Low Energy, Wind Catcher Assisted Indirect - Evaporative Cooling System for Building Applications

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Abstract

Increased consciousness of the environmental problems has aroused people's interest of renewable energy systems, especially the application of green features in buildings.

The demand for air conditioning / cooling in domestic and non-domestic buildings is rising throughout the world; this increases the reliance on conventional fuels and the global warming effect from greenhouse gas emissions. Passive cooling and energy efficient design can substantially reduce reliance on fuel based heating and cooling. Passive and Hybrid Downdraught Cooling, in different forms, is now technically viable in many parts of the world. This has been established through a combination of research projects.

In some hot arid regions, a major part of the energy consumed consists of air-conditioning requirements. Alternative methods, using passive cooling techniques, can assist in reducing the conventional energy consumption in buildings. Evaporative cooling, which can be tracked back several hundreds of years in ancient Egypt and Persia [1–3], is one of the most effective strategies, because of the enormous latent heat needed for evaporation of water.

Green features are architectural features used to mitigate migration of various air-borne pollutants and transmission of air from outside to indoor environment in an advantageous way [9].

The reduction of fossil fuel consumption and the associated decrease in greenhouse gas emissions are vital to combat global warming and this can be accomplished, in part, by the use of natural ventilation. To assess the performance of several innovative cooling systems devices and to develop improved models for more established technology, quantitative measurement of output was necessary. This was achieved in this study by the development of simply constructed low energy cooling systems which were calibrated by the innovative use of wind and water as a source. These devices were found to be consistent and accurate in measuring the temperature and cooling load from a number of devices. There were some problems in the original evaporative units. Therefore, a number of modifications have to be made to enhance the systems performance. The novel Windcatcher – PEC cooling system was assessed and different cooling loads were achieved.

PUBLICATION

The following articles has been published by the author during preperation of this thesis.

1- **Elzaidabi, A. A**.; Omer, S. A and Riffat, S. B. (September 2007) Development and Experimental Evaluation of Indirect Evaporative Cooling System Employing a Psychometric Energy Core System, SET6th, Chile, Santiago.

2- **Elzaidabi, A. A**.; Omer, S. A and Riffat, S. B. (August 2008) Experimental evaluation of a novel combined Wind catcher - indirect evaporative cooling System for cooling application in buildings, SET7th , Seoul, Korea.

3- **Elzaidabi, A. A**.; Shauli Ma, Omer, S. A and Riffat, S. B. (August 2008) Experimental performance of a novel Liquid Desiccant Dehumidification System. SET7th, Seoul, Korea.

- Other publications during author research period are:

1- **Elzaidabi, A. A**.; Omer, S. A, Design approach for sizing a hybrid fuel cell-solar system for building energy, ATE - 2007- 410R1 (under review).

2- **Elzaidabi, A. A**.; Omer, S. A, (2006) Fuel cells a technology for sustainable renewable energy supply- an approach for a hybrid fuel cell-solar system for building energy, ses.org – Sudan.

3- Garba, M. M., **Elzaidabi A**., Omer, S. and Riffat, S.B, (2008), Environment and Experimental Evaluation of Passive Solar Cooking System for Sustainable Applications, SET7th, Seoul, Korea.

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Abdalla Elzaidabi

Nomenclature

A	Cross sectional area of the duct (m^2)
AC	Air Conditioning
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CFCs	Chlorofluorocarbons
COP	Coefficient Of Performance
c_p	specific heat of the air
DF	Dehumidification Fraction
ERV	energy recovery ventilators
FAFC	Fresh Air Flow Conditioning
HCFCs	hydro chlorofluorocarbons
h_{fg}	heat of vaporization of water
h_{in}	Enthalpy at inlet (kj/kg)
h_{out}	Enthalpy at outlet (kj/kg)
HVAC	Heating, ventilation and air conditioning
LHR	latent heat ratio
LSR	latent to sensible ratio
$\dot{m}$	mass flow rate (kg/s)
m_{vent}	mass flow rate of ventilation air
Q_c	cooling capacity (kilowatts)
$Q_{vent, sen}$	sensible ventilation load
$Q_{vent, lat}$	latent ventilation load

SHR	sensible heat ratio
$T_{\mathrm{db,in}}$	dry bulb temperatures of the air at the inlet
$T_{\mathrm{db,out}}$	dry bulb temperatures of the air at the outlet
T_{OA}	outdoor air temperature
$T_{\mathrm{wb,in}}$	the wet bulb temperature of the air at the inlet
T_z	building zone temperature
V	air velocity (m/s)
VAV	variable Air Volume
$\mathrm{W_e}$	the electrical energy consumed by the fan and the pump.
W_{OA}	outdoor air humidity ratio
W_z	building zone humidity ratio

Greek Symbols

ρ	*Density of the air (kg/m^3) at ambient temperature.*
η	Enthalpy efficiency(%)

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CHAPTER 1

INTRODUCTION

1.0 Introduction

The way energy is produced and used play a major role on the amount of pollution emitted to the environment.

Greenhouse gas emissions come mostly from energy use. These are driven largely by economic growth, fuel used for electricity generation, and weather patterns affecting heating and cooling needs.

The largest single source of atmospheric carbon dioxide (CO2) is the burning of fossil fuel (coal, oil and gas), which currently accounts for 80% of the annual emission of CO2 into the atmosphere.

Environmental concerns, about the effects of the emissions from the burning of these fuels have lead to establishment of protocols such as the Kyoto agreements, aimed at reducing the amount of amount of CO_2 [1]. Most of these emissions consist of oxides of nitrogen (NO_2), carbon monoxide (CO), and oxides of sulphur [2]. Other pollutants include carbon dioxide, which is of particular concern due to its being one of the green gases, which may create unbalance in the natural green house gas composition thus leading to global warming and climate change. In an attempt to reduce atmospheric emissions of carbon dioxide, various new technologies and fuel sources are being explored.

Different methods of power generation have been developed over the years in a quest to satisfy the ever growing energy requirement for domestic and commercial applications. Renewable energies such as wind power, solar energy, geothermal, the tides and waves are among other energy sources being considered.

Buildings account for about 40 percent of energy consumption in most developed countries and this consumption produces enormous emissions of CO_2 which cause indoor pollutants and lead to sick building syndrome that affect health and comfort of building occupants.

Recent research indicates that pollutant concentration levels in the air inside buildings may be 2 to 5 times higher than the air outside and as people spend 75 to 90 percent of their time indoors, the quality of the indoor air is an issue of major concern. Indoor Pollutants are generated from many sources e.g., fireplaces, woodstoves, smoking, cleaning up products, furniture, some building materials, surrounding soil, and ambient air. A major energy demand in the domestic sector includes heating and cooling of buildings.

The challenge then is to design more energy-efficient systems that will decrease the power demands in the face of increased building cooling and heating loads.

Building cooling is one of the main energy consumers and handling larger cooling loads leads to a bigger problem as when removing larger cooling loads, greater demands are placed on power supply, and thus additional greenhouse gases are produced by the power generation plants.

With greater awareness of the need to reduce energy consumption comes a growth of interest in passive cooling or low energy evaporative cooling, particularly as an alternative to air-conditioning.

Low-energy cooling refers to techniques to cool buildings with minimum reliance on air conditioning by using naturally available cooling sources (outdoor air, ground, or water), non-compressive techniques (such as desiccants), and efficient delivery systems (such as radiant cooling combined with displacement ventilation). These strategies are not only energy efficient, but many are also environmentally beneficial because they do not use chlorofluorocarbons

Passive cooling is considered an alternative to mechanical cooling that requires complicated refrigeration systems. Passive cooling reduces the use of fossil fuel and therefore produces less CO2 emission. Employing passive cooling techniques into modern buildings can eliminate mechanical cooling or at least reduce the size and cost of the equipment.

Ventilation and evaporative cooling are often supplemented with mechanical means, such as fans. Even so, they use substantially less energy to maintain comfort compared to refrigeration systems. It is also possible to use these strategies in completely passive systems that require no additional machinery or energy to operate.

Low cost ventilation techniques include a wide range of fresh-air systems that boost indoor air quality such as wind catcher systems which research shows can significantly reduce energy usage for air-conditioning and could boost the overall energy efficiency and greatly benefit the environment.

1.1 The project aims

The general aims of the research are to supply clean and fresh cooled air using renewable energy technologies in order to reduce the concentration of CO2 inside the buildings especially in crowded buildings such as libraries, cinemas and hospitals.

Another aim of the research is to Increase the awareness of energy efficiency in buildings to minimise the consumption of non-renewable energy by using system such as wind catcher for ventilation and cooling, as the Wind catcher system when associated with (PEC) as indirect evaporative cooling system can save large amounts of energy compared to the traditional air ventilation/cooling methods.

1.2 Research objectives

The objectives of the research are to investigate indirect evaporative cooling systems for buildings applications. The systems comprise an indirect evaporative cooling unit utilizing a psychometric energy core (PEC) unit.

The performance of the system is investigated through laboratory testing and use of computational fluid dynamics (CFD) analysis which enabled assessment of the air flow in and around the integrated PEC wind catcher system to be performed.

1.3 Research methodology

Different methods have been used in this study first the research included a review of literature of the aspects that related to this study and this included:

- Review of ventilation in buildings, purposes of buildings ventilation, the types of ventilation, Sick Building Syndrome, Indoor air quality and discussed in particular the natural ventilation concept, it`s advantages over mechanical ventilation, natural ventilation and human thermal comfort and the factors affecting thermal comfort. The literature review helped the research by understanding the issues related to the air properties and the primary methods for improving indoor air quality in buildings.

Evaporative cooling and the performance of psychometric energy core (PEC) have been reviewed and all the aspects related to design parameters and mode of operation has been looked at and these include: direct, indirect and direct-indirect evaporative cooling. The review also covered factors affecting evaporation rate, heat exchanger, the PEC Cooling Pads, factors affecting the indirect evaporative cooling (IEC) performance, the psychometric chart and air properties, cooling load and energy conservation.

Other method used in the research is experimental study and a number of experimental work were carried out; firstly experimental work has been carried out to establish behaviour of the system using different configurations and different sizes of PEC cooling units under different conditions to establish its cooling capacity range and performance.

Based on the results of the PEC experiments a prototype of indirect evaporative cooler has been built and tested.

Another novel indirect evaporative cooler has been built with combination of a modified wind catcher and a diamond shape PEC unit, this PEC-Wind catcher system has been tested at different wind speed, different fan speed and different water flow rate.

The final method used in this research is modelling study where the details of airflow distribution of the integrated PEC-Wind catcher have been investigated using computational fluid dynamics (CFD) analysis to understand the behaviour of the system and the air flow passage.

1.4 Thesis layout

This thesis comprises seven chapters. Chapter one discusses the impact of the environmental pollution on buildings, source of pollution in buildings and how it affects the indoor air quality. The chapter also explains how using an environmentally green feature and natural forms of energy to power the buildings could significantly reduce the use of fossil fuel thus reducing the CO2 emission.

The chapter also presents the proposed area of research as well as aims and objectives of the project. The chapter then concludes with the thesis outline.

Chapters two discusses various concepts relating to ventilation and stress on natural ventilation. Also the chapter outlines the advantages of natural ventilation over the mechanical type of ventilation. The chapter is concluded by a discussion of the natural ventilation strategies.

Chapter three introduces the evaporative cooling techniques and designs, also presents the traditional methods of evaporative cooling as well as describes the Psychrometric chart. The chapter discusses the aspects related to evaporative cooling and explains how the evaporative cooling methods can be used to achieve thermal comfort.

Chapter four explained the psychometric energy core (PEC) and how it works. The chapter also presents an experimental study carried out for indirect evaporative cooling system and discusses how the results of the test led to the building of a new prototype system.

Chapter five present a description and operation of the design of a newly developed evaporation air cooling system comprising a Psychometric Energy Core (PEC) cooling unit integrated with wind catcher technology.
The chapter also presents the computational fluid dynamics (CFD) simulation of the wind catcher PEC system. These include variations of wind speed and different PEC channel widths.

Chapter six presents the results of an experimental work of the novel wind catcher integrated PEC indirect evaporative cooling system. The chapter states the methodology of the test, the tests setups and concludes with a discussion of the results.

Chapter seven presents general discussions of the results including issues relating to environmental evaluation of the systems. The chapter then concludes with suggestions and recommendations for further research.

CHAPTER 2

BUILDING VENTILATION

2.0 Introduction: scope of this chapter

This chapter describes ventilation in buildings in general and emphasises on natural ventilation in comparison to the mechanical ventilation strategies. It also demonstrates the relationship between the natural ventilation and human comfort, including: the definition of human thermal comfort and the factors affecting this.

The chapter also discusses the advantages and disadvantages of natural ventilation and gives an overview of the related heat transfer mechanism, and highlights the role of natural ventilation in improving the thermal comfort conditions.

The chapter concludes by reviewing the wind catcher as one of the natural ventilation techniques and describe the relationship between natural ventilation and the factors affecting thermal comfort.

2.1 Purpose of the Ventilation

Ventilation is generally defined as a supply of outside air into the building’s interior allowing air motion and replacement of stagnant exhaust air by fresh outside air. [3]

According to ASHRAE Standard 62 [4] and the ASHRAE Handbook [5] Ventilation air is the air used for providing acceptable indoor air quality. Ventilation air is necessary to dilute odours and limit the concentration of carbon dioxide and airborne pollutants such as respirable suspended particles (RSPs) and volatile organic compounds (VOCs). Ventilation plays an important role in providing good indoor air quality and thermal comfort for the occupant [6].

The primary aim of ventilation is to preserve the qualities of air and having proper ventilation is important for any building. Maintaining a healthy environment and human comfort are two key reasons for providing ventilation in buildings. Indoor Air Quality (IAQ) deals with the content of interior air that could affect health and comfort of building occupants. The IAQ may be compromised by microbial contaminants (mold, bacteria), chemicals (such as carbon monoxide, radon), allergens, or any mass or energy stressor that can induce health effects, e.g., tobacco smoke, dust particles, biological micro organisms, and other toxic gases. Recent findings [7] have demonstrated that indoor air is often more polluted than outdoor air, although this has not changed the common understanding of air pollution. In fact, indoor air is often a greater health hazard than the corresponding outdoor setting [8].

Lack of ventilation has been claimed to cause sick building syndrome **(SBS)** a combination of ailments (a syndrome) associated with an individual's place of work; typically, but not always, an office building (though there have also been instances of SBS in residential buildings [9,10,11,12,13]. It is reported that many people have complained of symptoms associated with acute discomfort, e.g., eye or throat irritation; headache; dizziness and nausea after spending some time in new buildings or newly renovated housings in recent years. These symptoms are defined as "Sick Building Syndrome". Investigations showed that it is caused by polluted air containing chemicals used in construction materials or furniture, or combustion gas generated by equipment such as heating [14]. Poor air circulation, air tightness in houses and poor ventilation systems designed for energy-saving are believed to be factors as well.

SBS can be cured by boosting the overall turn-over rate in fresh air exchange with the outside air.

A 1984 World Health Organization report into the syndrome suggested up to 30% of new and remodelled buildings worldwide may be linked to symptoms of SBS.

Using ventilation to dilute contaminants, filtration, and source control are the primary methods for improving indoor air quality in most buildings

2.2 Types of buildings ventilation

Buildings may be ventilated through a combination of infiltration and purpose-provided ventilation.

2.2.1 Infiltration

Infiltration is the unintentional or accidental introduction of outside air into a building, typically through cracks, gaps in the building envelope, through use of doors for passage and porous material used in building construction [15]. Infiltration is sometimes called air leakage and the presence of cracks and variety of unintentional openings, their sizes and distribution determine the leakage characteristics of a building and its potential for air infiltration. The distribution of air leakage paths in a building determines the magnitude of wind and stack – driven infiltration and the nature of air flow patterns inside the building. Typical air leakage paths in a residential building are shown in Figure 2.1 and Figure 2.2.

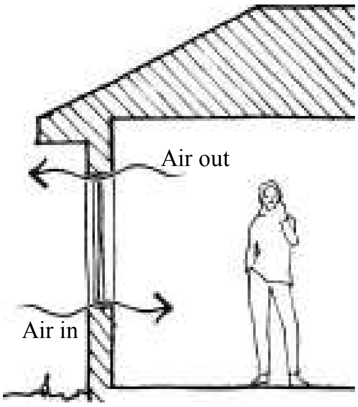


Figure 2.1 infiltrations through window gaps

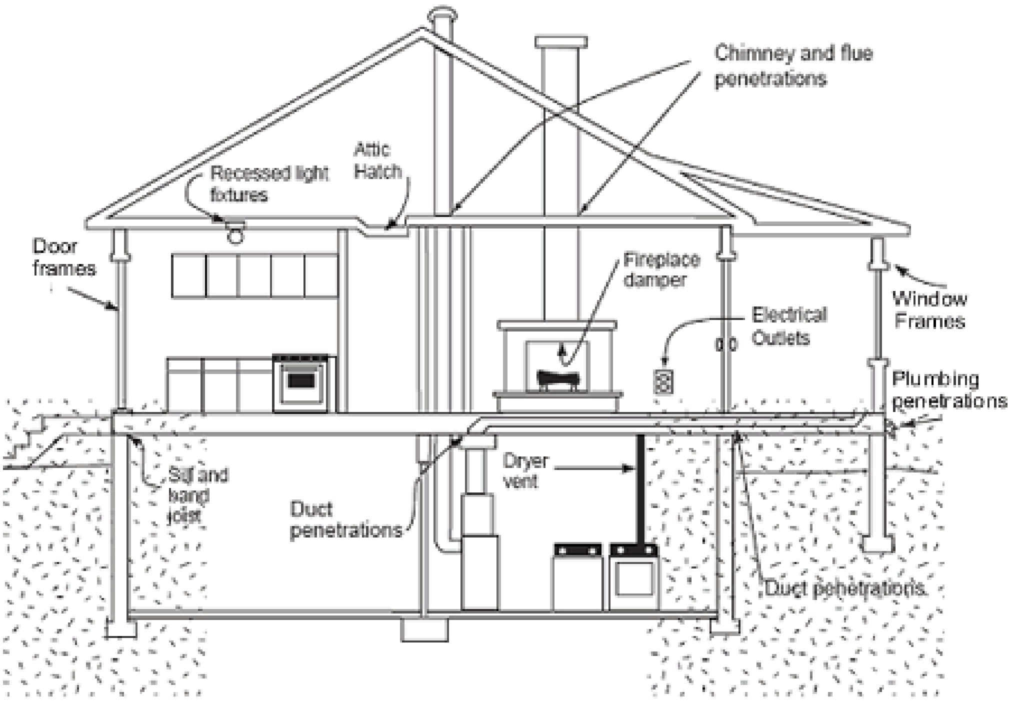


Figure 2.2 Air leakage paths in a building

2.2.2 Purpose-provided ventilation

Purpose-provided ventilation is the controllable air exchange between the inside and outside of a building and can be performed through one of the following:

- Mechanically – where air is brought into the building and extracted through an air handling unit or direct injection to a space by a fan.

- Or using natural ventilation where air enters the building through openable windows, trickle vents, etc; without the use of mechanical systems. Natural ventilation can also be achieved through temperature and pressure differences between spaces.
- Or a mixture of both (mixed mode ventilation) - e.g. where the perimeter of a building is naturally ventilated and the core of the building is mechanically ventilated.

Essentially all ventilations of a building achieve two main functions:

1- Provision of “fresh air” for the occupants.

2- Dilution and/or extraction of contaminants.

In winter ventilation must be combined with heating, to bring the incoming air up to a temperature where the occupants of a building remain comfortable.

In summer, in cooler climates, ventilation can reduce peak temperatures if the incoming air is cooler than the indoor temperatures (this is called ambient cooling).

2.3 Mechanical ventilation

2.3.1 Types of mechanical ventilation

There are many different configurations of mechanical ventilation. Some of the main ones are:

a- Local Exhaust Ventilation (LEV)

This works on the basis of capturing a contaminant at source; e.g., a kitchen extractor hood ducted to the outside. LEV is the most effective way of removing contaminants from a space and is widely used in industry where levels of hazardous emissions must be minimised. The air removed by the LEV is replaced either through infiltration or by another mechanical supply. Figure 2.3 showing schematic of the Local Exhaust Ventilation concepts.

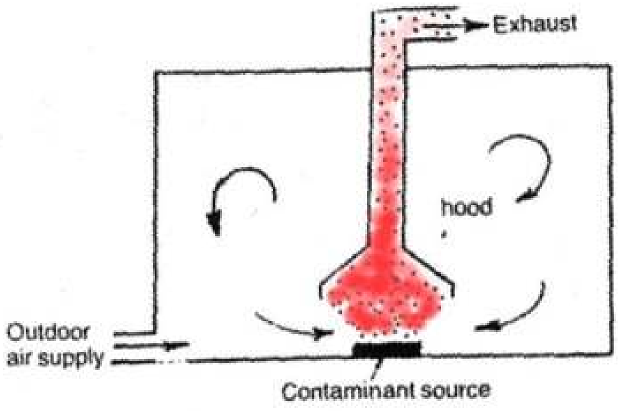


Figure 2.3 Schematic showing Local Exhaust Ventilation concepts

b- Piston Ventilation

In this type of system there is a uni-directional flow of air (usually from ceiling to floor), where the supplied air propels the contaminated air out of the space, the room air being continuously swept by the momentum of the incoming air. This type of ventilation is often used in clean rooms where the supply air is passed through a high efficiency particulate air (HEPA) filter. Turbulence must be kept to a minimum to avoid contaminant dispersal. Figure 2.4 showing the principles of the Piston ventilation.

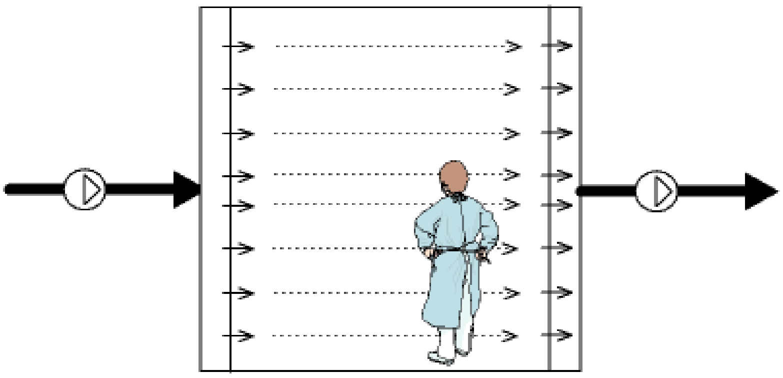


Figure 2.4 Schematic showing the Principles of Piston ventilation

c- Displacement Ventilation

As the name suggests this form of ventilation relies on the displacement of the contaminated room air with the incoming supply air. Displacement ventilation is often used in spaces with high occupancy and high heat loads. The heat loads are used to provide the buoyancy force to drive some of the ventilation: momentum and buoyancy being the two driving forces. In upward displacement ventilation systems, air is supplied at floor level at low velocity (0.3 m/s) which then is heated (by occupants and equipment in the space), it then rises and is extracted at high level as shows in Figure 2.5. The heated air rising above a heat source is known as a thermal ‘plume’ [16].

If the temperature of the surface is less than the surrounding air, the thermal plume will move downwards (e.g. from cold windows) to avoid re-circulation of contaminated air, the incoming volume of supply and extracted air must equal the air flowing in the thermal plumes into the upper part of the room.

