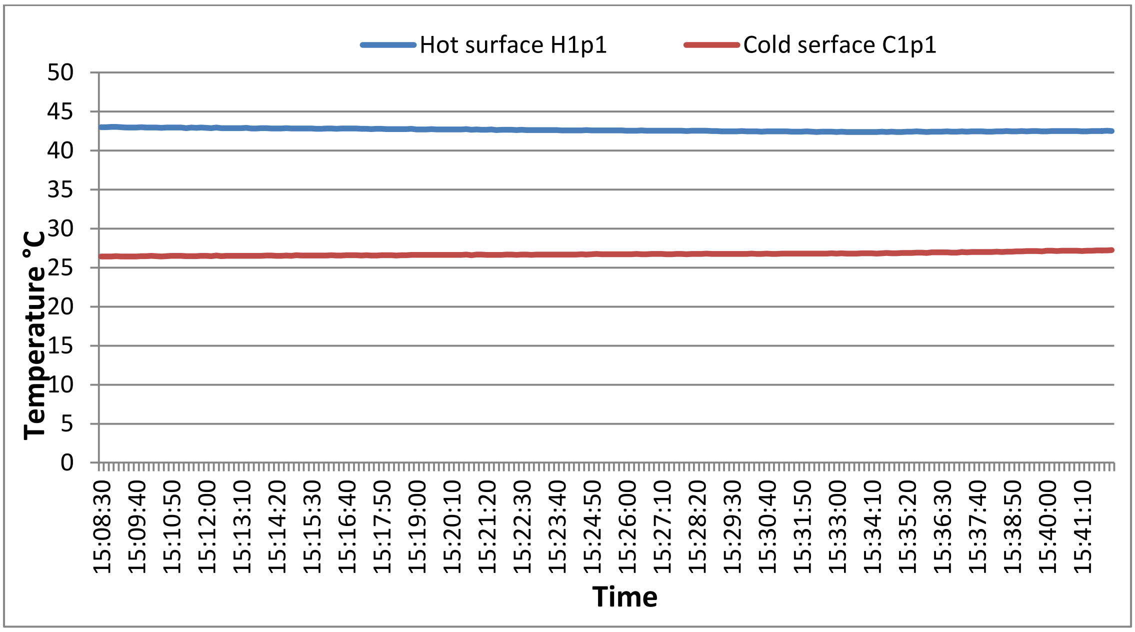


Figure 4-28 Presentation of the steady state period.

Using equations 4-1 and 4-2

$$\text{Heat flow} = A \times \text{heat flux} \qquad m^2 \times W/m^2 \quad = W$$

$$q = 2.80 \times 0.8 = 2.241 \text{ W}$$

Using equations 4-3

$$K = \frac{0.241 \times 2.241}{0.8 \times 15.5}$$

K=0.0435 W/m K

Using equation 2-1

$$R = \frac{0.241}{0.0435} \quad m^2K/W$$

R= 5.54 m²K/W

Using equation 4-4

$$U = \frac{1}{5.54} \text{ W/m}^2\text{K.}$$

$$\boldsymbol{U = 0.1805 \text{ W/m}^2\text{K.}}$$

4.7.9.2. Wall panel 2

As illustrated in Figure 4-29, the steady state condition occurred when the difference between the temperature Δt at H1p1 hot side of the wall and C1p1 cold side of the wall was about 32°C. Heat flux was calculated using the data from the data logger that comes from the heat flux sensors at the steady state period. Thus, as the heat flux sensitivity was 64.6 µV/ W.m², the heat flux was the result coming out from the divided voltage (result from the data logger) by the sensitivity of the sensor (Heat flux thermal sensors).

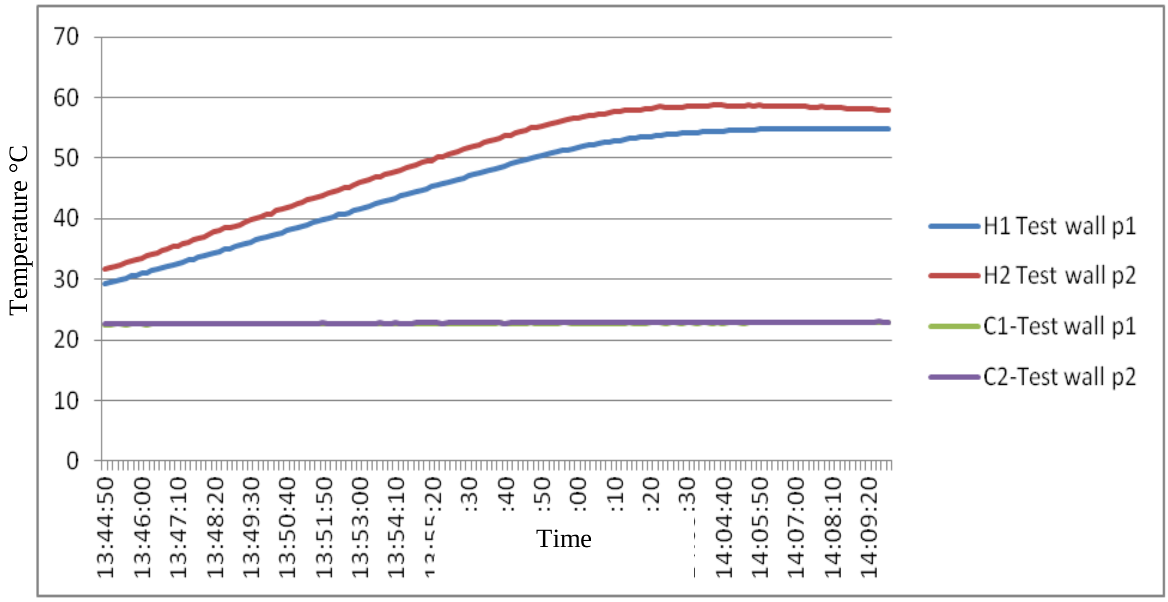


Figure 4-29 Presents a steady state period.

Heat flux Q (W/m²) = 0. 3195*1000/64.6= 4.9458 (W/m²)

Using equations 4-1 and 4-2

$$q = 4.9458 \times 0.8 = 3.956 \text{ W}$$

Using equations 4-3

$$K = \frac{0.266 \times 3.956}{0.8 \times 32} \text{ W/m K}$$

K=0.04111 W/m K

Using equation 2-1

R= 6.47 m²K/W

Using equation 4-4

$$U = \frac{1}{6.47} \text{ (W/m}^2\text{K)}$$

U= 0.153 W/m²K

4.8. Calculation method to obtain the U value for panels 1 and 2

A calculation was made to find out the U value of the walls, which was then compared with results from the experiments by using equations 2-1, 4-4 and 4-5. The U value targets are shown in Table 4-2.

4.8.1. For wall panel 1 (241mm)

$$R(total) = 0.123 + \frac{12}{0.16 \times 1000} + \frac{50}{0.045 \times 1000} + \frac{125}{0.034 \times 1000} + \frac{50}{0.38 \times 1000} + \frac{4}{0.75 \times 1000} + 0.055$$

R ($total$) = 0.123+ 0.075+ 1.111+3.67+ 0.132+0.0053+0.055

R= 5.17 m²K/W

$$U = \frac{1}{5.18} \quad (\mathrm{W/m^2k}\quad)$$

U= 0.1930 W/m²k

4.8.2. For wall panel 2 (266mm)

$$R(total) = 0.123 + \frac{12}{0.16 \times 1000} + \frac{50}{0.045 \times 1000} + \frac{150}{0.034 \times 1000} + \frac{50}{0.045 \times 1000} + \frac{4}{0.75 \times 1000} + 0.055$$

R (total) =0.123+ 0.075+ 1.111+ 4.41+ 1.11+ 0.0053+ 0.055

R(total)= 6.88 m²K/W

$$U = \frac{1}{6.88} \quad (\mathrm{W/m^2k}\quad)$$

***U*=0.145 W/m²k**

4.8.3. Analysis of the results

The test was run until the steady state conditions were achieved (McMullan, 1992) where the temperature difference on both sides of the wall was shown as a constant pattern. Figure 4-28 shows the period of time that Δt remained constant. From the results of the wall panel 1 test, the calculations show that the U value of the panel is 0.1805 W/m²K. This meets the codes for Sustainable Homes levels 3, 4 and 5 but not level 6. However, the calculated results of the same panel shows that the U value of the panel = 0.1930 W/m²k. This meets the codes for Sustainable Homes level 1 and 2 but it is above the target of level 3,4,5 and 6. However, both results meet the Building Regulation 2006.

For wall panel 2 experiment results shown the U value = 0.153 W/m²k and calculation result shown that the U value = 0.145 W/m²k. Panel 2 shows that it could meet the building regulation 2010 and the Code of Sustainable Homes level 1,2,3,4 and 5 but not level 6.

4.9. Conclusions

It can be concluded that using the Tru-Stone coating will help to keep the same appearance of the building. Also, aerogel has a low thermal conductivity of 0.0135 W/mK compared with rock-wool insulation at 0.045 W/m K, and glass wool Insulation (0.04 W/mK) which makes the panel thin. On this basis,, Tru-Stone with Aerogel panel will increase the resistances of the existing wall constructions.

After more than 4 hours of the experiment, the panel (aerogel with Tru-Stone) maintained the difference between both sides of the room (Δt) at about 32 °C. In addition, the result from the experimental is validated through the calculations and shows the results are close as the U value of the Aerogel with Tru- stone coating panel was obtained by experiment to be 0.362 W/m²K and by modelling to be 0.354 W/m²k.

For solid walls more Aerogel layers should be added to the panel to increase the resistance of the panel as the resistance of the solid wall is very low (R= 0.448 m²K/W). From the result, it was clear that the panel of Tru-ston with aerogel could help to meet the building regulations 2010 and the Code of Sustainable Homes level 3, 4 and 5. Thus, by adding thicknesses of *7cm* of aerogel layer to solid wall or *3.5cm* to cavity wall and a fine layer of 4mm Tru-Stone coating it is possible viable to achieve Sustainable Code Home Level 3, 4 and 5 in terms of U value. In addition, it is important to state that the aerogel has a strong ability as a moisture resistance material.

According to the experiment test in section 4-3 under BS 874-3.2 the Tru-Stone with aerogel panel can improve the existing walls in terms of U-value to meet the Building Regulation 2010 and the Code for Sustainable Homes level 3, 4 and 5 where the U-value target is 0.18 W/m²K by adding the panel to cavity walls.

Testing wall panel 1 and wall panel 2

After 1 hour the wall maintained the difference between both sides of the room Δt about 15.5 °C. For this; as the U value of wall panel 1 was obtained by experiment to be 0.1805 W/m²K and by calculation to be 0.1930 W/m²k, it is recommended to increase the thermal resistance to meet the Code of Sustainable Homes level 4 and 5. According to the experimental test under BS 874-3.2, wall panel 1 can meet the Building regulation 2010 however, it need to be improved to meet the Code for Sustainable Homes level 5and 6.

Panel 2 was tested under BS 874-3.2 and the result shows that the U value of the panel 2 is 0.153 W/m²k, while the calculation result of the U value is 0.145 W/m²k. The difference between the results =0.008 W/m²k which is about 5% difference. Thus, from the result, it is clear that the Panel 2 could meet the building regulations and Sustainable Homes code level 3, 4 and 5. However, panel 2 did not meet Sustainable Home code level 6.

CHAPTER 5: COUPLED PHASE CHANGE MATERIALS (PCMs) WITH OTHER CONSTRUCTION MATERIALS

"Just as the ice –house used to store cold from the winter months for use in the days of summer; the thermal mass of building can be used to store the cool of the night winds to lower internal temperature during the day."

Sue Roaf *Roaf et al., 2003)*

5. Coupled Phase change materials (PCMs) with other construction materials

5.1. Introduction

This chapter presents the work of coupling Micronal Phase Change Material (MPCM) with other construction materials to enhance the thermal conductivity of the MPCM so it will charge and discharge more heat faster.

Mixing materials such as cement, gypsum or clay with PCMs is still under research and is widely used as part of construction materials (BASF, 2007, Toppi and Mazzarella). For instance, brick could be made from different materials such as clay and Calcium Silicate and this brick can be mixed with PCM and used for internal finishing, or even constructed as panels and used as final internal surfaces. Clay is the most widely used material to produce brick, which is an economical material in the UK (Clayworks, 2010).

Several researchers have examined the mixing of Phase Change Materials (PCMs) with other materials in an attempt to improve the thermal conductivity of PCMs as has been mentioned in chapter 3 (Toppi and Mazzarella, Schossig et al., 2005). Darkwa (2005) experimented with a mixture of gypsum and encapsulated PCM, where the results concluded that the mixture could enhance the thermal performance of the sample (gypsum and PCM) and suggested that more experiments should be carried out to examine more mixtures under different conditions. In 2006 (Shilei et al.) tested the effect of mixing PCM with gypsum and tested panels in a full scale room. The results were compared with results of another room without any modifications under the same conditions. From the results Shilei et al (2006) concluded that use of the PCM panels can improve the indoor thermal comfort.

5.1 Mixing Phase change materials (PCM) with clay

Use of unfired clay may have a positive impact on the building users' health, as this is a natural material. Andresen (Not available), stated that pure clay or clay mixed with other materials such as sand and straw have been used thousands of years ago in different climates and different cultures. Andresen (ND) further confirmed that clay was used widely in Germany and other European countries as a building construction material for decades without problems.

5.1.1 The advantage of using Clay

- Recyclable material, that can be used again and again (Clay UK, 2009)
- Sustainable as it is obtained from natural resources (Materials-world, 2006, Clay-UK, 2009)
- Low embodied energy, being 100% natural.
- Breathable as it has porous properties.
- Non- toxic (Clayworks, 2010).
- Clay can help to keep spaces cool in summer and warm in winter (Clay UK, 2009)
- Minimum waste of the material which could be used again in other building construction processes (Materials-world, 2006).
- It is a cheap material (Clayworks, 2010).

5.1.2 Mixing Clay and PCM with cement

It is important to highlight the need of cement in a mixture that contains clay with PCMs, as the clay needs to be fired at high temperatures between 1500-1600 °C (Giese, 2002). In this case, the unfired clay method was used. Thus, cement works as a binding material to make the mixture stick together and dry without the need of firing. Extension of the mixture should be taken into account if the component has a large amount of clay and mesh may be used to avoid the problem of cracking (McMullan, 1992). Venkatarama Reddy and Jagadish (2003) have pointed out that there is no need for firing the clay by adding about 7% cement. In addition, the advantages of adding cement to the mixture including clay or sand are:

- No need for firing the clay so this will reduce CO_2 (Galán-Marín et al., 2010).
- It saves energy by 70% (because there is no need to burn the clay).
- It costs 20-40% less compared with brick masonry.
- It presents a good finish.

However, the disadvantage of adding cement is linked to the processes of producing cement at factories, which affects the environment.

5.1.3 Problem of cracking

Cracking results from rapid evaporation of water through the surface, and the gap between drying the top surfaces of the panel or slab contrasted with the rest of the component (Sakrete, 2013). A simple classification of intrinsic cracks, provides an important initial guide in any diagnosis because in very broad terms the periods in which these types of crack appear are the results of the following cases (Dhir and Jones, 1996):

(a) Plastic: the cracks appear in first few hours.

(b) Early thermal contraction: after one day up to three weeks

(c) Long-term drying shrinkage: after several weeks or even months.

5.1.4 Controlling cracks

- The current most popular method of controlling cracks is to provide sufficient reinforcement such as fibers, if necessary in conjunction with movement joints, to produce many fine cracks rather than a few wide cracks (Sika, 2011, Dhir and Jones, 1996).
- Using low shrinking materials.
- Covering the element with cling film and sackcloth as this will minimize evaporation time.
- Use white surface to reflect heat radiation (Hewitt and Philip, 1999).

5.1.5 Mixing Phase change materials (PCM) with gypsum

Mixing PCMs with gypsum is widely used where the final product looks the same as gypsum board. The main principle of using PCM is reducing the energy demand which has a significant effect on other aspects such as the concern about the environment, increase in fossil fuel cost as well as the health and comfort of the people using the buildings (Tyagi et al., 2011). Gypsum comes as one of the materials extensively used with PCMs and a large number of researchers have become interested in this topic as presented earlier in section 3.12.

5.1.6 The advantage of using gypsum

- It is a cheap material.
- Durability: it is strong enough to be used in building construction
- Availability: as it is natural resource.
- Light in weight compared with cement (Saint-Gobain, 2013).
- High workability as it is easily mixed with PCM and water.

- Good fire resistance-according to ASTM E 84 (DW et al., 1988, Gypsum-Association, 2011).

5.2 Lab experiment to test the thermal conductivity of MPCM components

Laboratory experiments were carried out at the Department of Architecture and Built Environment at the University of Nottingham to test the thermal conductivity of MPMC panels. The reason for these tests was to obtain real data under equivalent conditions for all samples. This should help to choose the final sample panel that will later manufacture in a large quantity for the full-scale test, as explained in the next chapter.

5.2.1 Aim of the experiment

- To improve the low thermal conductivity of MPCM by coupling it with other materials. Darkwa and Kim (2004) highlighted the problem of insufficient heat transfer for the duration of the energy recovery. Improving the heat capacity and enhancing the MPCM ability of heat discharge by mixing Phase Change Materials with materials that have higher thermal conductivity such as clay and cement will increase the thermal conductivity of the component.

5.2.2 Methodology adopted for the test

A combination of Phase Change Material (PCM) with other building materials (Clay, gypsum, silica and cement) in different percentages was investigated for improving the thermal conductivity of PCM. Homogeneity of the mixture of the materials was important in order to obtain results that are more accurate. Different samples were mixed in different percentages in order to improve the thermal conductivity of the mixture and investigate the samples' conductivities by using

Heat Flow Measure, HFM (Darkwa and Kim, 2005). It is important to highlight that according to Sittisart and Farid (2011) one of the four methods of creating fire retardants is adding clay and silica to the PCM (paraffin).

5.2.3 Materials and equipment used in the test

Phase Change Material PCM

Microencapsulated PCM produced by BASF Company and which is known as Micronal PCM 23°C was used as thermal heat storage in this work. Figure 5-1 shows the physical form of the PCM used. The purpose behind use of this material was essentially to avoid leakage of the material during the phase change process from solid to liquid. As illustrated in Figure 5-2, the Micronal core is about 5μm and contains wax. The process of changing phases occurs within the microcapsule core. The product code is DS 5008 from BASF and has a melting point of 23 °C, latent heat capacity of 441 kJ/kg, storage capacity of 55 kJ/kg and thermal conductivity of 0.16 W/mK. The microcapsule density is 980 kg/m3 (BASF, 2011)

Figure 5-1 physical form of Microencapsulated PCM.

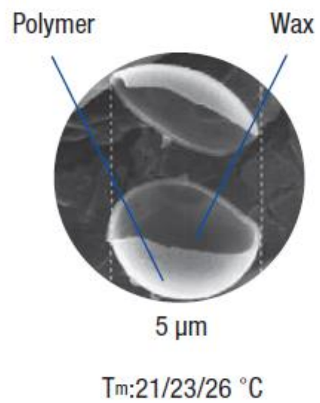


Figure 5-2 The Micronal core contain the wax (BASF, 2011)

The mixture contains a number of materials including clay, gypsum and silica.

Clay

Smooth clay was purchased from Potclays Ltd, product code 190-118 for use in the mixture. The clay is light grey in colour and is made up of a low toxicity dust with melting point of over 1200 ^{o}C. The thermal conductivity of the clay is between 0.15 - 0.19 W/mK (Potclay, 2010).

Gypsum

Gypsum material was obtained from the local Wickes shop a under product code 220056 as illustrate in Figure 5-3 (Wickes, 2011e). The advantage of using gypsum is to reduce the period of fire spreading for up to 3-4 hours as stated in Euro-gypsum (2011).

Figure 5-3 British Gypsum- Multi finish (Wickes, 2011e).

Silica

According to British Standards Institution (BSI) 1199 and 1200:1976 the selected silica has to be clean, strong and tough. Natural sand as illustrated in Figure 5-4 is made from crushed stone sand and crushed rock sand or a mix of both is the main source of silica (BSI, 1976). Silica (sand) was obtained from local Wickes (product code 224666), illustrated in Figure 5-4 (Wickes, 2011b).

Figure 5-4 Plastering Sand (Wickes, 2011b).

No crack concrete

This material was used to avoid cracks in the clay panel. The no crack concrete material was obtained from Sika Company under the name of Sika-Cim No Crack Concrete (see Figure 5-5). This material has more advantages as it improves the workability and durability of the mixture to obtain smooth surfaces. It is also water resistant (Sika, 2010, Sika, 2011).

Figure 5-5 Sika-Cim no crack concrete(Sika, 2011).

Honeycomb

To enhance the heat exchange between the MPCM and other constructed materials used for the panels, a honeycomb material is used. This is a light metallic material structured as a aluminium honeycomb with two dimensions 10 mm and 20 mm (Figure 5-6). The purpose of using this material is to enhance the heat exchange of the MPCM panels used as it allows a large area of MPCM to conduct heat in a short period of time (Hasse et al., 2011, Jegadheeswaran and Pohekar, 2009).

Figure 5-6 Honey-comb.

5.2.4 Apparatus

Heat Flow Meter HFM

Heat Flow Measure machine used to measure the thermal conductivity of the materials. More details about the HFM are provided in section 5-5.

Digital scale

KERN 440-53 illustrated in Figure 5-7 was used to weigh the materials. The accuracy is ±1% and can measure up to 6 Kg while the minimum capacity is 2g (Kern Scale Technic, 2009). This balance was calibrated from German Calibration service Certificate number 963-128 (Kern balances)

Concrete mixer

Electronic mixer MC 130 was purchased from Wickes (product code 505040). The motor power is 450W and the capacity of the drum is up to 130 L. For easy use, the drum can be rotated 360^{o} as illustrated in Figure 5-8 (Wickes, 2011a).

Wood cutting machine

Wood cutting machine at the workshop in the Department of Architecture and the Built Environment was used to cut the wood, which was used for casting the mixture (Figure5-9).

Wooden moulds

Smooth wood was used to manufacture wooden frames 30cm×30cm×2cm and wood plates about 60cm*60cm (Figure 5-10).

Plastering Trowel

Plastering Trowel 45.7cm from Wickes was employed for the final finishing (Figure 5-11), making the surface of the panels smooth with a product code of 167359 (Wickes, 2011c).

Smooth aluminium stick 120cm

Purchased from Wickes under code number 167363 for the large panels final finishing as shown in Figure 5-12 (wickes, 2011d).

5.2.5 Curing

Sackcloth

Sackcloth, illustrated in Figure 5-13 was used to make the surface of the manufacturing panels wet. Thus, the whole panel dried in a converged time to avoid cracks.

Cling film.

Cling film was been used as part of the curing system to minimize the water evaporation to avoid cracks on the manufactured panels (see Figure 5-14).

Figure 5-7 Kern scale.

Figure 5-8 concrete mixer.

Figure 5-9 Wood cutting machine.

Figure 5-10 Wooden frames.

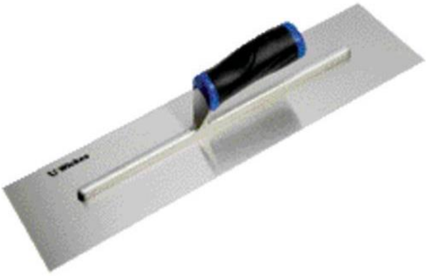


Figure 5-11 Plastering Trowel(Wickes, 2011c)

Figure 5-12 Smooth aluminium stick(wickes, 2011d)

Figure 5-13 Sackcloth.

Figure 5-14 Cling film.

5.3 Procedure of manufacturing panels

During the casting process, the wooden frame was attached to a flat wood panel as illustrated in Figure 5-18.

- Wooden frames dimensions for frame 1 is 30cm×30cm×1cm and frame 2 is 30cm×30cm×2cm were prepared to set the mixture.
- Water have been added to each mixture, between one liter of water for frame 1 and 2 liters of water for frame 2

- The dry combination of PCM, clay, gypsum and cement has been mixed well until obtaining a homogeneous mixture with extra care for PCM micro capsulation see Figure 5-19.
- The mixture was placed into the frame with carful pressure to ensure there are no air gaps, which could cause weakness. Moreover, for consolidation it was necessary that the tamping is not too hard see Figures 5-20 and 5-21 (Andresen, Not available)
- Curing system was considered to avoid any cracking which could damage the panels. Thus, panels were covered by using cling film to reduce the amount of evaporation as can be seen in Figure 5-22 and also, using sackcloth to keep the surface wet over the cling film
- Material known as No crack concrete material has used with the mixture of PCM with clay.
- Honeycomb as can be seen in Figure 5-23 has been used to increase the thermal conductivity of the MPCM panels and more details of full-scale room test by using MPCM panel with honeycomb will be presented in chapter 7.
- Finishing the panels' surfaces required extra care to achieve smooth surfaces.
- After 7 to 10 days, the panels were dry and ready to be tested by using Heat Flow Meter (HFM) in the Civil Engineering Department- University of Nottingham to measure the thermal conductivity of each panel.
- As some panels consist of MPCM (melting point 23 °C) the test has carried slightly above the melting point around 28-30°C to determine the conductivity under the liquid phase of the material. And the difference in temperature between the hot plate and the cold plate about 15 °C.

Figure 5-15. Wooden frame attached into the flat wood.

Figure 5-16. Homogeneous mixture.

Figure 5-17 Mixture placed into the frame.

Figure 5-18 Smooth flat surface.

Figure 5-19 Curing.

Figure 5-20 Honeycomb.

5.4 Heat Flow Meter (HFM)

The heat flow through the samples under specific conditions was measured using HFM, which was designed and manufactured under the specification of ISO 8301 and BS874-2.2: 1988 (Figure 5-24). The rig consists of a cold and a hot plate as shown in Figure 5-25. The cold plate temperature was controlled using a refrigerator and a heater was used to heat the hot plate. Additionally, the sample, illustrated in Figure 5-26, was located in a high efficiency insulated box and adjusted to control the thickness between plates (Figure 5-27). The HFM was designed for one dimension heat transfer with an accuracy level of ±1 (Darkwa and Kim, 2005).

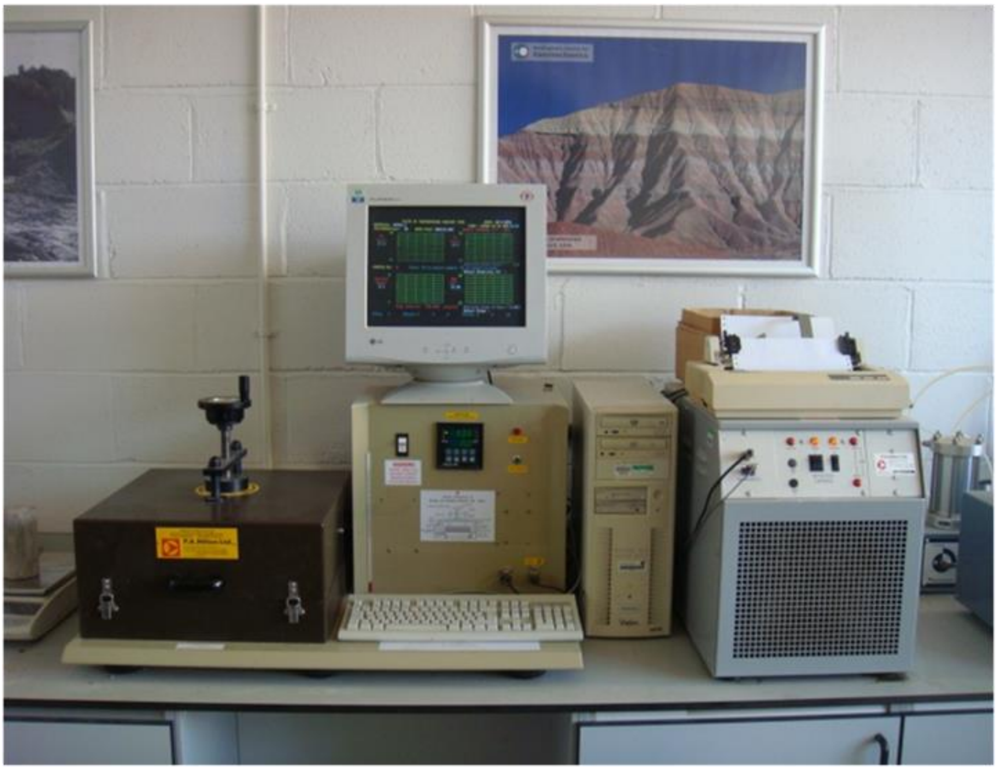


Figure 5-21 Heat Flow Meter HFM.

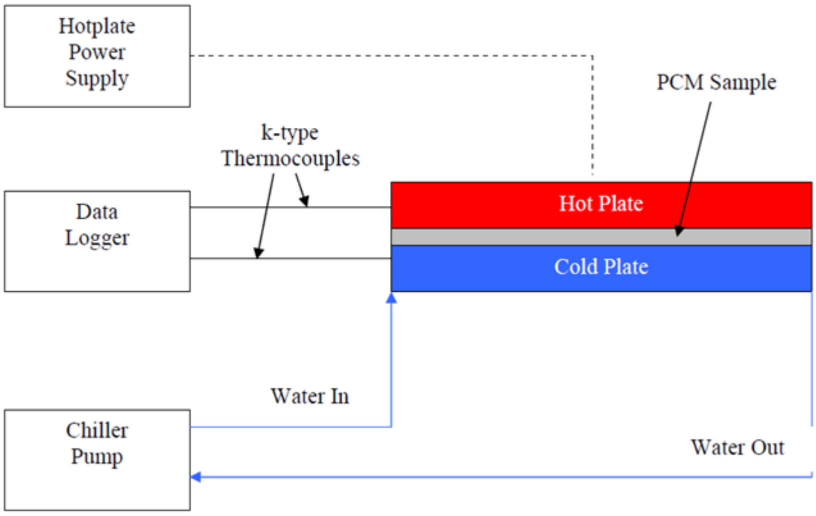
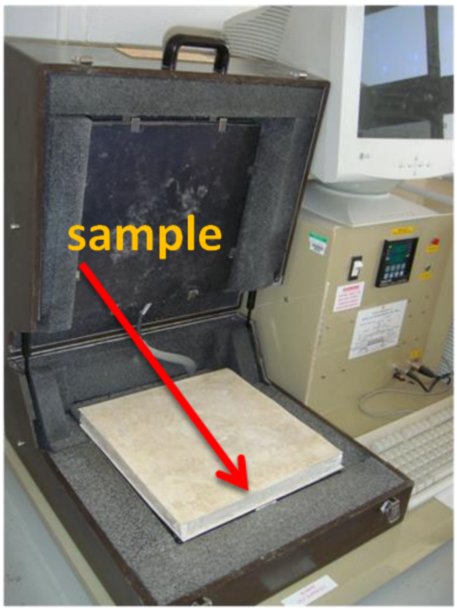


Figure 5-22 Diagram of HFM.

Figure 5-23 place of the sample.



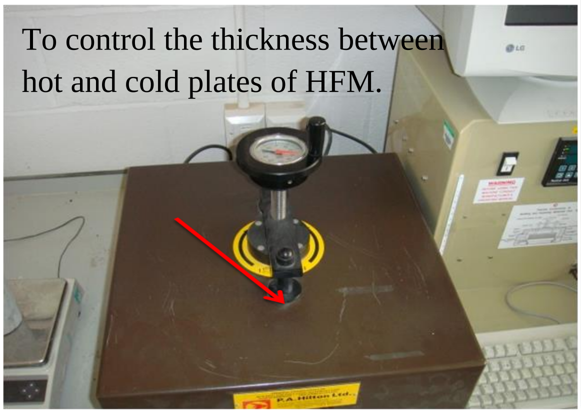


Figure 5-24 Adjustment of HFM plates.

The heated plate consists of double metal such as copper or aluminium 3mm-5mm, with heating element.

The cold plate was constructed from high conductivity metal, and liquid was circulated to cool down the plate as illustrated in Figure 5-28 (BSI, 1988).

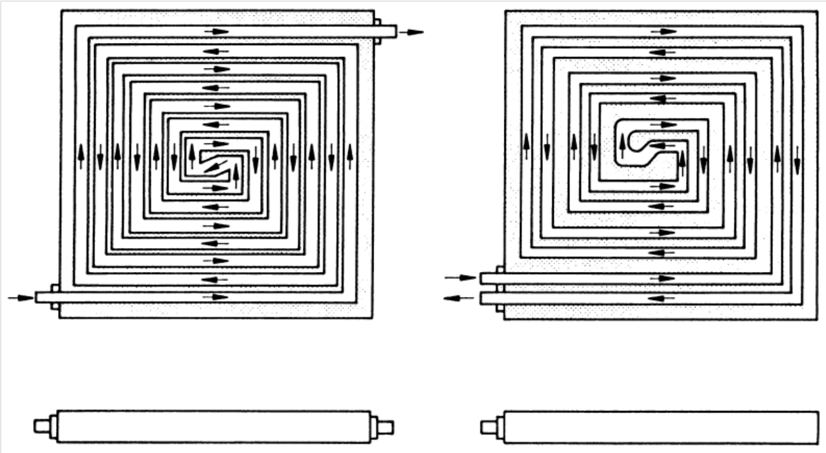


Figure 5-25 Cold plate designs.(BSI, 1988).

Data included for running the test:

- Temperature of hot plate
- Temperature of cold plate

The test for MPCM coupled with construction materials was run above the melting point of the MPCM with a difference between the hot and cold plates kept between 15-20°C. The information below should be added to the HFM system for each panel:

- Density of the panel.
- Tackiness of the panel.

5.4.1 Method of the test

The test method is based on BS874-2.2: 1988 as the of hot plate was maintained at steady state conditions to measure the thermal conductivity of the material in the temperature range between -20 ^{o}C to 100 ^{o}C. HFM presented in section 5.5 also meets the standard BS874-2.2:1988. The tested panels were manufactured as explained in section 5.4. The temperature was recorded in both plates using thermocouples, with one at the centre of the plate and a minimum of four thermocouples in each plate to record the sample's surface temperature. The maximum thickness of the panel that could be tested by HTM was 7cm. The dimension of the panel was 30 cm × 30 cm. In addition, the two surfaces of the specimen must be flat and smooth and the deviation should not exceed 0.2mm from the flatness of the sample. To ensure effective thermal contact between HTM plates and the sample, a sheet of 3mm silicon rubber was inserted between each plate and sample surface.

5.4.2 HFM test procedure

- The sample was placed in the HFM box and the hot plated adjusted to allow the hot plate to touch the sample surface as illustrated in Figure 5-26.
- The sample data was entered into the HFM using a PC connected to the system as shown in Figure 5-24.
- The temperature of the hot plate was determined and the HFM switched on. The refrigerator provided cold water to control the temperature on the cold plate.
- The hot plate was heated while the cold plate was cooled to attain the steady state condition of the sample.

After adding all the required information into the system, it took 10 to 24 hours to finish the test. The system provided more than 1 result with a little variation. The results represent the conductivity of the panel. Thus, by obtaining the conductivity, the U and R-values were calculated using equation 2-1 and equation 4-4. According to BSI (1988) the accuracy of the test is better than ±3%.