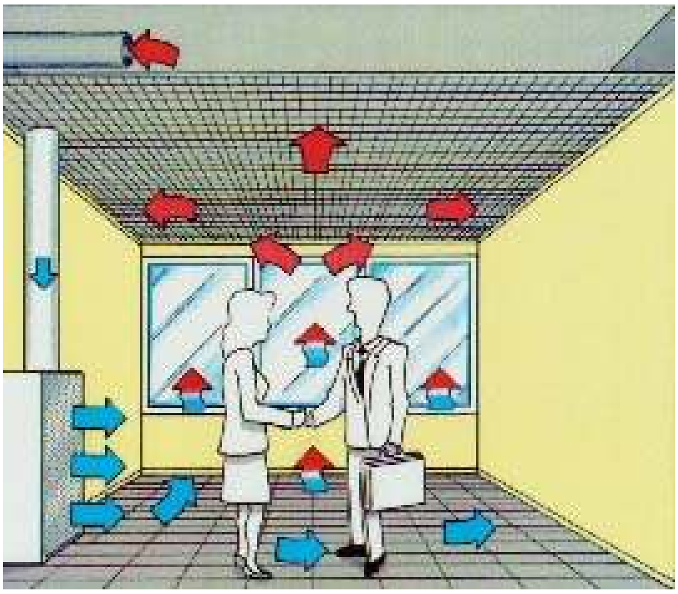


Figure 2.5 Schematic showing the Displacement ventilation operation concepts

d- Mixing Ventilation / Dilution Ventilation

Mixing ventilation requires that the room air and supply air are well mixed through the actions of incoming air momentum and buoyancy. This is the most widely used form of ventilation as it can be used for supplying heating and cooling (air conditioning) as well as fresh air. The supply air is used to dilute the contaminants in the room and is often supplied at high level. Although with this type of ventilation system high contaminant levels can exist close to contaminant sources. Figure 2.6 illustrates the idea of the Mixing ventilation.

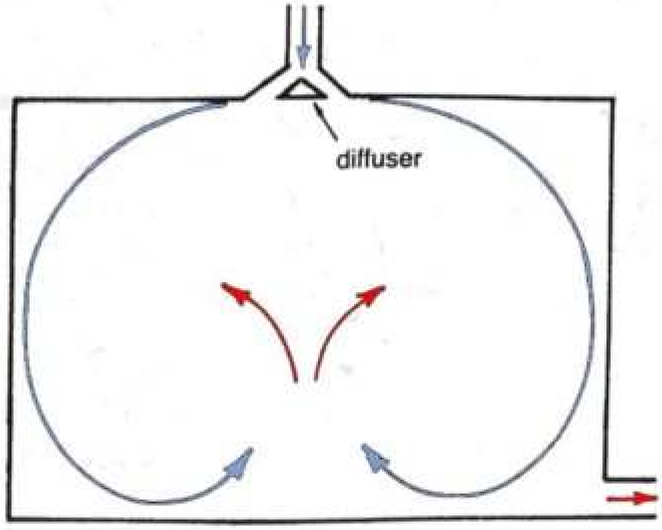


Figure 2.6 Schematic showing the Mixing Ventilation concepts.

2.3.2 Advantages and disadvantages of mechanical ventilation

The mechanical ventilation has advantages and also some disadvantages. Among the advantages of the mechanical ventilation systems are:

1. A precise temperature and flow rates can be set.
2. Mechanical ventilation is also controllable.
3. Does not require window opening.

The disadvantages of mechanical ventilation systems are: -

1. Use a considerable amount of energy.

2. Might be Expensive to install.

3. Produce noise particularly after wear and tear.

4. Requires annual maintenance, as filters have to be cleaned or replaced.

5. It is claimed that it sometimes leads to Sick Building Syndrome [17].

2.4 Natural Ventilation

2.4.1 Natural ventilation concept

Natural ventilation is the process of supplying and removing air by means of purpose-provided aperture (such as openable windows and ventilators) and is driven by natural forces of wind and temperature and pressures difference. Natural ventilation may be divided into two categories, i.e. controlled natural ventilation and infiltration.

1- Controlled natural ventilation is intentional displacement of air through specified openings such as windows, doors, and ventilations by using natural forces (usually by pressures from wind and/or indoor-outdoor temperature differences).

2- Infiltration as mentioned earlier is the uncontrolled flow of air through unintentional openings driven by wind, temperature and pressures difference and/or appliance-induced pressures across the building envelope. In contrast to controlled natural ventilation, infiltration cannot be so controlled and is less desirable than other ventilation strategies, but it is a main source of ventilation in envelope-dominated buildings.

Operation of Natural ventilation depends on wind movement or the difference in temperature from one space to another to move air through a building. Natural

Ventilation has served as an effective passive cooling design strategy to reduce energy used by air-conditioning systems.

Natural ventilation in buildings if can be provided is always an alternative to mechanical ventilation. Natural ventilation relies on two effects to promote air movement: wind pressure and buoyancy.

The most common form of natural ventilation is using openable windows and can be categorized as single sided, single sided double opening or cross flow. Other ventilation types include stack ventilation that uses buoyancy to induce air into the building at a low level and exhaust contaminated air at a higher level.

1- Single Sided Ventilation

Single-sided ventilation typically serves single rooms and thus provides a local ventilation solution. Cold air will stream in, and warm air will stream out again through the same window. Figure 2.7 shows a schematic of single-sided ventilation in a multi-room building. Ventilation airflow in this case is driven by room-scale buoyancy effects, small differences in envelope wind pressures or turbulence. Consequently, driving forces for single-sided ventilation tend to be relatively small and highly variable. Compared to the other alternatives, single-sided ventilation offers the least attractive natural ventilation solution but, nevertheless, a solution that can serve individual offices.

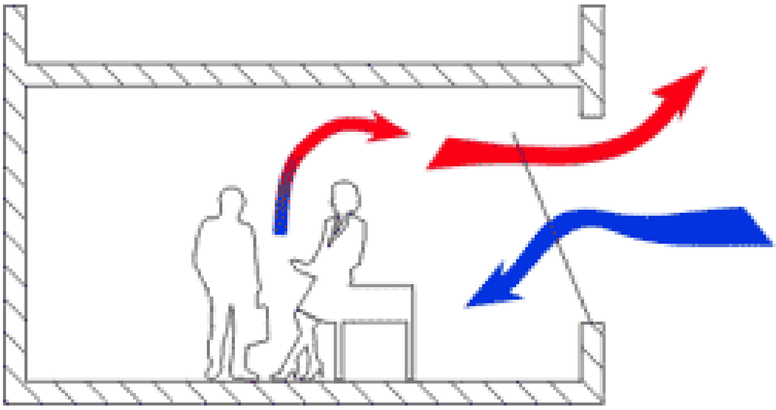


Figure 2.7 Schematic showing single- sided ventilation

2- Single Sided Double Opening

Figure 2.8 illustrates advancement of the single sided principle; to double openings single sided ventilation which is considerably more effective when compared to the single sided single opening ventilation method.

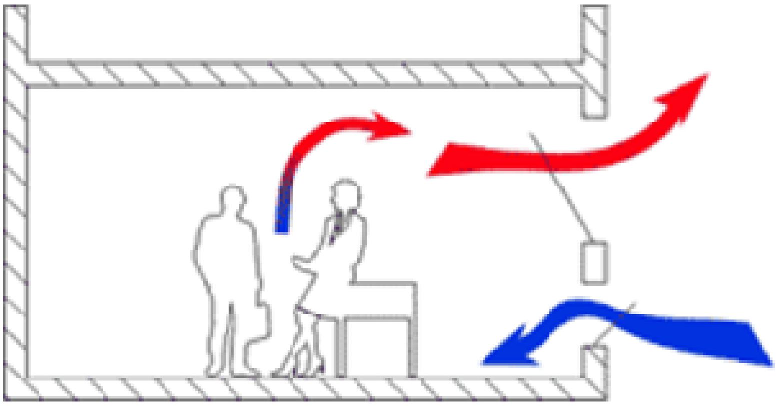


Figure 2.8 Schematic showing single- sided double opening ventilation

3 - Wind-Driven Cross Ventilation

Wind-driven cross ventilation occurs via ventilation openings on opposite sides of an enclosed space. Figure 2.9 shows a schematic of cross ventilation serving a multi-room building, referred to here as global cross ventilation.

The building floor plan depth in the direction of the ventilation flow must be limited to effectively remove heat and pollutants from the space by typical driving forces. A significant difference in wind pressure between the inlet and outlet openings and a minimal internal resistance to flow are needed to ensure sufficient ventilation flow. The ventilation openings are typically windows.

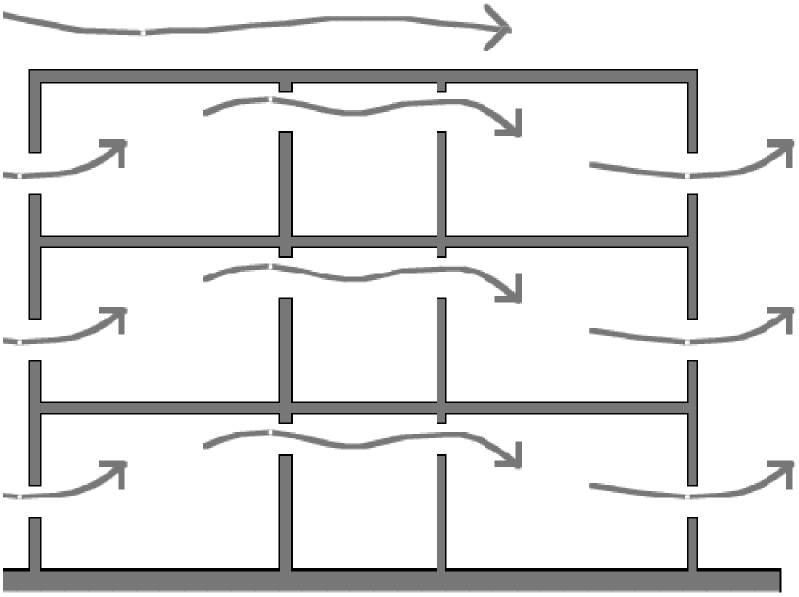


Figure 2.9 Schematic showing a wind-driven cross ventilation arrangement

4 - Buoyancy-Driven Stack Ventilation

Buoyancy-driven stack ventilation relies on density differences to draw cool, outdoor air at low ventilation openings and exhaust warm, indoor air at higher ventilation openings. Figure 2.10 shows a schematic of stack ventilation for a multi-room building. A chimney or atrium is frequently used to generate sufficient buoyancy forces to achieve the required air flow. However, even the smallest wind will induce pressure distributions on the building envelope that will also act to drive airflow.

Indeed, wind effects may well be more important than buoyancy effects in stack ventilation schemes, thus the successful design will seek ways to make full advantage of both.

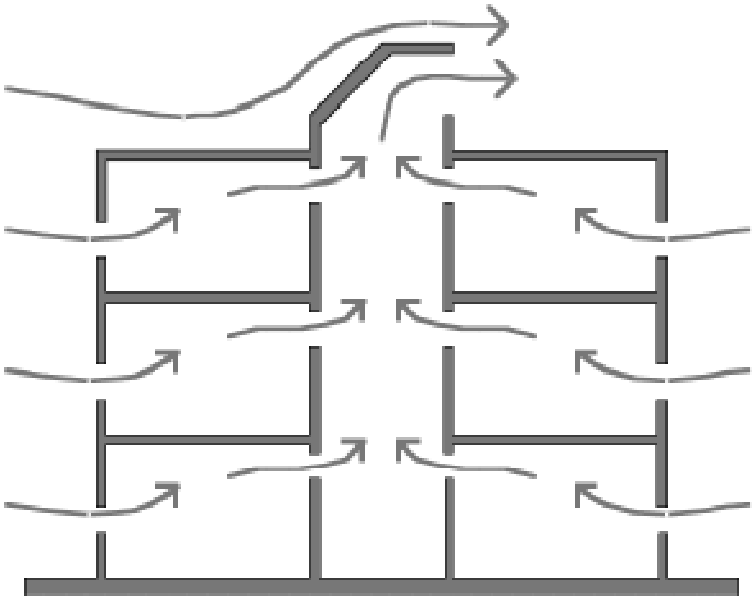


Figure 2.10 stack ventilation

2.4.2 Elaborations of the Basic Strategies

Many built examples employ elaborations of these basic schemes. In some instances these three schemes have been used in a mixed manner in single buildings to handle a variety of ventilation needs. The most notable example of such an approach is the Queens Building of De Montfort University in Leicester, England that has proven, perhaps, to be the most influential of the first generation of the newer naturally-ventilated buildings [18, 19]. See Figure 2.11 for a schematic of mixed local/global and stack/wind ventilation strategy.

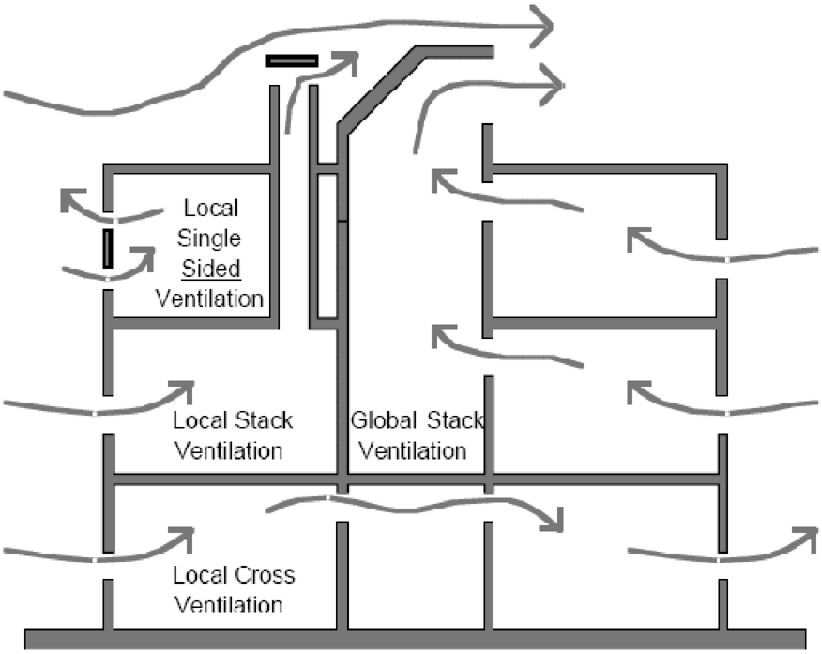


Figure 2.11 Schematic of mixed natural ventilation strategies

In other instances, the elaboration resides in the details of inlet, exhaust, and distribution tactics. One common approach involves the use of in-slab or access-floor distribution of fresh air to provide greater control of air distribution across the building section. Figure 2.12 shows a schematic of stack ventilation with a sub-slab distribution system.

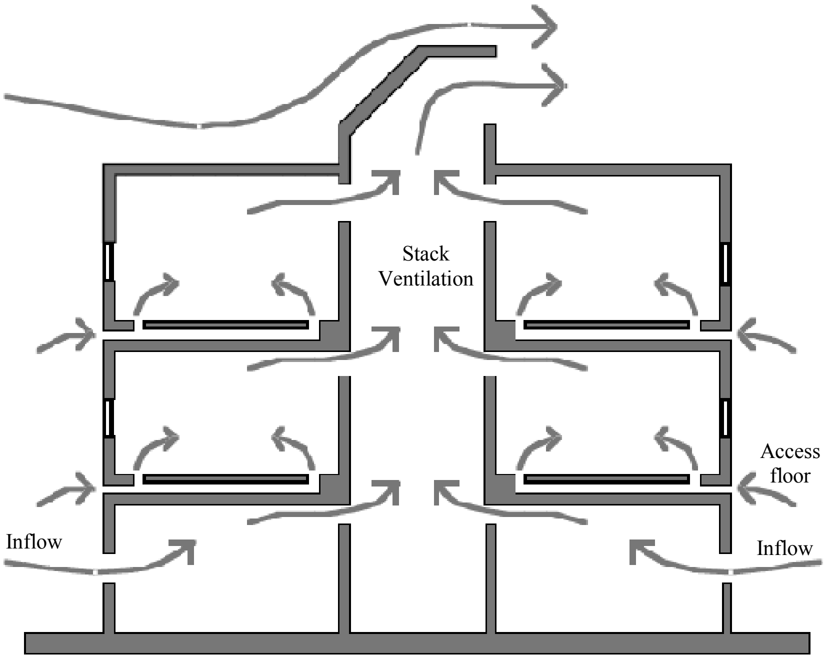


Figure 2.12 Schematic of stack ventilation with sub-slab distribution

Unlike mechanical ventilation, natural ventilation is variable and cannot be used in deep plan buildings or buildings with very high heat gains. However, it has the advantages of not requiring fan power and creating a more natural environment when designed effectively.

2.4.3 Advantages of Natural Ventilation

Naturally ventilated buildings generally use less energy than those with mechanical ventilation. They generate the driving force for air movement by relying on the stack effect, using air passages at differing heights and wind effects, often by ventilating from at least two facades. Buildings relying on natural ventilation can generally provide the following advantages:

- Lower running costs through lower energy consumption
- Require little maintenance and replacements.
- Clean i.e. no environmental pollution and produce little or no noise.
- Relatively inexpensive to install and operate.
- Creation of healthy room conditions as precondition for physical and mental wellbeing.
- Saving in potential investment costs by operating without air conditioning plant.
- Reduction of energy consumption and operating expenses increases the value of a property.

2.4.4 Disadvantages of Natural Ventilation

Despite all the advantages mentioned above natural ventilation still have some disadvantages which include

- Climatically sensitive i.e. not applicable in all climates

- Limited load capacity.
- Need to limit façade load and internal loads.
- Not suitable to all buildings types.
- Less controllability and pre-determined temperatures cannot be set.
- No guarantee of airflow rates/performance.
- Requires correct operation by occupants.

2.5 Natural ventilation and indoor air quality

Indoor air quality as explained earlier has a major influence on the health, comfort and well being of building occupants. Natural ventilation is essential to achieve an acceptable indoor environment; it also helps improvement of the indoor air quality in the building and is necessary for supporting life by maintaining acceptable levels of oxygen in the air, to prevent carbon dioxide (CO_2) from rising to unacceptably high concentrations and to remove odour, moisture and pollution produced internally. [20]

The basis for any natural ventilation strategy is to provide fresh air to the occupants. The amounts of ventilation require is given within BS5295: 1991" the code of practice for ventilation principles" and the recommended amount are listed in Table 2.1.

Type of space	Recommended per person l/s	Minimum per m^2 floor area l/s
Office (open plan)	-	1.3
School class rooms	8	-
Corridors	-	1.3

Table 2.1: Recommended outdoor air supply rates

Ventilation serves three distinct functions. The first is to maintain the quality of the air in the building above a certain minimum level by replacing indoor air by fresh outdoor air. This requirement may be termed health ventilation and should be ensured under all climate conditioned.

The second function is to provide thermal comfort by increasing the heat loss from the body and preventing discomfort due to moist skin; this may be termed thermal comfort ventilation. The third is to cool the structure of the building when the indoor temperature is above that of outdoors, and this may be termed structural cooling ventilation.

2.6 Natural ventilation and passive cooling

Buildings absorb heat build-up during daytime usage through a combination of solar gain, electronic equipment and user occupancy. As the external temperature drops at night, the building can be cooled by partially opening the vents around the building - often called night-cooling or night-purging. The example shown in figure 2.13 uses an atrium design (utilising stack and cross ventilation) for this effect.

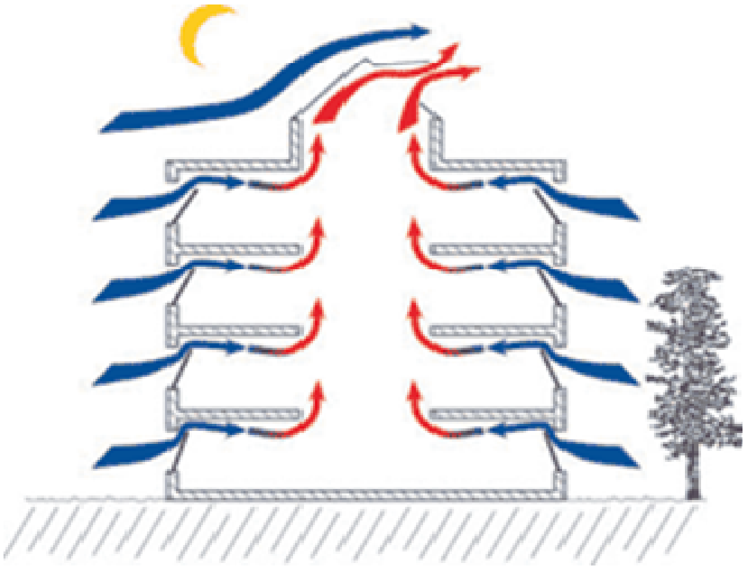


Figure 2.13 Typical passive cooling arrangements

2.7 Solar induce ventilation

This method relies upon the heating of part of the building fabric by solar irradiation resulting in a greater temperature difference, hence larger air flow rates, than in conventional systems which are driven by the air temperature difference between inside and outside [21]. This strategy includes Solar Chimney and Trombe Wall.

2.7.1 Solar Chimney

Several interesting investigations on various aspects of passive ventilation of buildings have been studied in the recent years [22] and there has been a growing interest in another, less obvious application of solar energy—passive cooling or ventilation of buildings based on induced flow of air into and out of the enclosed space [23]. Among the ideas explored were the so-called Solar Chimneys, as an element attached to the building and heated by solar radiation, this has gained significant attention [24].

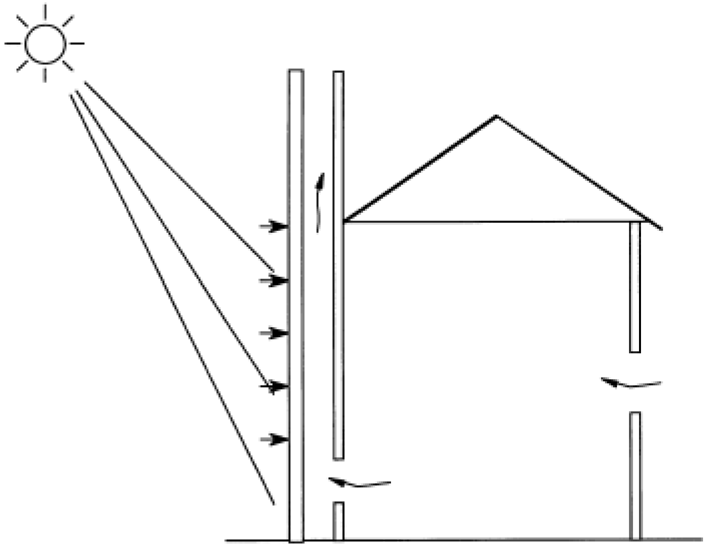


Figure 2.14 Schematic showing ventilation using solar chimney concepts

A solar chimney — often referred to as a thermal chimney — is a way of improving the natural ventilation of buildings by using convection of air heated by passive solar energy. As illustrated in figure 2.14 a simple description of the solar chimney is that of a vertical column utilizing solar energy to enhance the natural stack ventilation through a building.

The solar chimneys have been in use for centuries, particularly in the Middle East, as well as by the Romans.

In its simplest form, the solar chimney consists of a black-painted chimney. During the day solar energy heats the chimney and the air within it, creating an updraft of air in the chimney. The suction created at the chimney's base can be used to ventilate and cool the building [25].

A solar chimney can serve many purposes. Direct gain warms air inside the chimney causing it to rise upwards and draws air in from the bottom. In this way the following air can be used to ventilate a home or an office.

The use of a solar chimney may benefit natural ventilation and passive cooling strategies of buildings thus helping to reduce energy usage, CO_2 emissions and indoor pollution in general. Potential benefits regarding natural ventilation and use of solar chimneys are:

- Improved ventilation rates on still, hot days.
- Reduced reliance on wind and wind driven ventilation.
- Improved control of air flow though a building.
- Improved air quality and reduced noise levels in urban areas.
- Allow ventilation of narrow, small spaces with minimal exposure to external elements.

2.7.2 Trombe wall

The Trombe wall is named after its French inventor, Felix Trombe. A Trombe wall collector consists of a wall of moderate thickness (thermal mass) with a lower and upper opening covered externally by a pane of glass. As illustrated in Figure 2.15 a gap between the glass and the wall allows the heated air to rise. The operation concept of the Trombe wall is quite similar to that of the solar chimney but using different building materials. Trombe wall can be utilised effectively for heating in winter by utilising solar radiation during the day time. The Advantages of the Trombe wall are: there are no moving parts and essentially no maintenance, relatively easy to incorporate into building structure as an internal or external wall and the materials are relatively inexpensive and can reduce heating bills by large amounts [26].

There is a limitation of the Trombe wall as the exterior walls become a heat loss source during extended overcast days.

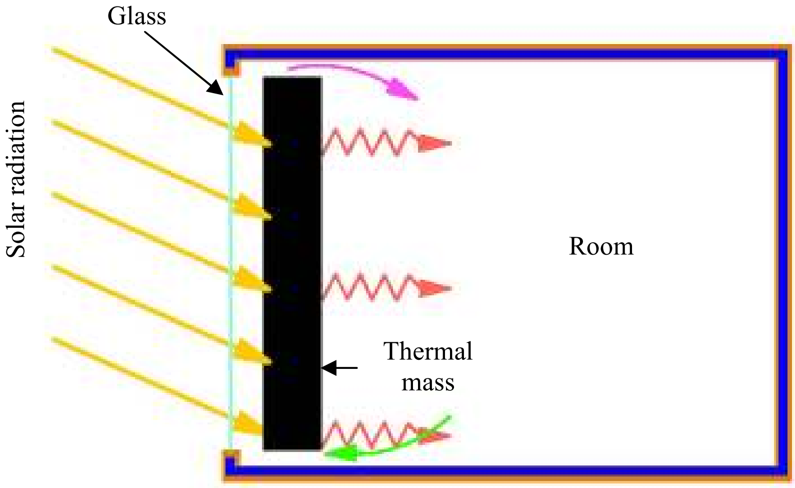


Figure 2.15 The concept of the Trombe wall

2.8 Wind-induced natural ventilation

Wind power technology dates back many centuries. There are historical claims that wind machines which harness the power of the wind date back to the time of the ancient Egyptians [27]. Hero of Alexandria used a simple windmill to power an organ whilst the Babylonian emperor, Hammurabi, used windmills for an ambitious irrigation project as early as the 17th century BC [28].

Wind-induced natural ventilation is increasingly being used in modern buildings to minimise the energy and maintenance costs associated with mechanical ventilation and air-conditioning systems. Wind-driven ventilators can effectively provide natural ventilation in a wide range of buildings, including new build and retrofit, if they are designed correctly.

There are number of wind induced natural ventilation systems, but in this part of the chapter, Wind Cowls and the Wind catchers will be reviewed in more details.

2.8.1 Wind Cowl ventilation

Modern methods of capturing wind energy are through the use of windmills and cowls. A cowl is a hood shaped covering used to increase the draught through a space. The Wind Cowl feature serves a practical role as a green ventilation solution. Wind Cowls are designed and manufactured using steel, Glass-Reinforced Plastic (GRP) and sail cloth, enabling the structure to turn with the wind on a number of steel wheels, whilst downward louvers ventilate the buildings. The cowl allows hot air to be exhausted as required. Figure 2.16 shows a schematic of a wind cowl.

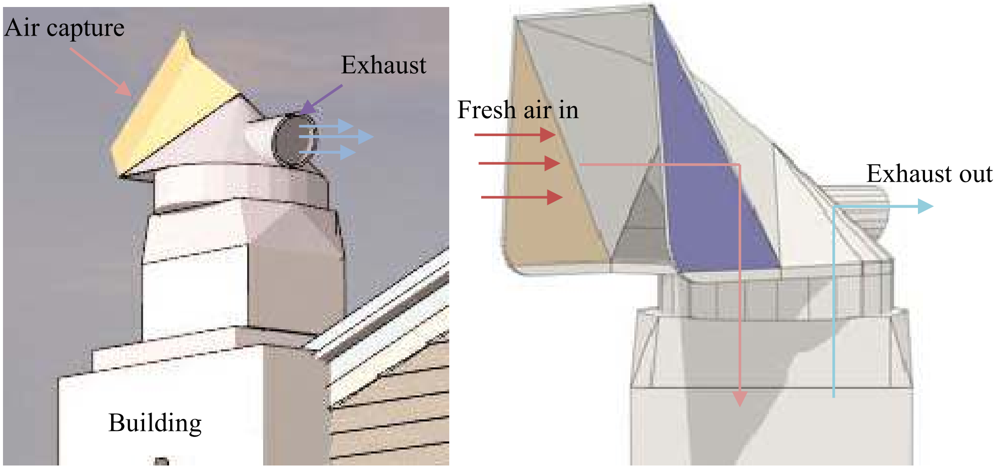


Figure 2.16 schematic of wind cowl

Source (www.zedfactory.com)

The Wind cowl does not lose heat like conventional buildings because the building is airtight. Air can only move in and out through the wind cowls on the roof. Cool air coming in is separated from warm air going out by thin plastic plates or heat exchangers. Heat extracted from the building (bathroom and kitchen) warms the clean air coming into the building. Figure 2.17 presents an example of wind cowl installed on a building at Nottingham University, Jubilee Campus.

Figure 2.17 Photo of wind cowls at Jubilee Campus, University of Nottingham

Figure 2.18 Photo showing a number of BedZED wind cowls in south London

The Wind Cowl ventilation system illustrates the application of energy-grading. Conventionally, large amounts of high-grade fan and pump electricity are consumed to deliver low-grade energy for room comfort temperature control and ventilation. This tends to be significant because these systems run for extended operating periods. Nonetheless, as building envelopes become more airtight to reduce uncontrolled heat-loss, then provision of controlled minimum ventilation becomes particularly important. Fresh air provision is needed for removal of condensation moisture from kitchens and bathrooms, as well as removal of toilet smells and kitchen fumes.

BedZed Wind Cowl system shows in Figure 2.18 are designed to deliver preheated fresh air to buildings and extraction of its vitiated air, complete with heat recovery from the extracted ventilation air. There is also development work on harnessing low velocity wind, and introducing heat recovery using wind power. Both positive and negative wind pressure can be used to deliver supply air and extract vitiated air and generate enough pressure for the air to be ducted down into the building. This delivers the preheated air to each living room and bedroom, and extracts air from each kitchen, bathroom and toilet.

2.8.2 Wind Catcher / Wind tower

A Windcatcher is a wind-driven natural ventilation system suitable for the ventilation of large- or small-scale public, commercial and institutional buildings, particularly during the summer months. Windcatchers encapsulate the prevailing wind from any direction to bring a flow of fresh air into the room below, and remove existing stale air. The required rate of air change is determined by the building type, and calculated according to the volume of the room below.

Windcatchers by definition are wind driven in as much as any wind movement above roof level is encapsulated by the wind catcher louvers, and this fresh air is carried down into the space below creating an element of displacement ventilation. Wind catcher are static and do not rotate with the wind like wind cowls. They are design to capture the wind from all direction, regardless of the wind direction and exhaust the state air in the opposite. This ensures constant flow of fresh air down into the buildings. Figure 2.19 showing the principles of the wind catcher.

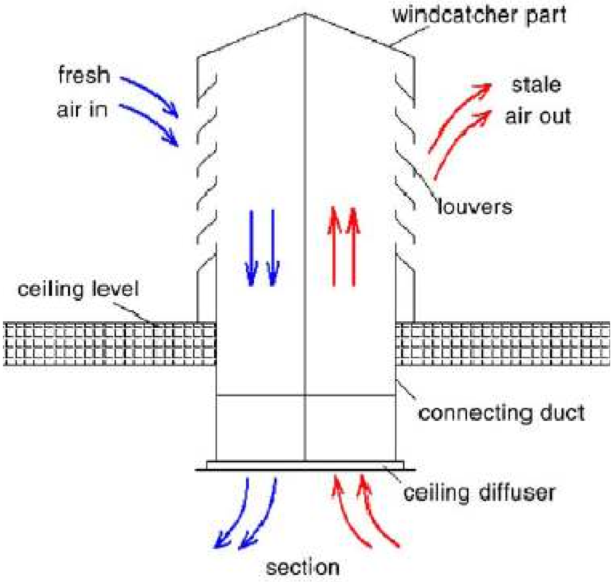


Figure 2.19 The principles of the wind catcher

2.8.2.1 Historical background of wind catcher

A Windcatcher is a traditional Persian architectural device used for many centuries to create natural ventilation in buildings [29]. It is not known who first invented the Windcatcher, but it still can be seen in many countries today. Windcatchers come in various designs, such as the uni-directional, bi-directional, and multi-directional.

The idea of a Windcatcher originated 2000 years ago in the Middle East [29] and referred to as wind tower. The Wind tower concept is similar to wind catcher in terms of function. Domed and vaulted roofs (VRs) had been extensively used in traditional and vernacular buildings; it has been frequently adopted by builders and architects throughout the Middle East and other hot dry regions such as Dubai, Jordan, Bahrain, Oman, Iran and Pakistan [30]. As shown in Figures 2.20 and Figure 2.21 below, such roofs were commonly constructed using stone or brick masonry with a plaster finish. Usually a small opening close to the top of the gable walls of vaults provides ventilation and exhausts hot air from the upper strata.

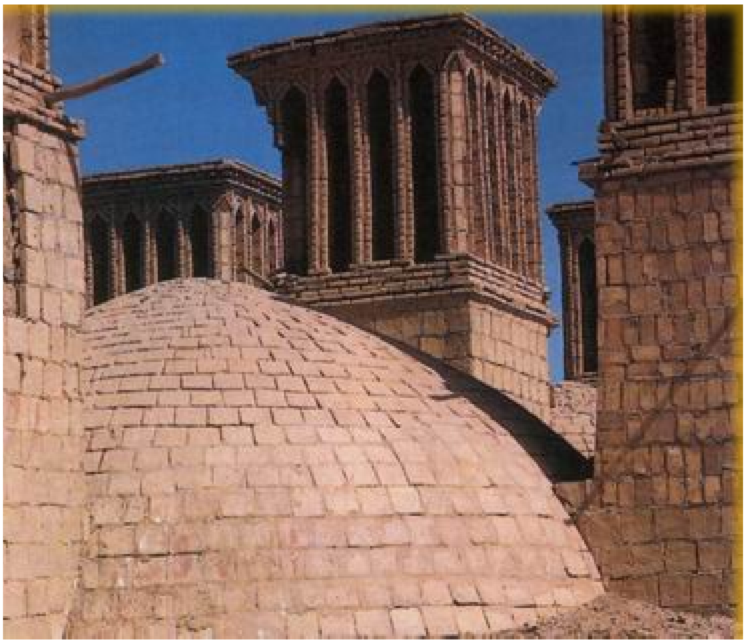


Figure 2.20 Traditional and vernacular buildings in Iran

Figure 2.21 Domed and vaulted roof located in the Iranian desert city of Naeen

(Source (http://wikimedia.org/wikipedia/commons/f/fe/AbAnbarNain2.jpg))

These towers (wind-towers or wind catchers) are ancient systems of ventilation mostly popular in central and southern Iran. As shown in Figure 2.22 and Figure 2.23 wind catchers are constructed at the top of (old) houses, high turrets with some long vertical openings are designed and oriented towards the direction of winds, catching the wind and directing it to the lower parts of the house for its ventilation purpose.

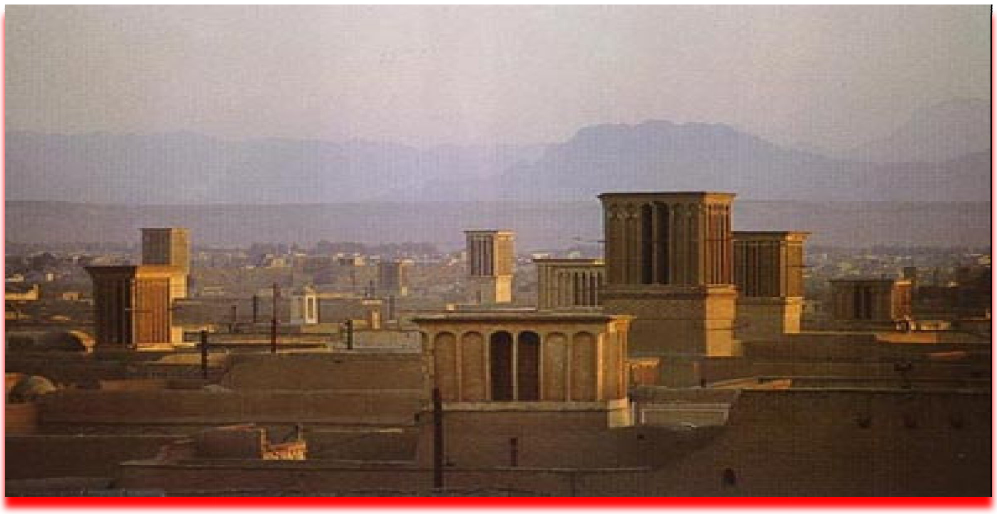


Figure 2.22 Photo of wind catchers at city of Yazd, Iran

Figure 2.23 Borujerdi ha House wind catchers in Dolatabad Gardens, Yazd, Iran

(Source (http://commons.wikimedia.org/wiki/Category:Houses_of_Iran))

The whole world has realized that the ancient systems of ventilation are the best practical way of ventilation in the hot and dry areas [31]. A number of companies started developing an improved version of the wind catchers, due to their potential ventilation capacity.

There are many shapes and types of modern Windcatchers designed by Monodraught. It's designed to suit any building style, acoustically treated to prevent traffic noise and normally installed on the highest point of the roof away from traffic pollution, dust & dirt. Figure 2.24 shows different styles of Monodraught Windcatchers.

The ventilation effect is similar to displacement ventilation as warm stale air is exhausted by the passive stack quadrants of the system and replaced by cool fresh air taken from roof level.

Figure 2.24 Different designs and styles of modern windcatchers

(Source (Monodrught.com))

2.8.2.2 Principles of modern Wind catchers

The principal of Windcatcher is to encapsulate any prevailing wind from any direction by means of internal segments and provide the required ventilation for the interior spaces. The opposite side of the system is the Passive Stack element which is designed on proven techniques relying on the stack effect, pressure and temperature difference to remove stale air from the building. Wind induced pressure differences and the temperature differential between internal and external conditions is the driving force. The displacement ventilation of internal building space can be achieved.

Through this process wind catchers are able to aid passive ventilation by directing air in and out of buildings.

The installation of the Windcatcher system is relatively simple and the Windcatcher could be controlled manually or automatically using upper and lower temperature sensors. The Windcatcher functions on several principles; first, a wind catcher is capped and has several directional ports at the top (traditionally four). By closing all but the one facing away from the incoming wind, air is drawn upwards using the Coanda effect, the wind would push the air down the shaft. This generates significant ventilation within the structure below, but is not enough to bring the temperature below the ambient alone.

A wind catcher, however, can create a pressure gradient which sucks at least a small amount of air upwards through a house.

Finally, in a windless environment a windcatcher functions as a stack effect aggregator of hot air. It creates a pressure gradient which allows less dense hot air to travel upwards and escape out the top. This is also compounded significantly by the day-night cycle mentioned above, trapping cool air below. The temperature in such an environment can not drop below the nightly low temperature.

When coupled with thick adobe that exhibits high heat transmission resistance qualities (R-value), the wind catcher is able to chill lower level spaces in mosques and houses in the middle of the day to frigid temperatures. Figure 2.25 shows a wind catcher on a mosque in city of Yazd, Iran which uses this method.

Figure 2.25 the wind catcher of Mohammad Hussein mosque at The City of Yazd, Iran

2.8.2.3 Advantages of the modern wind catcher

- The system is totally energy free in its natural mode.
- It provides clean fresh air, free of dust & dirt particles.
- It offers a high level of ventilation to the building without compromising performance.
- There is no maintenance, nothing to go wrong, no replacement and any prevailing wind externally is encapsulated by the Windcatcher system.
- It has maintained that one of the main advantages of the wind catcher system is the night-time cooling facility, which with the dampers open fully allows the cooler night air to fall to floor level, slightly pressurising the building but also forcing the stale air out of the opposite side of the Windcatcher system.

A further advantage of the Windcatcher system is that since all the air is drawn from roof level, it is relatively free from dust and dirt that so often prevails at ground level and contaminates low level air intakes.

CHAPTER 3

EVAPORATIVE COOLING AND PSYCHOMETRIC ENERGY CORE (PEC)

3.0 Introduction

The objective of this chapter is to review and discuss the aspects that relate to evaporative cooling and to explain how the evaporative cooling methods can be used to achieve thermal comfort. The chapter starts with some background on some traditional methods of evaporative cooling and describes the Psychrometric chart as well as the factors affecting evaporation rate including relative humidity, air temperatures, solar radiation, air movements, evaporation surface area and air pressures. The chapter concludes with presentation of different evaporative cooler designs, their advantages and disadvantages.

3.1 Evaporative cooling

The process of evaporation happens all the time. The simplest example would be perspiration or sweat, which the body secretes in order to cool itself. The amount of heat transfer depends on the evaporation rate; this in turn depends on the humidity of the air and its temperature, which is why people sweat more on hot humid days. Whenever dry air passes over water some of the water will be absorbed by the air that is why evaporative cooling naturally occurs near waterfalls, rivers, lakes and oceans. The hotter and drier the air the more water that can be absorbed by the air, this happens because the temperature and the vapor pressure of the water and the air attempt to equalize. Liquid water molecules become gas in the dry air, a process that uses energy to change the physical state. Heat moves from the higher temperature of the air to the lower temperature of the water. As a result, the air is cooler. Eventually the air becomes saturated, unable to hold more water, and evaporation ceases.

Before refrigeration technology first appeared, people produce cooling using natural methods such as breezes flowing through windows, water evaporating from springs and fountains as well as large amounts of stone and earth absorbing daytime heat.

People in hot arid areas, such as the African community where there is no electricity, purposely utilize a simple solution to build a pot-in-a-pot fridge, using basic clay pots, sand and water. Figures 3.1 and Figure 3.2 show the “zeer” pot invented by a Nigerian teacher, Mohammed Bah Abba and introduced to Darfur – Sudan [32, 33]. The zeer pot is composed of two earthenware pots; the space between them is filled with sand. The sand is made wet with water (twice a day) and a wet towel is put on top of the two pots to keep warm air from entering the interior. As water in the sand evaporates through the surface of the outer pot, it carries heat, drawing it away from the inner core, thus cooling the inside of the inner pot which can be filled with soft-drinks, water, fresh fruit, vegetables or even meat. In this way, fresh product can be kept for long periods without the need for electricity, or camping coolers which use high embodied energy.

Figure 3.1 “Zeers” at the Women's Development Association in Darfur - Sudan

(Source: SciDev.Net)

Figure 3.2 Passive Cooling and “Zeer” Pots

(Source http://permaculturetokyo.blogspot.com/2006/11/passive-cooling.html)

These ideas were developed over thousands of years as integral parts of building design. Today they are called "passive cooling." Ironically, passive cooling is considered an "alternative" to mechanical cooling that requires complicated refrigeration systems. By employing passive cooling techniques into modern buildings, you can eliminate mechanical cooling or at least reduce the size and cost of the equipment. Evaporative cooling is often supplemented with mechanical means, such as fans. Even so, they use substantially less energy to maintain comfort compared to refrigeration systems. It is also possible to use these strategies in completely passive systems that require no additional machinery or energy to operate.

Evaporative cooling is a physical phenomenon in which evaporation of a liquid, typically into surrounding air, cools an object or a liquid in contact with it. Latent heat describes the amount of heat that is needed to evaporate the liquid; this heat comes from the liquid itself and the surrounding gas and surfaces. When considering water evaporating into air, the wet-bulb temperature, as compared to the air's dry-bulb temperature is a measure of the potential for evaporative cooling. The greater the difference between the two temperatures the greater the evaporative cooling effect. When the temperatures are the same, no net evaporation of water in air occurs, thus there is no cooling effect.

Evaporative cooling is a very common form of cooling buildings for thermal comfort since it is relatively cheap and requires less energy than many other forms of cooling. However evaporative cooling requires an abundant supply of water as an evaporate source, and is only efficient when the relative humidity is low, restricting its effective use to dry climates.

Evaporative cooling can also create a desired amount of humidification to increase efficiency of machinery or comfort in buildings. Because of its effectiveness in cooling and humidification, evaporative cooling is the primary choice in such industries as: gas turbine, greenhouse, livestock farming, automobile painting, residential cooling, and commercial building climate control.

3.2 Evaporative coolers

An evaporative cooler is a device which uses simple evaporation of water in air. They differ from refrigeration or absorption air conditioning, which use the vapor-compression or absorption refrigeration cycles. Evaporative cooling is especially well suited for climates where the air is hot and humidity is low. In dry climates, the installation and operating cost of an evaporative cooler can be much lower than refrigerative air conditioning. But evaporative cooling and vapor-compression air conditioning are sometimes used in combination to yield optimal performance. Some evaporative coolers may also serve as humidifiers in the heating season.

In moderate humidity locations there are many cost-effective uses for evaporative cooling, in addition to their widespread use in dry climates. For example, industrial plants, commercial kitchens, laundries, dry cleaners, greenhouses, spot cooling (loading docks, warehouses, factories, construction sites, athletic events, workshops, garages, and kennels) and confinement farming (poultry ranches, hog, and dairy) all often employ evaporative cooling. In highly humid climates, evaporative cooling may have little thermal comfort benefit beyond the increased ventilation and air movement it provides.

Figure 3.3 illustrates a typical residential and industrial evaporative cooler which can be described as an enclosed metal or plastic box with vented sides containing a centrifugal fan or 'blower', an electric motor and a water pump to wet the evaporative cooling pads. The units can be mounted on the roof (down draft, or down flow), or exterior walls or windows (side draft, or horizontal flow) of buildings. To cool, the fan draws ambient air through vents on the unit's sides and through the damp pads. Heat in the air evaporates water from the pads which are constantly re-dampened to continue the cooling process. Thus cooled, moist air is then delivered to the building via a vent in the roof or wall.

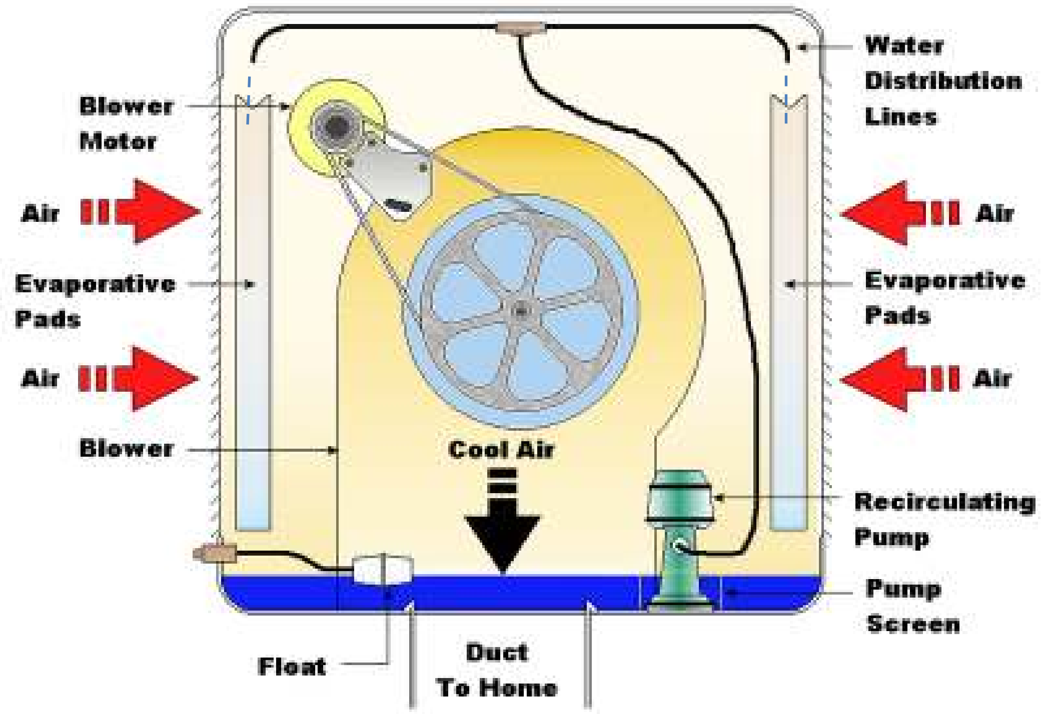


Figure 3.3 Evaporative cooler illustrations

(Source http://en.wikipedia.org/wiki/Evaporative_cooler)

3.3 The Psychrometric chart and Air Properties

The atmospheric air that surrounds us is a mixture of dry air and water vapor and is called moist air. Psychrometric is a name given to the study of air-water vapor mixtures.

A Psychrometric chart is a graph of the physical properties of moist air at a constant pressure. The chart graphically expresses how various properties relate to each other, and is thus a graphical equation of state. Figure 3.4 presents the thermo physical properties found on the Psychrometric charts which are dry-bulb temperature, wet-bulb temperature, moisture content, specific enthalpy, specific volume and percentage saturation. Only two properties are needed to characterize air because the point of intersection of any two property lines defines the state-point of air on a psychometric chart. Once this point is located on the chart, the other air properties can be read directly.