5.5 Thermal conductivity test of the PCM panels

Materials such as cement, gypsum and clay were widely used with PCMs as part of the construction materials. However this concept is still under investigation (BASF, 2011). Venkatarama Reddy and Jagadish (2003) mixed 20-25% sand with 6-7% cement and the remaining proportion was made up of red clay for natural colour. Shawabkeh (2005) tested the mix of clay, cement and sand and investigated the solidification and stabilization of the mix. Fifteen samples were tested, with each sample having different percentages of sand, clay and cement. More details are presented in section 3-12. Table 5-1 presents the conductivity of the materials used to manufacture (PCM mixed with construction materials) panels in the following sections.

Table 5-1 The thermal conductivity of the materials that are used in different mixture (Engineering-toolbox)

Material	**Thermal Conductivity W/mK**
Cement	0.38
Clay	0.15 - 0.19
Gypsum	0.17- 0.2
PCM	0.16
Silica	0.15- 0.25

5.5.1 Mixture of MPCM and Clay

Two panels were prepared for assessment as follows:

Panel 1

This consists of 100% Clay mixed with one litre of water. Frame 1 was used to construct the clay and left for day to dry. However, some wide cracks appeared on the top surface of the panel as shown in Figures 5-29 and 5-30.

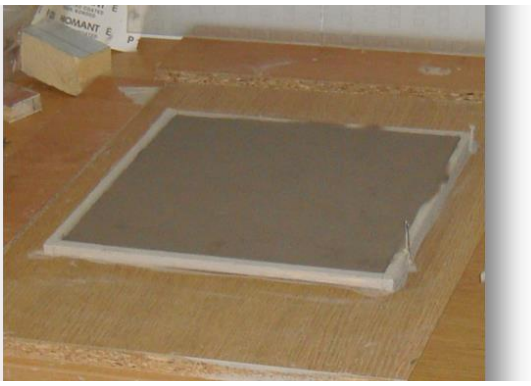


Figure 5-26 100% Clay panel.

Figure 5-27 100% clay panel showing Crack appear on the surface of the panel.

The thermal conductivity of the panel is presented in Table 5-2. The thermal conductivity of the clay was 0.186 W/mK. Thus, the results of the thermal conductivity of the constructed panels are shown if there is any enhancement by comparing them with the thermal conductivity of the raw materials.

Table 5-2 Properties of Buff stoneware clay.

Panel 1	Conductivity W/mK	Density Kg/m³
Clay (Buff stoneware)	0.186	1667

Panel2

Panel 2 consists of 90% clay and 10% Phase Change Material. The test investigates the effect on admixture thermal conductivity of the mixed clay and MPCM. However, the panel presented serious cracks that exceed acceptable use for construction and it was not accepted as a panel for a thermal conductivity test. Four causes maybe behind these large cracks:

- The mixture has a large percentage of clay.
- There is no adhesive material added to the mixture.
- The evaporation rate was very fast as this panel was not covered with cling film.

  This sample was discarded and all issues have been taken into account in the preparation of the other panels.

Figure 5-28 A panel made of 90% clay and 10% MPCM, showing enormous cracks on the surface of the in panel.

A number of panels (12 panel in total) are produced with varying type of MPCM , clay and cement, these have tested and the results are presented in Table 5-4. This presents the results of tests using Heat Flow Meter HFM. In addition, another 3 panels were constructed from clay and cement only and these have been tested to understand the effect of the varying component and compared with panels made using PCM. The results of panel 7 which is constructed of 40% PCM, 20 %clay, 40% cement has found to have the highest value of thermal conductivity of 0.253 W/mK compared with all the other samples. Panel 12 was constructed of 35% PCM, 50% clay, 15% cement and has the next highest value of thermal conductivity between panel 10 to panel 14 where the thermal conductivity is 0.234W/mK.

Table 5-3 The results of the tested panels that consisted different percentage of PCM, clay and cement.

Panel NO	**Panels components**	**Thermal Conductivity W/mK**
	Group1	
Panel 3	PCM 10%+ Clay50%+cement 40%	0.203
Panel 4	PCM 20%+ Clay40%+ cement 40%	0.207
Panel 5	PCM 25%+ Clay35%+cement 40%	0.210
Panel 6	PCM 30%+ Clay30%+cement 40%	0.232
Panel 7	**PCM 40%+ Clay20%+cement 40%**	**0.253**
Panel 8	PCM 45%+ Clay15%+cement 40%	0.245
Panel 9	PCM 50%+ Clay10%+cement 40%	0.236
	Group2	
Panel 10	PCM 15%+ Clay70% +cement 15%	0.217
Panel 11	PCM 25%+ Clay60% +cement 15%	0.221
Panel 12	**PCM 35%+ Clay50% +cement 15%**	**0.234**
Panel 13	PCM 45%+ Clay40% +cement 15%	0.229
Panel 14	PCM 50%+ Clay35% +cement 15%	0.227
	Group3	
Panel 15	Clay50%+Cement 50%	0.331
Panel 16	Clay85%+Cement 15%	0.307
Panel 17	Clay90% + cement 10%	0.298

5.5.2 Mixing MPCM with gypsum and silica

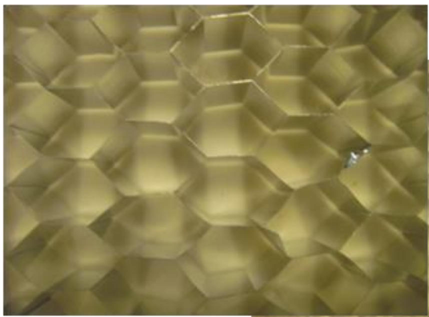
As presented earlier in section 3-12, PCMs mixed with gypsum to produce gypsum panels were able to control the temperature inside the building spaces, which lead to reduced heating and cooling demand. Figure 5-32 shows the raw materials used to construct the panels in Table 5-5. Figures 5-33, 5-34 and 5-35 show the process of mixing to produce the panels. The gypsum and silica were first mixed in and then MPCM was added with extra care and finally, 1.3 to 1.7 litres of water. The workability of the mixture affected the amount of water that should be added to the mixture as different panels have different percentages of raw materials. Figure 5-36 shows the honeycomb used to enhance the thermal conductivity of the panel (refer to section 5.3.3 for more information about the honeycomb used).

Figure 5-29. Sample raw materials for gypsum and PCM panel product in.

Figure 5-30 Added silica to gypsum.

Figure 5-31 Add PCM.

Figure 5-32 Mixing of the raw materials with water.



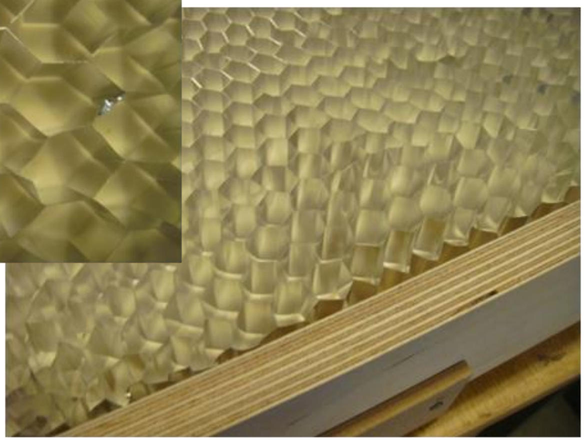


Figure 5-33 Honeycomb used for production of

Six panels made of MPCM, gypsum and silica were constructed in different proportions, half of them with honeycomb to examine the influence of these materials on thermal conductivity.

5.5.2.1 Results of HFM test of mixing MPCM with gypsum and silica

As illustrated in Table 5-5, panel 18 made up of 20% PCM + 75% Gypsum + 5% silica has the highest thermal conductivity value of 0.282 W/mK compared with panels 20 and 22 which were made without honeycomb. However, panel 19, constructed from 20% PCM + 75% Gypsum + 5% silica with honeycomb has the highest thermal conductivity value of 0.306 W/mK compared with the rest of the panels. Comparing panels 18, 19, 20, and 21 illustrated the effect of changing the amount of gypsum and silica as well as the influence of adding honeycomb. Furthermore, panels 20, 21, 22 and 23 present the effect of changing the rate of PCM and the impact of honeycomb on heat transfer.

Table 5-4 The results of the tested panels that consisted different percentage of PCM, gypsum and silica.

Panel NO	**Panels components**	**Thermal Conductivity W/mK**
Panel 18	PCM 20%+Gypsum 75%+ Silica 5%	0.282
Panel 19	**PCM 20%+Gypsum 75%+ Silica 5% with Honeycomb**	**0.306**
Panel 20	PCM 20%+Gypsum 70%+ Silica 10%	0.165
Panel 21	**PCM 20%+Gypsum 70%+ Silica 10% with Honeycomb**	**0.252**
Panel 22	PCM 25%+Gypsum 65%+ Silica 10%	0.189
Panel 23	PCM 25%+Gypsum 65%+ Silica 10% with Honeycomb	0.228

5.6 Discussion of the results

5.6.1 Mixed MPCM, clay and cement panels

The first panel was made from 100% clay and on the second day, water was spread on the panel surface to reduce the probability of cracks. However, after two days, cracks appeared due to what is known as early thermal contraction (refer to section 5.2.4), which suggests that the surface of the panel has to be covered by a moistened cloth or cling film to reduce the rate of drying.

The second panel was constructed of 90% clay and 10% Phase Change Material, and the results still show considerable cracks. Consequently, the resulting panel was excluded from the thermal test. These results highlighted the need for another material to work as an adhesive between the clay and the MPCM. Therefore, cement was chosen for two reasons. Firstly, it has a high thermal conductivity and secondly, the ability of cement to solidify in short period when mixed with water is advantageous in this instance.

Test results from panels 3 to 17 in three groups are presented in Table 5-4. Panels 3 to 9 were composed of cement fixed at 40% with varying percentages of the clay and PCM. The amount of PCM was increased from panel 3 to panel 9, whereas the amount of clay was decreased in equal amounts.

It is clear from Tables 5-1 and 5-4 that the thermal conductivity of the mixture of PCM, clay and cement was enhanced at different levels depending on the percentage of each material. In the first group the highest thermal conductivity value obtained was 0.253 W/mK in panel 8 where the amount of PCM was 40%, clay 20% and 40% cement. The lowest value was 0.203 W/mK with 10% PCM, 50% clay and 40%

cement. It is important to indicate that the thermal conductivity results of panel 9 from group (1) where the mixture is composed of PCM 50%+ clay 10% + cement 40% is 0.236 W/mK.

When comparing the results from the fourth panel with the first and 9 panels, it becomes clear that exceeding the amount of PCM over 50% of the other components will reduce the thermal conductivity value. Thus, the quantity of clay and cement has to be over 50% of the total weight of the mixture. Furthermore, by comparing the result of the 19 panels in Table 5-4 in the second group with the first panel in group (1), where the amount of clay in both cases was 50%, the value of thermal conductivity was higher at about 15% in panel 12 than in panel 3.

Comparing the panel 9 in group (1) and panel 14 in group (2) where the amount of PCM is 50% with the panel 8 and panel 13 shows reduction in the value of thermal conductivity from 0.245 to 0.236 W/mK and from 0.229 to 0.227 W/mK, as illustrated in Table 5-4. However, the decrease in the panel 9 is larger than in panel 14 where the amount of cement was 15%. This is less than the amount of cement in panel 9. Panels 15, 16 and 17 in Table 5-4 show an increase in thermal conductivity due to the increase in percentage of cement in the mixture.

5.6.2 Mixing the PCM with gypsum and sand

It is clear from the results in Table 5-5 that the thermal conductivity of the panels made up of MPCM, gypsum and sand was enhanced by the use of honeycomb. The thermal conductivity increased from 0.282 W/mK in panel 18 without the use of honeycomb to 0.306 W/mK whereas in panel 19 it was enhanced by over 8.5%. Moreover, in panel 20 the thermal conductivity was 0.165 only and has increased following the addition of honeycomb by more than 52.7%. In panel 21, the thermal conductivity reached 0.252 W/mK and this increased in panels 22 and 23 to above 20.6% when honeycomb is added.

It is to be noted that by increasing the amount of silica from 5% to 10% as shown in Table 5-5 the thermal conductivity was affected and dropped from 0.282 W/mK in panel 18 to 0.165 W/mK in panel 20. In panel 22, the effect of sand is noticeable.

5.7 Conclusions

It could be concluded that construction materials, made of a mixture of clay, gypsum, cement, silica and MPCM could be manufactured to produce panels that can be attached to internal wall surfaces of buildings. The mix of these materials was found to enhance the thermal conductivity of the MPCM as an energy storage material for building energy comfort.

Increasing the amount of MPCM to about 50% (in weight) of the mix could reduce the potential benefit of the mixture to enhance thermal conductivity. Thus, the percentage of MPCM should not be above 50%.

It is important to note that the amount of cement has a considerable effect on mixtures, which include MPCM and clay for heat conduction. In addition, their use immensely improves thermal conductivity. Also, increasing the amount of silica from 5% to 10 % has shown a negative effect on thermal conductivity. In the other hand, literature shows that adding silica helps to decrease the combustion process under any circumstances. Furthermore, increasing the amount of MPCM from 20% to 25% when the volume of gypsum and sand together were about 75% improves the thermal conductivity by 20% (without prejudice to the effect of increasing the proportion of silica).

The best thermal conductivity was obtained by mixing 20% PCM, 75% Gypsum and 5% Silica with honeycomb, which gave a value of 0.306 W/mK (panel 19). On the other hand, by using clay, the best thermal conductivity was obtained by mixing 40% MPCM, 20% Clay and 40% cement, which gave a value of 0.253 W/mK (panel 7).

CHAPTER 6: MODELLING SIMULATION USING MICRONAL PHASE CHANGE MATERIAL (MPCM) AS HEAT STORAGE SYSTEM

"If one way be better than another, that you may be sure is Nature's way."

Aristotle (384BC-322BC)

"The reality is the picture; it is most certainly not in the picture."

Georg Baselitz [6]

[6] http://www.saylor.org/site/wp-content/uploads/2012/02/ARTH208-7.5.2-Georg-Baselitz.pdf

6. Modelling simulation using Micronal Phase Change Material (MPCM) as a heat storage system

6.1. Introduction

This chapter presents the influence of using lightweight construction (known as high-insulated building) on rising the temperature inside building's spaces. The construction system that was used in the modelling simulation was tested in real climatic conditions under Nottingham-UK weather conditions. It is important to use an advanced dynamic simulation program to build up the case and simulate real conditions. Thermal Analysis System TAS modelling software was used to build and simulate a simple model of an existing building.

6.1.1. The simulation software

TAS simulates the thermal performance of buildings and can determine the building's natural ventilation, thermal behaviour and energy consumption, alongside phase change materials and other function analysis can also be included. The work on TAS was divided into two sections. Firstly, 3D modelling where by the building geometry is produced and secondly, the simulation phase which simulates the thermal performances of the building by defining each of the following: building materials, weather data, the schedule of any use of equipment, schedule of occupants and the ventilation system.

6.1.2. Nottingham climate

Nottingham is one of the cities in the East midlands in the UK, is on latitude 53^{o}N and its longitude is 1.25^{o}W at an altitude of 117m. Weather data are from CIBSE (DSY) for the city of Nottingham.

6.2. Aim of the simulation

The aim of the simulation was to find out firstly, the effect of using lightweight construction system (low thermal mass system) on overheating problems. Secondly, the effect of using Micronal phase change material (MPCM) on reducing overheating and how it works as back up during the day. Finally, the effectiveness of natural night ventilation by opening window on discharging the MPCM, which should be ready for full capacity use the following day.

6.3.Method

MPCM gypsum panels were used to determine the effect on room temperature using night ventilation by opening the window. This was to help the MPCM as a passive cooling system to reduce overheating in buildings that has been obtained by conduction and radiation from the building surrounding. Five cases were simulated, with the first case known as a basic case. This was used to find out the overheating period during the year. The results obtained were then used as a reference for comparison with the other four cases. These were simulated to study the effect of natural ventilation on MPCM to discharge heat for use the following day and to absorb any unwanted heat.

Base case: Simulating the ordinary rooms in zone 1 and zone 2 without MPCM.

Case 1: Attaching MPCM on the whole surface of two walls – South wall and East wall- without natural ventilation.

Case 2: Attaching MPCM on the whole surface of two walls – South wall and East wall- with night natural ventilation.

Case 3 Attaching MPCM on the whole surface of three walls – South wall, East wall and North wall- without natural ventilation.

Case 4: Attaching MPCM on the whole surface of three walls – South wall, East wall and North wall- with night natural ventilation.

6.3.1. Assumptions

- The schedule of using equipment's was divided into summer schedule and winter schedule.
- Equipment were used from 6:00 pm to 10:00 pm.
- No occupants.
- Thermal transfer between the two rooms was ignored.
- The analysis was based on the recommended temperature in Table 6-1
- The comfort temperature was taken to be between 18^{o}C to 23^{o}C.

Table 6-1Recommended comfort temperature range for dwelling buildings (CIBSE, 2006)

Dwelling zone	**Comfort temperature ^{o}C**
Bathroom	20-22
Bedroom	18-23
Living room	22-25
Kitchen	17-23

6.4.Description of the construction of the simulated building

The building was divided into two rooms known as room 1(zone 1) and room 2 (zone 2) (Figure6-1). MPCM gypsum panels were attached to the walls. The 3D modelling presentation of the external walls, roof, floor, windows and doors are illustrated in Figure 6-2. Dimensions of the building are as follows: L=6m, W=3m and h=2.5m.

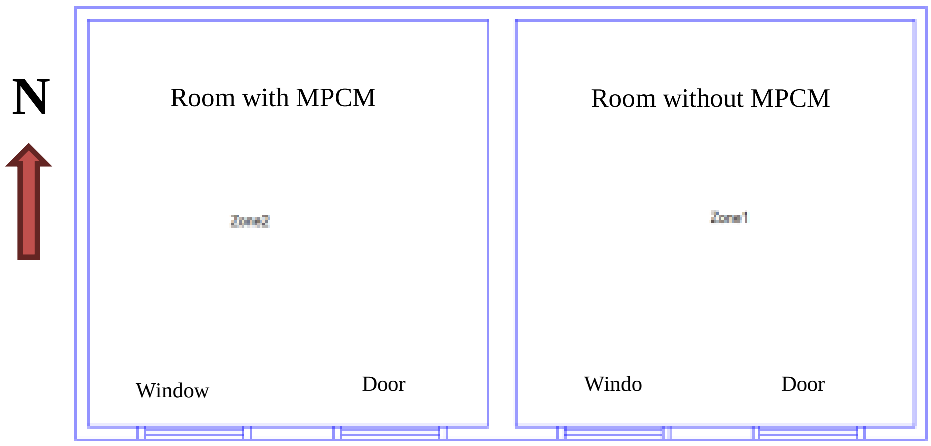


Figure 6-1 Presents room1 (zone1) and room2 (zone2 with MPCM panel).

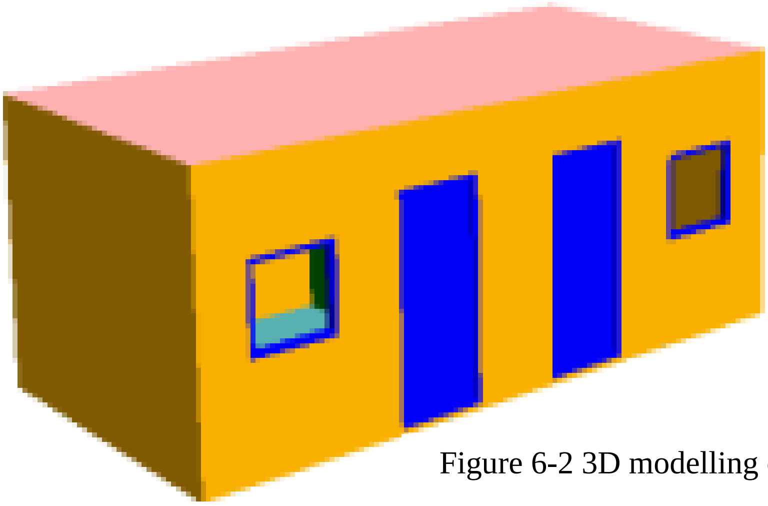


Figure 6-2 3D modelling of the building.

6.4.1. Properties of the building elements

The properties of the building elements walls, roof, floor, windows and doors are presented in the Tables 6-2, 6-3, 6-4 and 6-5.

Table 6-2 External walls Construction properties.

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.700	0.700	0.900	0.900	0.263	0.000

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	plywood	3.0	0.13	0.001	9999.000	500.0	1500.0	
2	Extruded Polyste...	75.0	0.02	0.001	9999.000	40.0	1300.0	
3	plywood	3.0	0.13	0.001	9999.000	500.0	1500.0	

* layer ignored in U-Value/R-Value Calculation

U/R Values (ISO 6946) (Homogenous)

Flow Direction	Internal U Value (W/m²·°C)	External U Value (W/m²·°C)
Horizontal	0.247	0.252
Upward	0.25	0.254
Downward	0.242	0.25

Show U Values

Show R Values

Table 6-3 Internal wall properties.

Opaque Construction | Name: internal wall | Description:

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.600	0.600	0.900	0.900	0.125	1.891

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	am1ins\17	200.0	0.025	0.0	98.000	30.0	1400.0	POLYURETHANE BOA...

* layer ignored in U-Value/R-Value Calculation

U/R Values (ISO 6946) (Homogenous)

Flow Direction	Internal U Value (W/m²·°C)	External U Value (W/m²·°C)
Horizontal	0.121	0.122
Upward	0.122	0.123
Downward	0.12	0.122

Show U Values | Show R Values

Table 6-4 Floor construction properties

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.760	0.400	0.910	0.900	0.103	314.120

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	am1ins\15	200.0	0.03	0.0	59.000	140.0	1380.0	POLYSTRENE, EXPAN...
2	am1soil\7	1000.0	0.329	0.0	99.000	1515.0	796.0	SAND, DRY *2

* layer ignored in U-Value/R-Value Calculation

U/R Values (ISO 6946) (Homogenous)

Flow Direction	Internal U Value (W/m²·°C)	External U Value (W/m²·°C)
Horizontal	0.1	0.101
Upward	0.101	0.102
Downward	0.1	0.101

Show U Values | Show R Values

Table 6-5 Roof construction properties.

Opaque Construction | Name: Roof flat-pack | Description:

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.700	0.700	0.900	0.900	0.263	0.000

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	plywood	3.0	0.13	0.001	9999.000	500.0	1500.0	
2	Extruded Polyste...	75.0	0.02	0.001	9999.000	40.0	1300.0	
3	plywood	3.0	0.13	0.001	9999.000	500.0	1500.0	

* layer ignored in U-Value/R-Value Calculation

U/R Values (ISO 6946) (Homogenous)

Flow Direction	Internal U Value (W/m²·°C)	External U Value (W/m²·°C)
Horizontal	0.247	0.252
Upward	0.25	0.254
Downward	0.242	0.25

Show U Values | Show R Values

6.5. Results

6.5.1. The base case

The base case involves the two rooms (zone 1and zone 2) without any modifications. As illustrated in Figure 6-3 the temperature during a year was found to be mostly equal. The highest temperature obtained from the modelling simulation inside the zones was in July, which is close to 36 °C and the second highest temperature in August above 34°C. On the other hand, the lowest temperature obtained from the modelling simulation inside the zones was in January -4 °C. In summer time, temperatures exceeded the comfort temperature between 18 °C to23°C and that caused an overheating problem.

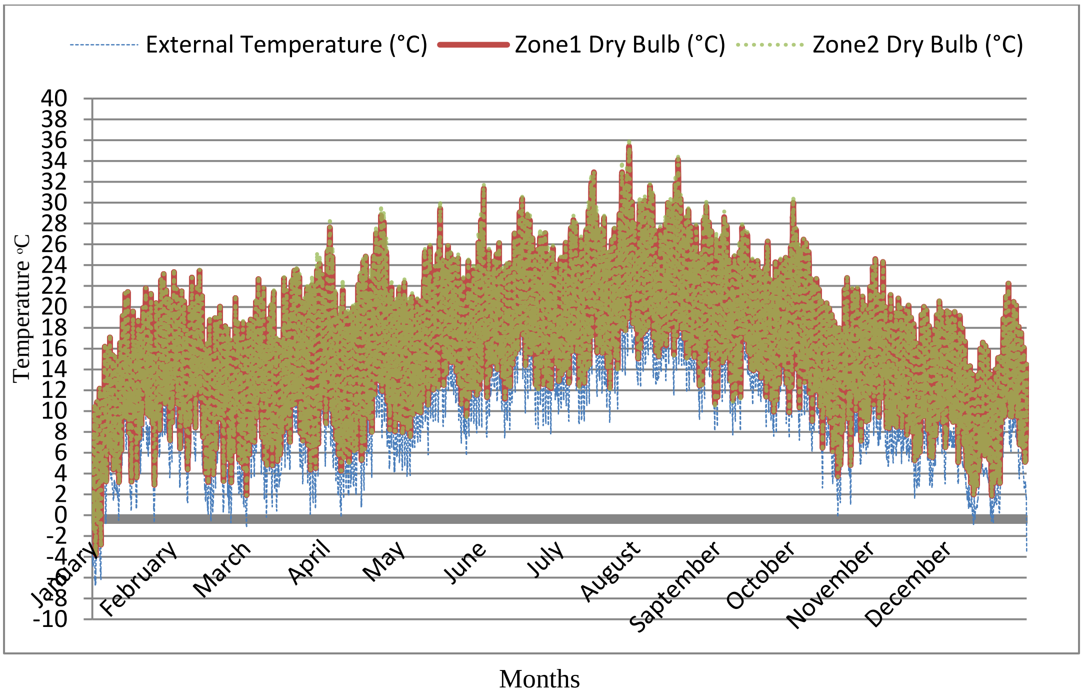


Figure 6-3 The temperature variation during a year of the two identical rooms in Nottingham, UK.

As the second highest and lower external temperatures during the summer time was obtained in August, simulations from this month will be presented in detail. As illustrated in Figure 6-4, the highest temperature is above 34°C and the lowest temperature is less than 13°C at night inside the zones 1and 2. In general, the temperature during the daytime was above the 23°C.

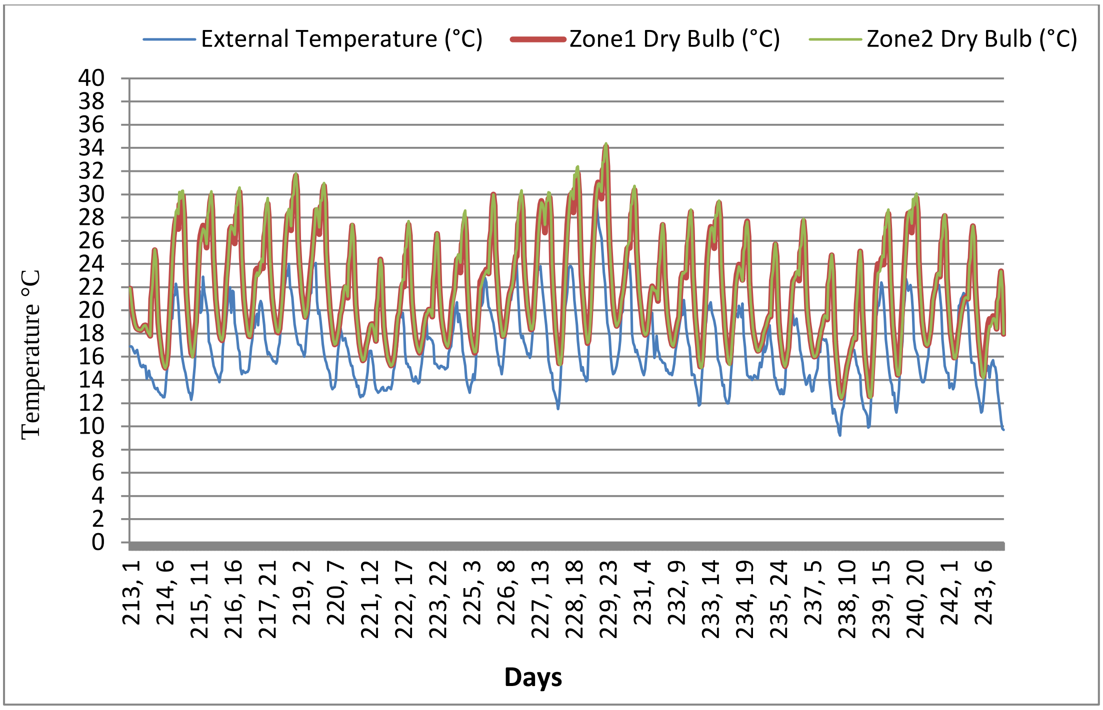


Figure 6-4 The temperature variation during August of the two identical rooms in Nottingham, UK.

Figures 6-5 and 6-6 show the external temperature and the temperatures in room 1 (zone1) and in room 2 (zone2). It is clear that differences exist between the temperature inside the rooms and the external temperature, which is the lowest.

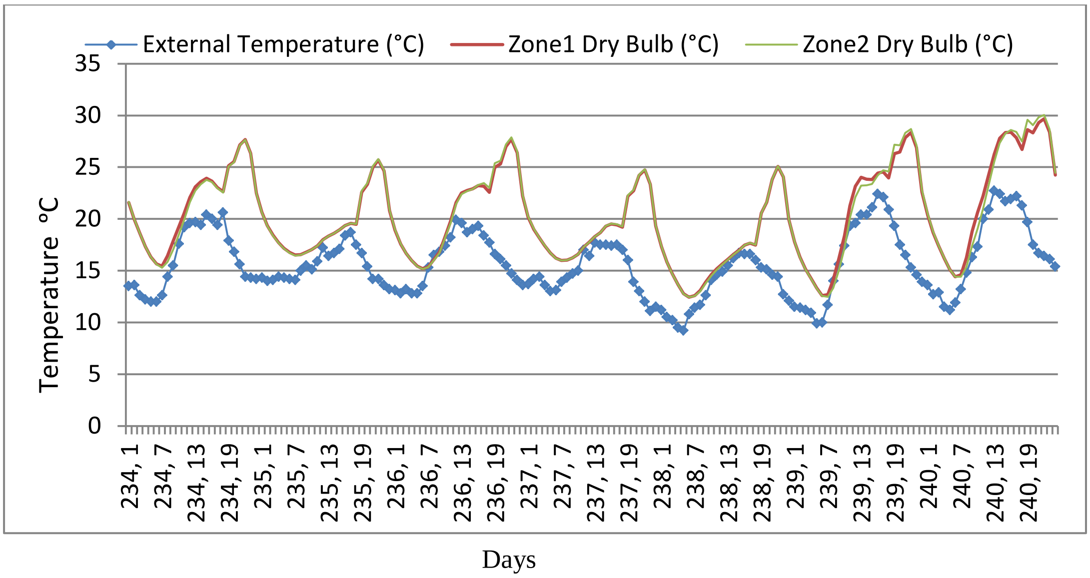


Figure 6-5 Temperature variation during a last week in August of the two identical rooms in Nottingham, UK.

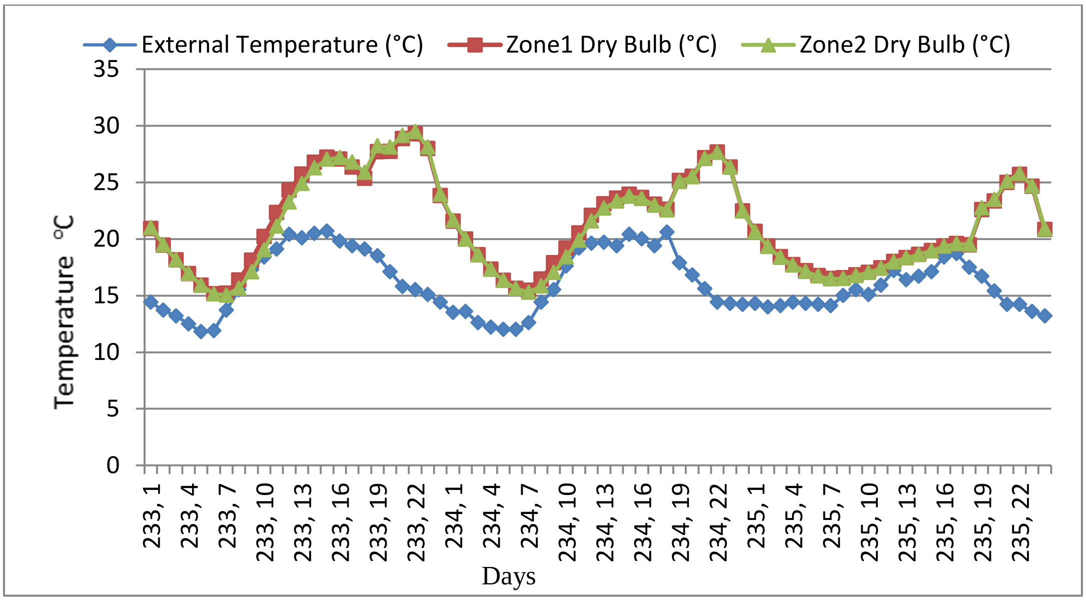


Figure 6-6 Temperature variation during a 3 days in August of the two identical rooms in Nottingham, UK.

6.5.2. Case 1

Figure 6-7 shows the external temperature and the temperatures inside two rooms (zone1 and zone 2 with MPCM) for the whole year. As illustrated in Figure 6-7, the effect of using lightweight construction (low thermal mass) increases the temperature inside the spaces. It is clear from the results that the temperature in room 1 (zone 1) reached over 25°C during daytime periods from April to October with record temperatures of over 32 °C for some days in June, July and August. On the other hand, during the night, temperatures dropped below 20°C for some exceptional days.

In winter months, the temperature for zone 1 went slightly beyond 20°C in February, March, November and few days in December. On the other hand, on comparing the temperature in room 2 (zone 2) when the MPCM was used in the same period in room 1 (zone 1), it became clear that the MPCM absorbed heat and reduced overheating at some stage during March, April, May and June. However, the reduction of heat was not enough to drop the temperature within the range of users' comfort (18 °C- 23°C). There are two possible reasons to explain the situation up to this stage. Firstly the amount of MPCM was not enough to absorb the whole amount of extra heat. Secondly, the MPCM did not release the all absorbed heat, thus, in the next case natural night ventilation was used to investigate whether adding any extra MPCM is necessary or not.

The next figures show the external temperature and temperature in room 1 (zone 1) and in room 2 (zone 2 with MPCM) for the whole month of August. According to the data, August is the second hottest month. This was used as an example for comparison with the results obtained from the experiment conducted in August.