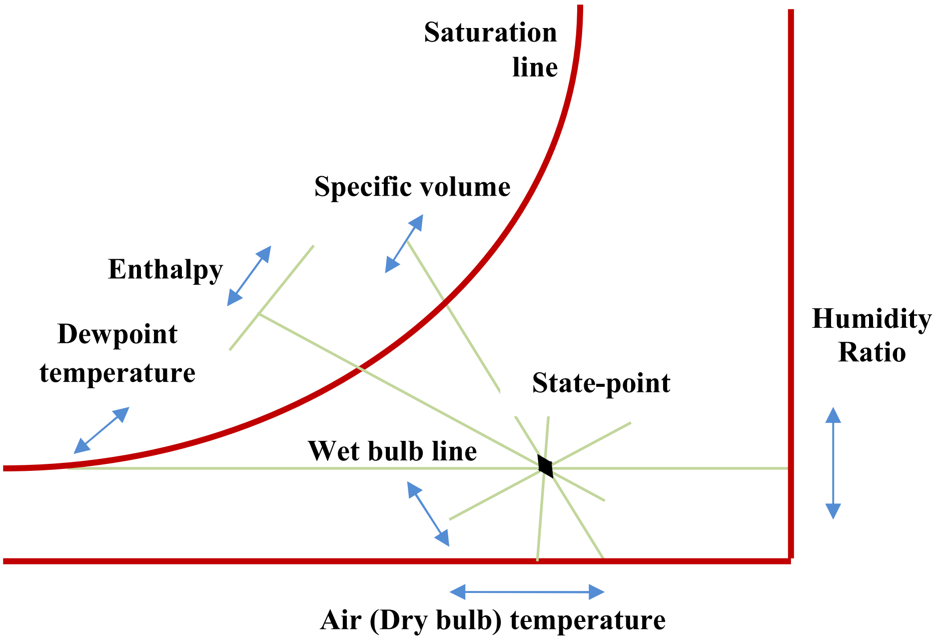


Figure 3.4 Psychrometric and the physical properties

3.4 Factors affecting evaporation rate

Evaporation rate is controlled and affected by some elements. These elements usually interact with each other to influence the total evaporation rate, and therefore the rate and degree of cooling. The main elements are: relative humidity, air temperature, air movement, evaporation surface area and air pressure.

a- Relative humidity

The humidity of air is the amount of water vapor present in the air. Humidity is measured in terms of absolute humidity, specific humidity or in terms of relative humidity. Absolute humidity is the measurement of the actual moisture content (measured in grams) in a given volume of air (measured on cubic meters) regardless of the air temperature. Specific humidity refers to the amount of water vapor in grams contained in one kg of dry air. The more common measurement is relative humidity, which is the measurement of the water vapor in the air as a percentage of the maximum quantity of water vapor that the air would be capable of holding at a specific temperature. Relative humidity, absolute humidity and specific humidity can be found simply by using the Psychrometer and Psychrometric chart.

The ability of air to hold water vapor decreases with the decrease of its temperature, and therefore the air would be close to saturation and have a higher relative humidity. The air temperature could be lowered further without decreasing its water content till the relative humidity reaches 100%. This point is known as a total saturation and is referred to as the dew point. At temperatures lower than the dew point, water vapor condense out of the air onto the cooler surfaces.

Air with low relative humidity holds only a small percentage of the total possible quantity of water vapor that it is capable of holding at the same temperature. In this case the potential of evaporating an extra amount of water is very high and therefore a large drop in temperature can be achieved. However, the evaporation rate decreases when the relative humidity is high.

In such cases, where the relative humidity is high, evaporative cooling may not be effective unless a desiccant (e.g. silica gel) is used to absorb the moisture from the air. When the humid air passes through the desiccant it loses some of its moisture content and gains heat released by the desiccant in return.

b- Air temperatures

The evaporation process requires heat. Higher temperatures increase the rate of evaporation, because the water vapor molecules or atoms have a higher average speed, and more particles are able to break free from the liquid's surface. For example, a wet street will dry faster in the hot sun than in the shade.

Therefore, the higher the air temperature the higher the evaporation rate assuming that the water content of the air and all other factors affecting the evaporation rate are unchanged.

The relation between the air temperature and its relative humidity shows clearly that the factors affecting the rate of evaporation do not usually work independently. These factors interact and affect each other as well as affecting the evaporation rate.

c- Air movements

An air movement (natural wind or an electric fan), is an important factor affecting the evaporating rate, as the air replaces the humid air above a wet surface with less humid air. This process increases or at least maintains a constant evaporation rate. Air movements provide a constant supply of drier air to the evaporation surface, therefore lowering the relative humidity which has a significant effect on increasing the evaporation rate.

d- Evaporation surface area

The rate of evaporation increases with the increase of the evaporation surface area. Because a larger surface area allows more molecules or atoms to leave the liquid, and evaporation occurs more quickly. For example, the same amount of water will evaporate faster if spilled on a table than if it is left in a cup, the greater surface area can get the wetted surface to interact more fully with the incoming air.

e- Air pressure

Air pressure determines how fast the water molecules will diffuse away from the water surface. Higher air pressure will slow down the diffusion process while low air pressure will speed up the diffusion process. Air pressure below the vapour pressure of water at the same temperature will make the water boil.

As the atmospheric pressure compresses the water molecules near the surface, more energy is required under higher pressures to speed up the water molecules in order to escape. For example, water molecules need more energy at sea level in order to evaporate than at higher altitudes under the same temperature and relative humidity.

3.5 Evaporative cooler designs

The evaporative coolers are classified as direct evaporative cooling, indirect evaporative cooling and two-stage evaporative cooling, or indirect-direct.

3.5.1 Direct evaporative cooling (DEC)

Direct evaporative cooling (open circuit) is used to lower the temperature of air directly by using latent heat of evaporation as the water is changed to vapor. In this process the warm dry air is changed to a cool moist air by using the heat in the air to evaporate water. With direct evaporative cooling as shown in Figure 3.5, outside air is blown through a water saturated medium and cooled by evaporation.

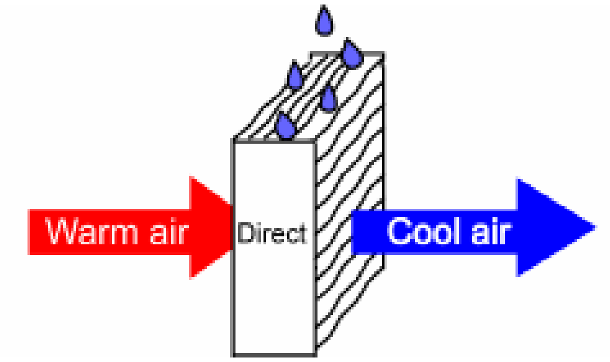


Figure 3.5 direct evaporative cooling

(Source http://www.wescorhvac.com)

Direct evaporative cooling adds moisture to the air stream until the air stream is close to saturation. During this process the dry bulb temperature of the air is reduced. It is obvious that during this process the moisture content of the air is increased. Therefore, this is called direct evaporative cooling. This process is presented on the psychometric chart by a displacement along a constant wet-bulb line, AB in Figure 3.6.

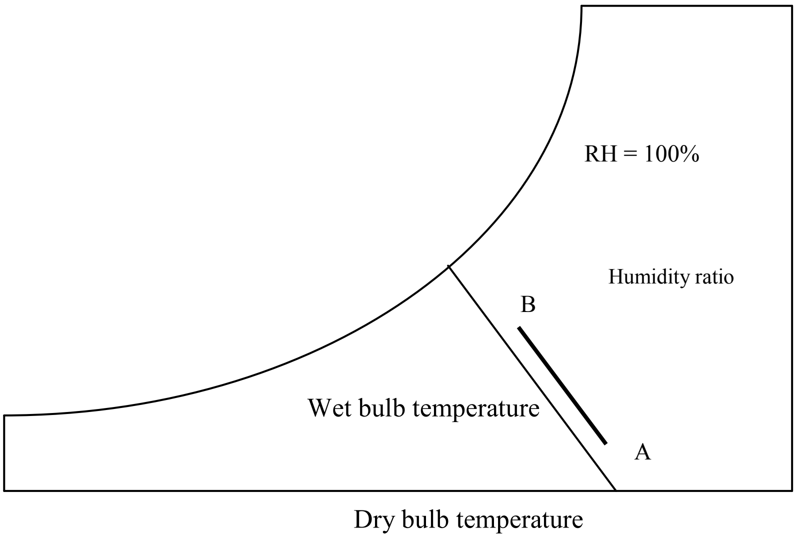


Figure 3.6 Direct evaporative cooling processes.

Direct evaporative cooling is used in many applications. One example is the passive downdraught evaporative cooling (PDEC) which has been used for centuries in parts of the Middle East, notably Iran and Turkey, and has been the subject of great interest worldwide since the energy crises in the seventies. Several experiments have been carried out, namely by Givoni [34], Brian Ford [35] and Pearlmuter et.al [36], to extend its effectiveness to both outdoors and indoors uses such as domestic, offices and refurbishments. Figure 3.7 shows an experimental building in Tucson, Arizona in1986 (Cunningham and Thompson, 1989). In this experiment a downdraught tower incorporating wetted cellulose pads is employed to drive a substantial air flow through the building. Givoni, in analyzing the test data, confirmed the effectiveness of this strategy [37].

As shown in Figure 3.8 the device consists of a single or multiple towers equipped with a water/vapour supply placed on the top of the tower. Constant water droplets descend through the tower maintaining conditions close to saturation along its entire length. The cool air descends the tower and exits at its base where it is delivered to the adjacent spaces.

In this process the water is converted from its liquid form to gaseous form within a local thermal imbalance with subsequence differences in air density. This leads to the movement of air from a zone of high pressure, where air is hot and less dense (top of the tower) to a zone of lower pressure, where air is colder and denser (bottom of the tower).

PDEC is especially useful in hot-dry climates and it has several advantages: it is an adiabatic process because there is no addition or extraction of energy (heat) from the system, therefore, it can be completely passive; it supplies ambient air with moisture raising the RH levels, thus improving the thermal comfort. It is a quite flexible system that can be easily adapted to new and existing constructions. Whenever applied to existing fabric, PDEC depends not only on the cooling power required but also on the existing fabric limitations, namely architectural form and envelope materials. The combination of these factors is essential to define a DEC strategy and often a system cannot be totally passive. For instance, when a shower system needs to be placed at low height PDEC based on free convection can result in discomfort. People may get wet from non-evaporated water droplets. The addition of a fan increases the length of time before water droplets reach the ground, helping them to fully evaporate and eventually switch from a downdraught passive mode to a mechanical one, thus becoming a hybrid system.

However, even on a hybrid or mechanical DEC system, energy savings are quite high and energy consumption rate is low enough to warrant its application to an existing fabric.

Compared with air conditioning, the benefits of cooling buildings in this way include lower capital, maintenance and energy costs and the elimination of a refrigerant therefore; the system can also offer an economical benefit. But the use of PDEC also has architectural implications, especially in the provision of transitional space to circulate the cooled air around the building.

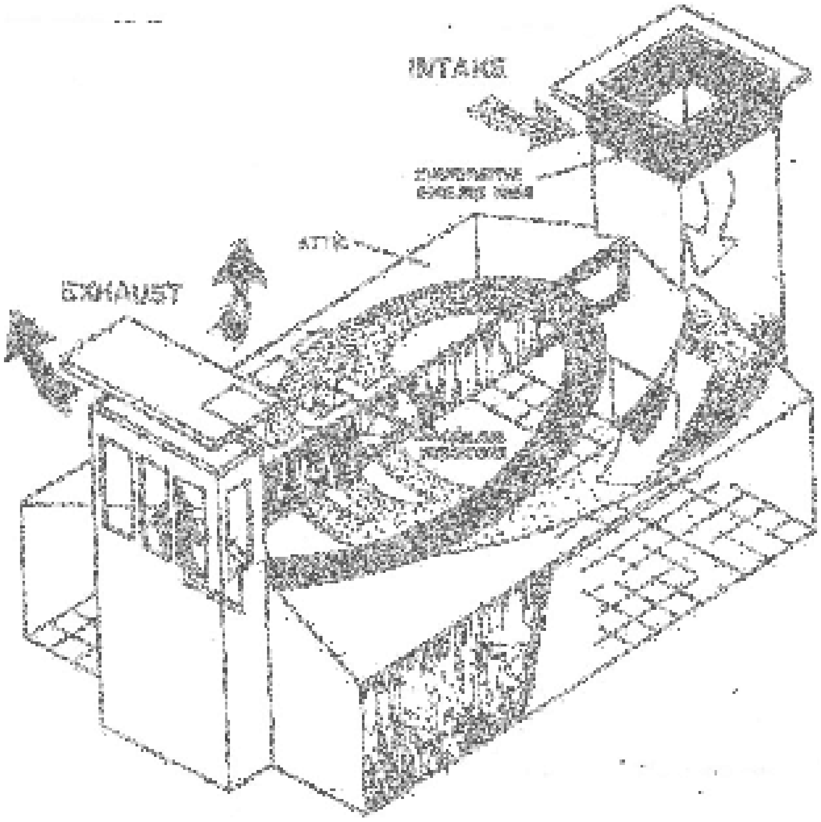


Figure 3.7 An experimental building with cool tower in Tucson, Arizona in 1986 (Source Passive downdraught evaporative cooling: principles and practice Brian Ford - http://journals.cambridge.org)

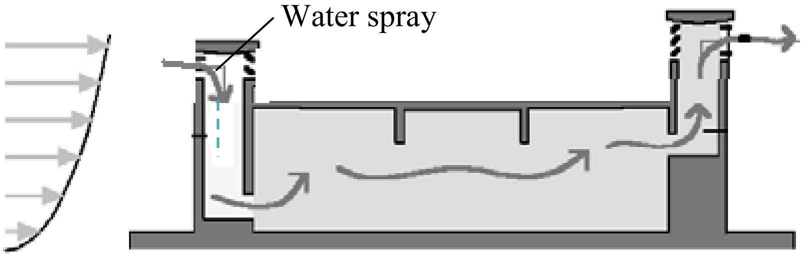


Figure 3.8 A diagram illustrating passive downdraught evaporative cooling (PDEC). (Adapted from Wachenfeldt and Bell, 2003)

Direct evaporative cooling can also be applied to roof cooling, where the roof is wetted by fine sprays, and the water evaporation causes lower temperatures at the roof's upper and lower surfaces. The roof cooling system could be constructed from a network of pipe with specially designed spray heads. The amount of water misted could be automatically controlled to give optimum evaporation, thereby cooling the roof more efficiently [38]. Such roof spraying system has been investigated by Y. Etzion et al. [39] for the purpose of reducing the water consumption.

Another rooftop evaporation system is the `skytherm` system, in which thin plastic bags of water are placed on a flat roof. During the summer, moveable insulation panels are placed over the bags during the day and removed at night. The opposite happens during winter. The tracks and supports for the insulation panels should be designed such that the system forms a tight assembly when closed. Hay and Yellot [40] have tested this concept on a test room in Arizona and Niles reported the performance of the system in full–scale house in California [9]. In a recent study from Iran, such a system is capable of reducing the heating demand of a building by 86% and the cooling load by 52% (Raeissi and Taheri, 2000) [40].

Another example of direct evaporative cooling is the indoor and outdoor curtain cooler which involves the use of an absorbent sheet as an evaporative surface. The sheet is hung from its top edge by ropes usually held by pulleys so that the sheet can be lowered and raised easily. The lower end of the sheet is secured in a trough of water large enough to permit the entire sheet to fit.

In hot, dry days the sheet is lowered into the trough of the water so that it becomes soaked with water, and then it is raised back up to its position. When hot dry air passes through the sheet, water evaporates from its surface, cooling the air and creating a cooler environment. This method is usually used in a semi–open space and can only serve a small space. The concept is similar to that shown in Figure 3.3.

3.5.2 Indirect evaporative cooling (IEC)

Indirect evaporative cooling (closed circuit) is similar to direct evaporative cooling, but uses some type of heat exchanger. The cooled moist air never comes in direct contact with the conditioned environment. As can be seen from Figure 3.9 in an indirect evaporative cooling, a secondary air stream is cooled by water. The cooled secondary air stream goes through a heat exchanger, where it cools the primary air stream, which is circulated by a blower. Indirect evaporative cooling does not add moisture directly to the primary air stream. Both the dry bulb and wet bulb temperatures are reduced. During the heating season, an indirect system's heat exchanger can preheat outside air if exhaust air is used as a secondary air stream. Here, the heat is removed from the secondary air stream and the resulting cool dry air is used to cool the desire environment.

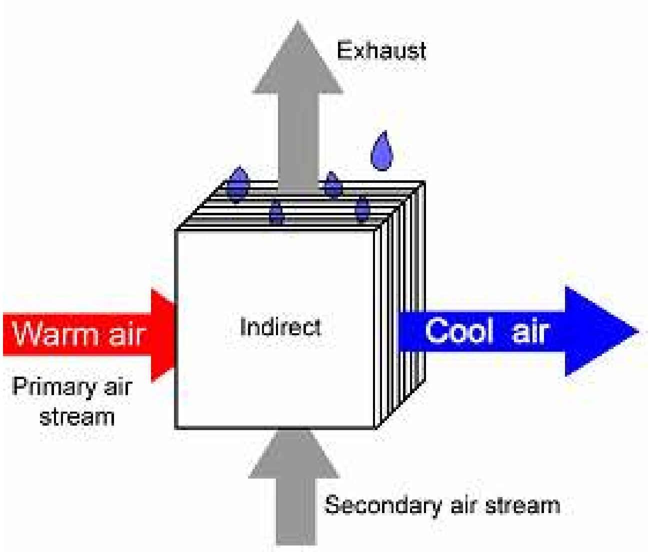


Figure 3.9 Indirect Evaporative Cooling
(Source http://www.wescorhvac.com)

The cooling process using a heat exchanger is known as sensible cooling. On the other hand, the process of cooling by evaporation that involves a heat exchanger is known as indirect evaporative cooling. The performance of this system depends on the type and performance of the heat exchanger. To obtain a highly efficient indirect evaporative system, an efficient heat exchanger should be used. It must be noted that, since the air temperature drops, its relative humidity will of course increase, but less than that of the direct evaporative cooling process. Since the humidity ratio of the air does not change, this process is presented on the psychometric chart by a displacement along a constant humidity ratio line, CD in Figure 3.10.

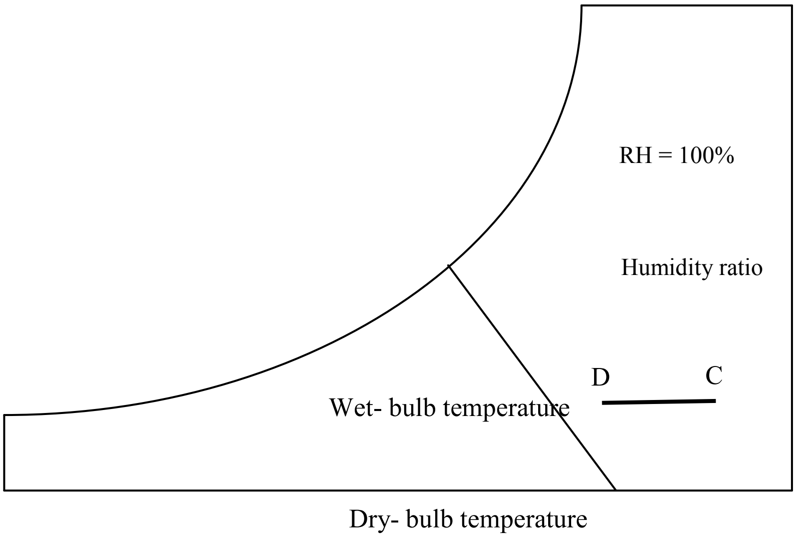


Figure 3.10 Indirect evaporative cooler process

The performance assessment of both direct and indirect evaporative cooling systems is based on the concept of the saturation efficiency, defined as

$$\text{Wet} - \text{bulb Efficency} = \frac{T_{db,in} - T_{db,out}}{T_{db,in} - T_{wb,in}} \tag{3.1}$$

Where $T_{\mathrm{db,in}}$ and $T_{\mathrm{db,out}}$ are the dry bulb temperatures of the air at the inlet and outlet of the system respectively and $T_{\mathrm{wb,in}}$ the wet bulb temperature of the air at the inlet of the system.

One example of indirect evaporative cooling is what is known as Psychrometric Energy Core (PEC), which is the subject of this research.

3.5.2.1 Factors affecting the (IEC) performance

In general, indirect evaporative cooling performance is influenced by the same factors that affect direct evaporative cooling. Use of heat exchanger however also affects the performance of the indirect evaporative cooling. This additional factor is the performance of the heat exchanger used in the Indirect Evaporative system. The maximum performance of different heat exchangers differs from one type of heat exchanger to another.

Heat exchangers have different maximum performances for two main reasons: one is the method of heat exchange and the other is the heat conductivity of heat exchangers material. The flow rate of air passing through the heat exchanger and air turbulence also affect the rate of heat transferred through the heat exchanger. The higher the air flow rate and air turbulence through the heat exchanger, the more efficient the heat exchanger.

3.5.3 Direct- indirect evaporative cooling (Two stage Evaporative Cooling)

Two-stage evaporative cooling is a combination of a direct and indirect evaporative cooling [41]. These systems are used when dry-bulb temperatures are lower than those achieved by a single–stage system are required. In a two stage evaporative system, an Indirect Evaporative Cooler is used first stage and a direct evaporative cooler is used the second stages as explained on the psychometric chart (Figure 3.11). The air to be cooled, initially at point A, is sensibly cooled by the indirect evaporative cooler until it reaches point B. Since the water content of the air does not change, line AB is parallel to the dry bulb temperature axis. This air then enters the second stage, where as a result of the Direct Evaporative Cooling process; it reaches point C. This is a constant wet bulb temperature process and therefore line BC is parallel to the wet bulb temperature lines. The association of a direct with indirect evaporative cooler results in reducing the working time of the equipment and therefore the energy consumed. Also double stage cooler offers lower dry bulb temperatures than a single stage.

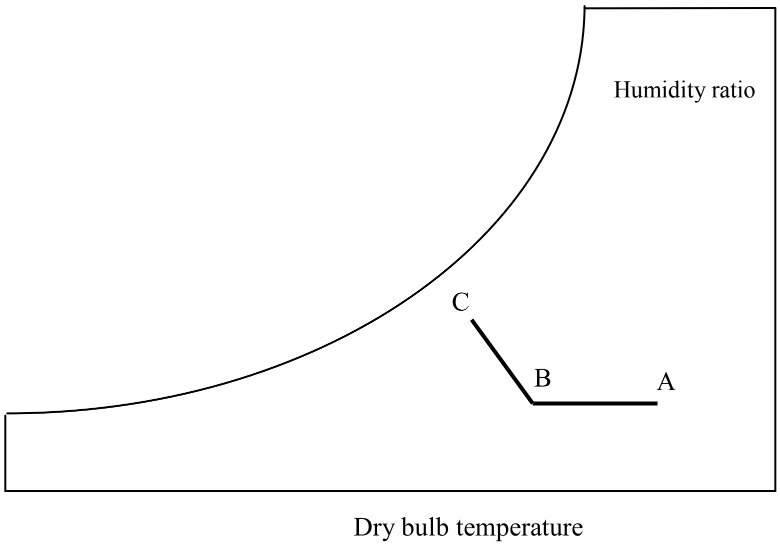


Figure 3.11 Two-stage evaporative cooling process

3.6 Conclusions

Evaporative coolers offer an interesting alternative for cooling. They can provide cooling whilst consuming only the necessary electrical energy for the operation of air fans and in some cases for small water pumps, this is far less than the electricity required for the operation of conventional air conditioners; this could even be met by using solar energy such as PV. Figure 3.12 shows an indirect evaporative cooler operate with a mounted PV panel [42]. Excessive air humidification can be avoided by using indirect coolers instead of direct ones, or by combining the two in the double–stage systems. Research in this field has led to devices that, in consciously designed buildings, can easily compete with conventional air conditioners.

Figure 3.12 evaporative cooler Powered by a mounted PV solar Panel

CHAPTER 4

Experimental evaluation of the performance of an Indirect Evaporative Cooling system employing a Psychro Energy Core (PEC)

4.0 Scope of the chapter

This chapter discus the concept of the Psychrometric energy Core (PEC) and presents results of an experiment conducted to investigate the performance of a three pre-prototype PEC during design optimisation process.

Investigations were first carried out into three different pre design sizes 1kW, 2kW and 3kW of PEC units in order to optimise the parameter that affect their performance. Some modifications were carried out and testing was conducted to the 2 kW PEC unit. Finally in this chapter a 2 kW prototype has been fabricated and tested.

4.1 Introduction

The PEC cooling is a means of air temperature reduction and operates on the principle that water absorbs heat from the surrounding air while it evaporates.

The PEC is made of cellulose papers (pads) that absorb and hold moisture and gives maximum surface area for air and water contact. The papers are separated by thin plastic sheets and impregnated with unique ingredients & additives to achieve high performance and structural strength. The PEC Pads are also treated with anti-rot chemical, which helps to prevent Algae, Bacteria or fungus .The pads are arranged in a special way so that the inlet air is divided into two streams within the core as illustrated in (Figure 4.1). This is done using horizontal channels through the core and vertical channels emerging from a certain number of the horizontal channels (Figure 4.2) and (Figure 4.3). Water is sprayed over the pads along the vertical channels and water droplets passing through the vertical channels.

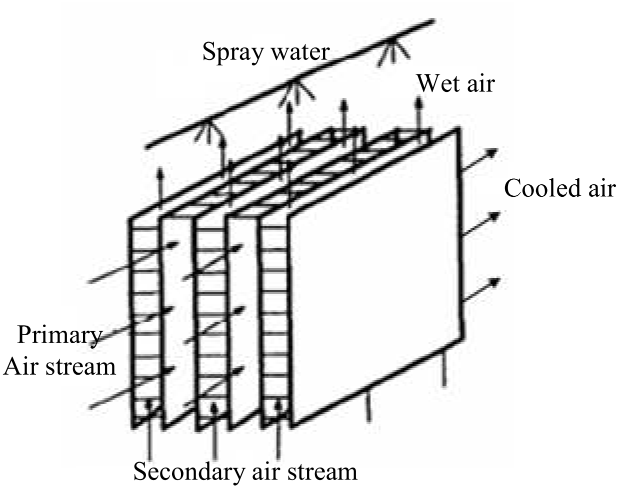


Figure 4.1 Schematic showing the air stream flow.

Figure 4.2 Structure of a PEC showing the Wet (Exhaust air) and the dry (Supply air) channels.

Figure 4.3 Photos showing the horizontal and vertical channels for primary and secondary air flow.

As can be seen in Figure 4.4 the PEC pads can be manufactured with any required shape or size.

Figure 4.4 different shapes and sizes of the PEC pads

As stated by the manufacturer and from their results of testing these cores, the cross fluted design of the diamond PEC pads results in two important effects. First, it optimizes the amount of surface area available to hold the water which the air flows over because of the number of paper used. And second, the angles cause the air to change direction in a way that ensures that sufficient air come in contact with the wetted media surface before leaving the pad. Therefore, the air leaves the pad with the greatest amount of cooling. PEC pads also act as a natural filter that purifies the inlet air. The carefully designed flute angle directs water towards both the air inlet and outlet side; the water then intrinsically flushes away dust, algae, and mineral build up on the evaporation surfaces.

The Advantage of the PEC is

- Low initial costs.
- Low operating costs.
- Does not use environmentally harmful refrigerants.
- Minimal maintenance.
- Consistent and predictable performance throughout life-span of pads.
- The core media acts as a self-cleaning air filter.

In an indirect evaporative air cooler, the primary air is passed over the dry side of the heat exchanger and a secondary or working air is passed over the opposite wet side of a plate in a counter flow channels. As illustrated in Figure 4.5 the wet side absorbs heat from the dry side and causes the water to evaporate, thus removing its latent heat and as a result the air on the dry side is cooled. The temperature on the dry side of the plate travels in counter flow to the air on the wet side, and ideally the product air temperature on the dry side of the plate could reach the wet bulb temperature of the incoming air [43].

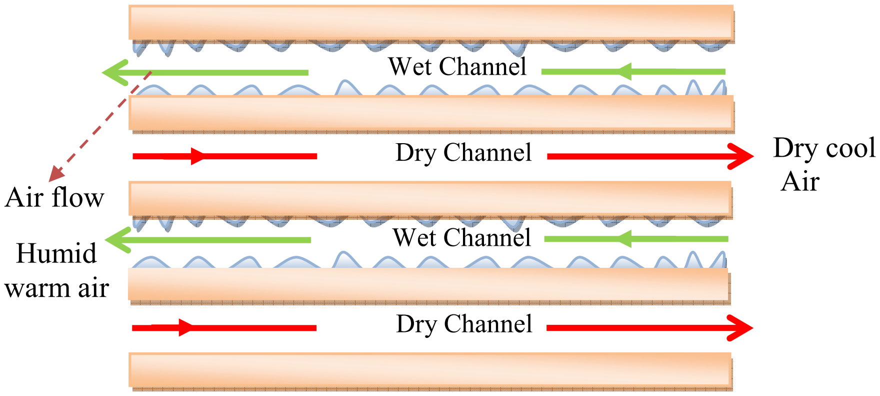


Figure 4.5 Indirect evaporative cooling channels arrangement

The cycle of Psychrometric energy core (PEC) is similar to the Maisotsenko cycle and uses the same wet side and dry side of a plate as described above, but the different is the PEC employs a special geometry to direct the airflow within the PEC core in vertical and horizontal channels. The cycle also been realized in a uniquely designed plate wetting and channel system to achieve optimum cooling temperatures within few degrees of the dew point for the product air same as the one in the Maisotsenko [44]. In addition to this, the working air is saturated with a high enthalpy, accounting for the sensible heat loss in the product air.

In this way the unsaturated inlet air is divided into two streams at two states, a low- temperature, low-enthalpy state, and a high-temperature, high-enthalpy state. The low-temperature, low-enthalpy air passes through the horizontal channels (supply channels), while the high-temperature, high-enthalpy air diverges and exits through the vertical channels (exhaust channels).

4.2 System description

The baseline of the original PEC cooling systems under investigation illustrated in Figure 4.6 consists of a fibreglass casing, an AC driven air supply fan, a water-moistened Psychrometric Energy Core (PEC), a motor driven water AC pump and water distribution pipes. Table 4.1 presents the dimensions of these units, their air inlet and air outlet sizes. It worth mentioning that these units built in China and their cooling capacity were rated by the manufacturer there at 1kW, 2kW and 3 kW.

System	Height(mm)	Width (mm)	Length (mm)	Inlet size (mm)	Outlet size (mm)	PEC size (mm)
Small	410	410	310	240mm*240mm	240mm*80mm	300*195*290
Medium	440	500	500	340mm*340mm	100mm*280mm	500*200*290
Large	700	500	440	340mm*340mm	350mm*150mm	500*200*350

Table 4.1 Geometrical dimensions of the three PEC units

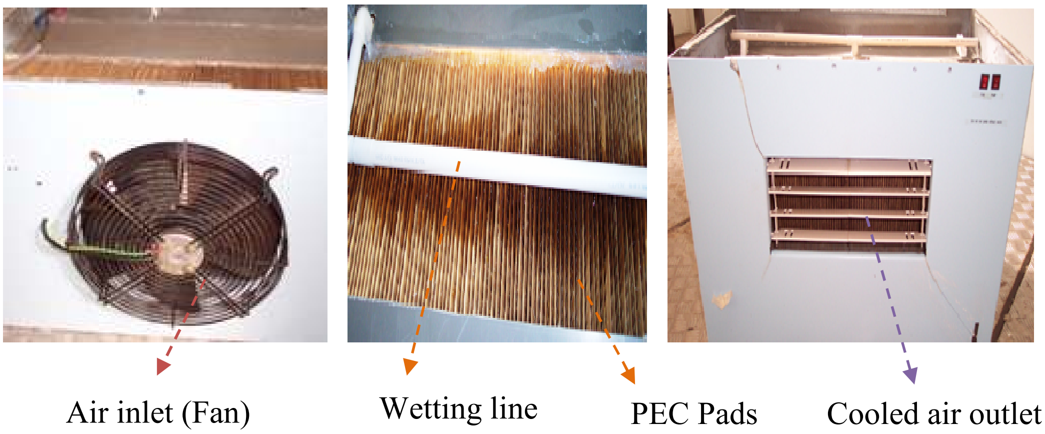


Figure 4.6 photos showing the different sides of the PEC unit

4.3 Operation of the PEC System

Figure 4.7 illustrates the operation of the system where a circulating pump connected to circulate water from a tray at the bottom of the PEC to the top of the PEC. The water is sprayed over the PEC pads and the droplets trickles through them to be collected at the bottom of the PEC.

As mentioned in section 4.1 the PEC used in the system is made of special papers (pads) that absorb and hold moisture and these papers are separated by thin plastic sheets. The fan draws fresh warm air from the ambient into the PEC housing unit. Heat is transferred from the dry side of the pads to the wet side by direct conduction. This causes the evaporation of the water from the wet surface releasing its latent heat of vaporisation. The water vapour is dragged by the passing air in the vertical channels to the exhaust exit at the top of the PEC core and the cooled air passes through the horizontal channels to provide the supply air.

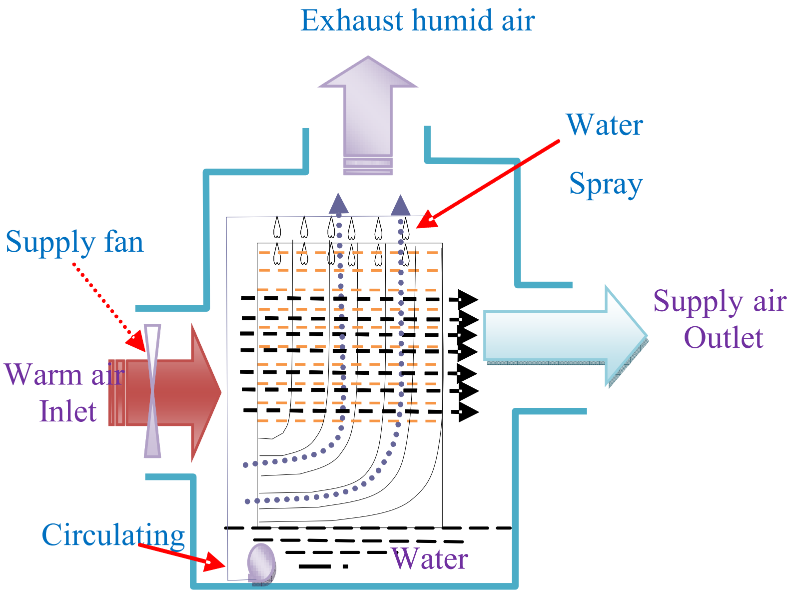


Figure 4.7 Schematic showing the operation of the PEC core unit

4.4 Experimental setups

Figure 4.7 presents the experimental setups of the pre optimized cooling systems. The parameters studied are the temperature and relative humidity for the inlet, outlet and the exhaust as well as air flow rate.

The inlet parameters were controlled using an environmental chamber which allows control of the room temperature and relative humidity.

Measuring was carried out using measuring sensors and thermocouples connected to a data logger and a PC. The tests were carried out under four different temperatures and tow relative's humidity, i.e., 25^oC, 30^oC, 35^oC, 40^oC, 40% and 50% respectively.

First the environmental chamber was operated until the setting conditions were maintained. The PEC was switched on and measurement were taken until steady state was achieved, the time for this varied for the different PEC, with average of one hour.

The humidity and the temperatures were measured using humidity and temperature probes and the air flow rate was measured using a hand-held Anemometer. Schematic showing the position of the sensors and the size of the air inlet, air outlet and air exhaust is shown in Figure 4.8. The system exhaust air was extracted outside the environment chamber through the hole on the wall as shown in Figure 4.9.

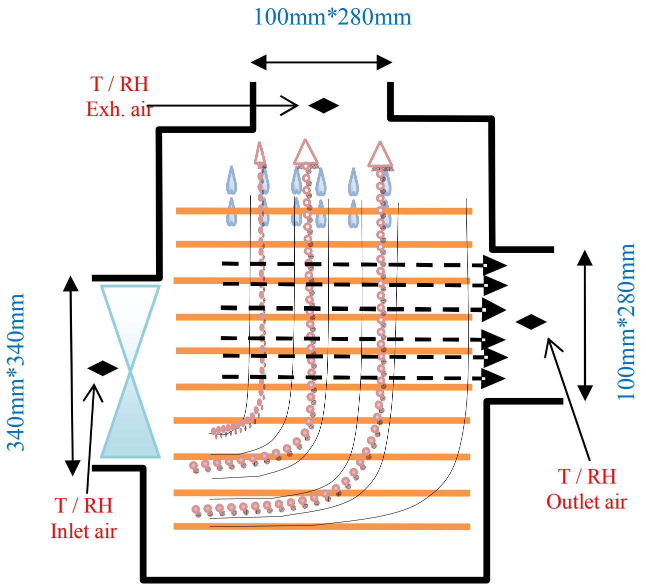


Figure 4.8 Schematic showing the position of the sensors and the size of the air inlet, air outlet and air exhaust.

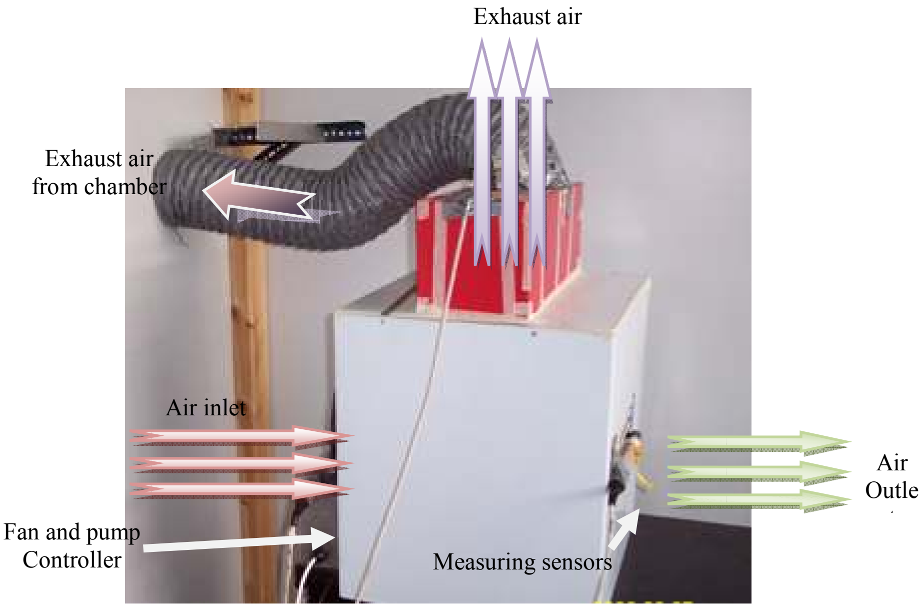


Figure 4.9 Photo showing the System test setups

4.5 Results and discussion

The tests were carried out for the PEC cooling unit and the cooling capacity of the system was assessed by measuring the temperature, relative humidity and air flow rate at the inlet, and the outlets ports at steady state conditions. Values of air enthalpy at inlet and outlet of the PEC are determined using the Psychrometric chart and engineering equation solver (EES) software at the measured temperatures and relatives humidity values obtained from the test. Examples of EES calculation are presented in Figure 4.10 and Figure 4.11.

The cooling capacity of the PEC is estimated using the following expression:

$$Q_c = \dot{m}\,(h_{in} - h_{out}) \qquad (4.1)$$

Where:

Q_c= *cooling capacity (kilowatts)*

$\dot{m}$= *mass flow rate (kg/s)*

h_{in} = *Enthalpy at inlet (kJ/kg)*

h_{out}= *Enthalpy at outlet (kJ/kg)*

The COP of the system is calculated as

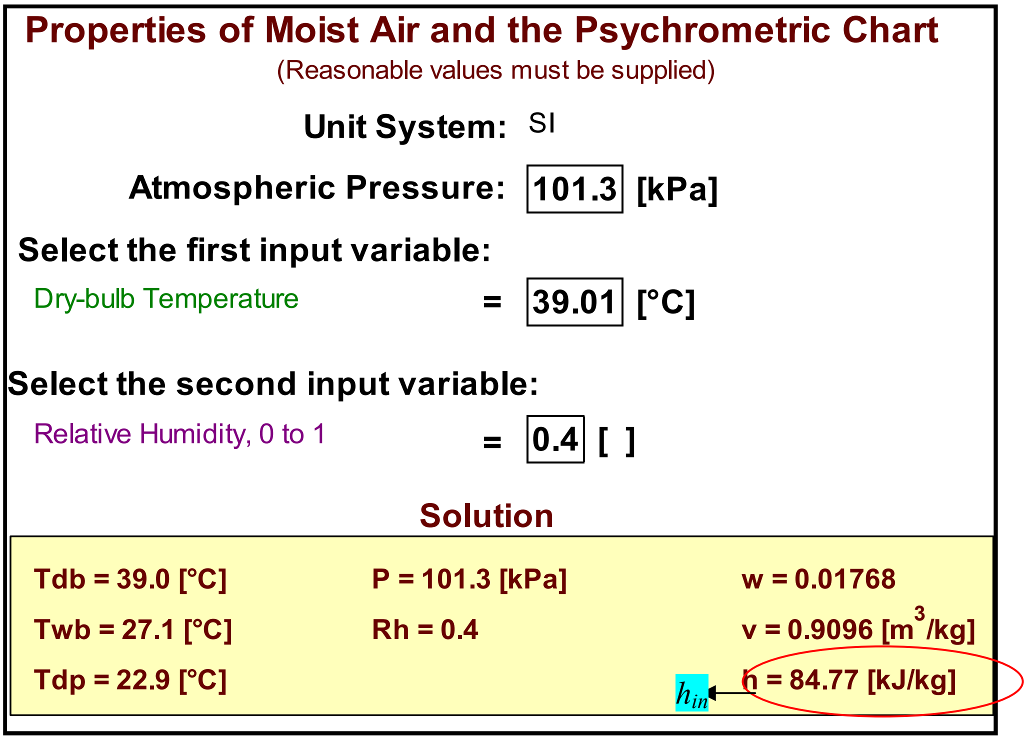
$$COP = QC \,/\, We \qquad (4.2)$$

Where:

Q_c= *cooling produced (kilowatts)*

We The electrical energy consumed by the fan and the pump.

$We = P_{pump} + P_{fan}$



Properties of Moist Air and the Psychrometric Chart

(Reasonable values must be supplied)

Unit System: SI

Atmospheric Pressure: 101.3 [kPa]

Select the first input variable:

Dry-bulb Temperature = 39.01 [°C]

Select the second input variable:

Relative Humidity, 0 to 1 = 0.4 [ ]

Solution

Tdb = 39.0 [°C]	P = 101.3 [kPa]	w = 0.01768
Twb = 27.1 [°C]	Rh = 0.4	v = 0.9096 [m^3/kg]
Tdp = 22.9 [°C]		h_{in} ← h = 84.77 [kJ/kg]

Figure 4.10 Sample calculation of air enthalpy value (h_{in}) using EES software

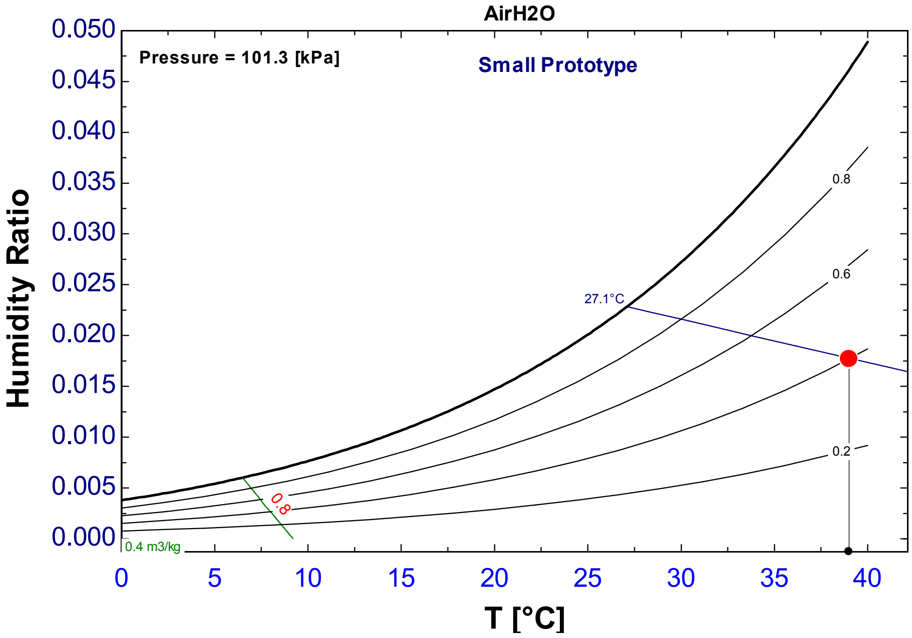


Figure 4.11 properties of the air at different temperature

4.5.1 Results of the 1 kW pre - prototype

The mass flow is calculated using the cross sectional area of the outlet duct (0.019 m^2) and the average air velocity measured at the inlet of the duct, which was 3.9m/s. Equations (4.1 and 4.2), are used to calculate the cooling load using the Enthalpy values obtained from the Psychrometric chart and EES software (Figure 4.10 and Figure 4.11). The cooling capacity achieved for the 1 kW unit varied from 334.4 Watt chamber setting of 25 °C and 40% Relative humidity to 459.2 W at 40 °C and 50% Relative humidity. The total power consumption for both fan and the pump$_{)}$ is estimated at 18.5W. The COP of the cooler has been calculated using equation 4.2. Table 4.2, Table 4.3 and Figure 4.12 present a summary of these results. The highest temperature difference was 7.2 °C and was obtained at chamber temperature 40°C and relative humidity 50%.

The Maximum cooling load obtained during the test was calculated as follows:

$$Q_c = \dot{m}\,(h_{in} - h_{out})$$

Where

$$\dot{m} = V_1 A_1 \rho_1$$

= 3.9*0.0192*1.100= 0.082 kg/s

Maximum Q_c = 0.082 (84.8-79.2) = 0.04592 kW = 459.2 watts.

RH_1 %	T_1 °C	RH_2 %	T_2 °C	h_{in}(kJ/kg)	h_{out}(kJ/kg)	$\dot{m}=AV\rho$ (kg/s)	$Q=\dot{m}(h_{in}-h_{out})$ watt
48.33	23.04	62.9	20.2	44.8	41.0	0.088	334.4
41.4	27.69	61.9	23.0	54.9	50.5	0.086	388.1
40.71	32.6	64.5	26.8	66.6	61.4	0.084	434.8
40.00	39.0	61.7	31.8	84.8	79.2	0.082	459.2

Table 4.2 1kW pre- prototype cooling load calculations

Chamber setting		Actual inlet condition		Outlet condition		Results			
Temp.°c	RH %	Temp.°c	RH %	Temp.°c	RH %	ΔT	Δ RH%	Cooling load	COP
25	40	23.0	46.4	20.2	61.9	2.8	15.5	334.4	18.0
30	40	27.7	41.4	23.0	61.9	4.7	20.5	388.1	20.9
35	50	32.6	40.7	26.8	64.5	5.8	23.8	434.8	23.5
40	50	39.0	39.6	31.8	61.7	7.2	22.1	459.2	24.8

Table 4.3 Summary results of the 1kW pre- prototype

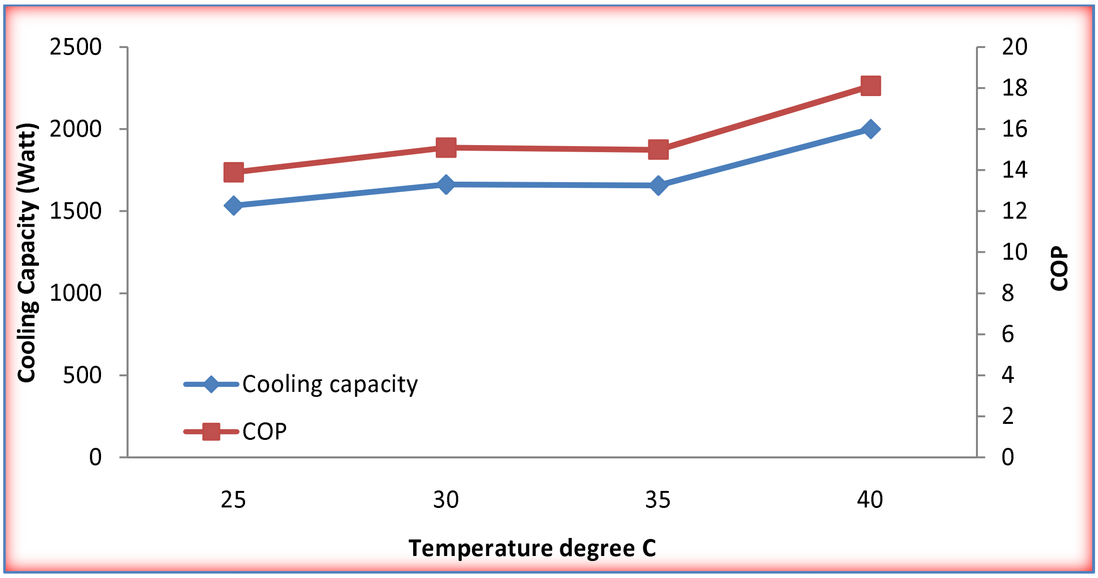


Figure 4.12 Variation of the cooling capacity and COP with ambient temperature for the 1 kW PEC cooling unit.