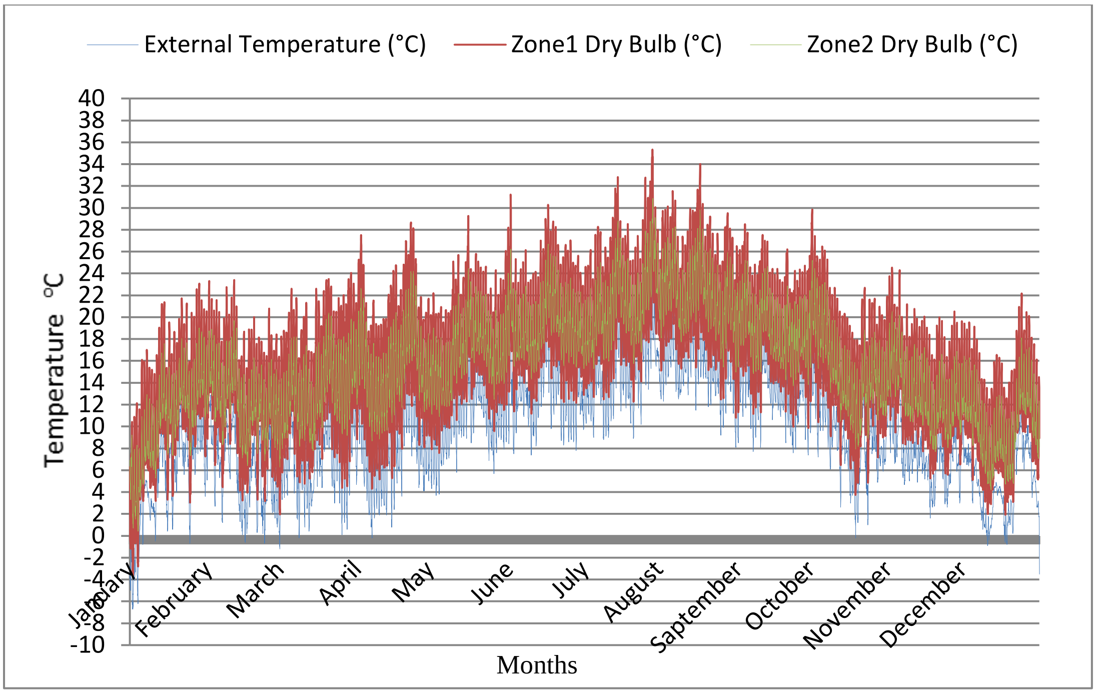
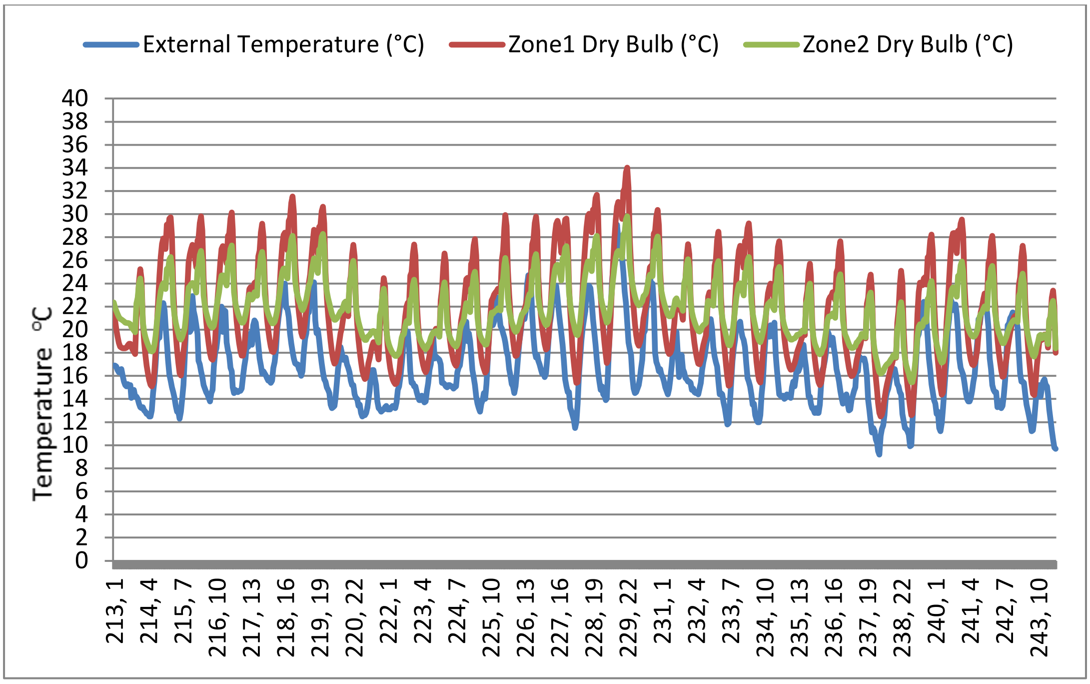


Figure 6-7 Case 1: The effect of using MPCM on the whole year.

In August, the using MPCM has shown a decent effect on the temperature inside the room2. However, as there is not any method used for ventilation, thus, the MPCM has shown a limitation on reducing completely overheating. As can be seen in Figure 6-8 about 29 day exceed the temperature of 23°C in the room 2 (zone 2 with MPCM) specifically when the equipment used was turned on according the arranged schedule. As a consequence, this highlights 2 important issues. Firstly, the amount of MPCM is not enough to absorb the whole amount of any extra heat and secondly, the MPCM did not release all the heat absorbed in the daytime (as clarified before for the whole year). Thus, another simulation with natural night ventilation was conducted to assess the cause of not removing all extra amounts of unwanted heat.

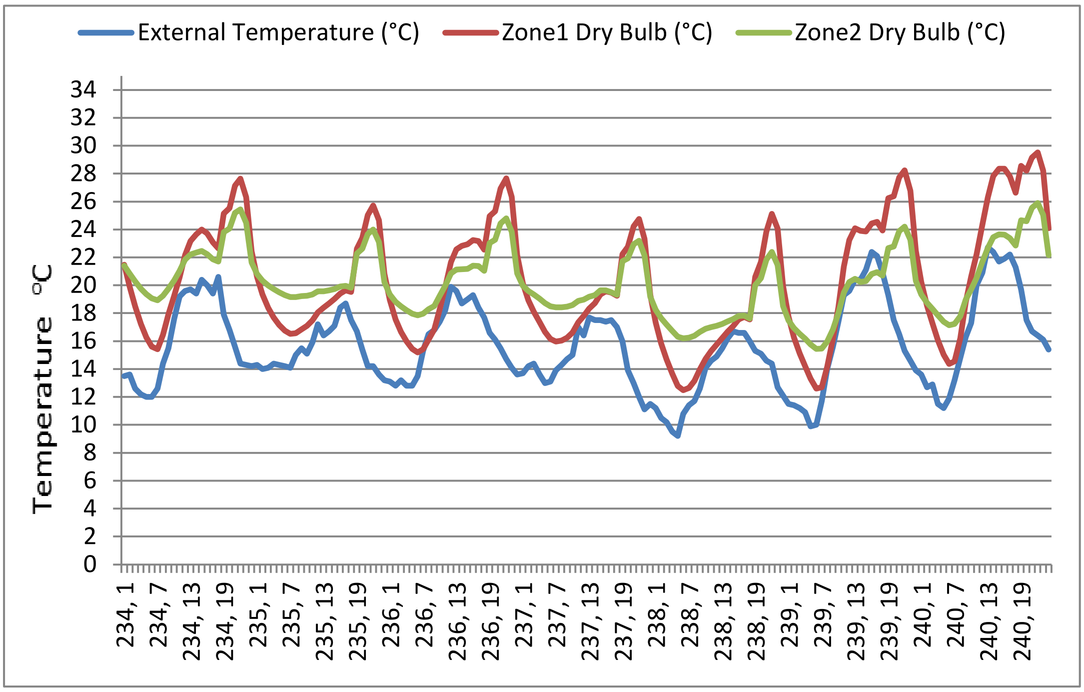


Days

Figure 6-8 Case 1: The effect of using MPCM on the whole of August month.

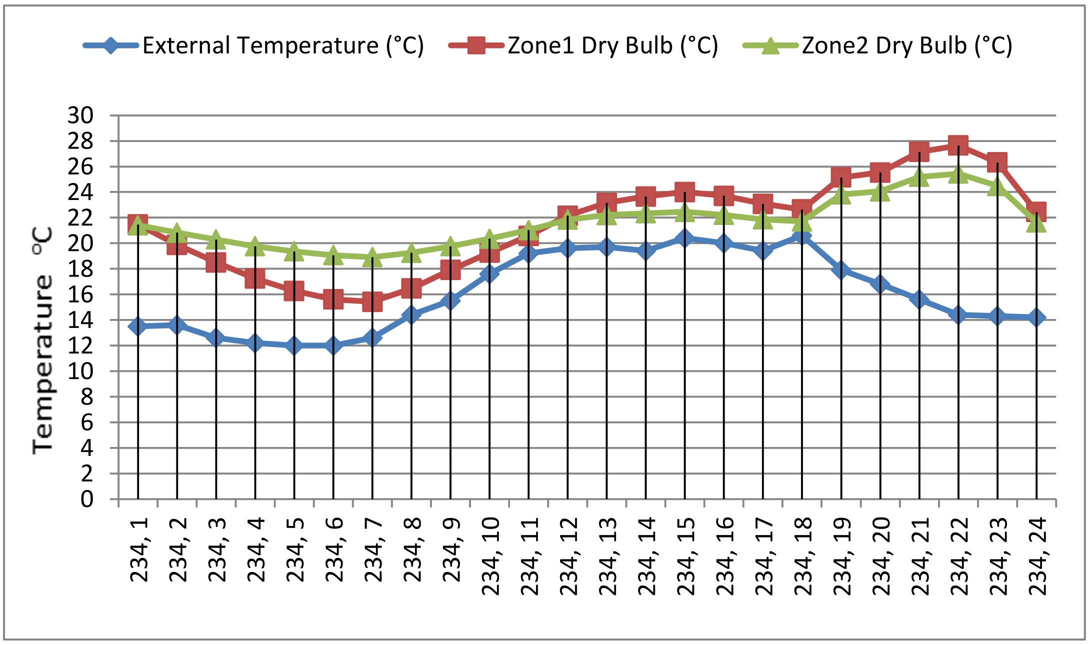
Figure 6-9 shows results obtained from simulation conducted for the period 20th to 26th August. As illustrated, MPCM slightly reduced unwanted heat. It however kept room 2 (zone 2) in uncomfortable temperatures above 18 °C to 23° C. Nevertheless, results from the last day of the week (Figure 6-9) illustrate that the temperature reached its highest at over 29 °C in zone 1 and 26 °C in zone 2 with MPCM for a few hours during the afternoon.

The Figure 6-10 shows that the use of MPCM could reduce the temperature from about 1.5 °C (at 2 pm) and up to 3 °C (at 10 pm). Moreover, when the temperature gradually dropped in room 1(zone1) from about 21° C at 1:00 am to below 15°C at 7am, the temperature in room 2 (zone 2) dropped from over 21° at 1:00am to 19° at 7 am. This is because of heat released from MPCM. The increase in temperature occurring from 6pm until 10pm was as a result of switching on the simulated use of equipment, which produced sensible heat above 16.6 W/m².



Days

Figure 6-9 Case 1: Temperature from 20th-26th of August.



Days

Figure 6-10 Case 1: Temperatures variation during the day of 20th August.

6.5.3. Case 2

Case two presents the effect of using night ventilation using windows as an advantage compared to case one where two walls in room 2 (zone2) were attached to MPCM panels. Results show slight effects on the peak temperature in July at 35°C. In August, night ventilation dropped the temperature compared to case 1. However, the overall temperature during the hot period of the year was still above the target comfort limit for about 50% of the duration in summer (Figure 6-11).

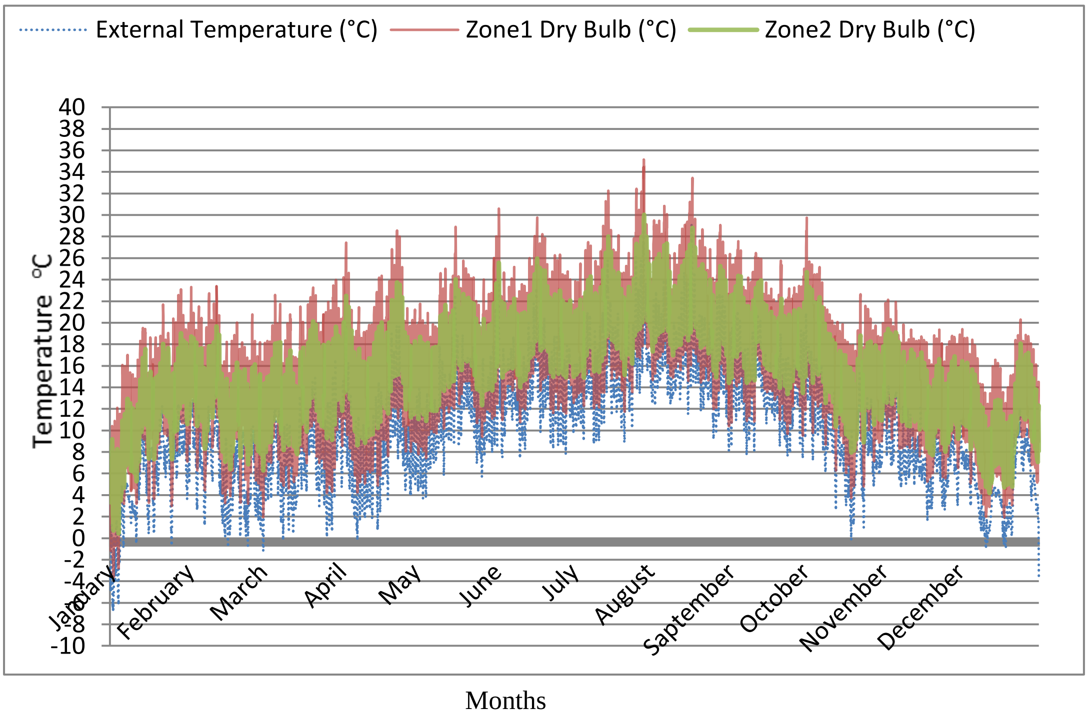


Figure 6-11 Case 2: The effect of using MPCM on the whole year with night natural ventilation.

Figure 6-12 presents the effect of natural night ventilation in room1 and room 2 (with MPCM) during the month of August. The average external temperature was between 22°C to 24°C in the daytime and 12°C -14°C at night. The temperature in room1 (zone 1) shows an average of 28°C in the daytime and 14°C at night on the first week. The higher temperature obtained from the simulation was in the middle of the month at nearly 34°C at daytime.

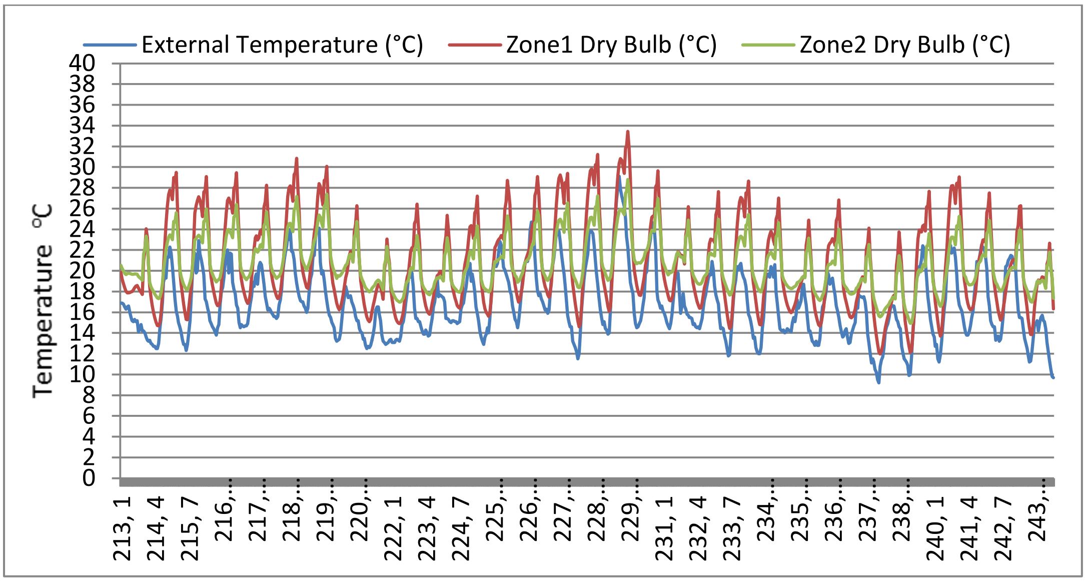


Figure 6-12 Case 2: The effect of using MPCM on the whole of August month with the effect of night natural ventilation.

Figure 6-13 presents the last week of August. This result shows that comfortable temperatures can be obtained most of the time at daytime except when the equipment in use as temperatures rose slightly over the comfort limit of 23°C in room 2 with MPCM. Nevertheless, temperatures for the last day of the week exceeded 25°C. At night as the MPCM released heat, the temperature in room 2 (zone 2) was higher between 2-4 °C compared to the temperature in room1 (zone1).

As illustrated in Figure 6-14, MPCM reduced the temperature in room 2 (zone 2) between 18°C to 23°C from 1:00am to 6:30pm. However, by using the equipment inside the rooms, which generated heat, the temperature was raised to 24°C at 9:00pm. Nevertheless, the temperature dropped within the acceptable range when the equipment were switched off.

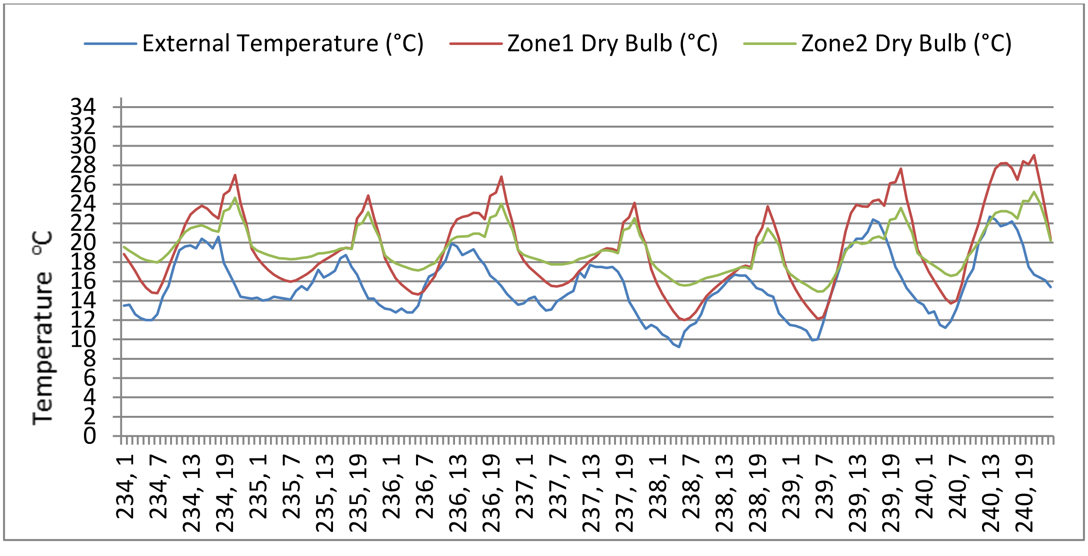


Figure 6-13 Case 2: Temperature variation from 20th August to 26th August (with night natural ventilation).

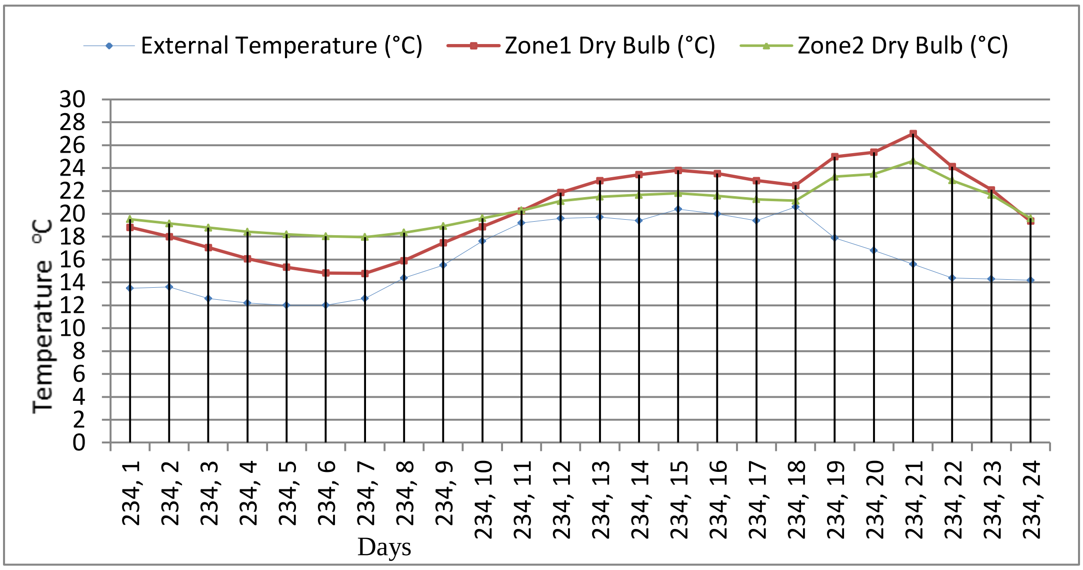


Figure 6-14 Case 2: Temperatures variation during the day of 20th August (with night natural ventilation).

6.5.4. Case 3

Case 3 presents the effect of attaching MPCM panels on three walls of room 2 (zone 2) on the North, West and South walls. As illustrated in Figure 6-15 in summer time, MPCM panels absorb heat during the day with temperature dropping within the acceptable range. However, more work needs to be done to reduce overheating during some periods in July and August (26°C to slightly above 28°C).

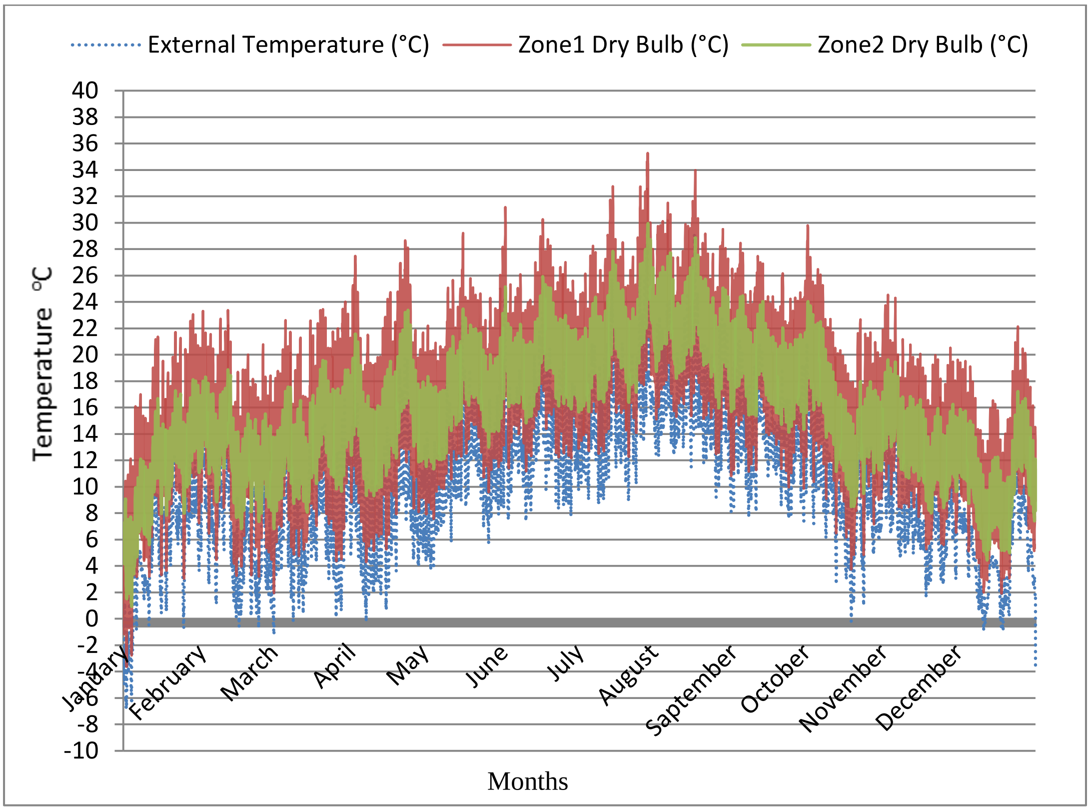


Figure 6-15 Case 3: The effect of using MPCM on the whole year (MPCM panels attached on 3 wall of the room).

The results show improvement by reducing overheating during the month of August. However, for a number of periods, temperatures rose over the comfort limit (Figure 6-16). The cause of the overheating was as the result of switching on equipment inside the rooms.

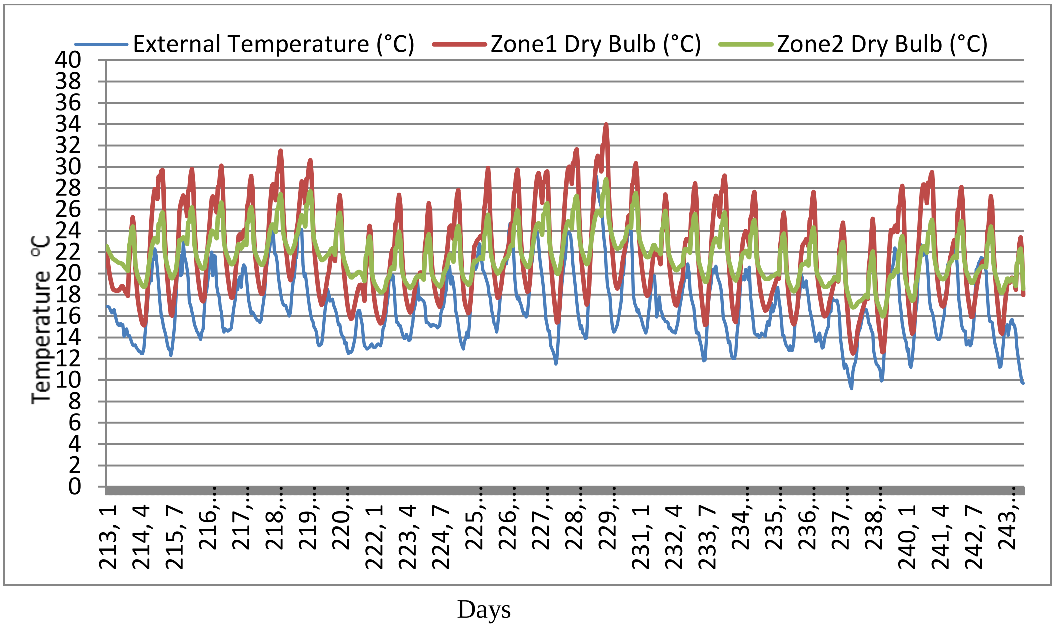


Figure 6-16 Case 3: The effect of using MPCM on the whole of August month.

During the last week of August the temperature inside room 2 (zone 2) was within comfort range from 18°C to 23°C. However, within the last 3 days, the temperature dropped below the target temperature at night from 16°C to about 18°C (Figure 6-17).

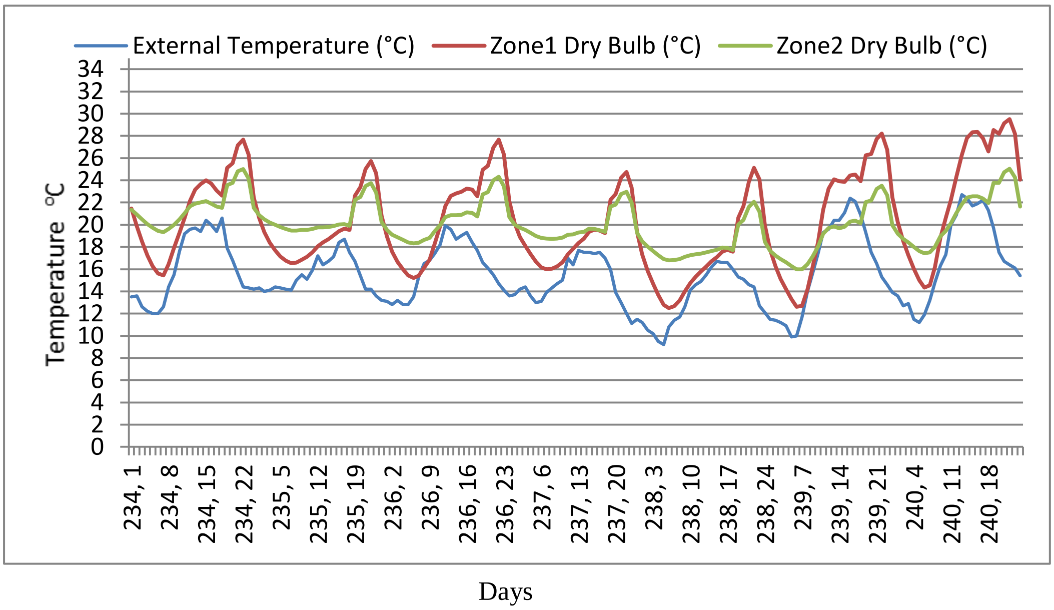


Figure 6-17 Case 3: Temperature variation from 20th August to 26th August.

As illustrated in Figure 6-18, temperatures on the 20th of August were framed within the comfort limits. It is clear from the result that absorbing heat during the daytime helped to reduce overheating. Releasing the heat at night also helped to increase the temperature.

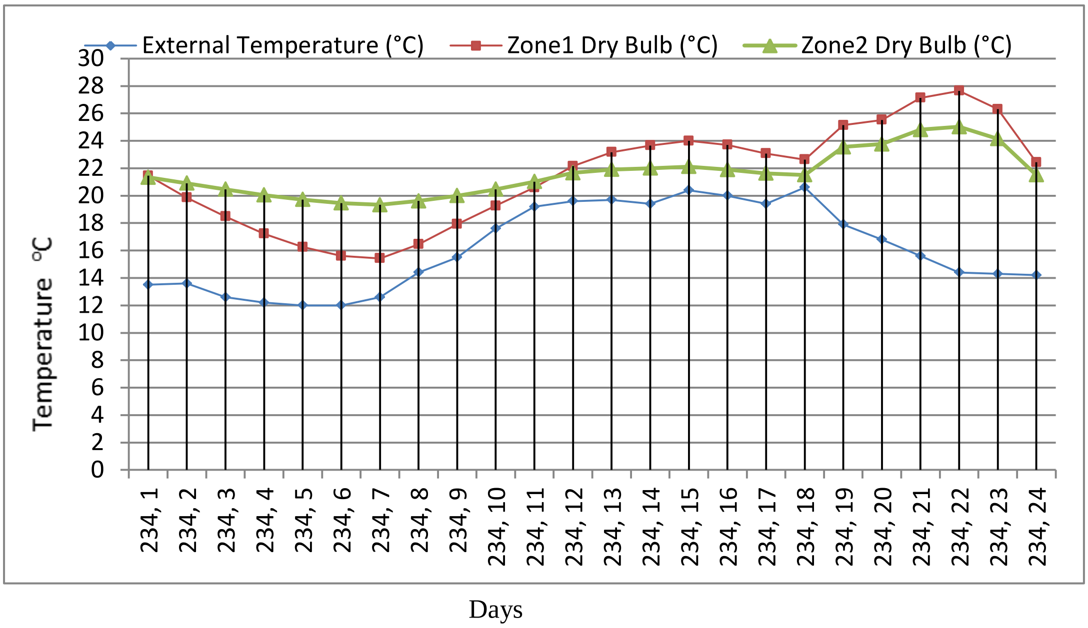


Figure 6-18 Case 3: Temperatures variation during the day 20th August.

6.5.5. Case 4

Figure 6-19 illustrates that in summer, the temperature in room 2 (zone 2) can be located within comfort limits between 18°C to 23°C. Moreover, in winter, the MPCM offered a little effect on heating demand by discharging heat.

The natural night ventilation showed a reasonable effect on helping MPCM to reduce overheating by recharging the panels during the night. As illustrated in

Figure 6-20, the temperature in August is mostly within acceptable ranges during the day and night, with some short times of not more than1.5 hours/day of overheating.

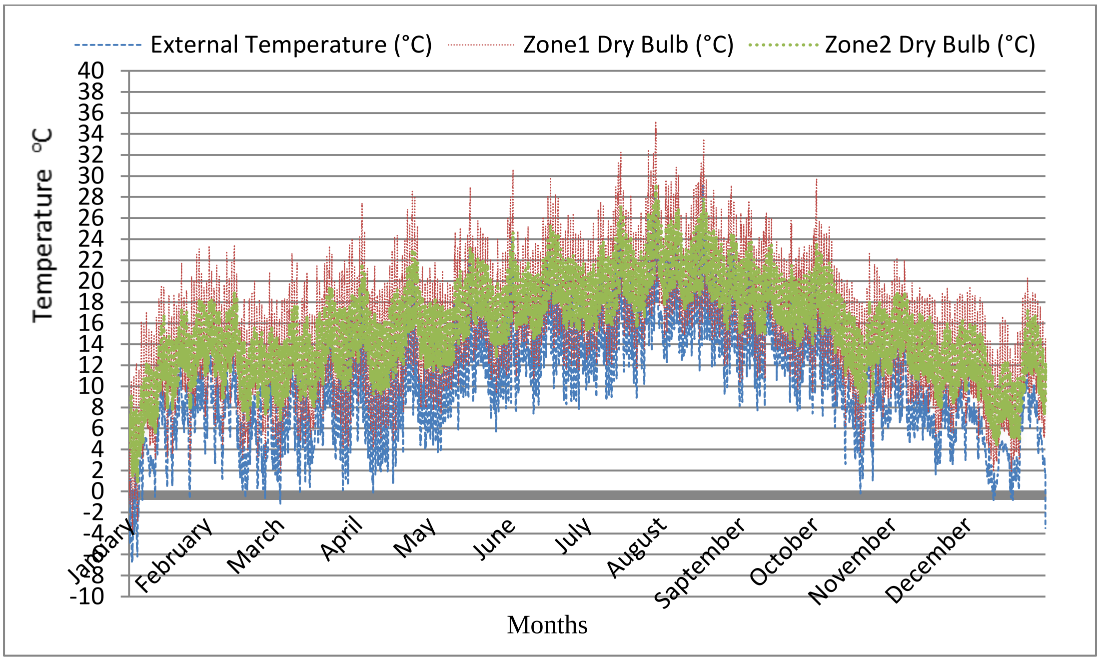


Figure 6-19 Case 4: The effect of using MPCM on the whole year with night natural ventilation.

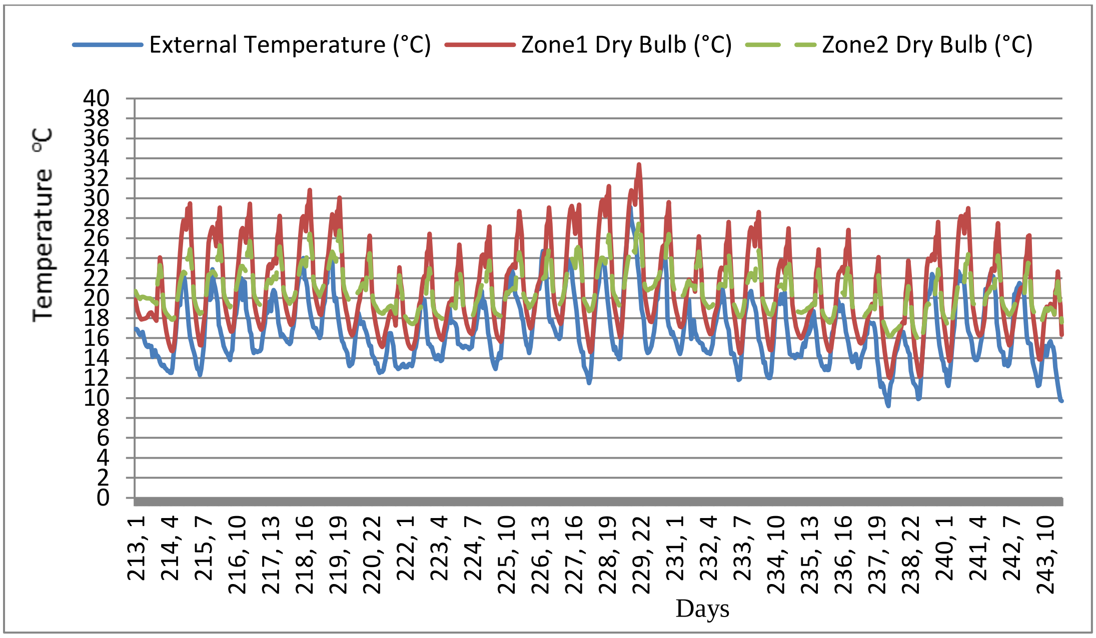


Figure 6-20 Case 4: The effect of using MPCM on the whole of August with the effect of natural night ventilation.