4.5.2 Results of the 2 kW pre – prototype

The mass flow is calculated using the cross sectional area of the outlet duct (0.028 m^2) and the average air velocity measured at the inlet of the duct, which were 3.1m/s. The tests were carried out with environmental chamber temperature set to 25°C, 30°C, 35°C and 40°C and relative humidity (RH) 40%. The system power consumption for both fan and pump (W_e) is 90 watts. The results of the cooling capacity achieved during the test of the medium PEC unit at varying chamber temperatures and relative humidity presented in Figure 4.13 ranges between 499.80 to 830.15.15 watts, samples of cooling load calculation and a summary of temperature and relative humidity and COP results are presented in Tables 4.4 and Table 4.5.

The maximum cooling load obtained from the test was calculated as follow:

$$Q_c = \dot{m}\,(h_{in} - h_{out})$$

$$\dot{m} = V_1 A_1 \rho_1 = 3.1*0.028*1.100 = 0.095$$

$$= 0.0954\ (83.5-74.8) = 0.830\ \text{kW}$$

Maximum Q c = 830.15Watt

RH1 %	T1 °C	RH2 %	T2 °C	h_{in}(kJ/kg)	h_{out}(kJ/kg)	$\dot{m}$ =AVρ (kg/s)	Q=$\dot{m}$(h_{in}-h_{out}) watt
48.2	23.7	65.3	18.8	46.3	41.4	0.1020	499.80
53.6	28.1	70.2	23.0	60.9	54.8	0.1004	612.44
43.8	32.8	70.3	25.0	68.3	61.0	0.0982	716.86
41.7	38.1	70.5	28.9	83.5	74.8	0.0954	830.15

Table 4.4 Medium prototype cooling load calculations

Chamber setting		System inlet		System outlet		Results			
Temp.°c	RH %	RH %	Temp.°c	RH %	Temp.°c	ΔT	Δ RH	Cooling load	COP
25	40	48.2	23.7	65.3	18.8	4.9	17.1	499.80	5.55
30	40	53.6	28.1	70.2	23.0	5.1	16.6	612.44	6.80
35	40	43.8	32.8	70.3	25.0	7.8	26.5	716.86	7.96
40	40	41.7	38.1	70.5	28.9	9.2	28.8	830.15	9.22

Table 4.5 Summary results of the 2 kW pre - prototype tests

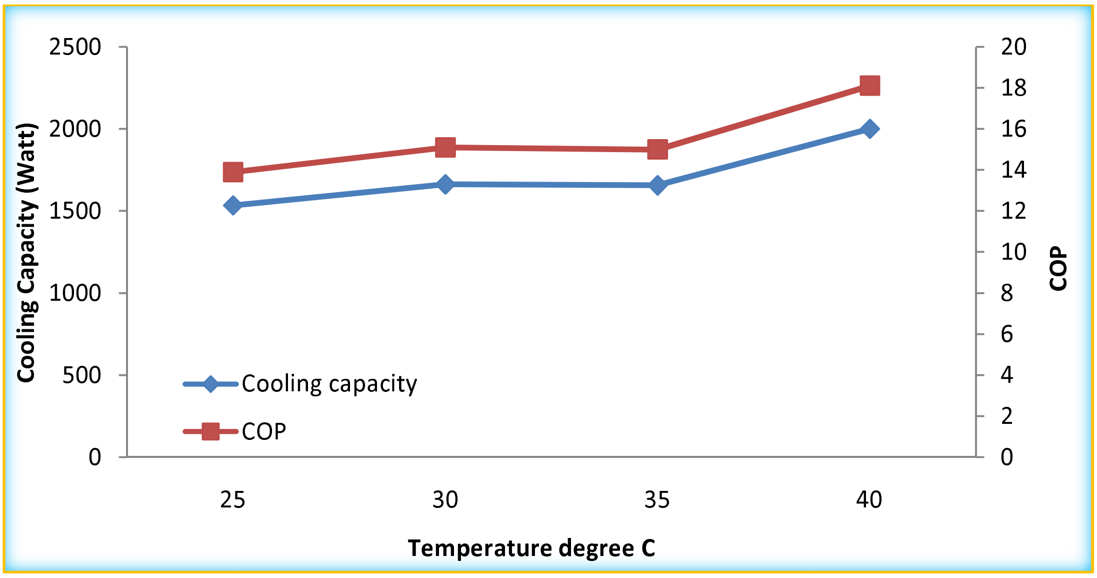


Figure 4.13 Variation of the cooling capacity and COP with ambient temperature for the 2 kW pre - prototype.

4.5.3 Results of the 3 kW pre - prototype

The cross sectional area of the large unit outlet duct was 0.056 m^2 and the air velocity at the duct was 4.4m/s. The cooling load has been calculated and the maximum capacities results from testing of the large unit was 2000 watts at Temperature 40 ^oC and Relative humidity 50% while the minimum cooling capacity achieved is 1534 watts at Temperature 25 ^oC and Relative humidity 40%. The higher temperature difference was 7.53 ^oC and this is achieved when the test was running with chamber temperature 35°C and relative humidity 50%. The prototype power consumption for both fan and pump (W_e) is 110 watts. The maximum cooling load of the system achieved from the following calculation:

$$Q_c = \dot{m}(h_{in} - h_{out})$$

$\dot{m} = V_1 A_1 \rho_1$ = 4.4*0.056 *1.100= 0.27104 kg/sec

0.27104 (97.4 – 90.02) = 200027 kW

Maximum Q_c = 2000 watts

Samples of the rest of the cooling load calculation results are presented in table 4.6, COP and summary of other results are illustrated in Table 4.7 and Figure 4.14 respectively.

RH1 %	T1 °C	RH2 %	T2 °C	h_{in}(kJ/kg)	h_{out}(kJ/kg)	$Q=\dot{m}(h_{in}-h_{out})$ watt
64.36	23.42	73.36	20.15	53.17	47.85	1534
58.12	28.15	64.36	25.1	64.02	58.19	1662
41.82	34.43	67.43	26.9	71.51	65.57	1656
49.89	39.19	58.31	35.29	97.40	90.02	2000

Table 4.6 cooling capacity calculation of the large prototype

Chamber setting		system inlet		system outlet		Results			
Temp. c°	RH %	RH %	Temp.c°	RH %	Temp.c°	ΔT	Δ RH	Cooling load	COP
25	40	64.36	23.42	73.36	20.15	3.27	9.0	1534	13.9
30	40	58.12	28.15	64.36	25.1	3.05	6.24	1662	15.1
35	50	41.82	34.43	67.43	26.9	7.53	25.61	1656	15.0
40	50	49.89	39.19	58.31	35.29	3.9	8.42	2000	18.1

Table 4.7 Summary results for the 3 kW pre – prototype

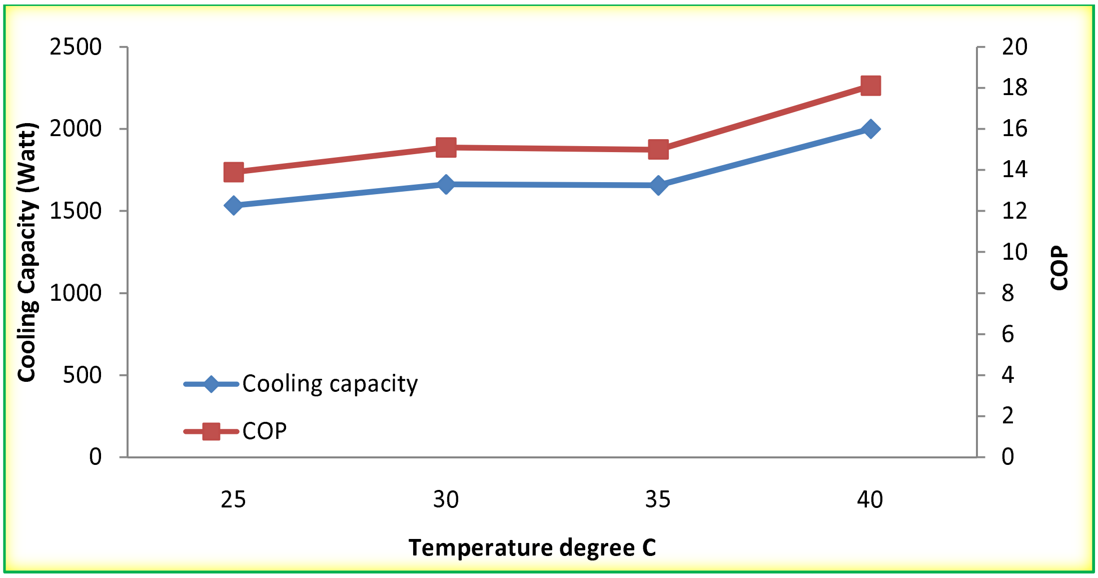


Figure 4.14 Variation of the cooling capacity and COP with ambient temperature for the 3 kW pre - prototype

4.5.4 Discussion of the results

The results obtained from the tests of the three pre - prototypes have shown low performance compared to the rating capacity given by their manufacturer of 1kW, 2kW and 3kW for the three units. For instant the rated 2 kW pre - prototype unit have produced only one quarter of its rated cooling capacity. This has increased to 830 W (i.e. under half of the rated capacity). Investigations of the design have highlighted a number of possible performance improvements. Among these is the geometry of the PEC core housing, which blocks the air flow. Most of the air recirculates inside the PEC housing with very little leaving at the supply air outlet. The supply fan was installed, a large gap between the fan blades and the PEC casing, causing some air to escape as a result before entering the PEC core. Another factor is the optimum ratio of the water flow to the air flow rates. The water spraying was not sufficient with only part of evaporative media wetted.

4.6 Improvements of the performance of the PEC cooling system

Test of the pre – prototype design have shown that the performance of the PEC could be improved by optimising the PEC pads wetting rated the air flow. Several tests were carried out at different water flow rates and air flow rates. During the tests it observes that for the 2kW system the best performance are achievable at air flow rate 4.4 m/s and water flow rate 11 *l*/s. The system is then modified by improving the air flow passage through the PEC and improving the water spray system. The physical geometry of the PEC housing which blocks the air flow was refined by reducing the effect of the corners to the air flow throughout the PEC casing (Figures 4.15). The gap between the fan blades and the PEC housing was also adjusted to prevent air leakage at the inlet (Figures

4.16). These two modifications have improved the air flow rate during the tests significantly.

Figure 4.15 Photos showing adjustment to the outlet corners

Figure 4.16 Photos showing adjustment to the fan inlet to prevent air leakage

As stated earlier in section 4.5.4 the water spraying unit of the pre – prototype system was able to wet only a small section of the PEC pads. The system was working using a single water tube with holes on the lower side and hence the wetting was achieved only in the middle part of the PEC core. The water spraying nozzle system has been redesigned as shown in Figure 4.17 with a second pipe added to the water distribution line. Preliminary tests have shown that the water spraying is taking place along the whole width of the PEC pads allowing larger wetting surface area and hence higher evaporation rate.

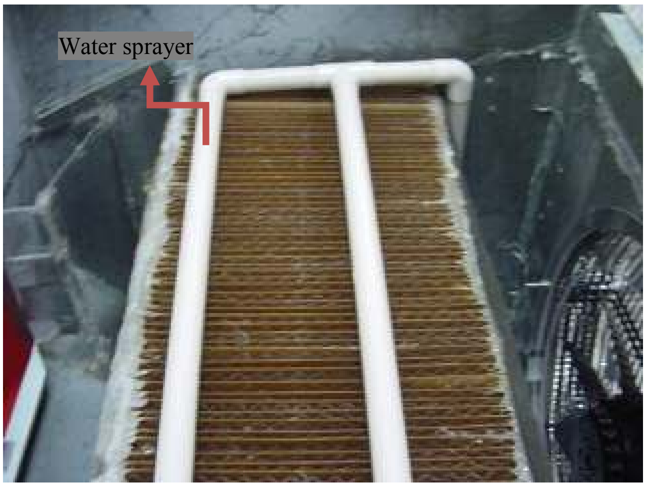


Figure 4.17 Water sprayer system using double tubing

4.6.1 Performance of the modified system

4.6.1.1 Effect of the air flow passage

The modified unit was tested under the same conditions as before with the fan and pump operated at the same speed. Results of the test presented in Table 4.8 and Figure 4.18, which show the cooling load and the COP of the system with improved air flow rates due to geometrical improvement of the PEC housing. A number of tests were carried out at different temperatures and relative humidity and maximum cooling capacity achieved was 1.6 kW.

Chamber setting	system inlet		system outlet		Results			
Temp. c°	Temp.c°	RH %	Temp.c°	RH %	ΔT	Δ RH	Cooling load	COP
25	23.27	38.52	19.27	48.64	4.00	10.12	868.67	9.65
30	28.3	40.06	21.27	60.28	7.02	20.22	1105.84	12.28
35	33.08	38.45	27.11	53.36	5.97	14.91	1338.45	14.87
40	38.59	38.11	32.09	53.04	6.50	14.93	1607.76	17.86

Table 4.8 Summary results of the geometrical improved prototype.

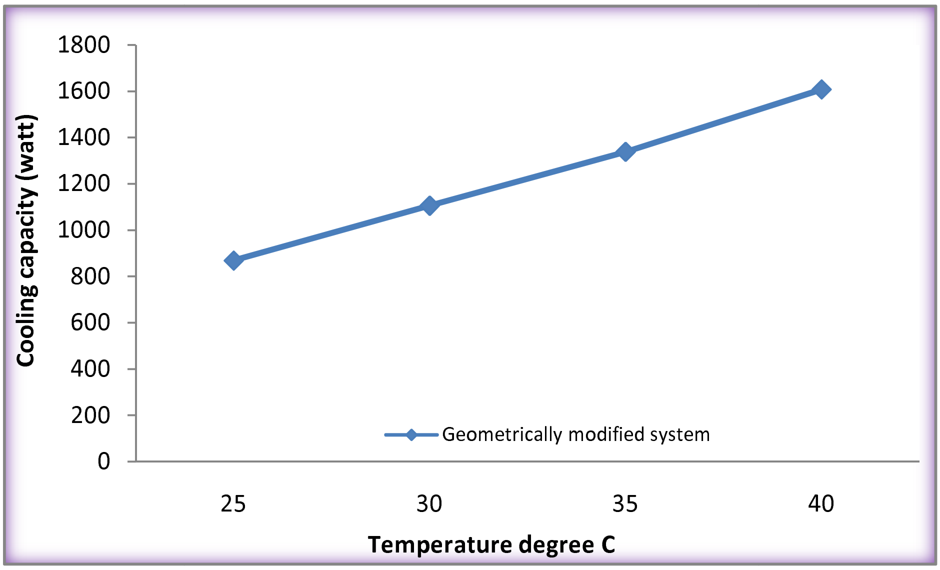


Figure 4.18 Variation of the cooling capacity for the geometrically optimised system.

4.6.1.2 Effect of the pads surface wetting area

The system has also been tested using double tube sprayer instead of a single tube. This has allowed larger pad surface to be wetted using the same amount of water. The cooling capacity of the system has increased considerably to 1.94 kW, at ambient temperature 40°C and relative humidity 50%. Table 4.9 presents sample of cooling load calculation data; COP obtained for the system geometrically modified and improved spraying system are presented in Table 4.10.

Chamber setting		system inlet		system outlet		Results			
Temp. ^{0}c	RH %	RH_1%	$T_1\,^0$c	RH_2%	$T_2\,^0$c	h_{in} (kJ/kg)	h_{out} (kJ/kg)	$Q = m(h_{in}-h_{out}t)$	COP
40	50	40.2	38.3	72.0	28.5	82.9	73.9	1.82	20.2
40	50	39.8	38.5	72.2	28.4	83.1	73.8	1.87	20.8
40	50	39.9	38.6	72.5	28.38	83.5	73.9	1.94	21.6

Table 4.9 Cooling loads and COP of the optimised system

It was obvious that the system performance could be improved significantly by optimizing the system design geometrically and improved the wetting capability of the system. As a result a prototype has been design and constructed taking into account the above points.

4.7 Design and construction of a full prototype PEC unit

4.7.1 Geometrical description

The system has been redesigned and re-fabricated using new materials for the purpose of fabrication; this design takes into account the improvement discussed in section 4.6.

Figure 4.19 presents the isometric view of the prototype system with the changes made to the air outlet, air inlet, air exhaust and to the system water spraying arrangements.

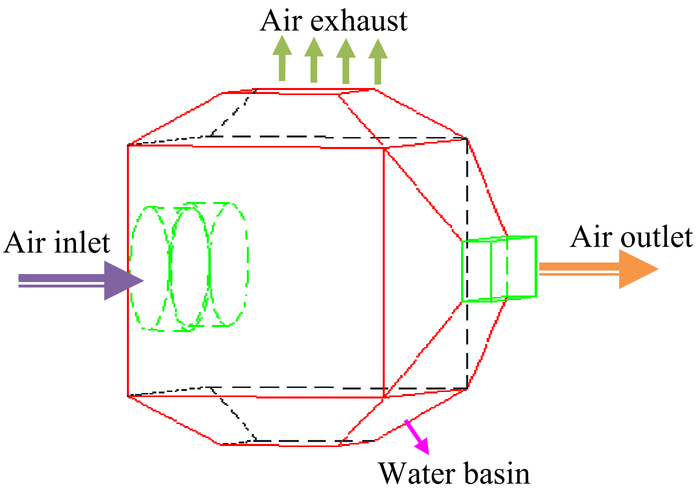
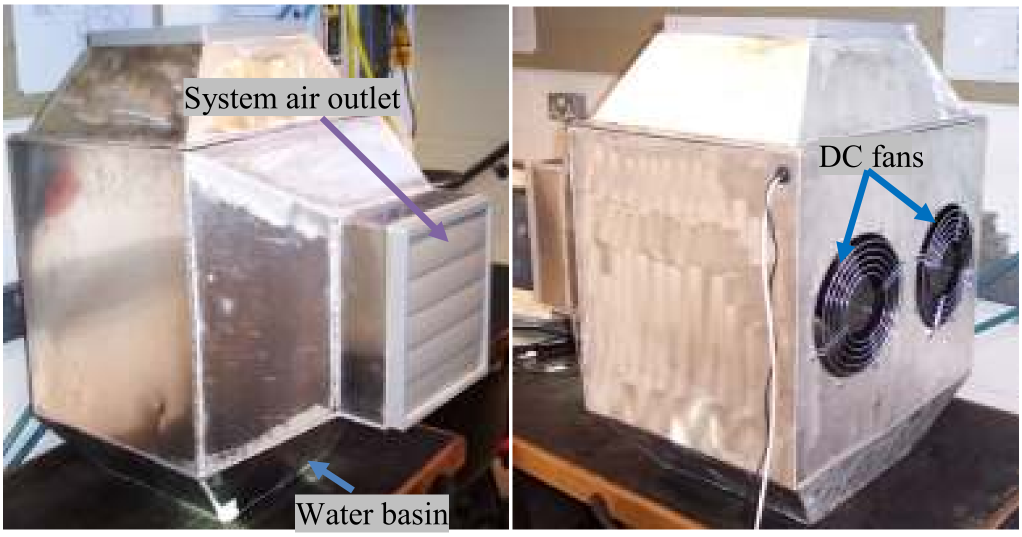


Figure 4.19 Schematic of the prototype unit

To maintain maximum air flow rate, two DC fans with a total power consumption of 29 watts were used instead of the AC fan. This enables the system to be operated using solar Photovoltaic power. The casing of the cooler is made using aluminium panels, and is geometrically shaped to minimise pressure losses along the air flow path (Figure 4.20). The dimensions of the core are 500*200*350 mm. The water sprayer is designed to maximise the wetting surface area. The water is circulated using a 15 watt DC motor-driven submersible pump located at the base of the PEC (Figure 4.20). Here only one pipe is used, but with further nozzle to allow maximum spraying efficiency. This is achieved by using further holes along the water pipe sprayer; along the lower surface and on either sides of the pipe at approximately 45^{o} from the top. This arrangement enabled water to be sprayed along the overall width of the PEC core while maintaining a uniform wetting surface.



(a) Front of the PEC cooling system (b) Rear of the PEC cooling system

Figure 4.20 Photos showing the inlet and the outlet ports of the prototype system.

(a) Exhaust shutter (b) PEC core and water spray

Figure 4.21 Photos showing the PEC core, the water distribution pipe and the exhaust shutter.

4.7.2 Performance evaluation of the prototype system

The new prototype has been set up for performance evaluation under a control environment as shown in Figure 4.22. Humidity and temperature sensors were connected at the inlet, outlet the exhaust ports of the PEC. The system was tested under controlled of temperature between 30 – 40 C^o and relative humidity 50%.

Figure 4.22 the prototype test setups

Figures 4.23 shows the Variation of the inlet and the supply air temperature as obtained from a test at relative humidity 50%. An average temperature difference of about 8 ^{0}C was achieved throughout the test.

The relative humidity of the outlet air has increased by 20% (Figure 4.24).

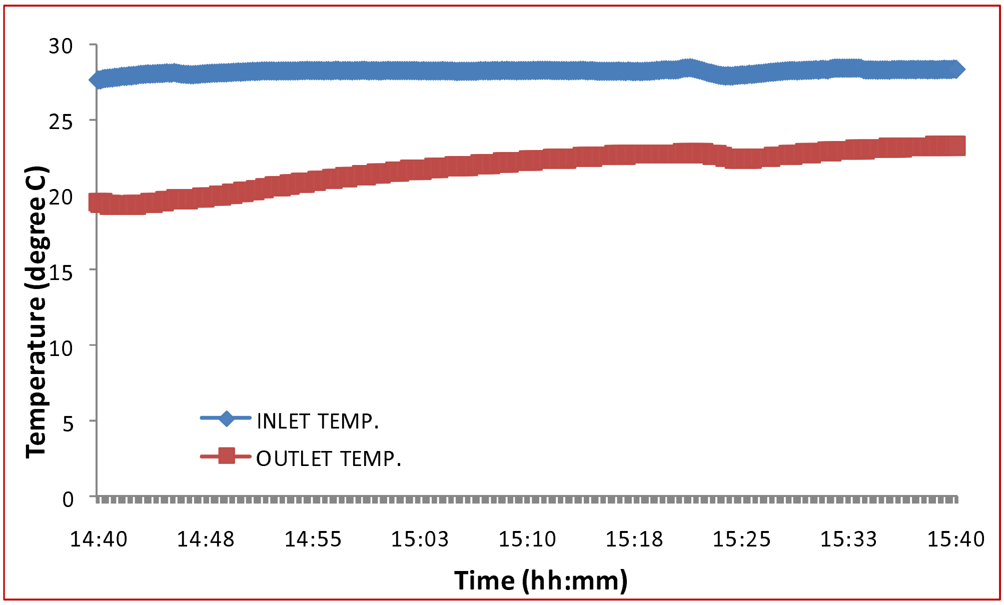


Figure 4.23 Variation of Inlet & Outlet air temperatures of the PEC unit with time.