Figure 6-21 shows that temperatures during the last week of August are mostly within the comfort range between 18-23°C. However, between 8:00pm to 9:30pm, the temperature increased to about 24°C. Moreover, the temperature dropped below 18°C during the night between about 16°C to 17°C in the last 3 days of the week.

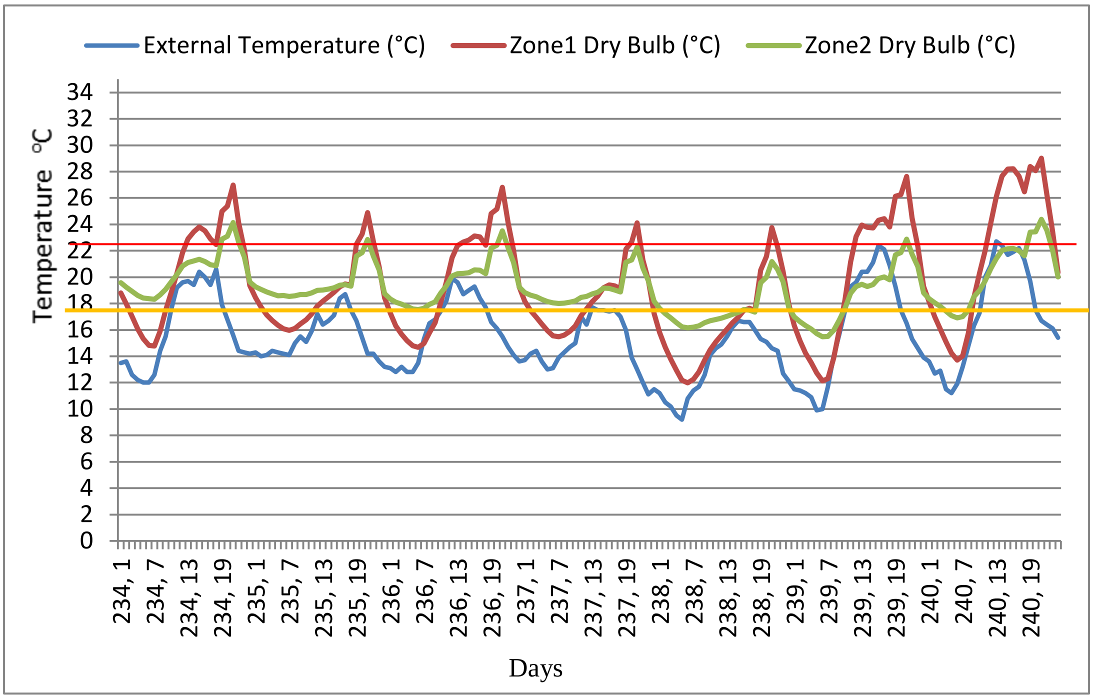


Figure 6-21Case 4: Temperature variation from 20th August to 26th August (with night natural ventilation).

During the day on the 20th of August, the temperature was within the comfort range in room 2 during the day and night except from 8:00pm to 9:00pm (Figure 6-22).

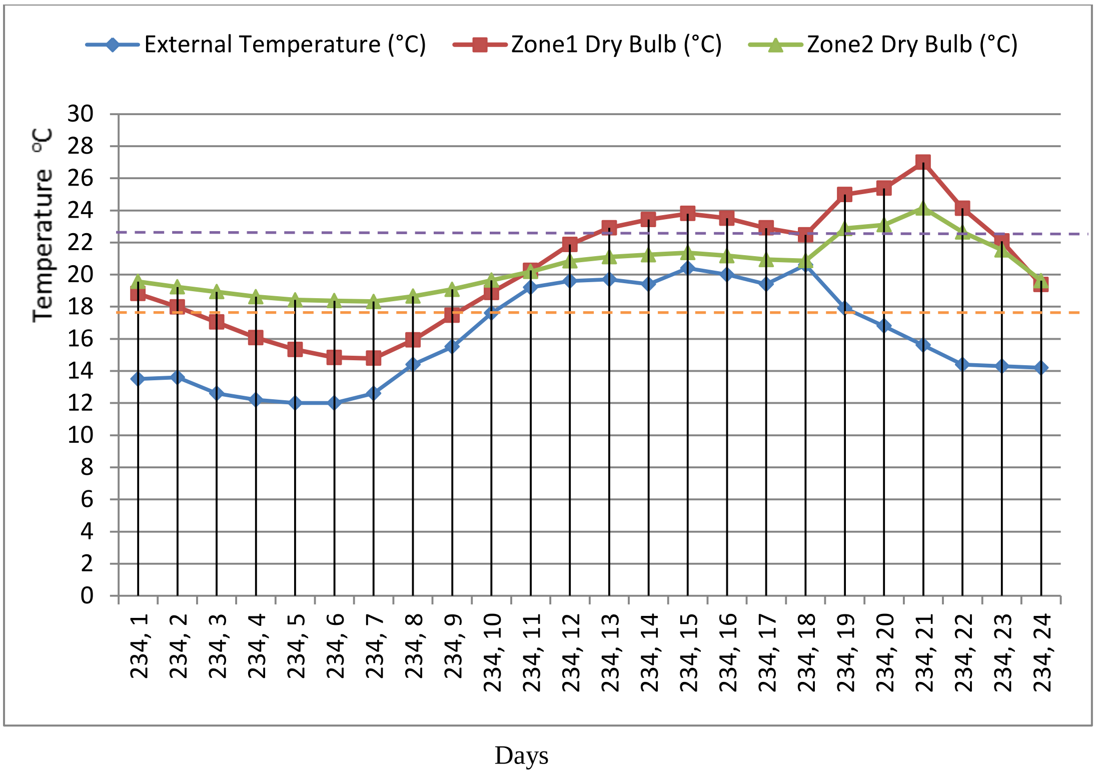


Figure 6-22 Case 2: Temperatures variation during the day of 20th August (with night natural ventilation).

According to the basic case, the number of hours of dry bulb temperature exceeds 23°C - Zone 1= 1029 hours and the number of hours dry bulb temperature exceeds 23°C - Zone 2=1049 hours. Table 6-6 presents the number of hours for the year when the temperature exceeds 23°C in different case scenarios. It is clear from the table that natural night ventilation facilitates the MPCM panels to reduce the temperature by discharging heat in cases 2 and 4.

Table 6-6 Number of hours for year when the temperature exceeds 23°C in different case scenario.

	Number of hours temperature exceeds 23° C - No PCM (zone1)	Number of hours temperature exceeds 23° C - With PCM (zone 2)
Case 1 MPCM attached on the South and East walls- without natural ventilation.	**1025**	**499**
Case 2 MPCM attached on the South and East walls- with night natural ventilation	**752**	**317**
Case 3 MPCM attached on the South, East and West walls- without natural ventilation.	**1023**	**424**
Case 4 MPCM attached on the South, East and West walls- with night natural ventilation	**753**	**255**

6.6. Conclusions

It can be concluded that using MPCM helps to reduce heating and cooling demand (case1, 2, 3 and 4). Moreover, the natural night ventilation by opening windows reduced the number of hours that the temperature is above 23°C from 499 hours/year in case1 to 317 hours/year in case2 and from 424 hours/year in case 3 to 255 hours/year in case 4. This means that natural night ventilation could help reduce the overheating period to about 50% with the use of MPCM.

Using MPCM can reduce the temperature that has been obtained from the building surrounding heat by means of conduction and radiation during the daytime from 1.5 ^{o}C to 3^{o}C. On the other hand, MPCM helped by releasing heat during the night to increase the temperature from 1.5^{o}C to about 4^{o}C.

Case 4- in August the temperature is acceptable by using MPCM with natural night ventilation, as the overheating period did not exceed 1.5 hours/day. Furthermore, during the year, MPCM could reduce overheating in summer time. It is important to note that it releases heat during winter at night but another heating system should be utilized to avoid temperatures falling below the comfort limit.

More MPCM should be used to absorb more heat. As a recommendation, adding MPCM panels to the fourth wall of the room 2 (zone 2) to absorb more heat can minimize the overheating period in buildings.

CHAPTER 7: FULL SCALE TEST, A CASE STUDY FOR NOTTINGHAM, UK

"*Study nature, love nature, stays close to nature. It will never fail you.*"

Frank Lloyd Wright [7]

"*We should concentrate our work not only to a separated housing problem but housing involved in our daily work and all the other functions of the city.*"

Alvar Aalto [8]

[7] http://www.flickr.com/photos/18761825@N00/3861924164/
[8] http://www.foundationsakc.org/people/legends/alvar-aalto

7. Full scale test, a case study for Nottingham, UK

7.1. Introduction

This chapter considers the full-scale evaluation of MPCM panels that were produced following the results of the investigations on modified materials for lightweight building reported in Chapter 5. Lightweight building construction faces the problem of low thermal mass, which causes considerable variation in the temperature inside the building spaces. This results in overheating during summer and high heating loads in winter.

A flat pack modular construction is an example of a lightweight building construction strategy, which has significant advantages in terms of improving energy efficiency. However, the tendency to overheat in the summer due to the structure's low thermal mass is a shortcoming of low/zero carbon modular construction. The impact of this is likely to become significant, if average temperatures rise due to climate change.

The Blue Planet-flat pack building system was used as a prototype unit for investigation of the produced material. The Blue Planet-flat pack building system is extensively used in different circumstances ranging from temporary site offices and classrooms to temporary shelters in disaster zones as illustrated in Figures 7-1A, 1B and Figure 7-2. The unit is very effective as a temporary building system because it's components can be transported to site easily and assembled quickly by unskilled operators. The existing Blue Planet units however have poor air tightness, low thermal mass and several areas of thermal bridging. These need to be considered and improved to meet the Building regulation part L and the Code for Sustainable Home for future construction in order to reduce the heating and cooling demand. Thermal comfort is another main issue that should be considered when designing a passive system to control temperature. It should be understood here, that feeling comfortable is not just affected by the temperature; it is a compound of many factors such as air temperature, air movement, humidity even the health, age and gender of the occupant, as highlighted by Szokolay (2008).

Figures 7-1 the use of the Flat pack units to build a school(Flat Pack, 2011)

Figure 7-2 Flat pack unit as a health services building (Flat Pack, 2011)

Blue Planet Building highlighted that the aim of it for improving this type of building is to help obtaining better future buildings and saving energy (Flat Pack, 2011). Given the strong global move towards sustainability and the aim to reduce CO_2 (Directgov, (2011) it is understandable that sustainability and saving energy with simple methods of construction have become one of the main targets of Blue Planet Flat pack system (Flat Pack, 2011). Although, the Blue Planet system has a number of advantages and disadvantages (which will be outlined in sections 7.4 and 7.5), additional sustainable solutions have to be considered to improve the Blue Planet flat pack system to meet building regulations. Examples of this include Part L and the Code Sustainable Homes levels 4, 5, and 6 (level 6 to be applied from 2013 for public sector building and from 2016 for private sector) (Kingspan, 2009). Figure 7-3 and Table 7-1 shows the U value target according to the Code for Sustainable Homes for the private sector. This work is considered as one of the most important elements that could enhance the thermal performance of the building envelope by increasing the thermal resistances of walls as well as reducing the cooling and heating demand by using unique MPCM panels.

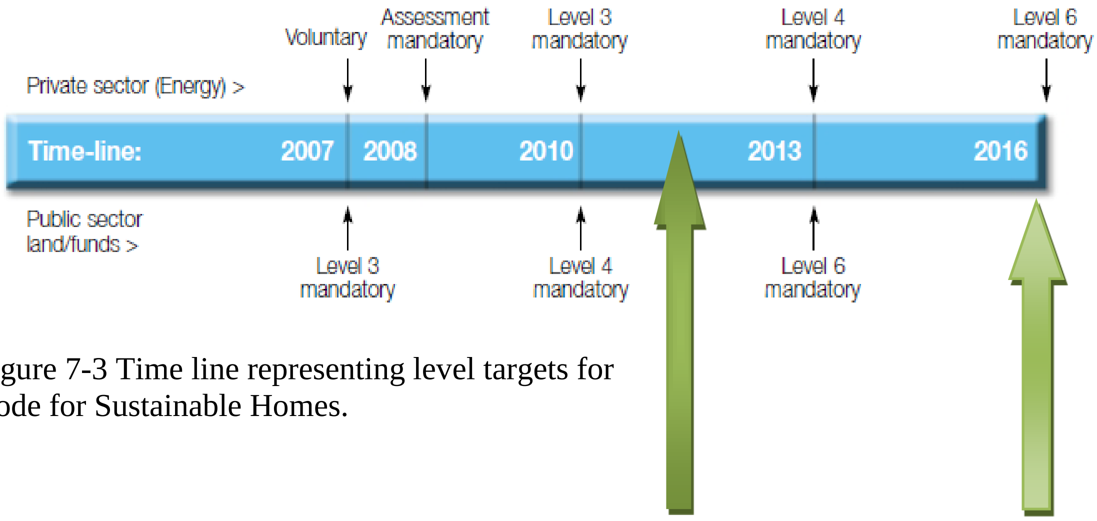


Figure 7-3 Time line representing level targets for Code for Sustainable Homes.

Table 7-1 The U value of the Code for Sustainable Homes with relation to the government timeline ((Kingspan, 2009).

Codes for Sustainable Homes	**Level 1&2**	**Level 3,4&5**	**Level 6**
U-value W/m²k	**0.2**	**0.18**	**0.11**

7.2 The purpose of the test

The main aim of the assessment is to develop a wall panel for low/zero carbon flat pack buildings that would help to save energy by reducing the heating and cooling demand. The concept of using Micronal Phase Change Material (MPCM) to save energy by absorbing and releasing heat is the basis of this research, through increasing the (MPCM) thermal performance by combining the MPCM with gypsum, clay and silica to produce better thermal performance building material.

As shown in Figure 7-4, a layer of Aerogel was added to increase the thermal resistance of the flat pack wall panel. It is understandable that insulation materials would normally be added as an internal layer or in the middle of the wall layers to allow the construction elements to absorb and hold the heat as latent heat in heavyweight construction. As McMullan (1992) stated, heavyweight structures have a higher thermal capacity than lightweight construction. Thus, lightweight constructions with low thermal capacities have quicker responses to the surrounding climate, so there the location of the additional insulation in the wall panel is not significant.

In this case the Flat Pack panel was already made mainly of insulation material (polyisocyanurate), which is considered a lightweight material thus the thermal mass was already low. As the target was improving the flat pack system performance to reduce heating and cooling demand using a passive system, a layer of 12 mm of the enhanced MPCM panel (MPCM coupled with gypsum and honeycomb) was added to the internal surfaces of the flat pack wall system as shown in Figure 7-5. The aim of using an enhanced PCM panel, as mentioned was to absorb unwanted heat from the space and store it for use when needed. Thus, it will work as a recovery passive system. An additional benefit of using the mentioned system as a direct result of reducing the heating/ cooling demand is the reduction of CO_2 emissions by reducing energy consumption.

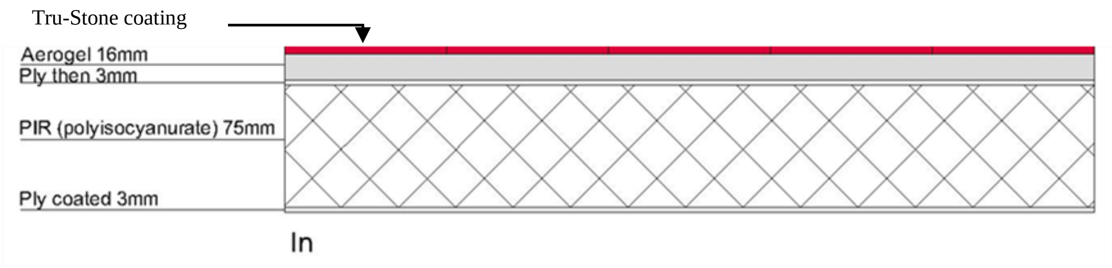


Figure 7-4 Flat pack unit – panel with Tru-Stone coating and Aerogel.

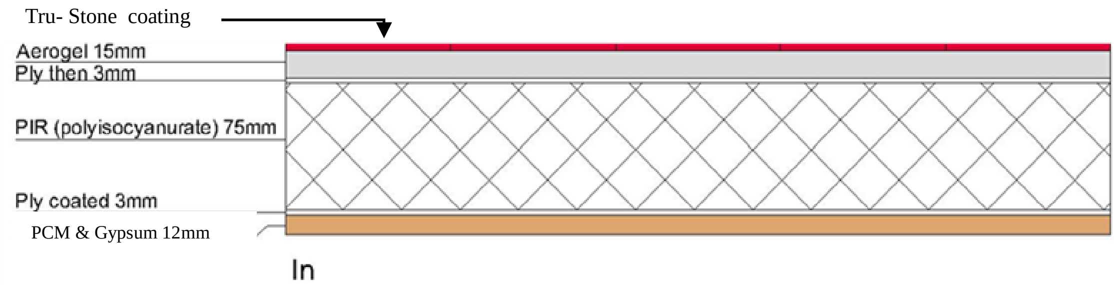


Figure 7-5 Flat pack unit panel with Tru-Stone coating, Aerogel and enhanced

7.3 Methodology of the test

The procedure of the test was divided into three stages. First is the pre-investigation stage through the calculation of necessary thermal resistance that should be added to the existing wall system of the Blue Planet unit in order to improve its performance and to meet the required U-value of in the building regulations 2010 and the Code for Sustainable Homes. Second is testing the panel by adding a layer of Phase Change Material (PCM) and Gypsum compound with honeycomb to improve the PCM conductivity (PCM panel) as detailed in section 7.5**.** Finally, a full-scale comparative test was conducted by dividing the flat pack unit into two rooms using 20cm of Polyistelin to ensure high thermal insulation between the two rooms. This was followed by the addition of the enhanced MPCM panels to one of the rooms, keeping the other room unmodified, as illustrated in Figure 7.26 to determine the effect of including MPCM panels to the existing wall system.

7.4 Description of the Flat Pack unit

The flat pack units are constructed of sandwich panels that have a U value of 0.24 W/m²K and consists of 3mm ply coated with Glass Reinforced Polyester GRP, a 75mm layer of PIR (polyisocyanurate) insulation (Celotex, 2012) and another 3mm of GRP (Wessex, 2008) as internal finishing, as illustrated in Figure 7-6and Figure 7-7. All water and electricity connections are part of the panel's construction. The floor panels have a 120 mm layer of insulation material (PIR). Figure 7.8 presents the whole flat pack unit and the details of the panel are shows in Figure 7-9.

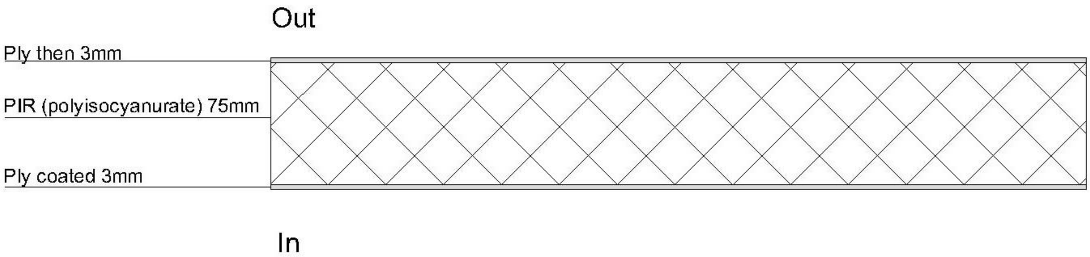


Figure 7-6 section of Flat pack – panel layers.

Figure 7-7 The layers of Flat pack panel showing details of the wall (Flat Pack, 2011).

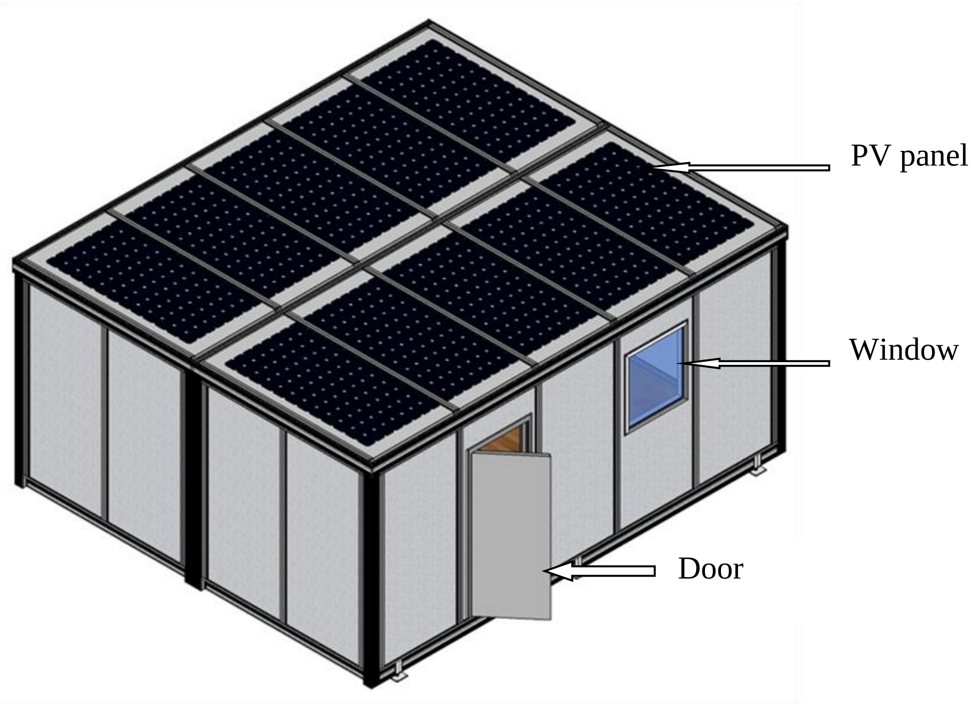


Figure 7-8 Two Flat Pack units(Flat Pack, 2011).

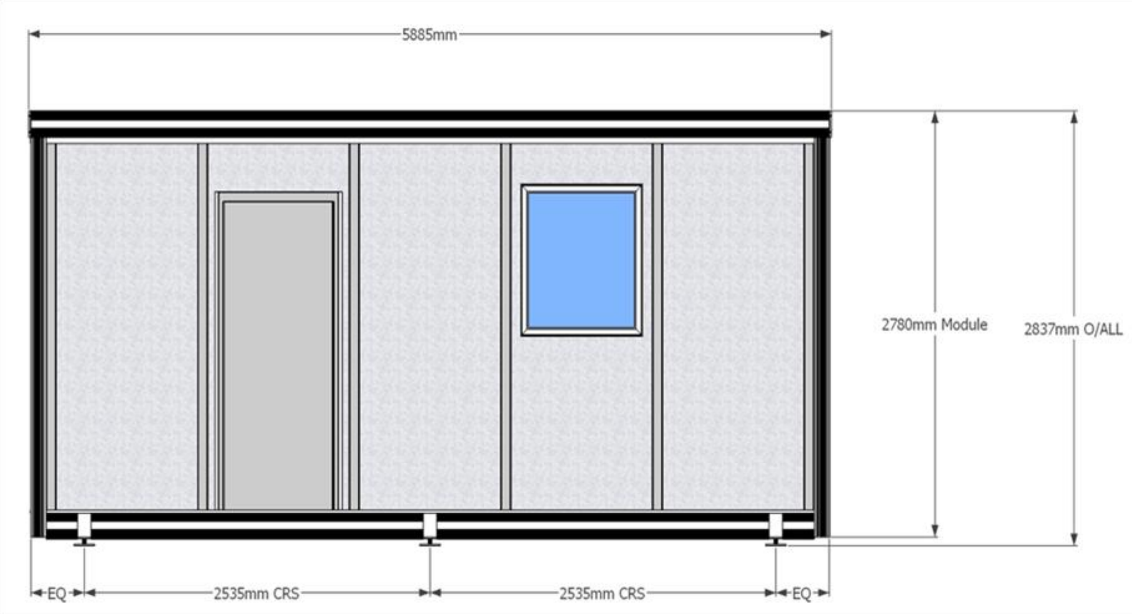


Figure 7-9 Flat Pack unit dimensions (Flat Pack, 2011).

7.5 Lab experiment to test enhanced flat pack wall by adding MPCM panel

First, a lab test was carried out to investigate the effect of adding a layer of the unique mix of PCM microcapsule with gypsum and honeycomb to the existing flat pack panel as illustrated in Figure 7-10 (refer to Chapter 5 for the conductivity test of this PCM mixture). The new layer plays two main roles: on one hand, as Alawadhi (2008) confirmed, it increased the resistance of the Flat Pack wall, and on the other hand, it was used as a thermal storage that absorbs and releases heat which helps to control the space temperature.

Figure 7-10 The panel with honeycomb.

7.5.1 The method used for the lab test

The method of the lab test is similar to that which was described in detail in Chapter 4. The steps of the lab test were made to comply with British Standards (BSI, 1990) as illustrated in Figure 7-11. Here, the Calibrated hotbox method was used to calculate the U value of the existing flat pack panel as well as the new flat pack wall panel with PCM. Figure 7-12 shows the Calibrated hotbox that was constructed in the lab at the Department of Architecture and Built Environment (DABE), University of Nottingham.

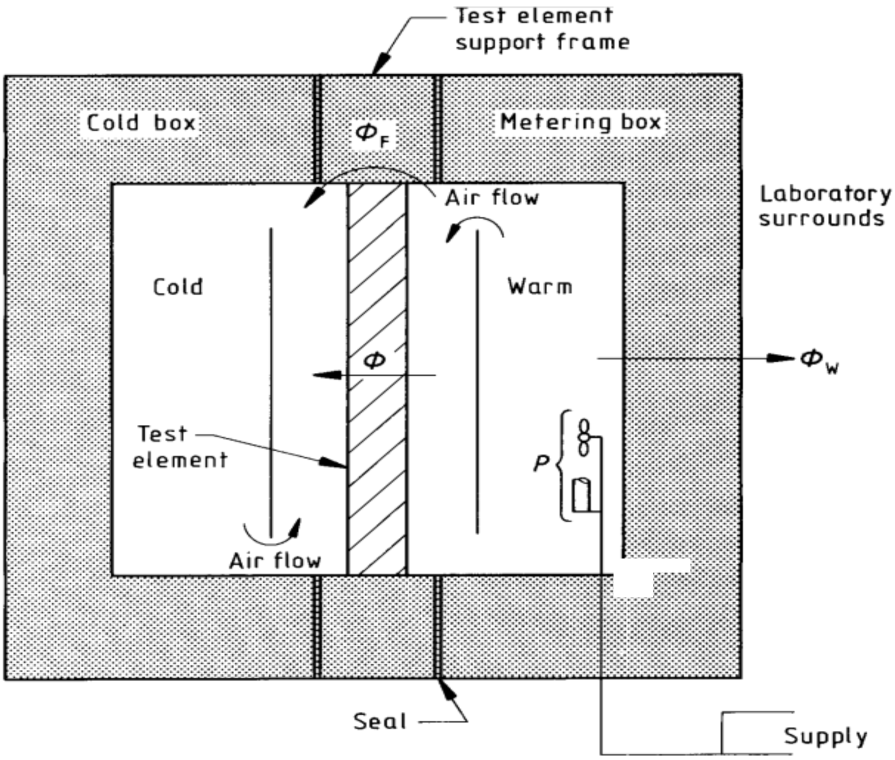


Figure 7-11 Calibrated hot-box apparatus (BSI, 1990).

7.5.2 Materials and equipment used in the test

As illustrated in Figures 7-12, 7-13 and 7-14, the system required the following equipment: temperature controller, data taker, thermocouples K type or T type, heat source, fan and heat flux, Laptop or a PC, pyranometer, and concrete mixer. In addition, Micronal Phase Change Material (MPCM), gypsum, silica, honeycomb, wood, water, sackcloth and cling film are needed to manufacture the enhanced PCM panel (details of these were presented in Chapter 5).

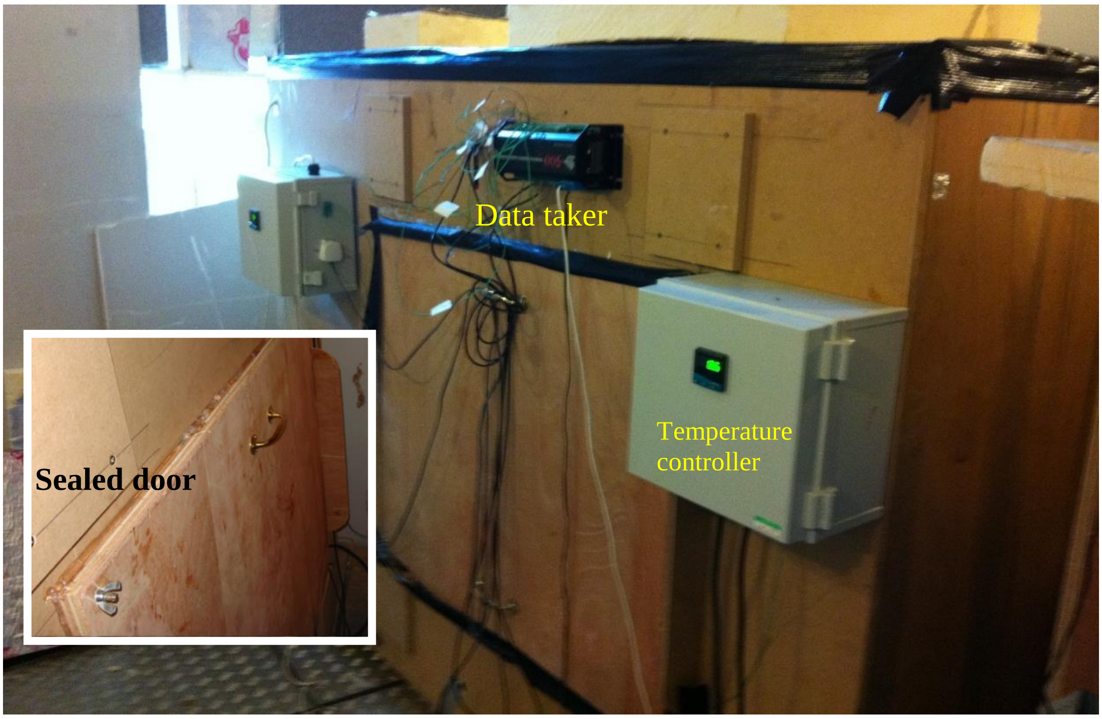


Figure 7-12 The temperature controllers on both sides and the sealed door of the test rig box.

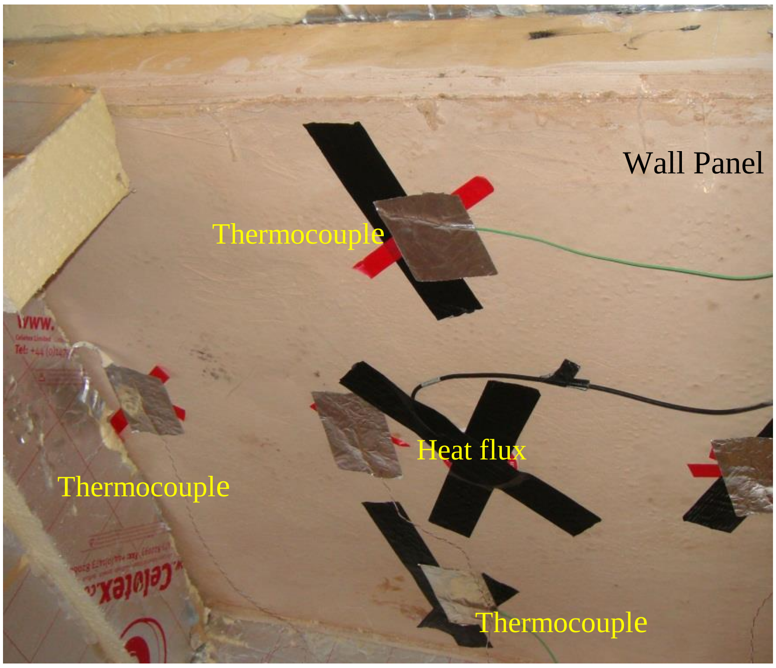


Figure 7-13 The position of heat flux and thermocouples on the wall panel.

Figure 7-14 The hot side and the cold side of the test box, heater and the fan.

7.5.3 Procedure of manufacturing the improved flat pack wall panel

Although PCMs are now used in a wide range of applications, there are limited commercial sources that provide type of panels that contain PCMs (Rodrigues, 2009). One of the sources is the DuPont Energain Board and a German company with a branch in London, called Clay UK (Clay UK, 2009).

The extra layer of PCM was added to the existing flat pack panel which is made up of 20% Phase Change Materials (PCM), 75% Gypsum and 5 % Silica by weight. About 6.5 litres of water was used to start the interaction between the mixture materials, and in this stage it was important to address the issue of cracks. Adding water provided an excellent workability to the mixture. However, evaporation of the water from the mixture leads to problems of cracking (Hewitt and Philip, 1999).

- All the above dry materials are mixed together. Water was then added while mixing continuously until a homogeneous mixture was achieved, as shown in Figure 7-15.
- A wooden frame was installed around the existing panel. The original thickness of Blue Plant-flat pack wall panel is 81mm. Extra 12 mm of MPCM panel will add extra thickness to the existing panel. So, the thickness of the new panel was 93mm.
- The frame was filled with the mixture along with careful compaction to insure that there are no bubbles as shown in Figure 7-16.

Figure 7-15 Process of producing homogeneous mixing.

- The honeycomb was then placed to increase the thermal conductivity of the MPCM panel as shown in Figure 7-17.
- Finishing the surface of the panel required special care in order to obtain a smooth surface.

Figure 7-16 Place the mixture on the panel

Figure 7-17 Honeycomb placed through the mixture.

- The panel took 7 to 10 days to dry, depending on weather conditions. Another way to decrease the drying time is by placing the panel in a steam-curing device under extra care to avoid cracking. The steam curing helps to speed the chemical reaction by setting the temperature and the humidity in the chamber room. However, timing is important when using this method of curing (Wise Geek, 2012).

- To avoid cracking during the curing process, the panel was covered with cling film as shown in Figure 7-18 and wet sackcloth. Water was sprayed every day to insure the sackcloth was kept wet. This minimized the speed of evaporation to avoid cracks as shown in Figure 7-19.

- The dried panels were then moved to the experimental stage as shown in Figure 7-20.