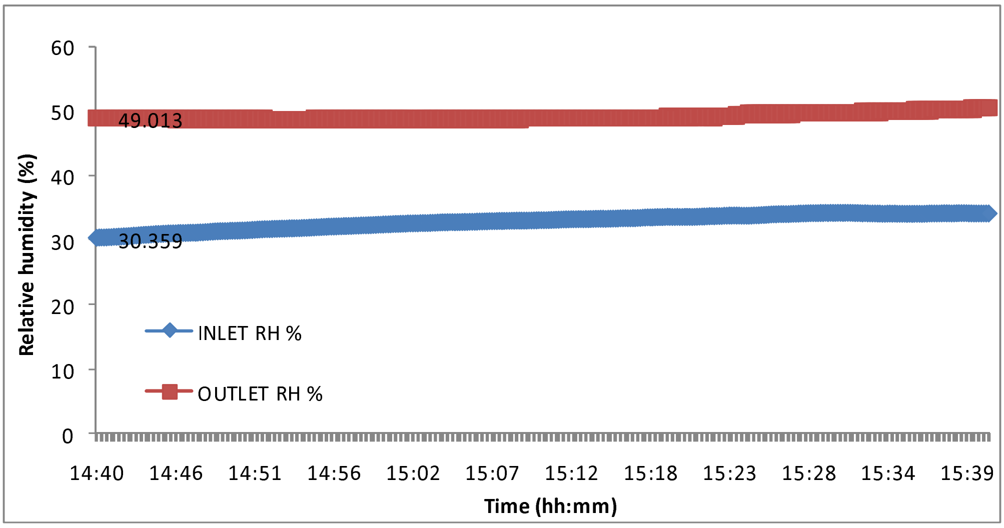


Figure 4.24 Variation of Inlet & Outlet Relative Humidity of the PEC unit with time.

The cooling load and COP of the system has been estimated using EES software. The maximum cooling capacity achieved of the optimised prototype was 2450 W, corresponding to COP of 33.56.

From equation 4.1 the Q_c can be calculated where,

$\dot{m} = V_1 A_1 \rho_1$ = 4.4 x 0.66 x1.100 = 0.3237

$Q_c = \dot{m}(h_{in} - h_{out})$

Maximum Q_c = 0.324(48.8-41.23) = 2.452

Table 4.10 presents' summary of the system cooling load results at different time of the test.

RH_1 %	T_1 ^{0}C	RH_2 %	T_2 ^{0}C	h_{in} kJ/kg	h_{out} kJ/kg	Q=m(h_{in}-h_{out})
33.7	28.3	49.1	22.7	49.1	41.9	2.33
34.2	28.3	49.8	22.7	49.2	42.1	2.28
34.0	28.3	50.0	23.1	49.3	42.2	2.29
33.2	28.3	48.9	21.4	48.8	41.23	2.45

Table 4.10 Cooling load calculation sample of Prototype system.

COP of the system is then calculated from equation 4.2,

$W_e = P_{pump} + P_{blower}$

System power consumption $15_{pump} + 58_{2fans}$ = 73 watt

COP = 2450/73 =33.56

Figures 4.25 and Table 4.11presents the cooling capacity and the COP of the system achieved at various stages of development, the results clearly shows that the prototype system produced the best cooling capacity and COP.

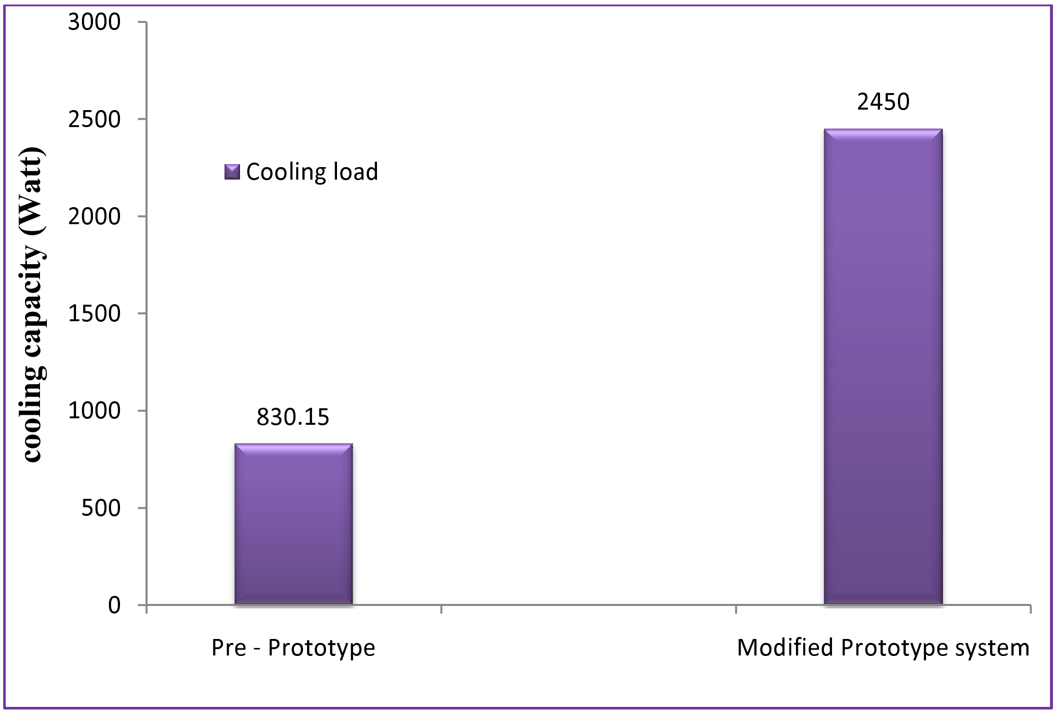


Figure 4.25 the cooling capacity of the system during various stages of developments.

System	Cooling load (Watt)	COP
First design	830.15	9.22
Prototype system	2.45	33.5

Table 4.11 cooling loads and COP of the system at different stages

4.8 Conclusions

An indirect evaporating system employing a Psychrometric Energy Core (PEC) unit has been developed through a progressive evaluation and optimisation of the air flow passage and PEC pads wetting rate. The geometry improvement enhanced the air flow and minimised pressure losses of the system and hence reduced fan power requirement. The improvement of the core pads surface wetting by proper distribution of water sprayer has also contributed considerably in improving the performance of the cooling system.

Results of the tests have shown that the performance of the system can be maximised by optimizing the PEC pads wetting rate and the air flow rate through the core. Based on the preliminary results the system design was optimised and performance of the optimised system in terms of cooling capacity was higher at 80%. The unit was able to produce about 2.4kW cooling capacity and achieved a COP of 33.5 under controlled operation conditions.

Air flow rate, air temperature, relative humidity and water flow rate have a great effect on the performance of the evaporative cooling. It has been found that the evaporative cooling works better at a high air temperature and low relative humidity.

The power required of the system can be provided using PV panel.

CHAPTER 5

Psychro Energy Core (PEC) integrated -Wind Catcher System

5.0 Scope of the chapter

The objective of this chapter is to present a design of a newly developed indirect evaporative air cooling system comprising a Psycho Energy Core (PEC) and wind catcher technology. The system was developed to enhance changes to the cooling method from air conditioning to fresh air flow conditioning (AC to FAFC). The chapter presents the description, operation and fabrication of the system and concludes with presentation of CFD modelling for the visualisation verification of the flow regime through the combined system.

5.1 Introduction and background

Historical uses of evaporation for cooling of interior spaces are well known for instance the traditional Middle Eastern wind scoop ('malqaf' or 'badgir'), where “Wind Towers " have different names in different region [45, 46, 47]. They have been used to channel air passing a wetted mat or pool of water and sometimes made to pass over water cisterns to produce evaporative cooling and a feeling of freshness (Figure 5.1) [48].

These wind towers were constructed, traditionally from wood - reinforced masonry with an opening at a height above the building’s roof ranging from 2 to 20 meter, with taller tower capturing winds at higher speeds. They were used in the hot arid regions of the Middle East to provide natural ventilation and hence thermal comfort [49].

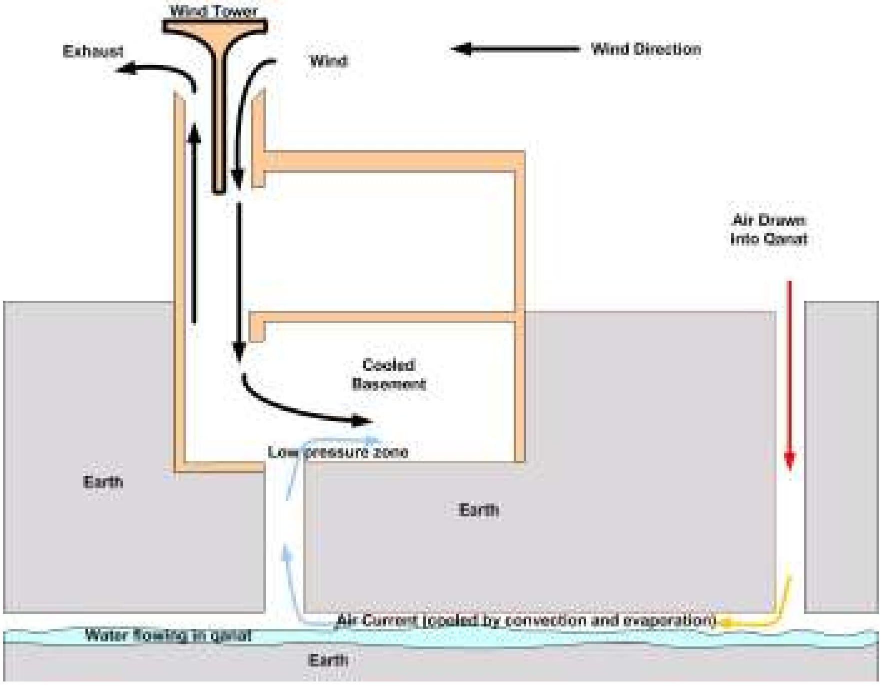


Figure 5.1 Wind towers assisted evaporative cooling system

These traditional systems have been produced in a modern design as shown in Figure 5.2, where the two ventilation principles of wind towers and passive stacks are combined in one design around a stack that is divided into two halves or four quadrants running the full length of the stack and is known by wind catcher [50, 51]. This system only provides ventilation.

Figure 5.2 Modern design of wind tower (wind catcher)

As mentioned in section 3.5.2 the cooling process using a heat exchanger involves sensible heat exchange, and when applied to evaporation the process is known as indirect evaporative cooling. Indirect evaporative cooling enables the ambient air to be cooled without increasing its relative humidity significantly. The performance of such a system depends on the type and performance of the heat exchanger. To obtain a highly efficient indirect evaporative system, a highly effective heat exchanger should be used. It must be noted that, since the air temperature drops during the cooling process its relative humidity is likely to increase, but at a lower rate compared with the direct evaporative cooling process. This process is presented in the psychometric chart by a displacement along a constant humidity ratio line, CD, shown in Figure 5.3.

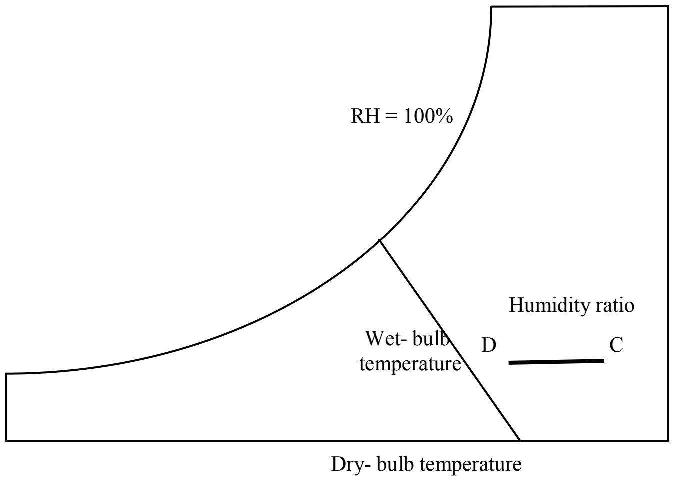


Figure 5.3 Indirect evaporative cooling processes.

The performance of both direct and indirect evaporative cooling systems is based on the concept of the saturation efficiency as defined earlier in equation 3.1.

In general, indirect evaporative cooling performance is influenced by the same factors that affect direct evaporative cooling, although an additional factor affects indirect evaporative cooling due to the use of heat exchangers in the process. The rate of evaporation increases with the increase of the evaporation surface area. The Psychrometric Energy Core (PEC) media used in this system is designed to give maximum contact surface between air and water.

An air movement (natural wind or an electric fan), is an important factor affecting the evaporating rate, as the air replaces the humid air above a wet surface with less humid air. Air movements provide a constant supply of drier air to the evaporation surface, therefore lowering the relative humidity which has a significant effect on the evaporation rate.

Air pressure affects how fast the water molecules will diffuse away from the water surface. Higher air pressure will slow down the diffusion process while low air pressure will speed up the diffusion process. More energy or higher temperature is required at higher pressures to speed up the water molecules in order for them to escape into vapour.

This study presents a combination of both concepts using a wind catcher and PEC media to form a system that can be used to provide both cooling and ventilation.

5.2 System Description

A laboratory scale of the combined system was designed and constructed using a wind catcher and the PEC unit (Figure 5.4). The purpose of the wind catcher is to assist air flow in and out of the PEC unit. This is achieved by modifying the traditional wind catcher into a double concentric hollow ducting system; an outer large circular duct for fresh air supply and a smaller central duct to allow exhaust air from the PEC to exit the system at the top of the wind catcher as shown in Figure 5.4.

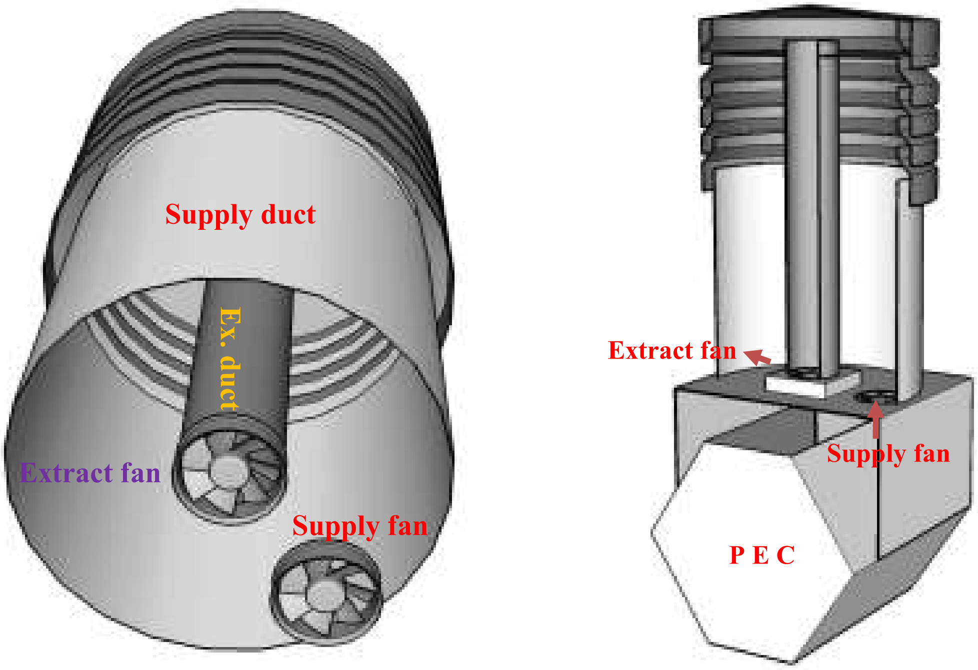


Figure 5.4 Incorporation of the modified wind catcher with the PEC and fans

The PEC used in this system (Figure 5.5) has a diamond shape which allows a cross flow arrangement; the PEC media is manufactured from a special cellulose paper (pads) that absorb and hold moisture and these are separated by thin plastic sheets to give structural strength and prevent moisture exchange. As presented earlier in section 4.1.the cross fluted design of the PEC media results in two important effects. First, it optimizes the amount of surface area available to hold the water which the air flows over, and secondly the way it is aligned causes the air to change direction in a way that ensures all of the air to be contacted with the wetted media surface before leaving the pad. A carefully designed flute angle directs water towards both the air inlet and outlet side; the water then intrinsically flushes away dust, algae, and mineral build up on the evaporation surfaces.

Fans are necessary to distribute air through the PEC and through the duct. In this system two fans have been used to assist air flow through the PEC and the exhaust duct for the test purpose. The exhaust fan pulls the air and blows it away from the system along the central duct. The supply fan pulls the air coming through the wind catcher inlets into the room through the PEC core inlet part as shown in figure 5.6.

A wind tunnel has been used to simulate the ambient air.

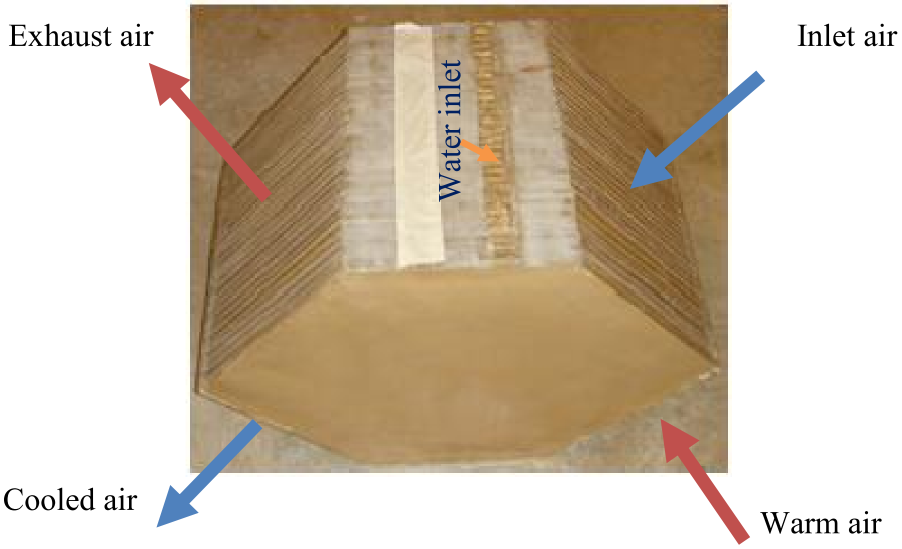


Figure 5.5 A photo showing the Diamond PEC unit used in the system

Figure 5.6 presents the details of the system components and shows the air inlet side, the supply duct, the exhaust let, the internal exhaust duct and the location of the extract fan and the supply fans in relation to the PEC and the model room.

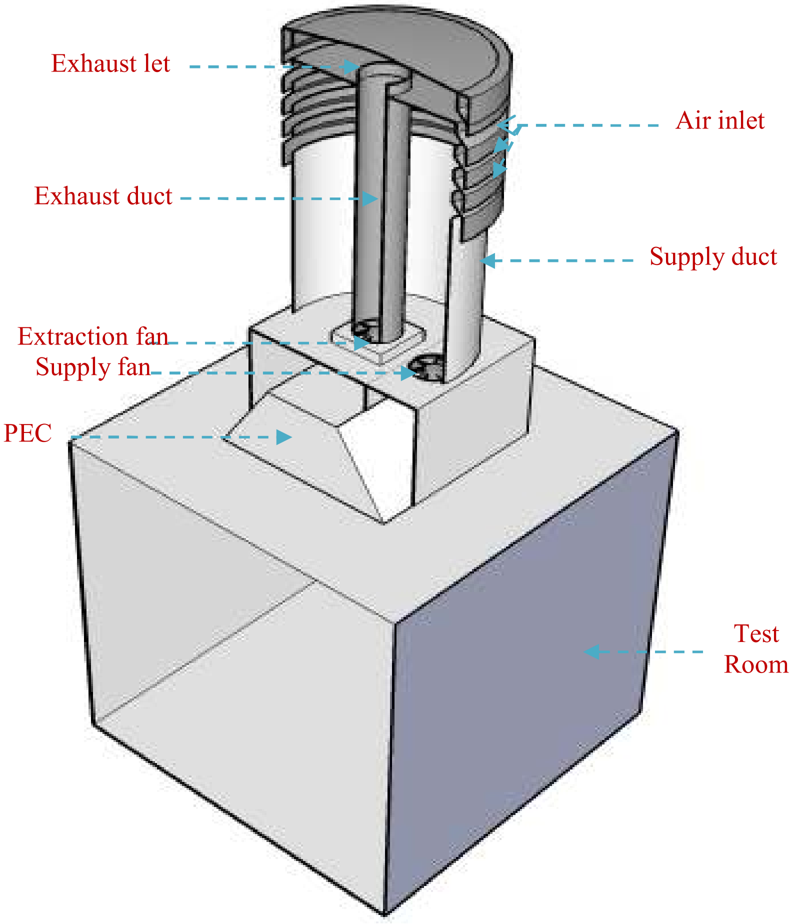


Figure 5.6 Section of the system showing the various components

As presented in Figure 5.7, water is pumped from a water tank and is used for the purpose of evaporative cooling in the PEC. The water is sprayed at the top of the PEC and the surplus water is collected at the bottom of the PEC and returned to the tank. Half of the PEC is situated in a well insulated box above the room and connected to both the wind catcher (supply air zone) and to the exhaust duct (extract air zone). The other half of the PEC, where the air goes to and from the room (cold air in and warm air out), is situated inside the room as shown.

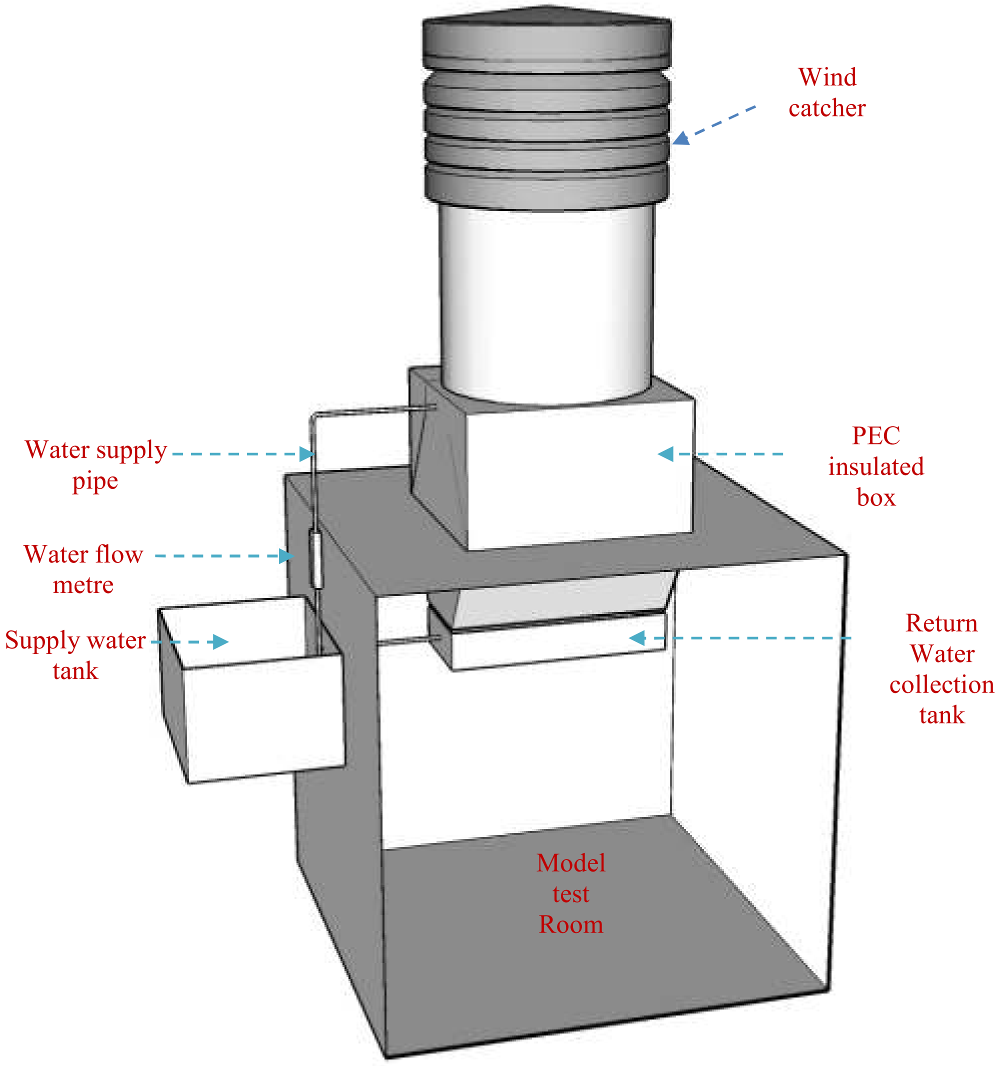


Figure 5.7 Schematic of the combined wind catcher Psychro energy core system

Figure 5.8 details the various assembly stages of the combined PEC - wind catcher system from the top supply duct and connection to the exhaust duct (1), the location of the supply and exhaust fans and their relation to the PEC (2 and 3), the installation of the PEC inside the box and the connection to the supply and return water tanks (4 and 5) and the connection of the lower system on the top of the model room (6). The location of the supply water tank is chosen to suit the tests, but in a real system this could be revised.