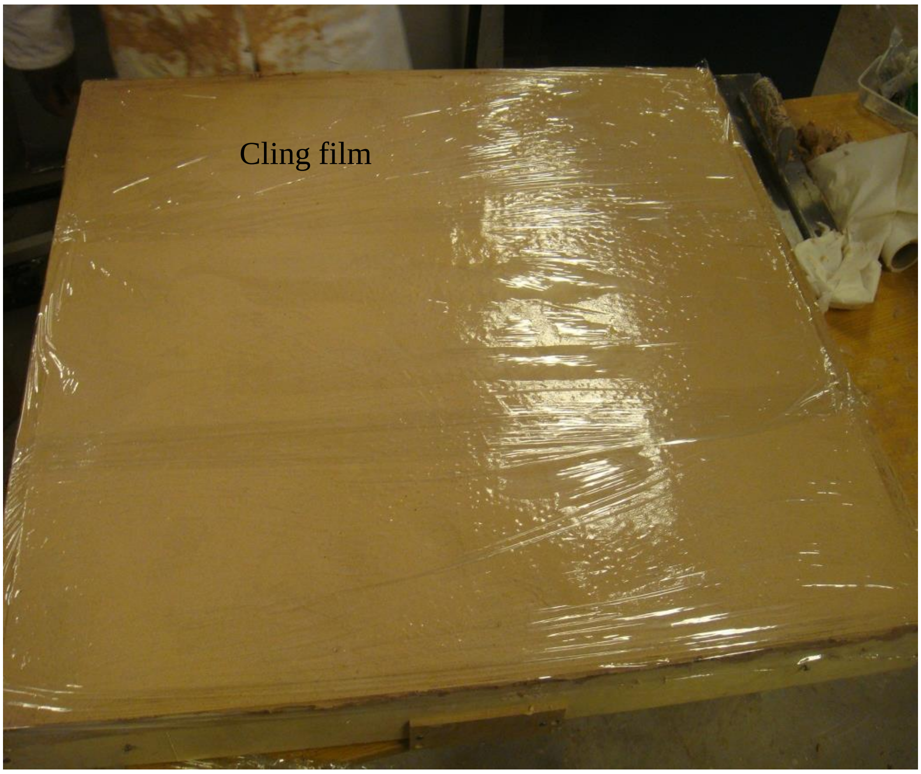


Figure 7-18 Curing process with a cling film.

Figure 7-19 Curing of the sample with wet sackcloth.

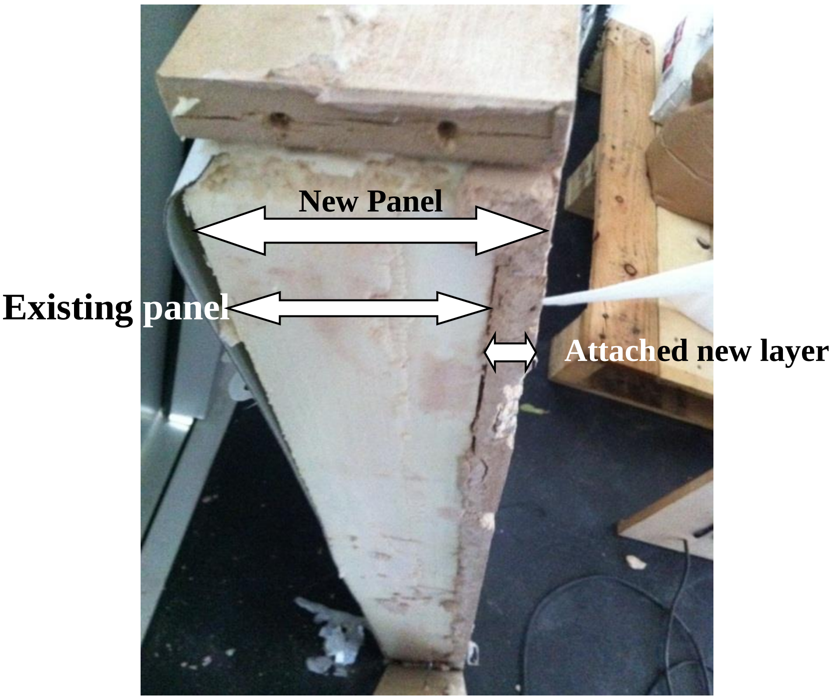


Figure 7-20 PCM panel attached to Flat pack panel.

7.5.4 The lab experiment Procedure

- First the wall panel was placed in the middle of Calibrated hot-box as shown in Figure 7-14, ensuring that there were no gaps between the two sides of the box by sealing around the wall on both sides to ensure that heat moves through the wall panel.

  Thermocouples are attached on both sides to measure the temperature (see Figure 7-13). Thermocouples were connected with a data taker, which was linked to a PC to measure the temperature on both sides of the wall panel at intervals of 20 seconds.

- Heat Flux was also attached on the cold side of the wall panel shown in Figure 7-13 to measure the heat flux through the wall panel.

- A heater was placed to provide the heat source. A wooden board was positioned between the heater and the wall panel (Figure 7-14). A fan was used to ensure an even distribution of heat around the hot side of the Calibrated hot-box. As a result of this step the heat moved by convection only, and then by conduction from the heated side to the cold side.

- The heater was turned on and set to 32 ºC. The fan was also turned on to distribute the hot air.

- The data was collected by the data taker and stored in the PC.

- The wall panel was set up inside a control chamber in the lab at the Department of Architecture and the Built Environment Department (DABE) according to BSI procedure, where the temperature was set below the melting point of the used PCM. The control chamber ran on 15 ºC where the melting point of the PCM is 23 ºC.

- The heat flux can be calculated using equations, 4-1 and 4-2.
- The thermal conductivity (K) is also calculated using equation 2-1.
- R-value and U-value are calculated using the equation 4-4

7.5.5 Results and analysis of the Lab experiment

Tests were carried out for about one day per test. Figure 7-21 shows the result of continuous testing for the existing flat pack panel, illustrating the relationship between temperatures on both sides of the Calibrated hot-box (hot side H1, H5 and cold side C1, C2) of the flat pack primary panel. As seen from Figure 7-21, the temperature increased sharply for about one hour at H1 and H2 then became fixed at about 32ºC using a temperature controller. On the other hand, the temperature increased on the cold side (C1 and C2) for about 16 hours to reach a steady state condition. After the first 4 hours, when the temperature reached about 32 ºC (H1 and H5), the difference in temperature between (H1, H5) on the hot side and (C1, C2) on the cold side was 5 ºC, which is not a large variation.

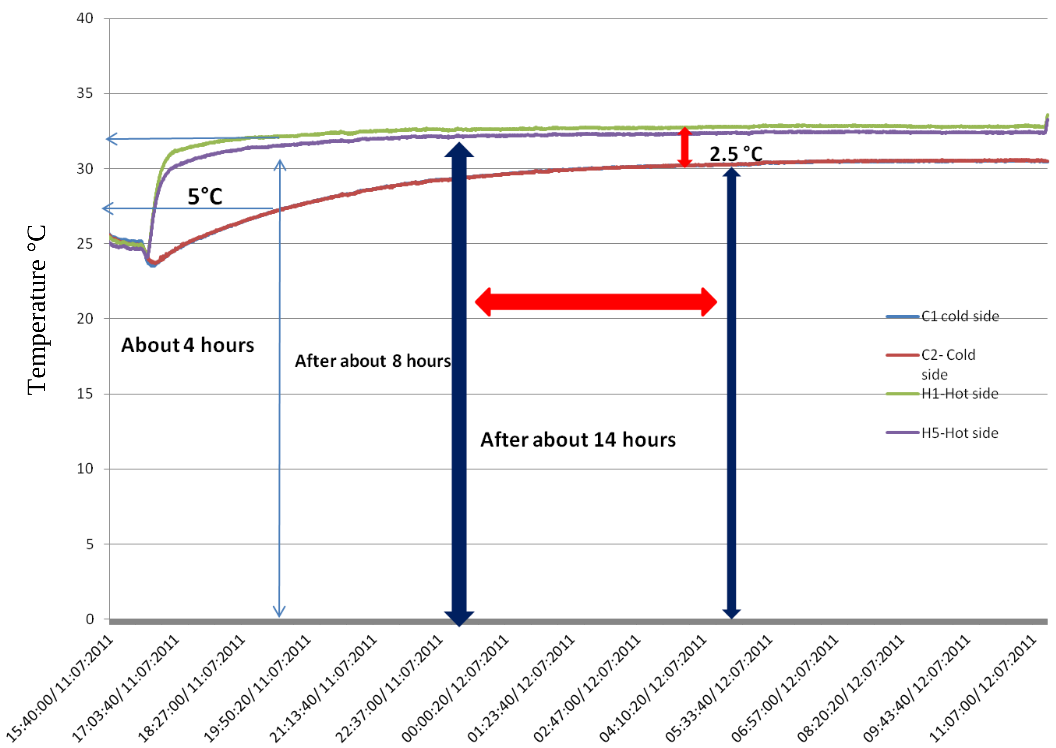


Figure 7-21 Test 1- the original Flat Pack panel.

About 8 hours the temperature further increased on C1and C2 to reach up to 29 ºC (Figure 7-21). The variation between H1, H2 and C1, C2 decreased to less than 3 ºC. The difference in temperature between the two sides of the panel after 14 hours was about 2.5 ºC. This instability between the two sides of the panel continued by the increase in temperature. After more than 24 hours, the steady state condition was achieved.

It can be seen that for an outside temperature of 32 ºC the inside temperature may reach about 30 ºC after 14 hours, which is above the target for comfortable temperatures in the UK. Nevertheless, it should be taken into account that temperature is not the only target to obtain a comfortable environment (Szokolay, 2008)

From the results obtained from the experiment in section 7.5.5, the U value of the wall panel could be calculated as mentioned in section 7.5.4 by using the equation 4-1.

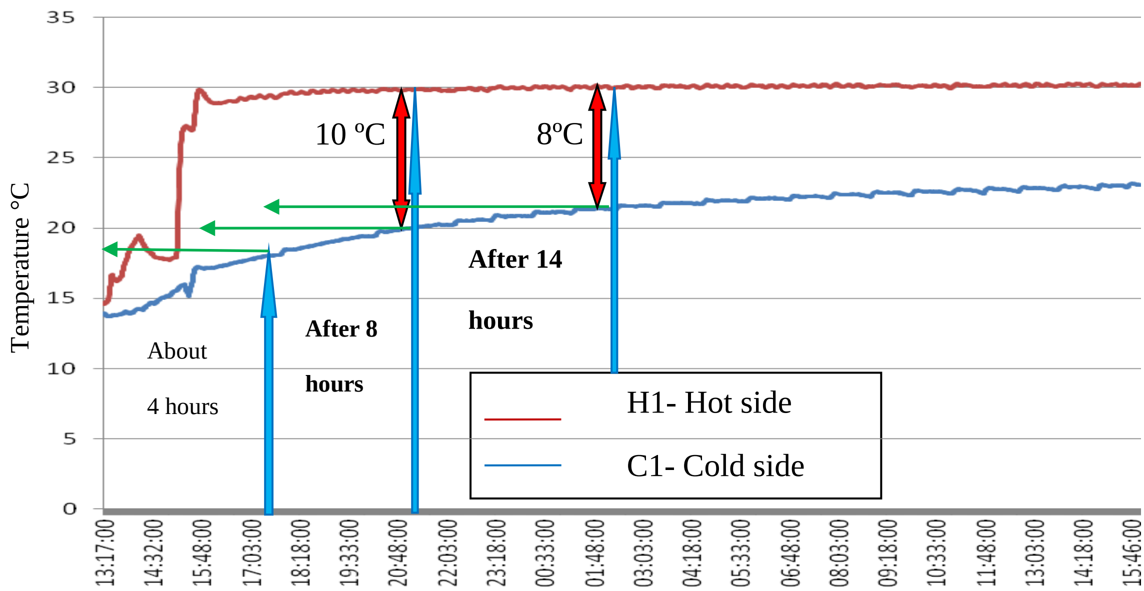


Figure 7-22 Test 2 the original flat pack panel with PCM panel.

As the heater was switched on, the temperature on the hot side of the panel (H1) sharply increased (Figure 7-22). After 8 hours, the temperature controller in the hot side of the calibrated hot-box was set at 32 ºC while the temperature in the cold side was gradually increased to reach 18.5 ºC. This was a good indication that the attached MPCM panel had absorbed the heat through the existing panel as the thermal mass of the new panel was increased. As illustrate in Figure 7-22, the difference between the hot side of the wall panel and the cold side of the panel after 8 hours was 10 ºC. This difference was decreased gradually by low acceleration of about 1 ºC every 8 hours. After 14 hours the difference between the two sides was 8ºC, while the temperature in the cold side reached 22 ºC, which is within the comfortable temperature range. Nevertheless, other factors affecting user comfort should be taken into account as mentioned before is the size of the window and the use of lover.

While results in the second test illustrates the difference between both sides of the panel, H1 and C1, which was about 8ºC after 14 hours, the difference in the first test was 2.5 ºC only. It is clear from the results that it is possible to reduce the temperature on the other side of the wall panel by adding an extra layer of PCM panel.

7.6 Full scale test

For the full-scaled test, flat pack unit was used to conduct the experiment. The use of the full scale building; which was surrounded by real climatic conditions will show the true effect of any modification done in the existing construction. The unit was setup at in the Department of Architecture and Built Environment, the University of Nottingham UK (Nottingham lies on latitude 53^{o} N, longitude 1.25^{o} W at an altitude of 117m).

7.6.1 Objectives of the outdoor test

- To investigate the thermal performances of the MPCM-Honeycomb wall panels regarding storage and release heat as well as their potential to reduce overheating in the Flat Pack in summer.

- To compare the experiment results with results obtained from computer modelling (refer to Chapter 6).

7.6.2 Procedure of the test

- The Flat Pack unit was divided into two rooms. One has the MPCM honeycomb panels attached to the walls and the second room was kept without any modifications Figure 7-23.
    - ➢ Room 1: on the right with original Blue planet panels.
    - ➢ Room 2: with PCM honeycomb panels on the wall.

Figure 7-23 shows Flat pack unit south façade.

- Panels used in the test are constructed in the SRB lab at the Department of Architecture and Built Environment in the University of Nottingham (Figure 7-24). Each panel consists of a PCM 20% + Gypsum 75% + Silica 5% with

Honeycomb. The thermal conductivity of the panels is 0.306 W/mK (according to the test in section 5.6.2.2)

- Thermocouples with a measuring range between -50 to +200°C and accuracy ±1°C were placed on every wall in both rooms. As illustrated in Figure 7-25 the thermocouples were placed on three levels. Also, a wooden model was placed in each room and thermocouples attached to them Figure 7-26
- Thermocouples were located on PCM panels in on the room 2 wall (Figure 7-26).

- Thermocouple sensors were installed and connected to the data taker.

Figure 7-24 PCM panels used in the test.

- Solar radiation was the heat source. As illustrated in Figures 7-27 and 7-28 solar radiation was recorded using a Pyranometer placed on the flat pack's roof. Details and accuracy of the Pyranometer is presented in Table 7-2.

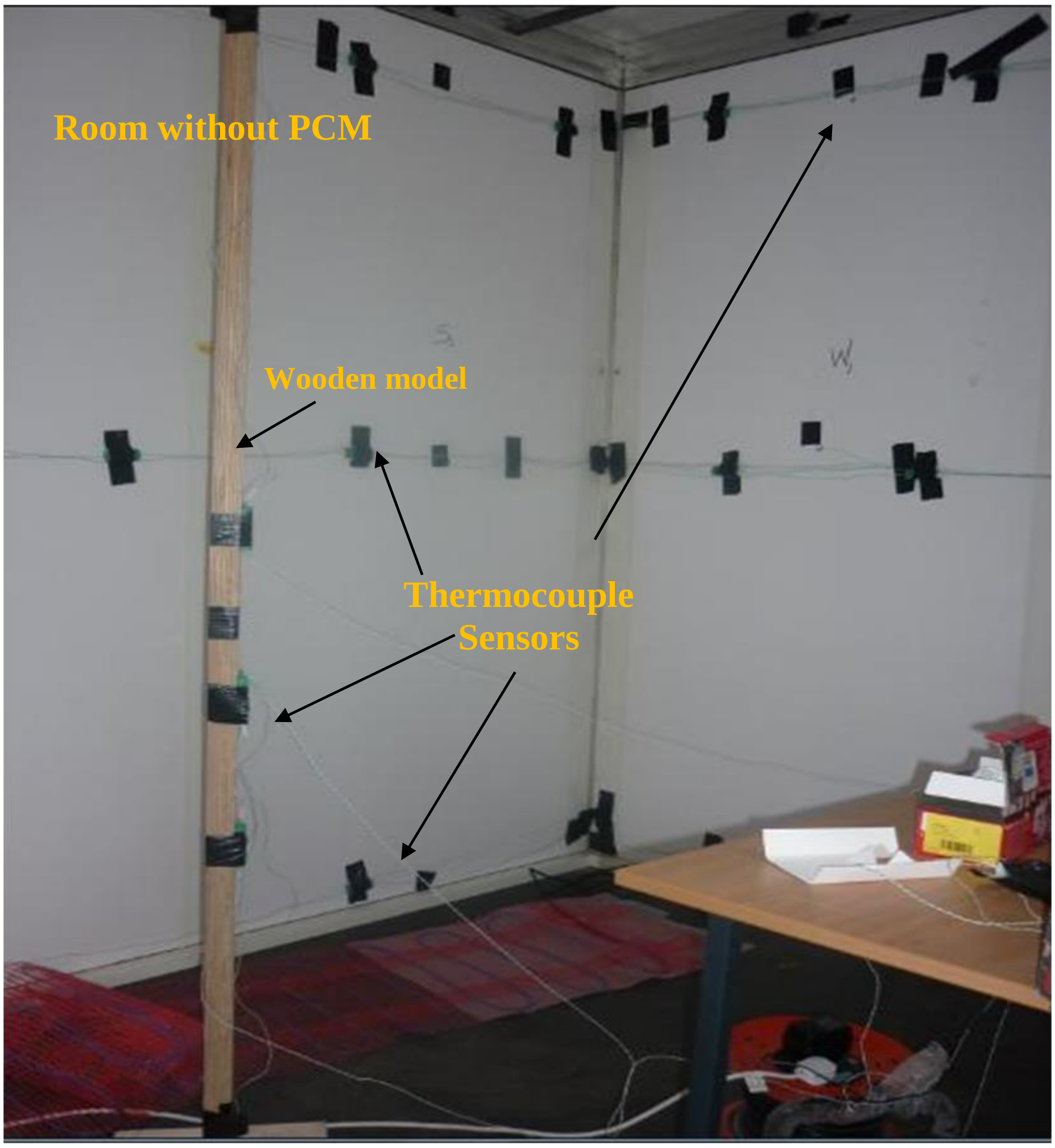


Figure 7-25 room 1 and attached thermocouples in three levels.

- MPCM panels were attached on the internal surface of room 2.
- The outside air temperature was also recorded (Figure 7-28).

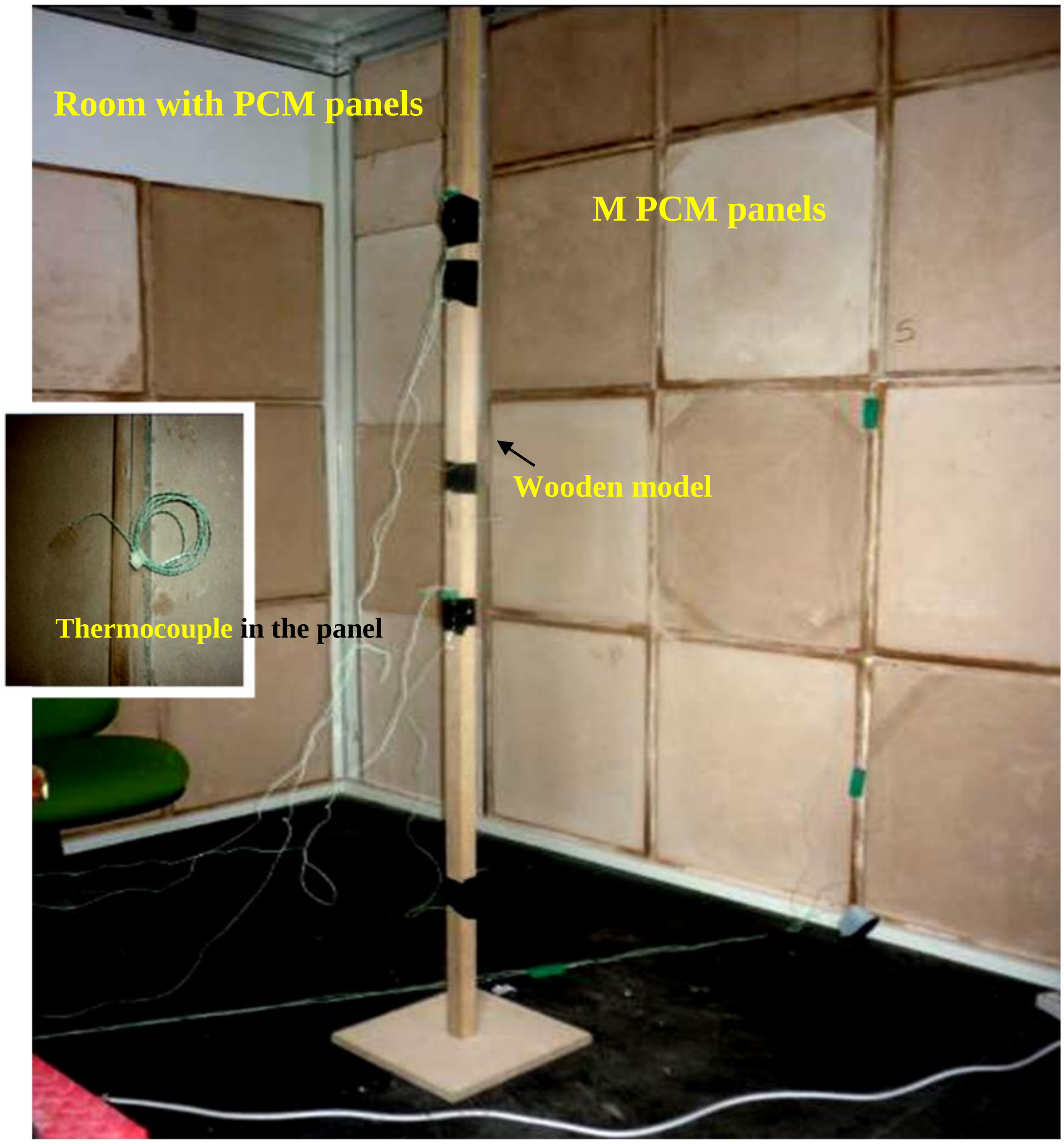
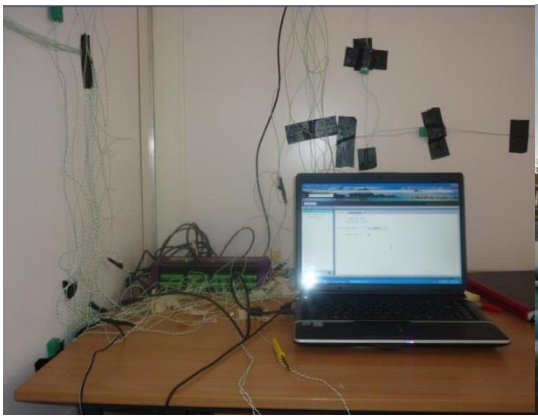


Figure 7-26 shows room 2 and attached thermocouples in three levels.

- Data was recorded every 2 minutes using the data taker, and then transferred to a spread sheet for examination (Figure 7-29).
- Thermocouples were attached on both windows to record the temperature. These present the effect of adding a new layer (Figure 7-30).

Figure 7-27 shows the location of Pyranometer on the flat pack's roof.



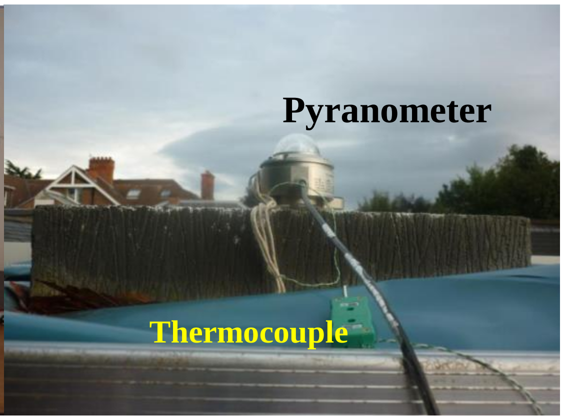


Figure 7-29 the data taker connected to laptop.

Figure 7-28 show thermocouple record outside temperature and the position of the Pyranometer.

Table 7-2 CM11 Pyranometer (Kipp & Zonen)

Specifications of the *CM11 Pyranometer*	
Spectral range	285– 2800 nm
Sensitivity	4.56*10-6 V/Wm2
Accuracy	Humidity : ±3.5%RH Temp. ±2^{o}C
Response time (95%)	< 2 sec
Operation Temperature	-40^{o}C to +80^{o}C

Figure 7-30 the position of the thermocouple on both windows.

7.6.3 Results of the full scale test

The results of the full-scale test are presented in the Figures 7-31 to 7-34. Statistic performances of the temperature behaviour inside ordinary room 1 of flat pack for one day and the temperature on all walls were recorded in addition to outside temperatures. The results are divided into four periods (afternoon, evening, night and morning). Moreover, solar radiation was presented during the full duration of the experiment so that the relationship between the internal temperature and the solar radiations are easily distinguished.

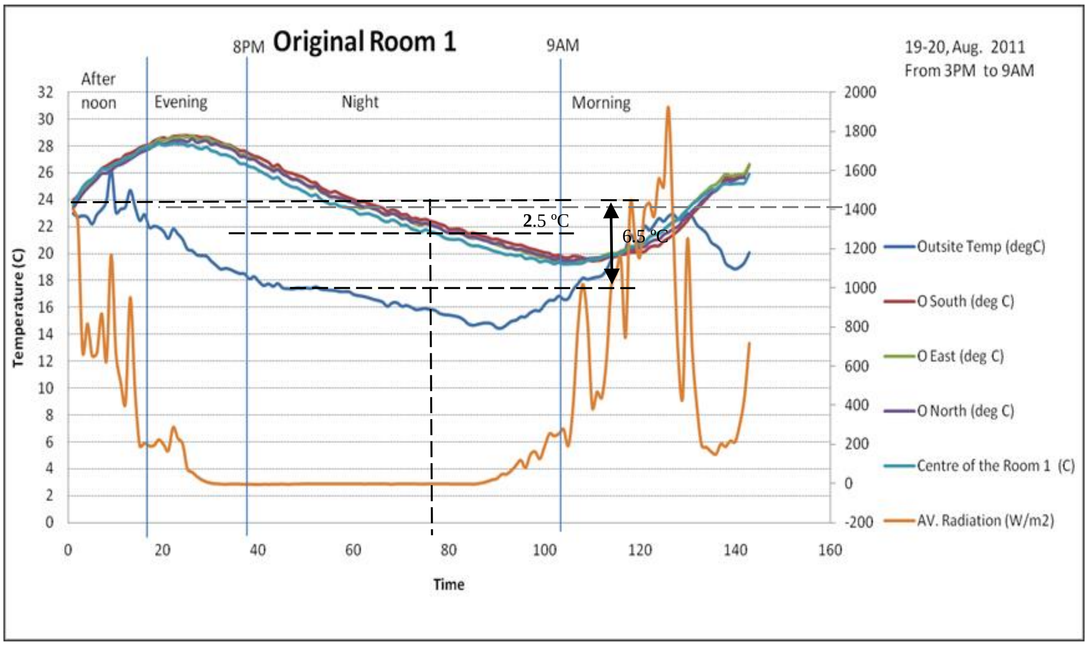


Figure 7-31 shows the temperature in room 1.

The temperature behaviour in the ordinary room 1 (original room without MPCM) is presented in Figure 7-31. As temperatures were measured at different locations inside the room 1 to search and compare it with room2 with PCM under the same climatic conditions, so that helped to illustrate the practical effect of adding MPCM panels into the components of the room's walls.

Figure 7-32 shows the variation of temperature for room 2 where MPCM panels have been attached to the walls. Similarly, Figure 7-31 and 7-32 was divided into four sections (afternoon, evening, night and morning), ensuring that comparisons between the two rooms are straightforward and valuable. Solar radiation data was added to Figures 7-31 and 7-32 so that the link between the solar radiations, internal temperature and walls surfaces temperatures can be easily be observed.

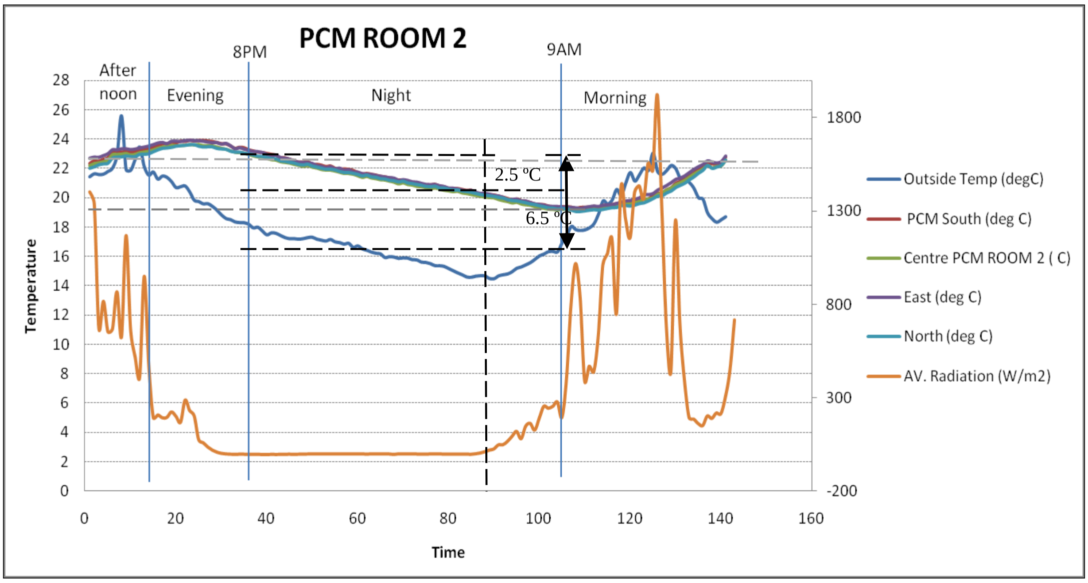


Figure 7-32 shows the temperature in room 2.

As part of the results, Figure 7-33 shows an important comparison between the temperatures at the center of both rooms in addition to the outside temperature. This chart has been divided into four periods as well to assist in a better understanding of the effect of adding a layer of Phase Change Material panels into the original wall panels.

As stated in the procedure of the test in section 7.6.2 thermocouples were located inside the PCM panels. As a result, the Figure 7-38 shows the diversity in temperature between three places: the centre of both rooms and outside temperature. Finally, Figure 7-34 presents the temperature during the day in the middle of the

PCM panel thickness compared with the temperature in the centre of both rooms and the temperature outside the Flat Pack unit.

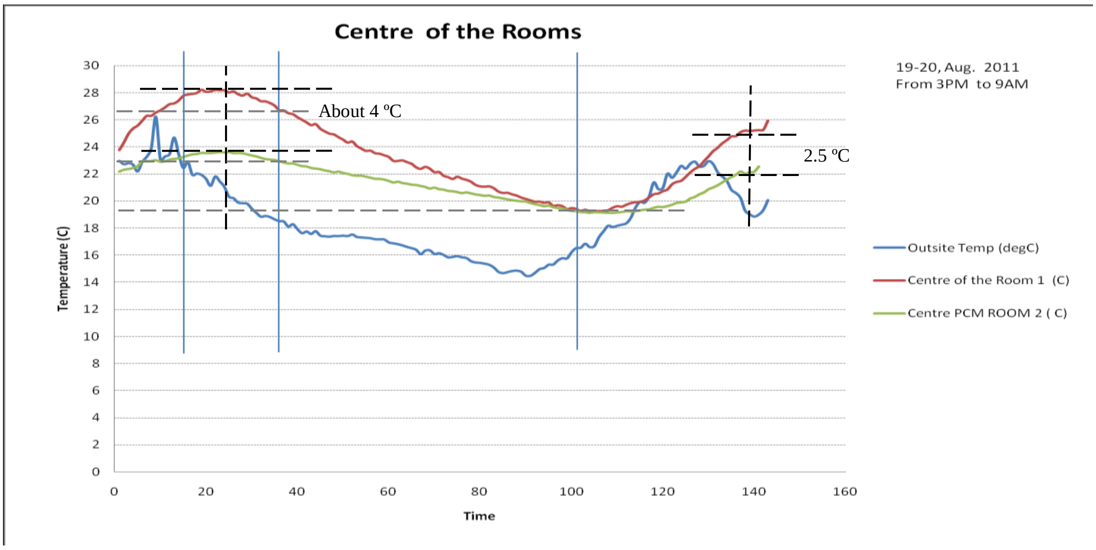


Figure 7-33 Comparing the central temperature in room1 & room2.

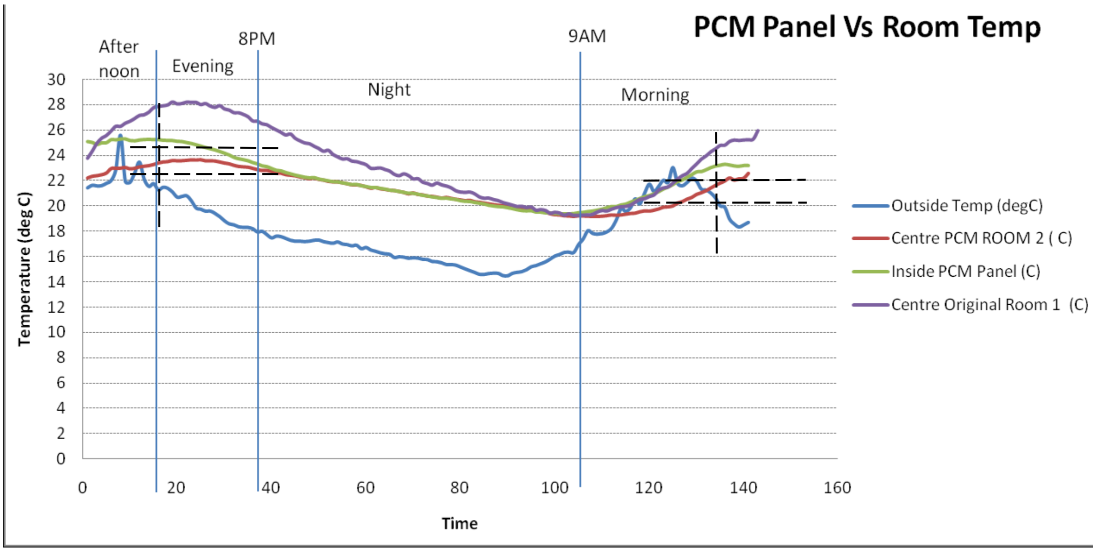


Figure 7-34 Temperature inside the PCM panel.

7.6.4 Analysis and discussion

The results of the experiment in Figure 7-31 show the ambient temperature and the temperatures on all internal wall surfaces of the room 1 in addition to the centre of room. It can be seen in Figure 7-31 that in the morning, there is a gradual increase in temperature in all internal wall surfaces in room 1. This was observed in conjunction with the increase in the ambient temperature in the first half of the morning period. Even with the drop in the ambient temperature at the latter stage of the morning, the increase in the internal walls temperature continued through conductivity as a means of heat transfer. The maximum ambient temperature during the afternoon period in room 1 was 26 ºC, while the maximum temperature on the walls' surfaces during the afternoon was around 28ºC. However, the highest temperature was recorded in the middle of the evening, reaching up to 29 ºC. From this point, the central room temperature and the internal walls' surfaces temperature start to decline as a result of the decrease in the ambient temperature that already started in the late afternoon.

The important part of the experiment results was the section that dealt with Phase Change Materials (PCMs) panels in room 2. The effect on the central part of the room temperate and internal walls surfaces by adding an extra layer of MPCM mixed with gypsum and sand can be observed in Figure 7-32 (refer to Chapter Five section 5.4 for MPCM panel construction). In the morning on one hand, the solar radiation increased and dropped sharply at different points and the ambient temperature gradually increased and dropped according to the solar radiation. However, on the other hand, the increase in central room temperature and internal walls surface temperature were gradual by the conduction of heat. Nevertheless, comparing Figure 7-31 for room 1 with Figure 7-32 for room 2 (with MPCM panels), differences in the central room temperatures and internal wall surfaces temperatures can be distinguished.

In the early morning, the temperature in room 1 starts from about 20 ºC on the South wall surface reaching up to 19 ºC in the centre of the room and between 19 ºC to 20 ºC on the other walls internal surfaces. In addition, the temperature in room 2 starts from 19ºC and 20ºC on all internal wall surfaces as well as the centre of the room in the early morning hours. Moreover, in both rooms the temperature increases gradually but at different rates. In addition, late in the morning when the temperature exceeded 26 ºC in room 1, it was slightly beyond 23 ºC in room 2. Because of using MPCM panels, the temperature dropped by 3 ºC. Furthermore, in the evening while the temperature in room 1 was 29ºC, it was 24ºC or slightly below at the centre of the room and on internal surfaces of the North wall. As a result of using MPCM panels, the temperature difference was shown to be 3 ºC to 5ºC between room 1 and room 2.

Figure 7-32 shows that the maximum temperature on room 2 with MPCM panels in the evening time was below 24 ºC, even when the ambient temperature in the evening dropped to less than 20 ºC. In contrast, Figure 7-31 shows that the temperature in room 1 reached up to 29ºC as a maximum on the internal south wall surface and about 28ºC in the centre of the room, which was the minimum value.

Night time is an important period of the day because the MPCM release the heat after absorbing it during daytime. According to Figure 7-31 when the internal night time temperature in room 1 was below 27ºC, in room 2 (with MPCM panels) the temperature was 23 ºC. The method here to distinguish the difference between room 1 and room 2 (with MPCM) was by comparing the rate of temperature decrease with time. By reviewing Figures 7-31 and 7-32 when the temperature dropped 2.5 ºC in both rooms, it was clear that in room 1 took less time compared with room 2. Moreover, according to Figures 7-31 and 7-32 late at night and when the temperature value dropped to 6.5ºC, the temperature on the internal south wall of room 1 was 20 ºC. When the temperature fell around 7 ºC, the other walls internal surfaces and central room temperature were around 19.5 ºC. In contrast, the temperature late at night in room 2 was slightly above 19ºC on all internal walls surfaces and in the centre of the room, where the temperature fell less than 4ºC between early and late night. This difference between room1 and room2 on dropping temperature compared with the time at night gives an indication of the effect of using the MPCM panels and concludes that MPCM releases heat during the night, which reduces time lag by dropping the temperature inside room 2 and on the walls internal surfaces. In addition, by the temperature dropping below 23 ºC, which is the melting point of the MPCM, it is clear that the MPCM could discharge heat without any mechanical interference for cooling.

In the morning, as illustrated in Figure 7-31, where the solar radiation increased with fluctuation, the temperature rise in the centre of the room 1 and on the internal walls surfaces were between 25.5 ºC to 26 ºC. In contrast, the temperature room 2 (Figure 7-32) in the morning starts to increase nearly in the same rate of that temperature in room1 (Figure 7-31). Nevertheless, by the end of the morning period, nearly at noon, the temperature in the centre of room 2 was slightly above 22 ºC and on inner walls surfaces were from 22 ºC to 22.5 ºC. Accordingly, the influence of the PCM panels was in absorbing heat and this caused the difference from 3.5 ºC to 4ºC between room 1 and room 2 under the natural air flow. In another word, during the day the MPCM panels succeeded in absorbing the heat and released it during the night under natural room ventilation as a consequence of improving the thermal conductivity of the MPCM when mixed with gypsum and silica with honeycomb as expounded in Chapter 5.

The biggest problem of Phase change Materials (PCMs) is the heat charge and discharge period as a result of poor conductivity. As illustrated in Figure 7-33, the temperatures in both rooms increased in the morning till the middle of the evening. However, it should be noted that in the centre of the room 2 the increase started at a different acceleration rate compared with the increase in room 1. It is clear that the MPCM panels already absorbed the heat, which produces the variation between the two rooms. Late in the morning, the variation was 2.5 ºC and the maximum difference was up to 4 ºC. As a result of the drop in the ambient temperature, the temperatures started to fall in both rooms by the reverse movement of heat transfer from inside to the outside of the rooms.

According to Figure 7-33, the temperature in both rooms dropped during the night with different acceleration rates. However, by the end of the night, both rooms obtained the same temperature around 19.5 ºC. The result from this test shows very clearly that MPCM panels had an influence on the temperature drop rate, where the temperature in room 1 dropped during the night to about 7ºC on the other hand, while the temperature in room 2 dropped just about 3.5ºC during the night. As a result of MPCM releasing heat, the acceleration rate on the temperature fall was reduced by 50%.

Previous results discussed the influence of adding MPCM panel to the existing flat pack walls system. The discussion pointed out the impact of MPCM on temperature on the internal surfaces of walls and at the centre of room 2. Figure 7-34 shows the temperature change inside the MPCM panel. In the morning according to the results from Figures 7-32 and 7-34, temperatures inside the MPCM panels and at the centre of the room 2 as well as on the internal surfaces of walls start at the same point (19 ºC). However, as a result of the heat transferred from outside to inside, the temperature rose inside the MPCM, which provided resistance by absorbing the heat. On the other hand, the internal MPCM panel surfaces absorbed the extra heat inside the room. In other words, as the melting point of the MPCM is 22 ºC to 23ºC, the MPCM absorbed the extra heats, which exceed temperatures above 22 ºC to 23 ºC. It is clear at this point that the MPCM plays two roles by absorbing heat: firstly by reducing any extra heat inside the space and secondly, by resisting movement of heat through the external walls.

At the latest, it was an arguable whether the MPCM could be efficient of the cycle of charge and discharge for a long period and is natural ventilation enough for MPCM to continue the processes of cycling or another method of ventilation is required. According to Zhou et al. (2008) "*heavy wall with external insulation is suitable for naturally-ventilated buildings".* By understanding the amount of heat, which needs to be reduced, we could supply enough PCM to absorb it. However, improving the thermal conductivity is to ensure the full heat charge and discharge of MPCM works with high efficiency. In addition, understanding the effect of climate and differences in temperature between day and night at different seasons will help to improve the cycle of charge and discharge of use PCM.

7.7 Comparing the modelling simulation results with results from the full-scale test

The results obtained from the modelling simulation and from the full-scale test were compared to validate results of the simulation with real conditions from the experiment.

- It was noted that the recorded temperature on the site of experiment is similar to the result obtained from the simulation of case 1. However, there is little variation, which could be neglected (less than 1 °C).
- From the simulation result, MPCM panels were found to reduce the temperature about from 1.5^{o}C- 3^{o}C. On the other hand, the result obtained from the full-scale test found that the MPCM panels reduced the temperature from about 3^{o}C to 5^{o}C.
- According to section 4.7.6, the thermocouples accuracy is ±1 °C. This can explain differences in results between the modeling simulation and the full-scale experiment.

7.8 Conclusions

It is being concluded that by using MPCM panels it was possible to achieve a much more comfortable ambient temperature without any active cooling system. However, passive cooling with MPCM is highly dependent on low temperatures occur during the night. Without these low temperatures, the stored heat cannot be discharged completely. This may lead to less usable storage for the next day and therefore the rooms would tend to overheat faster.

Improving the conductivity of MPCM helped the panels to absorb and release heat without any mechanical ventilation. As a consequence of the use of unique MPCM panels, the temperature dropped in the Flat Pack unit in a satisfactory manner between 3 ºC to 5 ºC.

The difference between temperatures on the walls surfaces was 7 ºC to 8ºC during the afternoon period. Ultimately, using MPCM panels can reduce cooling and heating demand and minimise the use of any equipment, which has a large impact on building cost.

CHAPTER 8: CONCLUSION AND FUTURE WORK

8. Conclusion and Future work

8.1. Conclusion

It can be concluded that climate change is one of the world's major problems and to prevent the problems related to climate change from increasing the amount of CO_2 emissions must be decreased. Energy used in houses has an enormous effect in increasing CO_2 emissions. As an example in the UK, the energy demand of the domestic sector has risen by 17% in 2009 compared with that of 1970. Thus, it was also responsible for approximately 27% of CO_2 emissions. In addition, in the UK (2007) there are about 26 million houses and from 2007 to 2016 the UK government aimed to build an extra 3 million houses. This means a rise in domestic buildings energy demand. One the other hand, the government is aiming to achieve zero carbon buildings by 2016 through the use of the Code of Sustainable Houses level 6 this can be done through careful planning with regards to construction materials used for insulation, ventilation systems, sizes of openings, lighting and using renewable energy applications as key parameters.

One of the aspects to achieve low carbon emission building and to save energy is by reducing the U-value of the building elements. Insulation materials help in achieving building comfort and energy efficiency. On the other hand, excellent insulated buildings could cause overheating issues in the buildings especially with lightweight construction building, which will then create uncomfortable zones for users. Therefore, care should be taken when building insulated, special lightweight construction systems by providing practical cooling systems. It is important to highlight key points that could help to reduce the risk of overheating:

- User behaviour.
- Solar shading and shading devices.
- Ventilation.
- Increasing thermal mass.

As one of the main points of reducing the overheating is increasing the building thermal mass thus, Phase Change Materials (PCMs) have been used to increase the thermal mass of lightweight buildings. MPCMs are used because of their ability to store a large amount of heat by changing their state at pre-determined temperatures. It is important to emphasise that temperature should be below the melting temperature of PCM in use at night in during the summer months. Otherwise, the PCM will not be able to reduce the overheating.

It has been suggested that lightweight wall systems were presented in chapter 4 by using different type of insulation materials namely, aerogel, vacuum insulation, and polystyrene. The target was achieving the U-value of the Code of Sustainable Homes. The uses of polystyrene increase the thicknesses of the wall (22.9 cm for U-value = 0.11 W/m²K). However, it is still cheaper than aerogel, vacuum insulation. The use of vacuum insulation in the various walls tested show results which achieve the minimum value (0.9cm, 1cm and 1.9 cm). However, using this type of insulation needs extra care as any damage leads to the ineffectiveness of this insulation. Use of aerogel can lead to reasonable increase in thicknesses by 4.8cm, 5.5cm, and 10.3cm, in addition to moisture resistance. However, the costs of the materials are still high.

For new buildings two walls have been designed to simulate the two methods of building construction. They have been manufactured in Tru-Stone Company and were tested at the laboratory for U-value and to understand both constructions systems' thermal behaviors. One is a lightweight construction system and the other, a heavyweight construction system. The thickness of heavyweight wall is 24.1 cm and the U value is 0.1805 W/m²K whilst the thickness of the lightweight wall is 26.6 cm and the U value is 0.153 W/m²K.

For future work on existing buildings with the expectation of decrease on the price of aerogel, the use of combination panels that consist of aerogel and Tru-Stone coating can improve the thermal resistances of existing domestic buildings and achieve building regulation 2010 and the Code for Sustainable Homes in terms of U-value by adding an extra layer to the external surfaces. Therefore, improving an existing solid wall needs 7 cm of aerogel and 0.4 cm Tru-Stone coating. So also, by the addition of 3.5 cm of aerogel and 0.4 cm of Tru-Stone coating, one can enhance insulation in existing cavity wall systems.

As the target of this research was increasing the thermal performance and reducing overheating, PCM microcapsules has been used as a high thermal store material. And as PCMs have low thermal conductivity this research addressed how it could be improved by combined two methods of improving the thermal conductivity. MPCM has been combined with other construction materials namely clay, cement, silica, and gypsum (first method). A honeycomb was used as heat-conductive material to enhance the heat exchange through the MPCM panels (second method). This helps the microcapsule PCM to conduct heat faster. The heat flow through the samples under specific conditions was measured the thermal conductivity using HFM, which was designed and manufactured under the specification of ISO 8301 and BS874-2.2: 1988. The test method was based on BS874-2.2: 1988 as steady state conditions used to measure the thermal conductivity of the material in the temperature range between -20 ^{o}C to 100 ^{o}C.

Thermal conductivity was improved from 0.16 W/mK to 0.253 W/mK when combined with clay and cement. Furthermore, the thermal conductivity was enhanced to 0.282 W/mK when the PCM was mixed with gypsum and silica (without honeycomb). Furthermore, use of honeycomb enhanced the thermal conductivity to 0.306 W/mK (panel 19 in chapter 5).

Thus, panel 19 that consists of PCM 20%+Gypsum 75%+ Silica 5% with honeycomb has been used on a full scale test (chapter 7), as this panel has the highest value of the thermal conductivity 0.306 W/mK compared with other constructed panels.

TAS simulates the thermal performance of buildings has been used to determine the building's thermal behaviour alongside Phase Change Materials (PCMs). TAS simulation was divided into two sections. Firstly, 3D modelling and secondly, the simulation phase which simulates the thermal performances of the building by defining each of the following: building materials, weather data (Nottingham), the schedule of any use of equipment, schedule of occupants and the ventilation system. Five cases were simulated to find out the overheating period during the year and study the effect of natural ventilation on MPCM to discharge heat for use the following day.

Base case: Simulating the ordinary rooms in zone 1 and zone 2 without MPCM. Case 1: Attaching MPCM on the whole surface of two walls without natural ventilation. Case 2: Attaching MPCM on the whole surface of two walls with night natural ventilation. Case 3 Attaching MPCM on the whole surface of three without natural ventilation. Case 4: Attaching MPCM on the whole surface of three walls with night natural ventilation.

According to the simulation results in chapter 6, the use of MPCM has shown reduction on overheating period during the year. Therefore, the use of MPCM Natural night ventilation can help to reduce the number of hours when the temperature is above 23°C. In chapter 6, natural night ventilation helped to reduce the period of overheating from 499 hours/year in case1 to 317 hours/year in case2 and from 424 hours/year in case 3 to 255 hours/year in case 4. As a result, it could help to reduce 50% of the overheating period during the year. More MPCM should be used to absorb more heat. As a recommendation, adding MPCM panels to the fourth wall of the room 2 (zone 2) to absorb more heat can minimize the overheating period in buildings. During the year, MPCM could reduce overheating in summer time, whilst it releases heat during the winter time at night. However, another heating system should be used to avoid temperature falling below the comfort zone.

The results in chapter 7 showed that, the temperature decreased in a satisfactory manner between 3 ºC to 5 ºC. The same panels (panel 19) also used to increase the thermal resistance of the existing flat pack wall system with an extra layer of aerogel 1.5 cm, which reduced the U- value from 0.24 W/m^2K to be 0.18 W/m^2K. Results also showed that due to the increase in thermal conductivity by the use of MPCM panel, there is no need to provide mechanical ventilation system. However, passive cooling with MPCM is highly dependent on low temperatures during the night. Thus, night ventilation is acceptable to discharge the MPCM.

Using MPCM can reduce the temperature during the daytime from1.5°C to 3°C. One the other hand, the experiment result showed reduction of temperature in the same period of time from 3°C to 5°C. It is important to take into account the calibration of the thermocouples used in the experiments. It is also important to note here also, that the variations in results obtained in the experiments and the modeling simulation can be attributed to the difference in real time weather data and that of weather data files used in the modeling.

From the architectural view, the combining of the Blue Planet and Tru-stone to invent, a new system of cladding can improve the building appearance of flat pack system.

8.2. Future work

- Continue testing the wall's performance from Tru-Stone Ltd after replacing a concrete layer by the PCM clay board and insulation.

- Use the test box in the laboratory chamber to simulate the UK future scenarios of temperature and test PCM clay board as a solution to reducing overheating in lightweight buildings under the UK Building Regulations and the Code for Sustainable Homes.
- Test building spaces with MPCM clay board and compare the result with that obtained from using MPCM with gypsum board in terms of reducing overheating in the UK.
- Presently, the MPCM is an expensive material, and thus not economically viable. Therefore, more research needs to be carried out, to find alternative means of encapsulating the PCM to be used in buildings, as can be seen in the Figure8-1

Figure 8-1 Adding encapsulate the PCM into gypsum panel.

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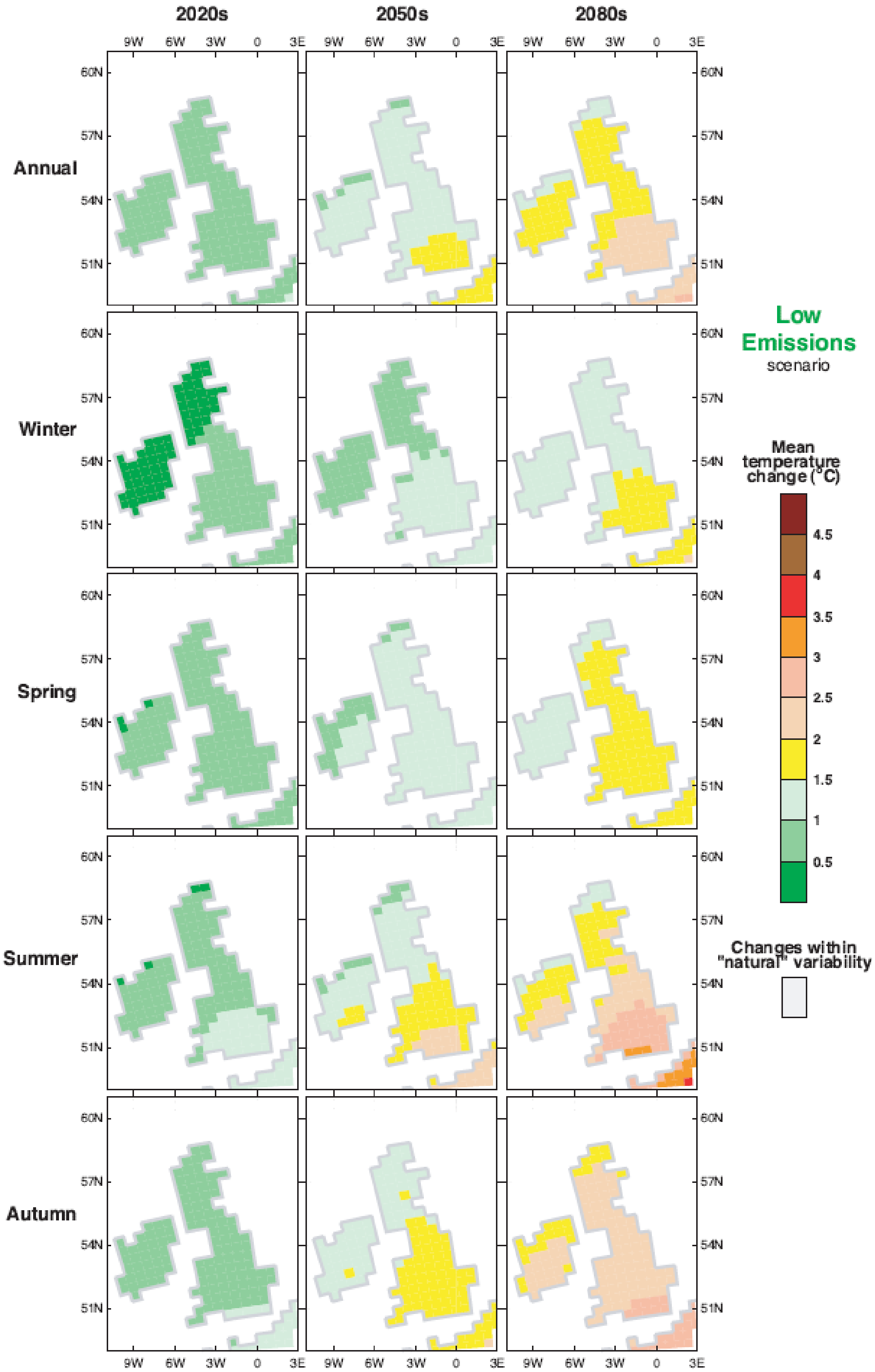
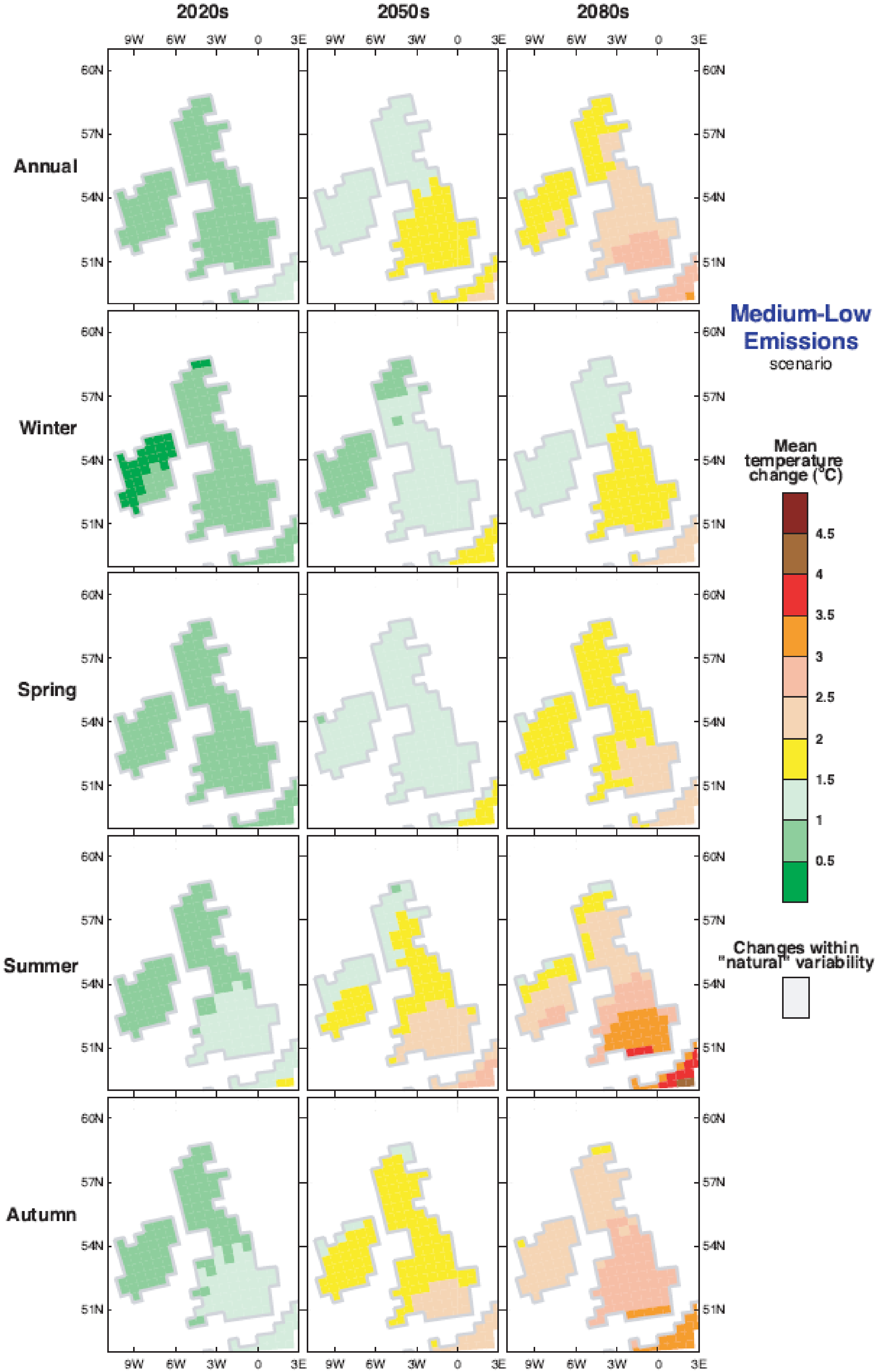
Appendix 1

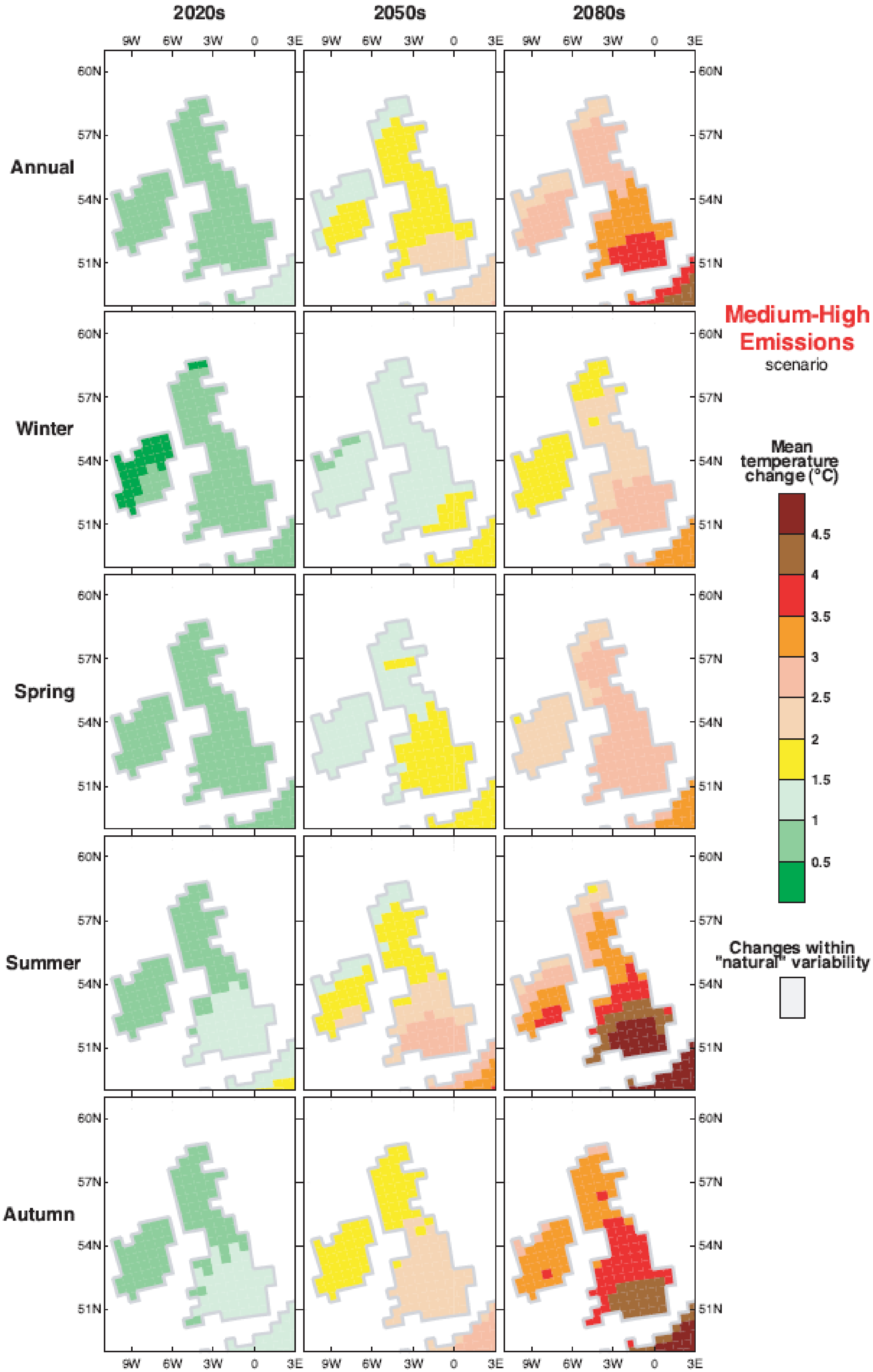
Climate Change Scenarios for the United Kingdom The UKCIP02 Scientific

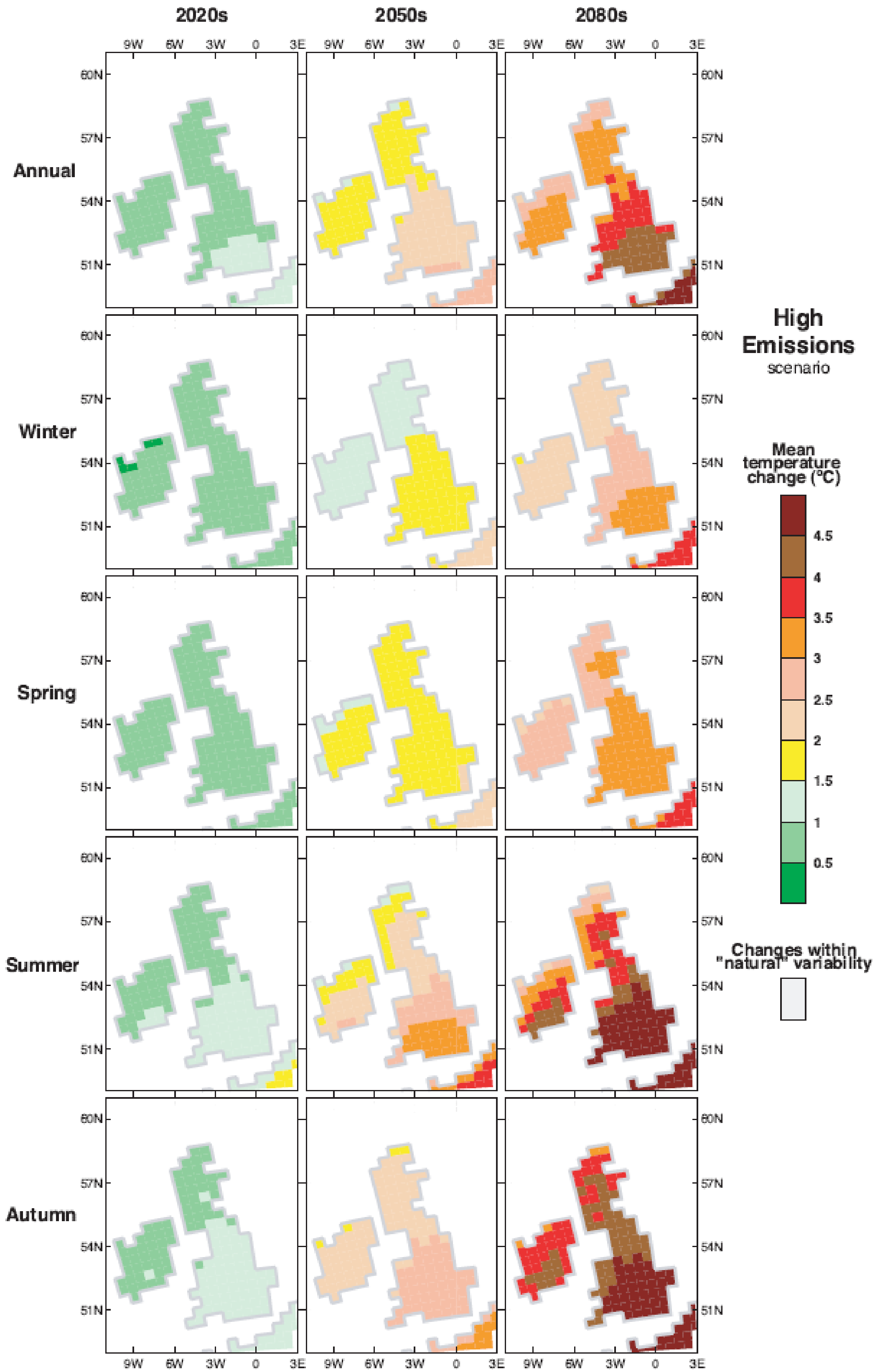
(UKCIP, 2002).





2020s
2050s
2080s
Annual
Winter
Spring
Summer
Autumn
9W 6W 3W 0 3E
60N 57N 54N 51N
Medium-Low Emissions
scenario
Mean temperature change (°C)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
Changes within "natural" variability


2020s
2050s
2080s
9W 6W 3W 0 3E
60N
57N
54N
51N
Annual
Winter
Spring
Summer
Autumn
Medium-High Emissions
scenario
Mean temperature change (°C)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
Changes within "natural" variability



UKCIP 2002. Climate Change Scenarios for the United Kingdom. Norwich, UK: School of Environmental Sciences, University of East Anglia.

Calculating the Target CO_2 Emission Rate (TER)

In part L1A is based on the mass of CO_2 (Kg/m² of floor area per year). Domestic buildings in document part L1A have been divided into two categories. Firstly, for buildings apply of 450m² or less, the version of Government's Standard Assessment Procedure applies (SAP2005). Secondly, for domestic individual buildings over 450m², applies the Simplified Building Energy Model (SBEM).

TER is being calculated by

TER= (CH × fuel factor+ CL) × (1-improvement factor)

Where:

The fuel factor shows in the table below (Approved document L1A, April 2006).

Improvement factor = 0.2 in part L edition.

CH the provision of heating and hot water.

CL the use of internal fixed lighting.

It is important to understand the results, which refer to the mass of CO_2 in units of KG/m² of floor area per year produced by the hot water, internal lighting, provision of heat and ventilation (Regulation19, L1A).

For multiple domestic buildings such as a block of flats the average of TER is calculated as shown in the formula [(TER1 ×floor area1) + (TER2 ×floor area2) +..... (TERn ×floor area n)]÷ [(floor area 1+floor area2+......floor area n)].

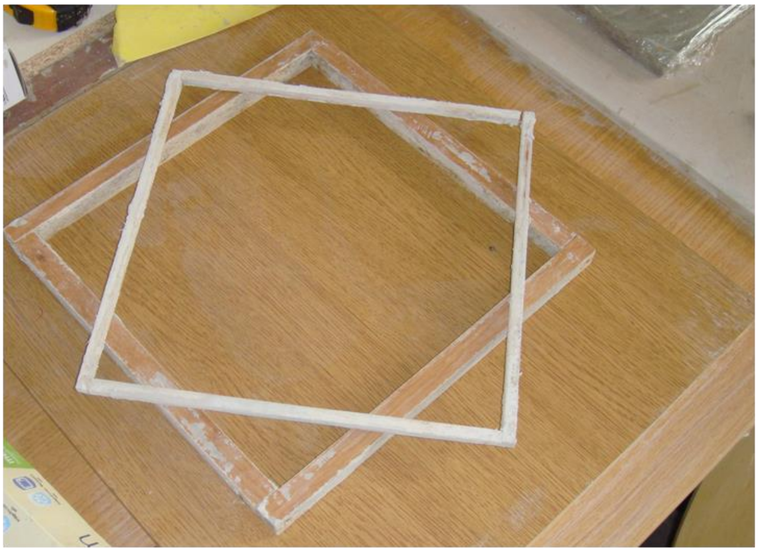
Building regulation part L has also addressed the calculation of Dwelling carbon dioxide Emission Rate (DER), U value as can be seen in Table below, solar gain and overheating, fixed internal and external lighting, building fabric, ventilation and insulation.

Fuel factor Approved document L1A(April 2010).

Heating fuel	Fuel factor
Mains gas	1.00
LPG	1.10
Oil	1.17
Grid electricity	1.47
Solid mineral fuel[9]	1.28
Renewable energy including bio fuels	1.00
Solid multi- fuel	1.00

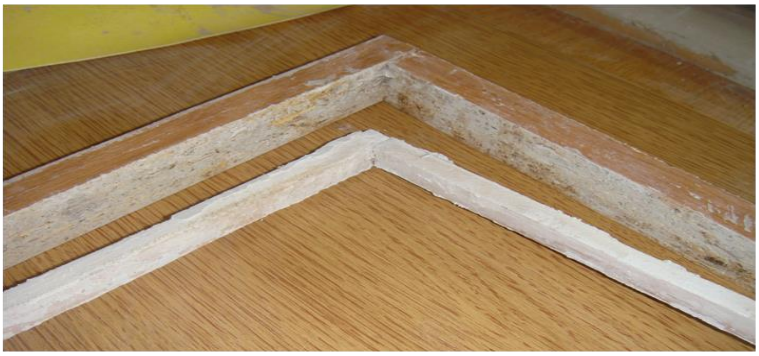
Appendix 2

Two frames used to precast PCM panels which are frame 1 30×30 thicknesses 1 cm and 2cm.



Dimention 30×30 cm frame 1 and fram 2.

Frames thicknesses 1 cm and 2cm.

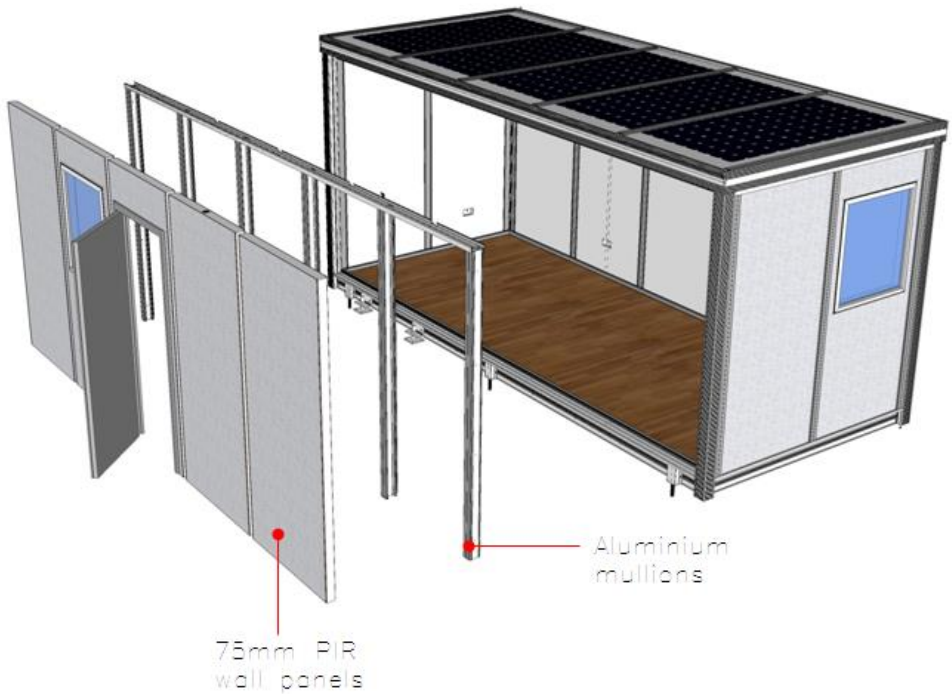


Panel 2 Cracks

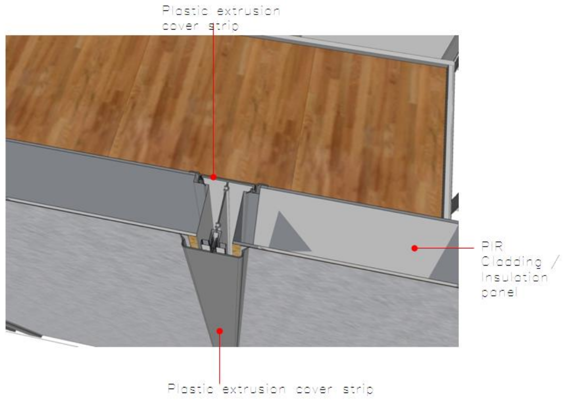
Cling film used for curing to minimize and avoid cracks.

Appendix 3

Existing wall build up for flat pack system.



Unit wall build up



Plan section detail

Aerogel could be added as external layer with another layer of Tru-Stone or internal as part of the unit panel.

Wall layers with external Tru-Ston coating with Aerogel insulation material.

Manufacturing extra PCM with gypsum panel as an extra layer with exsisting Flat pack wall panel.

Adding PCM with gypsum panel to existing Flat Pack panel.

Smoothen the surface.

Result of testing the existing wall panel of flat pack system.

1	Time	C1-PCM-Center	C2- inside-wall T	C3-room T20cm	C4-PCM-T-doorSi	C5-PCM-T-SIDE2	C6-room center T	H1-Insulation- center	H2- inside- wall T	H3-room-T 20cm	H4-Insulation-T doorSi	H5-Insulation-T-side	H6-room center-T	C7-PCM-Top cente	C8-PCM-rDown cente	H7-Insulation-t Top cent
2	16:18:00	30.064	30.533	29.831	30.386	29.77	30.711	50.177	46.365	51.59	49.173	47.185	52.889	29.672	29.761	34.991
3	16:18:30	30.065	30.535	29.833	30.388	29.772	30.713	50.178	46.396	51.621	49.203	47.215	52.949	29.674	29.791	34.963
4	16:19:00	30.043	30.512	29.869	30.395	29.749	30.72	50.213	46.432	51.656	49.265	47.278	53.013	29.681	29.769	34.941
5	16:19:30	30.044	30.513	29.84	30.396	29.75	30.721	50.242	46.462	51.715	49.266	47.306	53.072	29.682	29.77	34.941
6	16:20:00	30.098	30.567	29.894	30.391	29.804	30.745	50.293	46.515	51.768	49.318	47.33	53.155	29.706	29.824	34.966
7	16:20:30	30.072	30.512	29.869	30.395	29.749	30.691	50.297	46.548	51.772	49.349	47.362	53.042	29.651	29.798	34.999
8	16:21:00	30.075	30.544	29.901	30.368	29.811	30.752	50.383	46.551	51.804	49.352	47.393	53.104	29.684	29.831	35.002
9	16:21:30	30.105	30.545	29.873	30.369	29.782	30.724	50.412	46.523	51.805	49.381	47.45	53.162	29.655	29.773	35.032
10	16:22:00	30.079	30.548	29.876	30.372	29.785	30.727	50.415	46.555	51.808	49.44	47.453	53.165	29.658	29.805	35.035
11	16:22:30	30.071	30.569	29.867	30.393	29.777	30.718	50.434	46.576	51.829	49.46	47.501	53.128	29.679	29.767	35.027
12	16:23:00	30.038	30.536	29.864	30.331	29.773	30.714	50.43	46.514	51.824	49.372	47.441	53.066	29.617	29.734	34.994
13	16:23:30	30.041	30.54	29.838	30.364	29.748	30.718	50.434	46.576	51.857	49.431	47.529	53.07	29.591	29.738	34.968
14	16:24:00	30.078	30.547	29.875	30.372	29.785	30.726	50.525	46.584	51.865	49.495	47.565	53.077	29.657	29.775	35.005
15	16:24:30	30.083	30.552	29.88	30.376	29.789	30.76	50.529	46.588	51.87	49.527	47.597	53.082	29.662	29.78	35.039
16	16:25:00	30.051	30.549	29.877	30.373	29.786	30.757	50.554	46.614	51.866	49.524	47.594	53.137	29.659	29.806	35.007
17	16:25:30	30.052	30.521	29.849	30.345	29.758	30.729	50.528	46.587	51.868	49.525	47.595	53.168	29.631	29.749	35.008
18	16:26:00	30.054	30.523	29.88	30.405	29.789	30.731	50.557	46.617	51.87	49.527	47.625	53.111	29.662	29.809	35.01
19	16:26:30	30.057	30.555	29.883	30.379	29.792	30.734	50.588	46.678	51.873	49.53	47.656	53.085	29.665	29.783	35.042
20	16:27:00	30.061	30.53	29.887	30.383	29.796	30.738	50.619	46.653	51.905	49.562	47.66	53.06	29.669	29.786	35.017
21	16:27:30	30.059	30.528	29.856	30.382	29.765	30.736	50.618	46.623	51.875	49.56	47.658	53.058	29.667	29.785	35.015
22	16:28:00	30.09	30.588	29.916	30.412	29.796	30.766	50.647	46.653	51.905	49.589	47.716	53.118	29.669	29.815	35.075
23	16:28:30	30.084	30.553	29.881	30.407	29.82	30.761	50.67	46.648	51.871	49.612	47.739	53.055	29.663	29.81	35.04
24	16:29:00	30.056	30.525	29.853	30.349	29.762	30.704	50.643	46.561	51.814	49.585	47.711	52.94	29.664	29.811	35.012
25	16:29:30	30.03	30.528	29.885	30.352	29.765	30.736	50.646	46.593	51.817	49.588	47.714	52.972	29.667	29.785	35.015
26	16:30:00	30.03	30.529	29.886	30.353	29.766	30.737	50.647	46.594	51.847	49.589	47.743	52.944	29.639	29.786	35.045
27	16:30:30	30.055	30.583	29.911	30.378	29.791	30.762	50.671	46.561	51.814	49.585	47.768	52.911	29.664	29.811	35.041
28	16:31:00	30.002	30.53	29.857	30.354	29.738	30.708	50.647	46.508	51.761	49.562	47.744	52.858	29.64	29.786	34.988
29	16:31:30	30.029	30.527	29.884	30.352	29.765	30.735	50.617	46.506	51.759	49.559	47.742	52.769	29.667	29.784	35.015
30	16:32:00	30.002	30.53	29.857	30.354	29.767	30.708	50.619	46.537	51.703	49.506	47.744	52.771	29.61	29.786	34.988
31	16:32:30	30.037	30.507	29.864	30.331	29.744	30.744	50.598	46.543	51.68	49.54	47.75	52.72	29.646	29.793	34.994
32	16:33:00	30.037	30.565	29.893	30.331	29.744	30.744	50.625	46.543	51.68	49.568	47.778	52.662	29.646	29.793	34.994
33	16:33:30	30.07	30.569	29.896	30.364	29.777	30.776	50.629	46.547	51.713	49.599	47.809	52.695	29.649	29.796	35.027
34	16:34:00	30.01	30.537	29.865	30.332	29.745	30.745	50.599	46.486	51.624	49.541	47.752	52.606	29.647	29.794	34.966
35	16:34:30	30.043	30.541	29.839	30.336	29.749	30.72	50.63	46.461	51.599	49.517	47.755	52.61	29.651	29.769	34.94
36	16:35:00	30.022	30.549	29.906	30.374	29.787	30.757	50.611	46.469	51.607	49.553	47.791	52.589	29.688	29.835	34.978
37	16:35:30	30.018	30.517	29.874	30.312	29.754	30.754	50.607	46.436	51.546	49.521	47.76	52.557	29.656	29.773	34.916
38	16:36:00	30.049	30.547	29.904	30.371	29.784	30.755	50.608	46.438	51.576	49.523	47.817	52.558	29.657	29.804	34.946
39	16:36:30	30.016	30.544	29.901	30.339	29.752	30.781	50.605	46.464	51.573	49.52	47.814	52.526	29.654	29.801	34.914
40	16:37:00	30.016	30.544	29.901	30.339	29.752	30.752	50.605	46.493	51.602	49.492	47.786	52.526	29.654	29.771	34.914
41	16:37:30	30.023	30.551	29.908	30.346	29.788	30.759	50.584	46.5	51.609	49.499	47.793	52.562	29.661	29.778	34.95
42	16:38:00	29.991	30.49	29.846	30.314	29.756	30.697	50.554	46.41	51.548	49.468	47.762	52.501	29.629	29.746	34.889
43	16:38:30	29.996	30.523	29.822	30.289	29.731	30.731	50.558	46.531	51.553	49.556	47.794	52.621	29.633	29.751	34.893
44	16:39:00	29.996	30.494	29.851	30.289	29.702	30.731	50.586	46.734	51.668	49.612	47.822	52.852	29.633	29.78	34.922
45	16:39:30	30.032	30.559	29.887	30.325	29.767	30.767	50.676	47.031	51.935	49.813	47.913	53.264	29.669	29.787	34.988
46	16:40:00	29.97	30.497	29.825	30.292	29.734	30.705	50.728	47.347	52.22	49.949	47.937	53.752	29.607	29.754	34.955
47	16:40:30	29.974	30.532	29.888	30.326	29.739	30.739	50.9	47.73	52.572	50.149	48.082	54.394	29.641	29.817	35.019
48	16:41:00	30.035	30.562	29.89	30.357	29.77	30.77	51.096	48.167	53.093	50.485	48.224	55.089	29.672	29.819	35.079
49	16:41:30	30.002	30.53	29.887	30.296	29.767	30.738	51.231	48.512	53.611	50.732	48.361	55.663	29.64	29.787	35.134
50	16:42:00	30.005	30.562	29.89	30.328	29.741	30.77	51.456	48.892	54.048	51.04	48.532	56.359	29.672	29.79	35.196
51	16:42:30	29.997	30.554	29.911	30.319	29.732	30.791	51.697	49.173	54.473	51.309	48.692	57.071	29.664	29.781	35.275
52	16:43:00	29.971	30.528	29.856	30.294	29.736	30.736	51.894	49.408	54.939	51.479	48.862	57.449	29.638	29.755	35.337
53	16:43:30	30.002	30.559	29.916	30.354	29.766	30.766	52.145	49.757	55.374	51.702	49.003	57.969	29.639	29.756	35.455
54	16:44:00	30.004	30.561	29.918	30.356	29.769	30.798	52.397	49.962	55.78	51.953	49.229	58.374	29.641	29.788	35.546
55	16:44:30	29.997	30.554	29.911	30.319	29.762	30.762	52.64	50.158	56.149	52.168	49.39	58.885	29.664	29.781	35.627
56	16:45:00	29.974	30.56	29.888	30.297	29.739	30.739	52.868	50.192	56.414	52.369	49.535	59.035	29.641	29.758	35.721
57	16:45:30	30.005	30.562	29.92	30.328	29.77	30.799	53.091	50.369	56.734	52.593	49.733	59.324	29.672	29.79	35.869
58	16:46:00	30.005	30.562	29.919	30.327	29.769	30.799	53.34	50.455	56.877	52.703	49.927	59.554	29.642	29.789	35.985
59	16:46:30	30.008	30.565	29.893	30.331	29.773	30.803	53.537	50.487	57.054	52.928	50.098	59.672	29.646	29.793	36.048
60	16:47:00	29.98	30.566	29.923	30.332	29.774	30.803	53.704	50.575	57.228	53.067	50.21	59.816	29.676	29.823	36.078
61	16:47:30	29.976	30.592	29.92	30.357	29.77	30.799	53.893	50.658	57.31	53.174	50.373	59.87	29.643	29.79	36.162
62	16:48:00	30.016	30.573	29.93	30.309	29.781	30.81	54.069	50.639	57.436	53.295	50.495	59.967	29.683	29.8	36.26
63	16:48:30	29.987	30.602	29.93	30.309	29.752	30.81	54.207	50.697	57.551	53.351	50.633	59.938	29.683	29.8	36.289
64	16:49:00	29.988	30.574	29.902	30.31	29.724	30.811	54.318	50.611	57.552	53.407	50.69	59.824	29.655	29.772	36.319
65	16:49:30	30.01	30.596	29.924	30.332	29.775	30.833	54.477	50.662	57.603	53.511	50.85	59.875	29.677	29.765	36.312
66	16:50:00	29.985	30.572	29.929	30.337	29.779	30.838	54.592	50.638	57.607	53.543	50.938	59.764	29.652	29.769	36.405
67	16:50:30	29.983	30.599	29.926	30.335	29.777	30.836	54.672	50.693	57.547	53.624	50.991	59.762	29.679	29.797	36.402
68	16:51:00	29.986	30.572	29.93	30.309	29.751	30.839	54.758	50.61	57.522	53.682	51.077	59.679	29.653	29.77	36.464
69	16:51:30	29.987	30.603	29.96	30.31	29.752	30.84	54.842	50.611	57.523	53.711	51.162	59.594	29.654	29.801	36.495
70	16:52:00	29.986	30.602	29.93	30.338	29.751	30.839	54.868	50.552	57.493	53.709	51.188	59.449	29.653	29.8	36.522
71	16:52:30	29.994	30.61	29.938	30.317	29.759	30.876	54.931	50.474	57.415	53.745	51.252	59.256	29.691	29.808	36.501
72	16:53:00	30.023	30.609	29.967	30.346	29.788	30.876	55.013	50.502	57.385	53.8	51.335	59.199	29.719	29.837	36.53
73	16:53:30	29.995	30.611	29.939	30.318	29.76	30.819	54.987	50.445	57.243	53.774	51.336	58.941	29.691	29.779	36.531

16:18:00	30.064	30.533	29.831	30.386	29.77	30.711	50.177	46.365	51.59	49.173	47.185	52.889	29.672	29.761	34.991	48.34	-0.06687
16:18:30	30.065	30.535	29.833	30.388	29.772	30.713	50.178	46.396	51.621	49.203	47.215	52.949	29.674	29.791	34.963	48.342	-0.06687
16:19:00	30.043	30.512	29.869	30.395	29.749	30.72	50.213	46.432	51.656	49.265	47.278	53.013	29.681	29.769	34.941	48.377	-0.06687
16:19:30	30.044	30.513	29.84	30.396	29.75	30.721	50.242	46.462	51.715	49.266	47.306	53.072	29.682	29.77	34.941	48.407	-0.0681
16:20:00	30.098	30.567	29.894	30.391	29.804	30.745	50.293	46.515	51.768	49.318	47.33	53.155	29.706	29.824	34.966	48.461	-0.06687
16:20:30	30.072	30.512	29.869	30.395	29.749	30.691	50.297	46.548	51.772	49.349	47.362	53.042	29.651	29.798	34.999	48.464	-0.06687
16:21:00	30.075	30.544	29.901	30.368	29.811	30.752	50.383	46.551	51.804	49.352	47.393	53.104	29.684	29.831	35.002	48.497	-0.06687
16:21:30	30.105	30.545	29.873	30.369	29.782	30.724	50.412	46.523	51.805	49.381	47.45	53.162	29.655	29.773	35.032	48.497	-0.06687
16:22:00	30.079	30.548	29.876	30.372	29.785	30.727	50.415	46.555	51.808	49.44	47.453	53.165	29.658	29.805	35.035	48.53	-0.06687
16:22:30	30.071	30.569	29.867	30.393	29.777	30.718	50.434	46.576	51.829	49.46	47.501	53.128	29.679	29.767	35.027	48.521	-0.06564
16:23:00	30.038	30.536	29.864	30.331	29.773	30.714	50.43	46.514	51.824	49.372	47.441	53.066	29.617	29.734	34.994	48.517	-0.06564
16:23:30	30.041	30.54	29.838	30.364	29.748	30.718	50.434	46.576	51.857	49.431	47.529	53.07	29.591	29.738	34.968	48.492	-0.06564
16:24:00	30.078	30.547	29.875	30.372	29.785	30.726	50.525	46.584	51.865	49.495	47.565	53.077	29.657	29.775	35.005	48.587	-0.06564
16:24:30	30.083	30.552	29.88	30.376	29.789	30.76	50.529	46.588	51.87	49.527	47.597	53.082	29.662	29.78	35.039	48.591	-0.06687
16:25:00	30.051	30.549	29.877	30.373	29.786	30.757	50.554	46.614	51.866	49.524	47.594	53.137	29.659	29.806	35.007	48.617	-0.06564
16:25:30	30.052	30.521	29.849	30.345	29.758	30.729	50.528	46.587	51.868	49.525	47.595	53.168	29.631	29.749	35.008	48.589	-0.06445
16:26:00	30.054	30.523	29.88	30.405	29.789	30.731	50.557	46.617	51.87	49.527	47.625	53.111	29.662	29.809	35.01	48.678	-0.06564
16:26:30	30.057	30.555	29.883	30.379	29.792	30.734	50.588	46.678	51.873	49.53	47.656	53.085	29.665	29.783	35.042	48.652	-0.06564
16:27:00	30.061	30.53	29.887	30.383	29.796	30.738	50.619	46.653	51.905	49.562	47.66	53.06	29.669	29.786	35.017	48.685	-0.06445
16:27:30	30.059	30.528	29.856	30.382	29.765	30.736	50.618	46.623	51.875	49.56	47.658	53.058	29.667	29.785	35.015	48.683	-0.06564
16:28:00	30.09	30.588	29.916	30.412	29.796	30.766	50.647	46.653	51.905	49.589	47.716	53.118	29.669	29.815	35.075	48.685	-0.06445
16:28:30	30.084	30.553	29.881	30.407	29.82	30.761	50.67	46.648	51.871	49.612	47.739	53.055	29.663	29.81	35.04	48.708	-0.06564
16:29:00	30.056	30.525	29.853	30.349	29.762	30.704	50.643	46.561	51.814	49.585	47.711	52.94	29.664	29.811	35.012	48.68	-0.06445
16:29:30	30.03	30.528	29.885	30.352	29.765	30.736	50.646	46.593	51.817	49.588	47.714	52.972	29.667	29.785	35.015	48.683	-0.06445
16:30:00	30.03	30.529	29.886	30.353	29.766	30.737	50.647	46.594	51.847	49.589	47.743	52.944	29.639	29.786	35.045	48.684	-0.06445
16:30:30	30.055	30.583	29.911	30.378	29.791	30.762	50.671	46.561	51.814	49.585	47.768	52.911	29.664	29.811	35.041	48.68	-0.06445
16:31:00	30.002	30.53	29.857	30.354	29.738	30.708	50.647	46.508	51.761	49.562	47.744	52.858	29.64	29.786	34.988	48.685	-0.06445
16:31:30	30.029	30.527	29.884	30.352	29.765	30.735	50.617	46.506	51.759	49.559	47.742	52.769	29.667	29.784	35.015	48.625	-0.06445
16:32:00	30.002	30.53	29.857	30.354	29.767	30.708	50.619	46.537	51.703	49.506	47.744	52.771	29.61	29.786	34.988	48.627	-0.06445
16:32:30	30.037	30.507	29.864	30.331	29.744	30.744	50.598	46.543	51.68	49.54	47.75	52.72	29.646	29.793	34.994	48.633	-0.06445
16:33:00	30.037	30.565	29.893	30.331	29.744	30.744	50.625	46.543	51.68	49.568	47.778	52.662	29.646	29.793	34.994	48.633	-0.06322
16:33:30	30.07	30.569	29.896	30.364	29.777	30.776	50.629	46.547	51.713	49.599	47.809	52.695	29.649	29.796	35.027	48.637	-0.06445
16:34:00	30.01	30.537	29.865	30.332	29.745	30.745	50.599	46.486	51.624	49.541	47.752	52.606	29.647	29.794	34.966	48.606	-0.06322
16:34:30	30.043	30.541	29.839	30.336	29.749	30.72	50.63	46.461	51.599	49.517	47.755	52.61	29.651	29.769	34.94	48.61	-0.06322
16:35:00	30.022	30.549	29.906	30.374	29.787	30.757	50.611	46.469	51.607	49.553	47.791	52.589	29.688	29.835	34.978	48.647	-0.06322
16:35:30	30.018	30.517	29.874	30.312	29.754	30.754	50.607	46.436	51.546	49.521	47.76	52.557	29.656	29.773	34.916	48.585	-0.06322
16:36:00	30.049	30.547	29.904	30.371	29.784	30.755	50.608	46.438	51.576	49.523	47.817	52.558	29.657	29.804	34.946	48.587	-0.06322
16:36:30	30.016	30.544	29.901	30.339	29.752	30.781	50.605	46.464	51.573	49.52	47.814	52.526	29.654	29.801	34.914	48.584	-0.06322
16:37:00	30.016	30.544	29.901	30.339	29.752	30.752	50.605	46.493	51.602	49.492	47.786	52.526	29.654	29.771	34.914	48.584	-0.06322
16:37:30	30.023	30.551	29.908	30.346	29.788	30.759	50.584	46.5	51.609	49.499	47.793	52.562	29.661	29.778	34.95	48.561	-0.06322
16:38:00	29.991	30.49	29.846	30.314	29.756	30.697	50.554	46.41	51.548	49.468	47.762	52.501	29.629	29.746	34.889	48.559	-0.06322
16:38:30	29.996	30.523	29.822	30.289	29.731	30.731	50.558	46.531	51.553	49.556	47.794	52.621	29.633	29.751	34.893	48.65	-0.06322
16:39:00	29.996	30.494	29.851	30.289	29.702	30.731	50.586	46.734	51.668	49.612	47.822	52.852	29.633	29.78	34.922	48.737	-0.06322
16:39:30	30.032	30.559	29.887	30.325	29.767	30.767	50.676	47.031	51.935	49.813	47.913	53.264	29.669	29.787	34.988	48.976	-0.06199
16:40:00	29.97	30.497	29.825	30.292	29.734	30.705	50.728	47.347	52.22	49.949	47.937	53.752	29.607	29.754	34.955	49.175	-0.06322
16:40:30	29.974	30.532	29.888	30.326	29.739	30.739	50.9	47.73	52.572	50.149	48.082	54.394	29.641	29.817	35.019	49.469	-0.06199
16:41:00	30.035	30.562	29.89	30.357	29.77	30.77	51.096	48.167	53.093	50.485	48.224	55.089	29.672	29.819	35.079	49.79	-0.06199

Results of testing full scale building

Timestamp	Time (minutes)	s1t (degC)	s1m (degC)	s1b (degC)	s2t (degC)	s2m (degC)	s2b (degC)	s3t (degC)	s3m (degC)	s3b (degC)	s1s2m (degC)	s2s3t (degC)	s3w1b (degC)	s3w1t (degC)	s3w1m (degC)	pyranometer (W/m2)	Radiation (W/m2)	w1t (degC)	w1m (degC)	w1b (degC)	w2t (degC)	w2m (degC)	w2b (degC)	n1t (degC)	n1m (degC)	n1b (degC)	n2t (degC)	n2b (degC)	n2m (degC)	Orig Win (deg
00:00.0	0	23.45	23.849	23.944	23.321	23.776	24.836	23.663	23.927	24.343	23.554	23.073	24.105	23.537	23.732	903.02	1401.9	23.355	23.568	24.187	22.813	22.986	24.083	23.034	23.047	24.027	22.878	23.936	23.23	23
00:00.0	10	23.913	24.325	24.472	23.848	24.264	25.289	23.909	24.316	24.762	23.969	23.514	24.537	23.792	23.814	604.56	1337.3	23.722	23.983	24.597	23.454	23.575	24.632	23.501	23.627	24.593	23.449	24.502	23.744	23
00:00.1	20	24.334	24.754	24.866	24.191	24.693	25.666	24.325	24.862	25.303	24.572	24.079	25.039	24.161	24.317	742.28	674.07	24.079	24.481	25.096	23.832	24.191	25.195	23.97	24.182	25.113	23.975	25.044	24.261	23
10:00.1	30	24.791	25.18	25.309	24.669	25.12	26.005	24.778	25.254	25.686	25.011	24.548	25.444	24.687	24.791	594.64	816.08	24.496	24.847	25.487	24.301	24.618	25.543	24.431	24.6	25.53	24.379	25.448	24.669	24
20:00.1	40	25.304	25.663	25.758	25.135	25.585	26.371	25.101	25.529	25.926	25.352	24.884	25.762	24.967	25.161	591.26	653.39	24.724	25.075	25.685	24.62	24.906	25.818	24.703	24.867	25.767	24.659	25.736	25.135	25
30:00.1	50	25.592	25.994	26.076	25.488	25.89	26.654	25.51	25.916	26.326	25.773	25.337	26.154	25.402	25.665	554.96	667.03	25.129	25.471	26.08	25.043	25.332	26.205	25.099	25.25	26.132	25.034	26.132	25.401	25
40:00.1	60	25.978	26.324	26.449	25.835	26.198	26.954	25.913	26.341	26.729	26.246	25.827	26.621	25.788	26.112	530.65	867.18	25.589	25.909	26.466	25.498	25.753	26.57	25.533	25.671	26.47	25.498	26.479	25.822	25
50:00.1	70	26.244	26.559	26.705	26.075	26.434	27.154	26.11	26.546	26.917	26.49	26.114	26.749	25.946	26.196	855.86	626.43	25.669	25.989	26.511	25.574	25.837	26.584	25.626	25.751	26.524	25.574	26.516	25.773	25
00:00.1	80	26.397	26.756	26.903	26.242	26.635	27.403	26.328	26.773	27.144	26.726	26.389	26.971	26.195	26.527	1620.8	1168.2	26.009	26.32	26.838	25.78	26.03	26.721	25.84	25.948	26.713	25.81	26.721	25.926	2
10:00.1	90	26.578	27.019	27.101	26.466	26.889	27.631	26.518	26.997	27.359	26.958	26.591	27.062	26.341	26.639	465.76	664.24	26.199	26.557	27.001	26.108	26.345	26.941	26.186	26.285	26.941	26.151	26.98	26.289	25
20:00.1	100	26.783	27.189	27.4	26.667	27.046	27.827	26.572	27.046	27.4	27.016	26.666	27.141	26.442	26.766	332.16	517.68	26.174	26.559	27.003	26.113	26.377	26.982	26.222	26.351	27.038	26.226	27.072	26.481	26
30:00.1	110	27.078	27.423	27.656	26.919	27.277	28.048	26.953	27.389	27.708	27.384	27.061	27.54	26.72	27.113	750.11	410.27	26.409	26.78	27.164	26.323	26.612	27.212	26.426	26.573	27.272	26.426	27.272	26.625	26
40:00.1	120	27.192	27.555	27.649	27.063	27.391	28.115	27.097	27.516	27.787	27.52	27.231	27.348	26.903	27.184	620.08	949.7	26.696	27.041	27.408	26.605	26.856	27.438	26.679	26.787	27.486	26.704	27.499	26.838	26
50:00.1	130	27.374	27.758	27.973	27.231	27.568	28.262	27.223	27.697	28.025	27.741	27.46	27.495	27.093	27.421	185.05	475.98	26.912	27.253	27.542	26.856	27.055	27.59	26.929	27.02	27.628	26.934	27.684	27.093	26
00:00.1	140	27.718	27.99	28.292	27.516	27.8	28.425	27.533	27.9	28.231	27.977	27.736	27.964	27.434	27.822	210.26	192.84	27.11	27.469	27.675	27.054	27.261	27.831	27.123	27.21	27.831	27.128	27.869	27.382	2
10:00.1	150	27.88	28.139	28.324	27.703	27.936	28.513	27.708	28.014	28.38	28.169	27.979	28.302	27.656	28.221	270.47	207.25	27.285	27.583	27.794	27.22	27.41	28.048	27.289	27.332	27.966	27.289	28.044	27.501	27
20:00.1	160	28.128	28.197	28.425	27.792	28.003	28.442	27.805	28.089	28.451	28.244	28.089	28.541	27.762	28.447	147.09	192.2	27.408	27.697	27.882	27.391	27.542	28.175	27.382	27.412	28.124	27.382	28.149	27.783	27
30:00.1	170	28.405	28.517	28.715	28.121	28.297	28.646	28.125	28.362	28.694	28.577	28.431	28.956	28.19	28.866	258.94	194.71	27.767	28.005	28.185	27.724	27.867	28.466	27.707	27.703	28.332	27.681	28.418	27.97	28
40:00.1	180	28.588	28.635	28.82	28.343	28.399	28.738	28.308	28.511	28.807	28.661	28.614	29.203	28.299	29.083	287.58	223.83	27.967	28.183	28.355	27.955	28.049	28.562	27.89	27.83	28.51	27.838	28.717	28.131	2
50:00.1	190	28.641	28.688	28.843	28.447	28.499	28.731	28.391	28.606	28.89	28.744	28.71	29.239	28.404	29.153	163.64	199.51	28.085	28.275	28.443	27.926	28.029	28.512	27.848	27.796	28.365	27.809	28.499	28.033	27
00:00.1	200	28.797	28.754	28.896	28.474	28.56	28.745	28.302	28.543	28.806	28.689	28.724	29.266	28.328	29.184	170.28	168.79	28.069	28.237	28.392	28.073	28.125	28.56	27.961	27.897	28.452	27.914	28.534	28.22	28
10:00.1	210	28.536	28.445	28.802	28.544	28.574	28.798	28.54	28.699	28.944	28.755	28.992	29.344	28.514	29.375	212.07	286.59	28.242	28.406	28.561	28.242	28.299	28.729	28.131	28.049	28.596	28.07	28.729	28.303	28
20:00.1	220	28.656	27.907	28.902	28.583	28.592	28.76	28.583	28.708	28.97	28.751	29.091	29.478	28.514	29.426	265.78	231.14	28.269	28.416	28.553	28.273	28.325	28.725	28.161	28.071	28.596	28.071	28.665	28.385	28
30:00.1	230	28.951	28.443	28.938	28.546	28.611	28.731	28.602	28.748	28.981	28.925	29.105	29.509	28.559	29.493	92.697	203.08	28.296	28.421	28.563	28.292	28.37	28.74	28.158	28.094	28.58	28.085	28.568	28.563	28
40:00.1	240	28.77	28.705	28.933	28.606	28.645	28.636	28.636	28.748	28.968	28.985	29.131	29.681	28.516	29.509	63.994	73.954	28.18	28.283	28.425	28.219	28.257	28.597	28.038	27.986	28.464	27.956	28.49	28.378	28
50:00.1	250	28.76	28.782	28.962	28.601	28.618	28.519	28.631	28.696	28.928	29.018	29.139	29.637	28.566	29.714	44.635	58.421	28.282	28.399	28.51	28.342	28.373	28.665	28.174	28.071	28.515	28.08	28.549	28.855	28
00:00.1	260	28.964	28.823	28.947	28.603	28.595	28.435	28.612	28.689	28.904	28.986	29.119	29.725	28.65	29.76	27.264	35.894	28.297	28.405	28.487	28.259	28.25	28.504	28.069	27.927	28.349	27.923	28.422	28.345	28
10:00.1	270	28.837	28.772	28.897	28.514	28.523	28.29	28.531	28.6	28.802	28.948	29.073	29.821	28.553	29.761	14.387	19.189	28.29	28.329	28.402	28.329	28.303	28.501	28.122	27.985	28.294	28.058	28.424	28.463	28
20:00.1	280	28.985	28.826	28.955	28.593	28.58	28.331	28.572	28.649	28.813	28.959	29.122	29.75	28.567	29.793	3.6779	8.1875	28.327	28.387	28.421	28.369	28.374	28.49	28.232	28.029	28.266	28.15	28.369	28.572	28
30:00.1	290	28.673	28.729	28.802	28.51	28.462	28.2	28.471	28.57	28.682	28.845	29.022	29.73	28.501	29.73	-0.4301	1.9379	28.243	28.29	28.316	28.178	28.174	28.247	28.058	27.838	28.006	27.972	28.105	28.174	2
40:00.1	300	28.623	28.546	28.666	28.348	28.339	27.982	28.335	28.391	28.528	28.589	28.842	29.53	28.391	29.586	-1.4097	-1.0858	28.072	28.107	28.128	28.128	28.133	28.223	28.064	27.81	27.986	27.982	28.137	28.331	2
50:00.1	310	28.459	28.424	28.48	28.084	28.158	27.843	28.149	28.274	28.373	28.527	28.704	29.271	28.02	29.323	-3.4049	-2.6032	27.869	27.869	27.861	27.912	27.874	27.938	27.843	27.55	27.688	27.774	27.826	28.282	28
00:00.1	320	28.384	28.397	28.448	28.139	28.147	27.794	28.031	28.117	28.229	28.358	28.56	29.231	28.057	29.342	-3.3673	-3.5794	27.859	27.846	27.842	27.949	27.876	27.936	27.781	27.557	27.704	27.738	27.902	27.975	28
10:00.1	330	28.126	28.19	28.259	27.928	27.945	27.626	27.988	28.066	28.143	28.298	28.474	29.097	27.971	29.235	-2.6232	-2.6322	27.799	27.777	27.76	27.846	27.803	27.82	27.721	27.476	27.592	27.678	27.682	27.954	28
20:00.1	340	28.094	27.986	28.042	27.723	27.758	27.469	27.762	27.853	27.943	28.085	28.279	29.078	27.771	29.009	-3.0516	-2.831	27.637	27.607	27.568	27.629	27.594	27.594	27.538	27.284	27.331	27.525	27.547	27.667	27
30:00.1	350	27.704	27.786	27.846	27.558	27.562	27.29	27.601	27.67	27.742	27.928	28.104	28.723	27.614	28.818	-3.014	-3.0549	27.497	27.428	27.39	27.351	27.269	27.277	27.213	26.998	26.997	27.217	27.148	27.273	27
40:00.1	360	27.721	27.781	27.846	27.94	27.532	27.307	27.544	27.652	27.721	27.85	28.074	28.835	27.428	28.624	-3.7581	-3.6278	27.316	27.26	27.225	27.243	27.251	27.256	27.165	26.937	26.993	27.174	27.157	27.191	27
50:00.1	370	27.54	27.6	27.613	27.372	27.329	27.122	27.324	27.467	27.501	27.643	27.893	28.482	27.35	28.547	-3.8759	-2.8781	27.243	27.195	27.178	27.044	27.049	27.057	27.001	26.786	26.803	26.984	26.924	27.075	2
00:00.1	380	27.397	27.402	27.427	27.143	27.186	26.915	27.177	27.255	27.35	27.449	27.755	28.399	27.371	28.374	-5.6372	-4.886	27.048	27.005	26.992	27.014	27.018	27.014	26.945	26.721	26.768	26.949	26.949	27.04	26
10:00.1	390	27.302	27.328	27.349	27.212	27.082	26.832	27.087	27.186	27.233	27.427	27.733	28.296	26.957	28.249	-4.347	-4.8637	26.871	26.798	26.768	26.776	26.811	26.776	26.656	26.505	26.496	26.733	26.626	26.811	26
20:00.1	400	26.985	27.11	27.149	26.985	26.86	26.597	26.929	26.99	27.028	27.187	27.549	28.142	26.886	28.229	-3.4441	-3.3579	26.752	26.727	26.679	26.593	26.572	26.571	26.481	26.326	26.287	26.511	26.429	26.563	2
30:00.1	410	26.964	26.951	26.96	26.787	26.706	26.417	26.735	26.818	26.874	27.033	27.433	27.85	26.792	28.023	-4.149	-4.3326	26.615	26.55	26.511	26.386	26.404	26.386	26.326	26.123	26.076	26.335	26.266	26.469	26
40:00.1	420	26.771	26.776	26.789	26.707	26.483	26.237	26.384	26.496	26.56	26.664	27.133	27.585	26.461	27.688	-3.1693	-3.4622	26.289	26.242	26.164	26.315	26.211	26.207	26.237	25.965	25.901	26.134	26.052	26.173	26
50:00.1	430	26.95	26.727	26.77	26.597	26.515	26.261	26.532	26.632	26.696	26.808	27.23	27.673	26.808	27.815	-3.2086	-3.3601	26.429	26.356	26.309	26.334	26.33	26.304	26.209	26.102	26.024	26.265	26.102	26.282	26
00:00.1	440	26.397	26.462	26.518	26.263	26.285	26.078	26.117	26.251	26.337	26.496	26.901	27.31	26.212	27.469	-3.171	-2.5134	26.1	26.018	25.983	26.074	26.026	25.979	25.94	25.729	25.686	25.945	25.72	25.983	2
10:00.1	450	26.337	26.281	26.307	26.225	26.052	25.841	25.962	26.065	26.117	26.259	26.686	27.112	26.013	27.211	-3.1318	-3.9725	25.858	25.806	25.759	25.815	25.806	25.755	25.694	25.535	25.44	25.75	25.604	25.819	25
20:00.1	460	25.878	26.085	26.116	26.072	25.857	25.676	25.87	26.004	26.068	26.18	26.62	27.037	25.926	27.149	-2.2324	-2.7191	25.827	25.749	25.706	25.633	25.572	25.577	25.516	25.357	25.309	25.559	25.322	25.602	25
30:00.1	470	25.881	26.054	26.071	25.929	25.817	25.64	25.769	25.83	25.911	25.998	26.433	26.829	25.786	26.911	-3.4441	-2.8927	25.666	25.593	25.541	25.61	25.567	25.541	25.45	25.334	25.234	25.536	25.286	25.571	2
40:00.1	480	25.789	25.815	25.858	25.854	25.6	25.44	25.634	25.759	25.802	25.94	26.32	26.681	25.569	26.656	-1.094	-1.5047	25.414	25.358	25.319	25.38	25.384	25.341	25.25	25.121	25.013	25.332	25.043	25.423	25
50:00.1	490	25.49	25.65	25.667	25.464	25.409	25.283	25.434	25.581	25.633	25.659	26.09	26.37	25.391	26.378	-0.9779	-1.0747	25.184	25.158	25.115	25.154	25.137	25.136	25.046	24.955	24.847	25.132	24.886	25.171	25
00:00.1	500	25.46	25.425	25.425	25.257	25.184	25.063	25.196	25.365	25.417	25.455	25.857	26.119	25.3	26.206	-1.6828	-1.3703	25.119	25.119	25.054	25.067	25.123	25.067	25.011	24.899	24.765	25.054	24.821	25.011	25
10:00.1	510	25.171	25.369	25.334	25.222	25.119	25.019	25.226	25.274	25.326	25.399	25.762	25.968	25.24	26.128	-1.6043	-1.6963	25.067	25.045	24.989	25.05	25.063	24.985	25.02	24.83	24.665	25.015	24.808	25.119	25
20:00.1	520	25.02	25.12	25.102	24.93	24.887	24.821	24.817	24.951	24.986	25.016	25.396	25.633	24.908	25.797	-0.9779	-0.7247	24.714	24.714	24.67	24.757	24.735	24.653	24.731	24.515	24.355	24.683	24.394	24.792	24
30:00.1	530	24.873	24.912	24.898	24.734	24.674	24.626	24.661	24.743	24.799	24.778	25.171	25.408	24.821	25.554	-1.3312	-1.511	24.488	24.497	24.454	24.553	24.536	24.475	24.449	24.32	24.151	24.454	24.259	24.614	24
40:00.1	540	24.692	24.722	24.696	24.519	24.488	24.449	24.501	24.562	24.614	24.648	24.968	25.192	24.549	25.352	-1.4097	-1.4825	24.35	24.311	24.276	24.368	24.359	24.276	24.234	24.143	23.983	24.294	24.052	24.311	24
50:00.1	550	24.735	24.713	24.679	24.566	24.428	24.437	24.601	24.644	24.666	24.726	25.041	25.248	24.657	25.417	-1.5275	-1.6145	24.437	24.411	24.372	24.338	24.299	24.217	24.234	24.087	23.949	24.229	24.044	24.338	24
00:00.1	560	24.513	24.526	24.496	24.397	24.289	24.25	24.418	24.457	24.479	24.513	24.829	25.027	24.444	25.157	-1.292	-0.9716	24.228	24.207	24.172	24.254	24.237	24.172	24.103	24.03	23.904	24.177	23.999	24.168	24
10:00.1	570	24.287	24.365	24.334	24.338	24.157	24.114	24.226	24.304	24.343	24.351	24.671	24.852	24.304	25.029	-0.9011	-1.17	24.11	24.067	24.027	24.118	24.105	24.04	24.027	23.872	23.777	24.053	23.833	24.17	24
20:00.1	580	24.124	24.232	24.189	24.09	24.004	23.96	24.086	24.177	24.185	24.202	24.518	24.72	24.15	24.871	-1.0974	-1.1703	23.978	23.926	23.895	23.956	23.956	23.9	23.852	23.749	23.662	23.913	23.679	23.913	2
30:00.1	590	24.069	24.095	24.056	23.883	23.858	23.81	23.978	24.018	24.065	24.069	24.389	24.557	24.026	24.717	-0.9404	-1.2464	23.81	23.784	23.749	23.81	23.827	23.771	23.749	23.607	23.52	23.775	23.577	23.935	23

nestamp	n2t (degC)	n2b (degC)	n2m (degC)	Original Window (degC)	n3t (degC)	n3d (degC)	e1t (degC)	e1m (degC)	e1b (degC)	e2m (degC)	cr (degC)	cm (degC)	cl (degC)	pt (degC)	pm (degC)	pb (degC)	Outsite Temp (degC)	O South (deg C)	O East (deg C)	O North (deg C)	Centre Original Room 1 (C)
00:00.0	22.878	23.936	23.23	23.008	22.83	23.481	23.719	23.368	23.507	23.55	22.722	22.757	22.605	24.213	23.39	23.68	22.978	23.977516	23.53140933	23.3477447	23.76101067
00:00.0	23.449	24.502	23.744	23.584	23.328	24.013	24.355	23.909	24.294	24.086	23.181	23.181	23.063	24.835	23.848	24.281	22.724	24.32885867	24.18603133	23.898446	24.32159933
00:00.1	23.975	25.044	24.261	23.949	23.832	24.719	24.862	24.36	24.918	24.633	23.593	23.723	23.753	25.502	24.516	24.853	22.807	24.83025733	24.71356	24.426348	24.957178
10:00.1	24.379	25.448	24.669	24.479	24.245	25.115	25.245	24.791	25.301	24.968	24.141	24.158	24.189	25.75	25.011	25.275	22.696	25.23895267	25.11221467	24.832264	25.34564933
20:00.1	24.659	25.736	25.135	25.044	24.607	25.317	25.503	25.127	25.693	25.287	24.534	24.473	24.482	25.853	25.3	25.537	22.197	25.518686	25.44092667	25.176912	25.56338867
30:00.1	25.034	26.132	25.401	25.081	25.051	25.795	25.92	25.531	26.132	25.631	24.908	24.926	24.947	26.136	25.648	25.985	22.888	25.91733867	25.86124267	25.5224293	25.92315333
40:00.1	25.498	26.479	25.822	25.481	25.481	26.194	26.35	25.922	26.488	26	25.364	25.347	25.394	26.492	26	26.375	23.275	26.32784067	26.253022	25.9331973	26.288938
50:00.1	25.574	26.516	25.773	25.379	25.548	26.248	26.326	25.976	26.494	26.058	25.401	25.418	25.405	26.507	26.062	26.291	23.884	26.524208	26.26514267	25.9540607	26.28665733
00:00.1	25.81	26.721	25.926	25.04	25.779	26.372	26.518	25.81	26.631	26.268	25.654	25.65	25.637	26.829	26.238	26.54	26.238	26.748566	26.3196	26.152544	26.53569667
10:00.1	26.151	26.98	26.289	25.974	26.129	26.596	26.747	26.38	26.868	26.488	25.835	25.896	25.796	27.014	26.376	26.673	23.054	26.958218	26.66479133	26.4733593	26.687732
20:00.1	26.226	27.072	26.481	26.226	26.161	26.779	26.779	26.584	27.146	26.71	26.092	26.057	26.023	27.245	26.597	26.882	23.298	27.00597	26.83627333	26.5929367	26.90818067
30:00.1	26.426	27.272	26.625	26.331	26.409	27.014	26.996	26.634	27.328	26.919	26.357	26.322	26.292	27.372	26.927	27.139	23.46	27.35000067	26.986116	26.7745047	27.14578067
40:00.1	26.704	27.499	26.838	26.562	26.657	27.235	27.283	26.666	27.192	27.067	26.48	26.445	26.29	27.524	26.882	27.201	24.692	27.46683667	27.04697867	27.0138373	27.202348
50:00.1	26.934	27.684	27.093	26.817	26.826	27.383	27.262	26.968	27.521	27.283	26.783	26.666	26.649	27.728	27.145	27.365	23.471	27.64840267	27.25030467	27.237214	27.41274467
00:00.1	27.128	27.869	27.382	27.33	27.141	27.693	27.581	27.451	28.003	27.607	27.115	27.076	27.089	28.051	27.477	27.757	22.452	27.88812067	27.67825533	27.4596573	27.76162
10:00.1	27.289	28.044	27.501	27.466	27.298	27.832	27.815	27.6	28.233	27.682	27.242	27.212	27.224	28.083	27.6	27.893	22.9	28.03369867	27.882894	27.6111847	27.85840867
20:00.1	27.382	28.149	27.783	27.878	27.447	27.899	27.977	27.697	28.421	27.723	27.335	27.322	27.326	28.033	27.697	27.994	21.948	28.11503867	28.03169	27.77164	27.90823133
30:00.1	27.681	28.418	27.97	28.043	27.849	28.306	28.203	27.858	28.474	27.802	27.56	27.517	27.586	28.026	27.832	28.086	22.04	28.39373067	28.17828	28.0231433	27.981472
40:00.1	27.838	28.717	28.131	28.08	28.028	28.343	28.566	28.14	28.76	28.015	27.877	27.83	27.812	28.157	28.101	28.372	21.938	28.54193867	28.488814	28.2288367	28.210356
50:00.1	27.809	28.499	28.033	27.943	27.973	28.223	28.512	28.038	28.641	27.908	27.796	27.779	27.779	27.986	27.969	28.21	21.644	28.629216	28.39659533	28.1136927	28.05487133
00:00.1	27.914	28.534	28.22	28.194	28.168	28.323	28.603	28.16	28.818	27.97	28.069	27.871	27.897	27.97	28.039	28.28	21.132	28.55010333	28.52704933	28.2227713	28.09643467
10:00.1	28.07	28.729	28.303	28.044	28.053	28.454	28.764	28.225	28.789	28.135	28.083	27.984	27.945	28.032	28.152	28.41	21.824	28.72775067	28.59282867	28.3674913	28.19809
20:00.1	28.071	28.665	28.385	28.381	28.204	28.433	28.76	28.239	28.82	28.079	28.049	28.011	28.002	27.98	28.122	28.424	21.455	28.75386867	28.606204	28.3735913	28.17548333
30:00.1	28.085	28.568	28.563	28.525	28.348	28.512	28.667	28.301	29.122	28.085	28.094	28.072	28.068	27.921	28.189	28.43	21.062	28.77704933	28.69660467	28.405384	28.17995533
40:00.1	27.956	28.49	28.378	28.442	28.244	28.361	28.623	28.227	29.015	27.956	28.02	27.973	27.969	27.671	28.076	28.279	20.335	28.78404267	28.62180067	28.2745473	28.00889467
50:00.1	28.08	28.549	28.855	28.932	28.317	28.51	28.704	28.338	29.186	27.998	28.106	28.084	28.075	27.709	28.17	28.385	20.221	28.75138267	28.74255533	28.4945253	28.08825667
00:00.1	27.923	28.422	28.345	28.478	28.237	28.349	28.702	28.194	28.745	27.815	27.979	27.94	27.97	27.474	28.009	28.173	19.906	28.73500867	28.547036	28.2299533	27.88526333
10:00.1	28.058	28.424	28.463	28.544	28.26	28.333	28.626	28.105	28.592	27.722	27.881	27.864	27.864	27.381	27.933	28.036	19.851	28.64464133	28.44096	28.3146367	27.78327933
20:00.1	28.15	28.369	28.572	28.632	28.559	28.348	28.606	28.271	28.907	27.848	28.158	28.064	28.034	27.46	28.064	28.245	19.814	28.67793333	28.59473067	28.363698	27.922924
30:00.1	27.972	28.105	28.174	28.32	28.144	28.144	28.501	28.023	28.592	27.58	27.838	27.825	27.829	27.239	27.83	27.92	19.447	28.574298	28.37198467	28.083578	27.66281533
40:00.1	27.982	28.137	28.331	28.33	28.107	28.141	28.365	27.9	28.602	27.482	27.728	27.732	27.71	27.072	27.741	27.9	19.144	28.41803533	28.28878067	28.1496487	27.57089267
50:00.1	27.774	27.826	28.282	28.446	27.869	27.869	28.097	27.736	28.36	27.274	27.559	27.537	27.533	26.916	27.533	27.654	18.857	28.26522467	28.06424	27.9608653	27.36778533
00:00.1	27.738	27.902	27.975	28.177	27.85	27.79	28.126	27.708	28.457	27.273	27.553	27.549	27.553	26.915	27.518	27.643	18.912	28.12566733	28.09680667	27.8716693	27.35884267
10:00.1	27.678	27.682	27.954	28.148	27.868	27.73	28.087	27.614	28.113	27.157	27.454	27.45	27.467	26.82	27.372	27.493	18.831	28.065612	27.937966	27.7714567	27.228498
20:00.1	27.525	27.547	27.667	27.736	27.586	27.487	27.784	27.383	28.076	26.969	27.258	27.237	27.275	26.659	27.176	27.301	18.66	27.85258	27.747648	27.5798093	27.045442
30:00.1	27.217	27.148	27.273	27.234	27.695	27.17	27.523	27.053	27.467	26.661	26.928	26.89	26.946	26.359	26.851	26.916	18.528	27.67090733	27.34787333	27.2128413	26.70850667
40:00.1	27.174	27.157	27.191	27.169	27.303	27.144	27.411	26.989	27.6	26.648	26.885	26.894	26.928	26.354	26.816	26.881	18.506	27.639054	27.33315933	27.17375	26.683736
50:00.1	26.984	26.924	27.075	27.161	27.127	26.924	27.195	26.803	27.299	26.445	26.686	26.682	26.734	26.139	26.609	26.704	18.127	27.43067533	27.098972	26.9941467	26.48381733
00:00.1	26.949	26.949	27.04	26.975	27.074	26.941	27.225	26.781	27.182	26.397	26.729	26.626	26.678	26.048	26.557	26.626	18.302	27.26081333	27.06263867	26.9794333	26.41017533
10:00.1	26.733	26.626	26.811	26.768	26.69	26.664	27.013	26.522	26.768	26.168	26.444	26.401	26.449	25.832	26.337	26.388	17.941	27.16859933	26.76774	26.723242	26.18551267
20:00.1	26.511	26.429	26.563	26.58	26.567	26.489	26.804	26.296	26.653	25.967	26.231	26.244	26.261	25.644	26.127	26.226	17.638	26.982298	26.584272	26.5009753	25.99900667
30:00.1	26.335	26.266	26.469	26.486	26.326	26.33	26.55	26.18	26.326	25.761	26.054	26.007	26.05	25.428	25.955	26.028	17.766	26.80890333	26.35203533	26.3563807	25.80396333
40:00.1	26.134	26.052	26.173	26.129	26.151	26.103	26.47	25.978	26.164	25.616	25.87	25.858	25.879	25.192	25.763	25.844	17.585	26.47995067	26.20398533	26.119278	25.59985267
50:00.1	26.265	26.102	26.282	26.188	26.252	26.214	26.601	26.024	26.201	25.666	25.972	25.959	25.998	25.338	25.873	25.83	17.785	26.62017	26.27542467	26.2164513	25.680022
00:00.1	25.945	25.72	25.983	25.88	25.863	25.893	26.19	25.733	25.992	25.388	25.634	25.634	25.659	24.986	25.517	25.5	17.461	26.23465333	25.971662	25.882592	25.33432267
10:00.1	25.75	25.604	25.819	25.802	25.729	25.681	25.845	25.487	25.854	25.18	25.444	25.414	25.453	24.787	25.297	25.332	17.414	26.04793467	25.728846	25.7244493	25.13878467
20:00.1	25.559	25.322	25.602	25.659	25.616	25.477	25.672	25.318	25.59	25.002	25.253	25.218	25.249	24.635	25.123	25.162	17.383	25.98060533	25.52634333	25.4946947	24.97365067
30:00.1	25.536	25.286	25.571	25.48	25.8	25.45	25.704	25.316	25.601	24.992	25.213	25.208	25.221	24.564	25.079	25.096	17.439	25.83668333	25.54063733	25.4644367	24.91303267
40:00.1	25.332	25.043	25.423	25.319	25.328	25.246	25.535	25.104	25.457	24.788	25.008	24.996	24.987	24.382	24.866	24.879	17.425	25.731942	25.36519533	25.2659467	24.70879867
50:00.1	25.132	24.886	25.171	25.184	25.102	25.024	25.283	24.882	25.046	24.631	24.821	24.8	24.825	24.203	24.662	24.726	17.459	25.54933533	25.07024667	25.0630747	24.53027267

A	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
Timestamp	St (degC)	Sm (degC)	Sb (degC)	Ct (degC)	Cm (degC)	Cb (degC)	Et (degC)	Em (degC)	Eb (degC)	Inside PCM Panel (C)	Epm (degC)	Epb (degC)	Nt (degC)	Nm (degC)	Nb (degC)	PCM Window (degC)	**Outside Temp (degC)**	PCM South (deg C)	Centre PCM ROOM 2 (C)	East (deg C)	East Panel (deg C)	North (deg C
10:00.0	21.693	22.508	23.328	21.82	22.31517	22.972438	22.157	22.581974	23.485	24.87731	24.00252	24.01103	21.47	22.2582	22.9679	20.8954	**21.5881**	22.5095	22.3693	22.7415	24.2970	22.231
20:00.0	22.02	22.659	23.26	21.941	22.39249	22.988248	22.414	22.729092	23.44	25.00283	24.02286	23.99205	21.534	22.33117	23.01038	20.8764	**21.6086**	22.6465	22.4407	22.8611	24.3392	22.291
30:00.0	22.07	22.722	23.477	22.105	22.50807	23.112864	22.512	22.801328	23.643	25.01319	24.04211	24.03757	21.593	22.42917	22.96798	21.0141	**21.7943**	22.7564	22.5754	22.9855	24.3643	22.330
40:00.0	22.385	23.094	23.835	22.446	22.90084	23.444946	22.77	23.186446	23.822	25.25718	24.28628	24.29932	21.956	22.7741	23.33527	20.9298	**22.017**	23.1046	22.9306	23.2593	24.6143	22.688
50:00.0	22.608	23.098	23.861	22.476	22.91389	23.4491	22.848	23.120246	23.769	25.24396	24.30366	24.29478	22.135	22.8089	23.33073	21.4603	**22.8611**	23.1891	22.9464	23.2458	24.6141	22.758
00:00.0	22.316	23.179	23.898	22.408	22.94216	23.529734	22.815	23.214326	23.933	25.31145	24.38424	24.38405	22.067	22.88976	23.34992	22.7759	**25.5909**	23.1312	22.9601	23.3209	24.6932	22.768
10:00.0	22.565	23.165	23.769	22.569	22.90606	23.554902	22.897	23.120542	23.958	25.31884	24.38729	24.36971	22.293	22.85366	23.35296	21.6581	**21.9344**	23.1662	23.0100	23.3252	24.6919	22.833
20:00.0	22.471	23.062	23.83	22.384	22.89096	23.456812	22.76	23.189236	23.865	25.19048	24.27622	24.27187	22.134	22.88642	23.35603	21.1872	**21.8666**	23.1209	22.9104	23.2712	24.5795	22.792
30:00.0	22.428	23.133	23.949	22.45	22.91825	23.49279	22.844	23.168296	23.905	25.16088	24.24661	24.25095	22.209	22.89631	23.27798	21.5918	**22.6163**	23.1701	22.9537	23.3057	24.5528	22.794
40:00.0	22.578	23.256	23.989	22.53	23.05465	23.594338	22.888	23.252092	23.989	25.23152	24.3479	24.38721	22.372	23.04595	23.38824	21.9123	**23.4671**	23.2744	23.0596	23.3764	24.6555	22.935
50:00.0	22.613	23.247	23.975	22.648	23.07194	23.615966	22.98	23.313252	24.028	25.26634	24.37406	24.42205	22.368	23.04584	23.43162	21.4781	**22.1267**	23.2785	23.1118	23.4404	24.6875	22.948
00:00.0	22.749	23.397	24.042	22.605	23.20414	23.665124	23.025	23.428222	24.068	25.28032	24.37482	24.39239	22.347	23.1648	23.41934	21.3957	**21.5493**	23.3962	23.1581	23.5071	24.6825	22.977
10:00.0	22.794	23.438	24.091	22.75	23.25354	23.744752	23.232	23.507864	24.078	25.26393	24.3843	24.40641	22.61	23.21382	23.53433	21.2168	**21.7606**	23.4410	23.2495	23.6058	24.6849	23.119
20:00.0	23.034	23.529	24.147	22.968	23.34443	23.78741	23.406	23.607628	24.134	25.26708	24.41372	24.44886	22.802	23.32231	23.62086	21.097	**21.2771**	23.5697	23.3665	23.7157	24.7099	23.248
30:00.0	23.185	23.663	24.181	23.076	23.43532	23.825532	23.427	23.650294	24.194	25.20905	24.38191	24.3821	22.954	23.40015	23.68981	20.9204	**21.482**	23.6764	23.4456	23.7569	24.6577	23.347
40:00.0	23.245	23.688	24.149	23.11	23.48241	23.846522	23.483	23.297858	24.245	25.19924	24.39401	24.42462	22.983	23.42531	23.71061	21.4019	**21.3975**	23.6942	23.4796	23.6752	24.6726	23.373
50:00.0	23.409	23.781	24.167	23.207	23.57543	23.895662	23.51	23.75975	24.242	25.18261	24.36434	24.39079	23.072	23.48354	23.69831	20.995	**21.1047**	23.7859	23.5594	23.8371	24.6459	23.417
00:00.0	23.363	23.74	24.161	23.222	23.5513	23.845076	23.582	23.744322	24.205	25.12811	24.3578	24.41051	23.205	23.51197	23.7706	20.9049	**20.6986**	23.7546	23.5396	23.8437	24.6321	23.495
10:00.0	23.494	23.823	24.301	23.214	23.60384	23.827668	23.534	23.704796	24.226	25.106	24.34455	24.35344	23.288	23.57321	23.73996	21.0585	**20.7554**	23.8729	23.5484	23.8217	24.6013	23.533
20:00.0	23.538	23.823	24.187	23.306	23.6084	23.818992	23.6	23.797064	24.24	25.02746	24.31415	24.34476	23.359	23.57342	23.73147	20.9708	**20.8083**	23.8497	23.5778	23.8788	24.5621	23.554
30:00.0	23.657	23.863	24.266	23.403	23.59093	23.854078	23.736	23.788296	24.196	24.95316	24.26589	24.26589	23.429	23.61286	23.74463	20.7292	**20.4088**	23.9285	23.6159	23.9067	24.4950	23.595
40:00.0	23.61	23.82	24.21	23.399	23.61861	23.776466	23.671	23.789698	24.18	24.84955	24.20153	24.23215	23.487	23.58364	23.73714	20.5154	**19.8385**	23.8802	23.5981	23.8802	24.4277	23.602
50:00.0	23.559	23.887	24.299	23.44	23.66826	23.755786	23.651	23.830454	24.137	24.74578	24.09336	24.15025	23.432	23.49716	23.55426	20.4245	**19.743**	23.9151	23.6214	23.8728	24.3298	23.494
00:00.0	23.607	23.883	24.269	23.423	23.58076	23.611578	23.66	23.804404	24.045	24.63228	24.00589	23.9972	23.362	23.47129	23.48433	20.2974	**19.5895**	23.9197	23.5385	23.8365	24.2118	23.439
10:00.0	23.634	23.927	24.081	23.397	23.59427	23.647012	23.555	23.787094	23.993	24.53186	23.8835	23.90996	23.419	23.49349	23.45398	20.1659	**19.5986**	23.8807	23.5461	23.7784	24.1084	23.455
20:00.0	23.701	23.705	24.143	23.403	23.58677	23.586962	23.53	23.744818	23.933	24.43689	23.84122	23.84992	23.42	23.48184	23.45537	20.0441	**19.4151**	23.8499	23.5255	23.7360	24.0427	23.452
30:00.0	23.593	23.737	24.018	23.33	23.51377	23.500726	23.54	23.750472	23.93	24.31557	23.74178	23.75066	23.356	23.30332	23.37347	19.9269	**19.157**	23.7827	23.4481	23.7403	23.9360	23.344
40:00.0	23.593	23.799	23.69	23.19	23.51866	23.378362	23.554	23.70715	23.672	24.18478	23.61508	23.64571	23.291	23.33014	23.30821	19.7206	**18.8316**	23.6940	23.3623	23.6444	23.8152	23.309
50:00.0	23.521	23.64	23.889	23.21	23.35008	23.341572	23.613	23.665834	23.793	24.04275	23.48622	23.57376	23.306	23.27558	23.27123	19.6221	**18.5874**	23.6834	23.3005	23.6907	23.7009	23.284
00:00.0	23.546	23.471	23.611	23.116	23.20374	23.238726	23.528	23.422908	23.625	23.85263	23.37034	23.45808	23.16	23.14227	23.16422	19.5808	**18.5108**	23.5428	23.1862	23.5253	23.5603	23.155
10:00.0	23.255	23.399	23.487	23.018	23.06587	23.206208	23.193	23.315888	23.456	23.74111	23.28506	23.40798	23.114	23.05698	23.11429	19.3238	**18.3548**	23.3802	23.0966	23.3217	23.4780	23.095
20:00.0	23.303	23.377	23.688	22.995	23.0702	23.12297	23.325	23.293744	23.57	23.66623	23.26311	23.38602	23.162	23.00873	23.08344	19.3019	**18.3107**	23.4560	23.0629	23.3961	23.4385	23.084
30:00.0	23.379	23.247	23.629	23.006	23.05007	23.045722	23.169	23.264916	23.467	23.58069	23.23844	23.41411	23.094	22.93148	23.03683	19.3212	**18.2994**	23.4185	23.0341	23.3001	23.4111	23.020
40:00.0	23.118	23.205	23.525	22.925	22.92897	22.973044	23.113	23.135136	23.403	23.43789	23.11338	23.32822	23.03	22.91573	22.97304	19.213	**18.1957**	23.2829	22.9423	23.2171	23.2932	22.973
50:00.0	23.103	23.098	23.41	22.77	22.88341	22.89249	22.993	23.07218	23.318	23.33108	23.07218	23.27832	22.91	22.90554	22.89684	19.1543	**17.9472**	23.2039	22.8485	23.1278	23.2272	22.904
00:00.0	23.035	23.039	23.293	22.706	22.80218	22.81977	23.149	23.021414	23.219	23.17518	22.93365	23.18823	22.89	22.75394	22.80218	19.0726	**17.9933**	23.1223	22.7759	23.1297	23.0990	22.815
10:00.0	22.971	23.036	23.3	22.721	22.8125	22.812876	22.949	23.01868	23.234	23.11533	22.9835	23.26454	22.822	22.77731	22.80398	19.0086	**17.7351**	23.1021	22.7820	23.0671	23.1211	22.801
20:00.0	22.93	22.96	23.215	22.609	22.73214	22.710378	22.785	22.960084	23.079	22.96481	22.88556	23.16227	22.746	22.69259	22.75862	18.8485	**17.4733**	23.0349	22.6840	22.9414	23.0042	22.732
30:00.0	22.851	22.908	23.154	22.505	22.6363	22.614536	22.694	22.772132	22.974	22.8251	22.79843	23.08386	22.641	22.66259	22.68473	18.7393	**17.6109**	22.9712	22.5852	22.8134	22.9025	22.662
40:00.0	22.842	22.82	23.101	22.491	22.63101	22.560814	22.837	22.876566	22.934	22.78028	22.81528	23.03451	22.675	22.62212	22.61341	18.7867	**17.5746**	22.9206	22.5608	22.8826	22.8767	22.636
50:00.0	22.789	22.661	22.802	22.389	22.49459	22.450874	22.644	22.670168	22.863	22.64387	22.70517	22.93766	22.538	22.45958	22.50783	18.619	**17.4287**	22.7506	22.4449	22.7257	22.7622	22.502
00:00.0	22.65	22.711	22.839	22.343	22.47436	22.386754	22.588	22.553268	22.882	22.54475	22.64106	22.85616	22.51	22.43917	22.45242	18.4932	**17.285**	22.7333	22.4013	22.6747	22.6807	22.467
10:00.0	22.589	22.606	22.708	22.409	22.33873	22.321504	22.532	22.50998	22.8	22.43978	22.53193	22.75594	22.418	22.40912	22.38282	18.4232	**17.2107**	22.6344	22.3565	22.6139	22.5759	22.403
20:00.0	22.535	22.517	22.574	22.28	22.30649	22.214326	22.386	22.420604	22.618	22.35929	22.47321	22.67945	22.377	22.30649	22.36819	18.3865	**17.2135**	22.5420	22.2670	22.4748	22.5040	22.350
30:00.0	22.395	22.417	22.496	22.193	22.24994	22.175562	22.334	22.438804	22.456	22.27209	22.40361	22.5968	22.285	22.23688	22.23253	18.4046	**17.1788**	22.4358	22.2062	22.4096	22.4242	22.251
40:00.0	22.403	22.311	22.649	22.127	22.15295	22.095788	22.359	22.310976	22.5	22.22317	22.38554	22.55659	22.276	22.19232	22.19686	18.391	**17.2138**	22.4543	22.1251	22.3900	22.3884	22.221
50:00.0	22.401	22.506	22.568	22.208	22.18574	22.142016	22.238	22.374418	22.524	22.24289	22.41832	22.60716	22.296	22.26901	22.23854	18.2346	**17.2866**	22.4915	22.1785	22.3788	22.4228	22.267
00:00.0	22.257	22.213	22.358	22.059	22.12915	22.036972	22.353	22.26523	22.353	22.12934	22.30914	22.4628	22.199	22.10719	22.13369	18.2749	**17.3051**	22.2756	22.0751	22.3238	22.3004	22.146
10:00.0	22.3	22.208	22.366	22.01	22.04973	21.992752	21.979	22.198874	22.344	22.05844	22.23843	22.3921	22.111	21.99692	22.11124	18.0849	**17.1765**	22.2912	22.0175	22.1740	22.2297	22.073
20:00.0	22.221	22.103	22.379	21.866	21.97114	21.914164	22.077	22.089636	22.23	21.98875	22.18616	22.33984	22.032	21.9931	21.97985	18.0545	**17.1064**	22.2345	21.9171	22.1321	22.1716	22.001
30:00.0	22.097	22.083	22.237	21.89	21.88146	21.864044	21.912	22.030818	22.136	21.91667	22.08779	22.23712	22.013	21.87711	21.89926	17.9647	**17.0519**	22.1391	21.8786	22.0265	22.0805	21.929
40:00.0	22.099	22.213	22.235	21.875	21.88771	21.861584	22.028	22.08533	22.178	21.9055	22.12034	22.24791	22.002	21.87029	21.94923	18.1958	**17.1555**	22.1820	21.8746	22.0971	22.0913	21.940
50:00.0	21.915	22.051	22.108	21.783	21.79606	21.84888	21.845	21.998048	22.038	21.82673	22.02436	22.1737	21.98	21.80931	21.87084	17.9275	**16.9928**	22.0244	21.8093	21.9601	22.0083	21.886
00:00.0	21.953	21.984	21.971	21.725	21.73811	21.725234	21.782	21.927044	22.291	21.76026	21.96661	22.11576	21.813	21.72504	21.80437	17.9577	**16.9436**	21.9695	21.7295	22.0002	21.9475	21.780
10:00.0	21.903	21.956	22.105	21.618	21.67078	21.657522	21.833	21.841926	21.904	21.68819	21.87714	22.02195	21.759	21.67513	21.69709	17.8108	**16.8403**	21.9883	21.6487	21.8596	21.8624	21.710
20:00.0	21.856	21.878	22.141	21.588	21.6979	21.64526	21.834	21.83402	22.01	21.70263	21.87813	22.01405	21.76	21.65852	21.70225	17.9215	**16.8943**	21.9585	21.6438	21.8926	21.8649	21.706