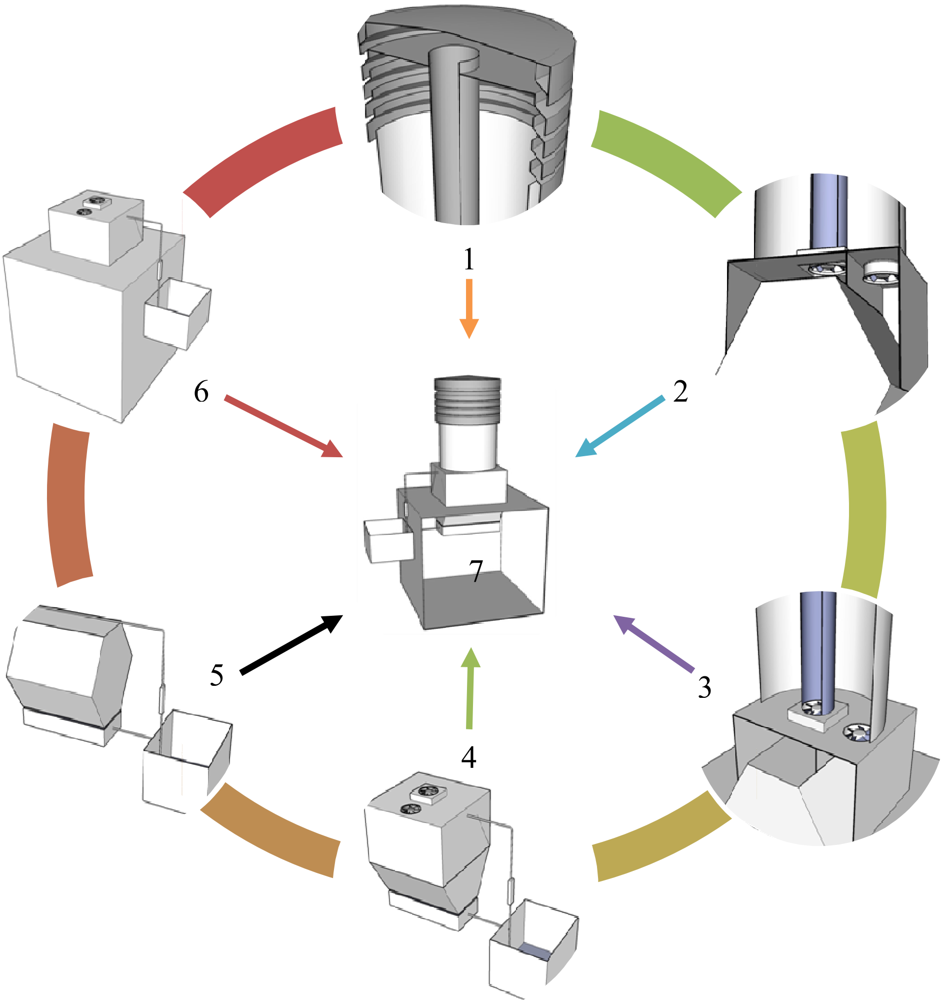


Figure 5.8 PEC – Wind catcher system Parts assembly

5.3 Fabrication of the system

The photos in Figure 5.9 show different sides of the model room which is constructed for the test. The dimensions of the room are 2000 mm x 2000 mm x 2000 mm, and it is made out of timber. The room is well insulated to prevent heat and air leakage. The room has provided with an opening on the top for the wind catcher – PEC insertion and has a side access door. The stages of the wind catchers fabrication is also presented in figure 5.10.

Figure 5.10 show the location of the supply and extraction fan inside the wind catcher duct.

Figure 5.9 Photo showing stages of construction of the test model

Figure 5.10 shows an internal small box which is been shaped to separate the exhaust fan from the supply and to suit the PEC diamond shape.

Figure 5.10 Rig fabrication stages

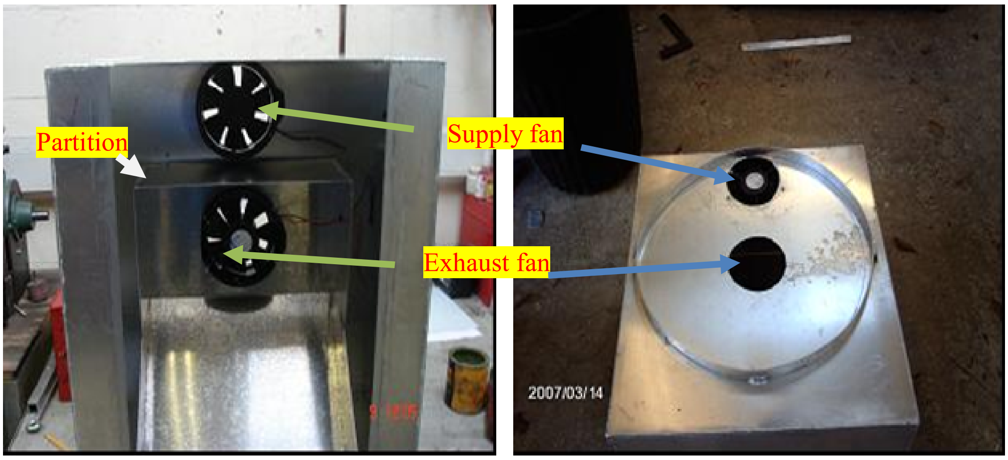


Figure 5.11 the supply and exhaust fan locations

5.4 System operation

The system could be operated in two modes, cooling mode or ventilation mode as required.

5.4.1 Cooling mode

Operation of the system is shown in Figures 5.12. Water is sprayed over the pads along the vertical channels using a circulating pump allocated in the supply water tank. Water droplets passing through the vertical channels soak the pads and trickles through them to be collected at the return water tank. Air which is taken in the system (supply air) passes through the wind catcher inlet`s port at the top of the wind catcher. The air is then drawn by the supply fan through the Psychometric Energy Core (PEC) and is split into two streams. One stream flows through the wet channels in the PEC to enhance evaporation of water sucked in the PEC and thus cools the other air stream in the dry channels within the PEC. The cooled air stream will then flow into the room carrying the warm exhaust air inside the room to rise through the PEC exhaust channel and leave the wind catcher through the exhaust air outlet by the help of the exhaust fan.

The warm air stream mixed with vapour will be discharged and pulled away by the extraction fan outside the room through the exhaust duct located at the centre of the wind catcher. If wind speed is sufficient to circulate the air the fan will be put in off state.

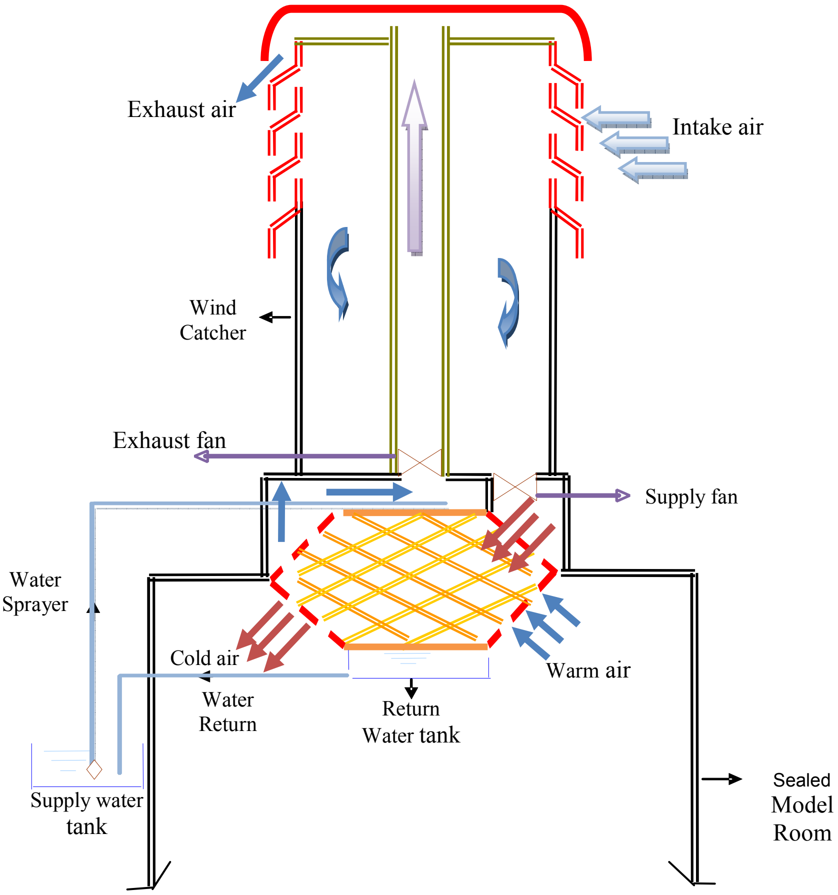


Figure 5.12 General concept of system Operation

5.4.2 Ventilation mode

When cooling is not require in the evening and night time hours, the system can be run with dry pads. This brings cool air into the homes and circulates it without using water.

If cooling pads have been allowed to dry out, either through non - use or by circulating air only, the pump must run and saturate the pads throughly before running the cooler fan. This ensures that cooler air begins to circulate sooner and reduces the introduction of dust and pollen into the building. The system has different speed fans and the adavantages of this is that low speed can be used at night when exterior temperatures drop or on days when temperatures are not excessive.

5.5 Flow verification using Computational Fluid Dynamics (CFD)

This section provides an overview of the *Computational Fluid Dynamics* (CFD) modelling which is subsequently employed to simulate the ventilation air flows through the system.

CFD defined as the analysis of systems involving fluid flow, heat transfer and associated phenomena such as chemical reactions, by means of computer based simulation [52]. The fundamental principles behind the process have been well established in the field of fluid dynamics analysis and numerical methods for many years. CFD has the capacity to simulate flow and energy and deliver solutions to complex solution. The purpose of the CFD in this study is to provide the flow visualisation throughout the system in order to verify the complete circulation of the ventilation flow. The cooling process through evaporation cooling is not considered in this modelling.

5.5.1 Methodology

The development and solution of a representative CFD model is a multistage process. The process is based upon the definition of the flow domain, and the construction and solution of the numerical equations representing the flow within the domain subject to specified boundary conditions. The resultant steady state or time dependent solutions may be graphically viewed as a series of 2 and 3 dimensional, vector, streamline, contour plots, etc. These stages of model development and solution are universally classified under the following headings which are undertakes to complete the modelling process.

- Pre-Processing
- Solving

 Post-Processing

a- Pre - Processing (CAD and Gambit software)

Geometry creation within modern CFD applications bears considerable resemblance to conventional *Computer Aided Design* (CAD) packages. The geometry can be imported from pre-built models or constructed from scratch using a combination of points, lines and surfaces that together form a volume. The creation of geometry in a CFD application differs slightly from its CAD counterpart in that connections between points, lines and surfaces must be computationally absolute. Often CAD packages produce visual connections only hence if geometry is imported, some degree of 'clean up' is required (Figure 5.13).

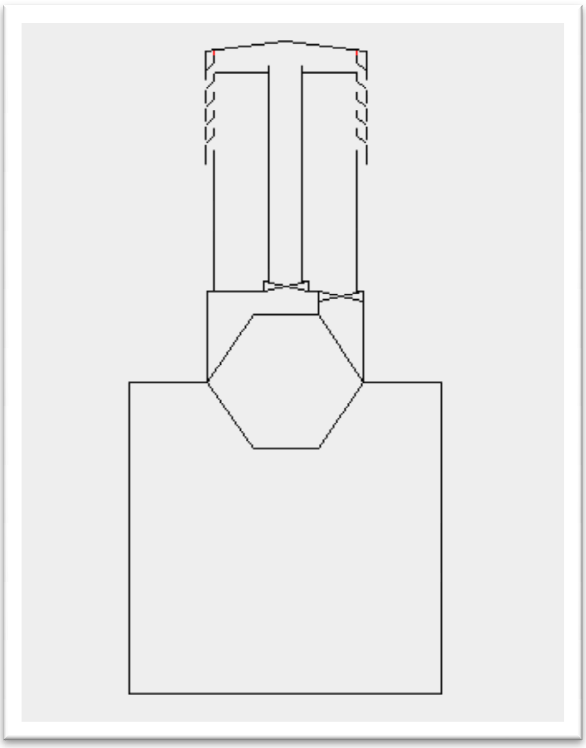


Figure 5.13 System geometry generated using CAD package

- **Domain and Grid Generation using GAMBIT Software**

Gambit is a pre - processor software, which facilitate the use of fluent software. Its CAD interface facilitates drawing in two and three dimensional geometry models, defining their boundary conditions and generates the calculation Grid or mesh. This calculation mesh is exported to fluent software, which is mainly used as a calculation tool. Figure 5.14 presents the system geometry drawn using gambit software.

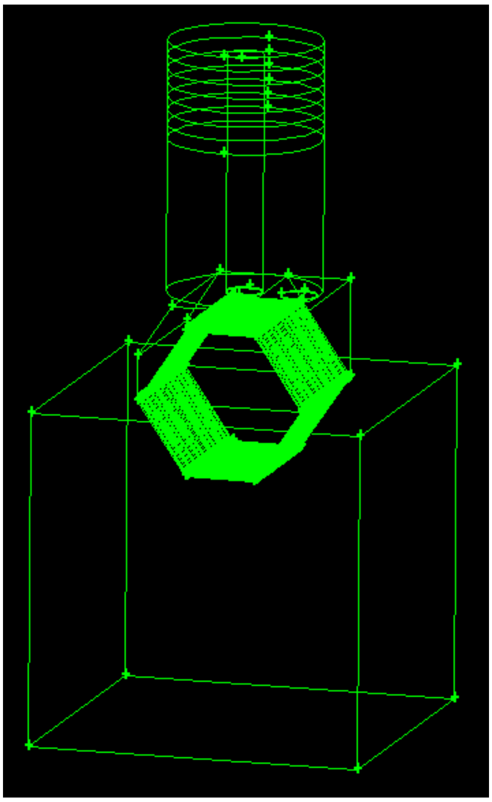


Figure 5.14 System geometry outline generated using gambit software

Definition of boundary condition

This is a shared task between Fluent and Gambit software's. However, the initial definition should be made in Gambit. This design is a three- dimensional model and the type of domain has been defined using interior, velocity inlet, pressure outlet and wall for the different parts of the geometry.

- **Generation of the Mesh**

Once the flow domain is defined (Figure 5.14), the free flow volume is sub divided into cells’, the total number of cells join together to form the flow domain that together create a large interconnected net. This net, whether in 2D or 3D such as in this case, is referred to as the “*mesh”*. The points of interconnection of the edges of each mesh are termed the nodes. The fluid flow equations are subsequently numerically solved at each of these nodes within the flow domain. The construction of the mesh plays a significant role in the ultimate accuracy of the CFD solution. Since the solution is only provided at this finite number of nodes on the mesh it is important that the distances between the nodes are sufficiently small to capture all the relevant detail and characteristics of the flow in that area. Ideally, to prevent any inaccuracies arising from inter node distance; the mesh density would simply be set as high as possible. “Unfortunately the greater the number of cells in the mesh the greater the demands on the computational hardware and hence time.*”*

The process of meshing a flow domain during the pre-processing stage has a number of options associated with it. The primary options concern the type of mesh; such as hexahedral, tetrahedral and hybrid. The mesh found to be suitable for this type of geometry after much trial is tetrahedral as shown in Figure 5.15 Figure 5.16, Figure 5.17 and Figure 5.18. The mesh size is (0.08) for the computational domain, (0.03) for the room and 0.02 for the heat exchanger.

Gambit has various methods of examining the quality of the mesh .i.e. aspect ratio, diagonal ratio and mesh skew. Equi Angle skew was used in this case to assess the quality range. The graphic window presented cell with a skewness value between 0.1 - 0.5, these low value (<0.5) for the maximum skewness indicates that the mesh is acceptable. Figures 5.15 to Figure 5.18 show the meshing as produced by GAMBIT for the different part of the system.

The meshing of the PEC unit is shown in Figure 5.15, while Figure 5.16 and Figure 5.17 show the meshing of the room combined with the PEC and the complete system respectively. Figure 5.18 shows the meshing of the system and the computational domain.

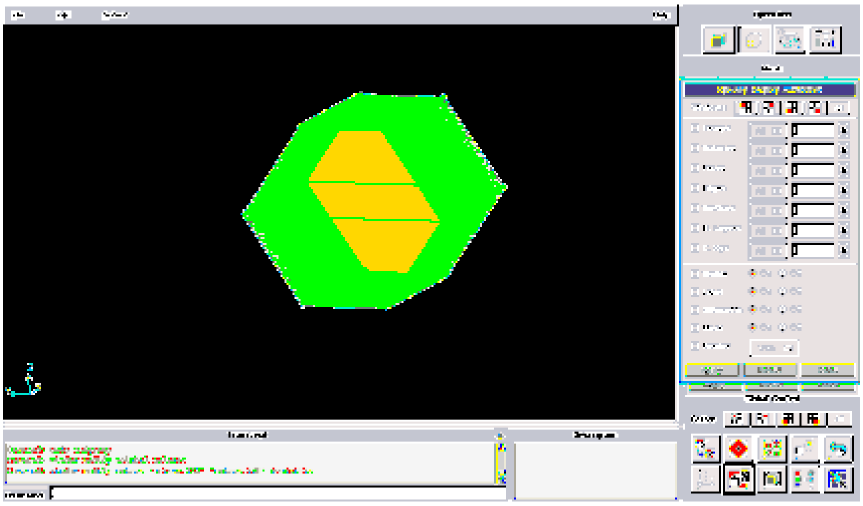


Figure 5.15 Generation of the Mesh for the Heat exchanger Section

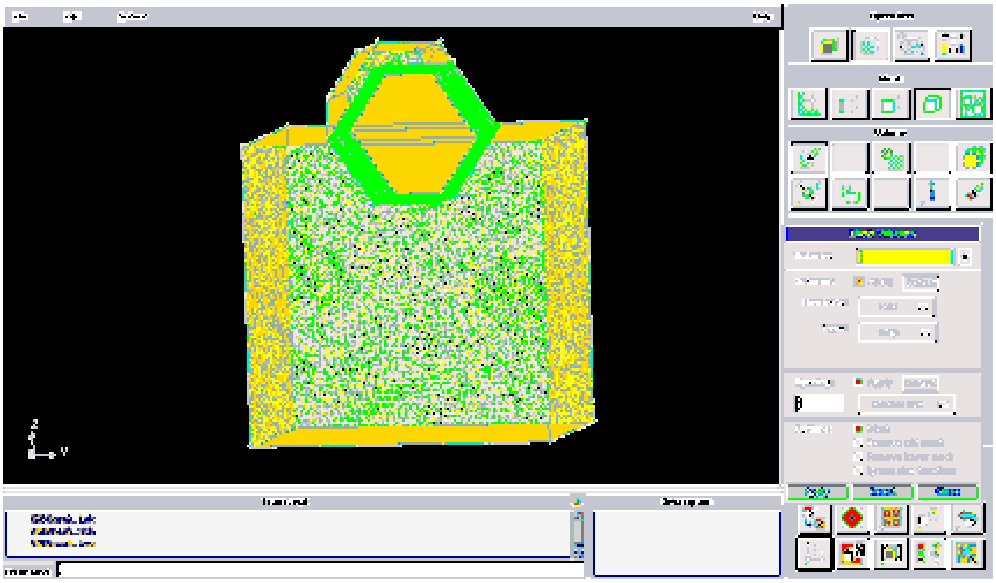


Figure 5.16 Generation of the Mesh for the PEC and the room

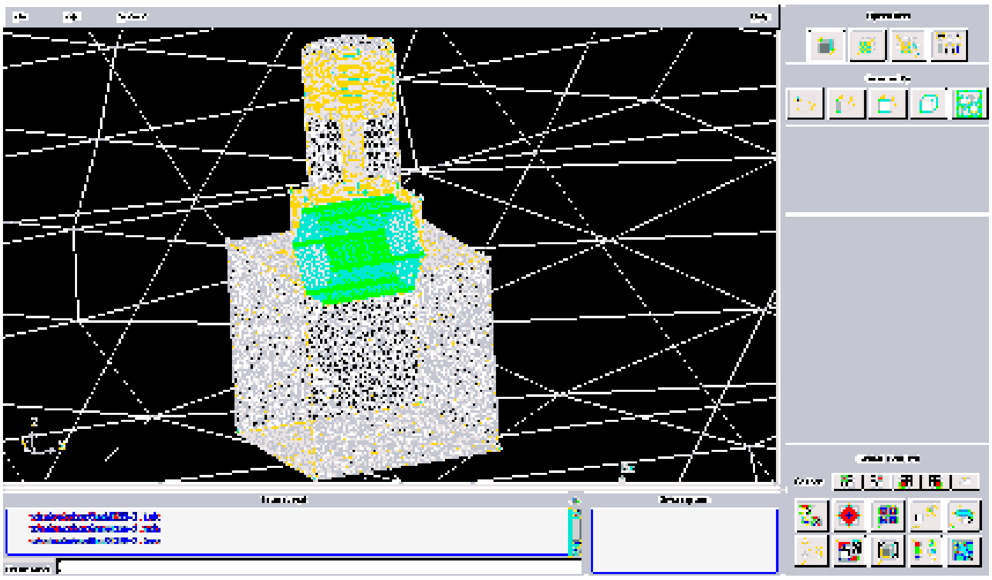


Figure 5.17 Generation of the Mesh for the whole system

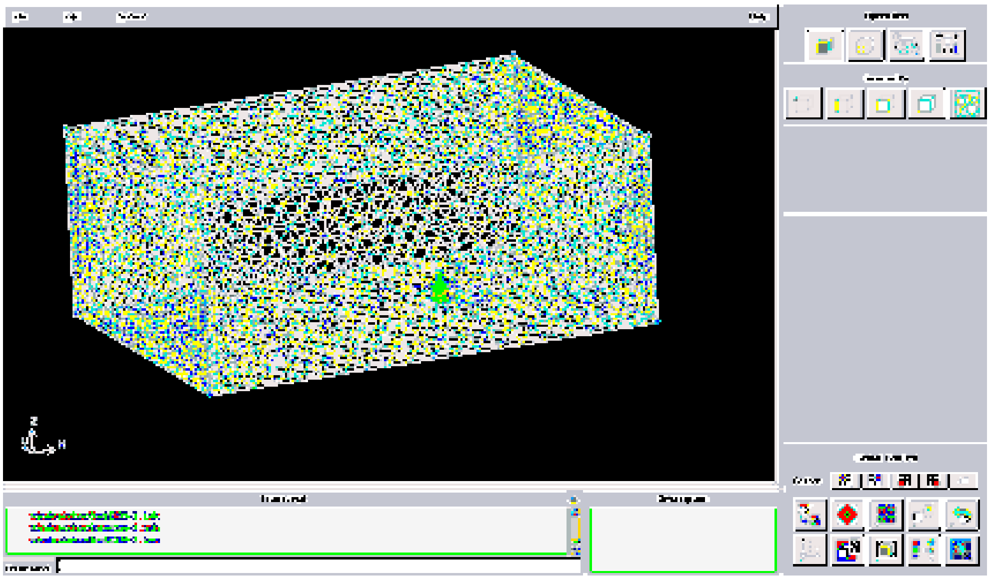
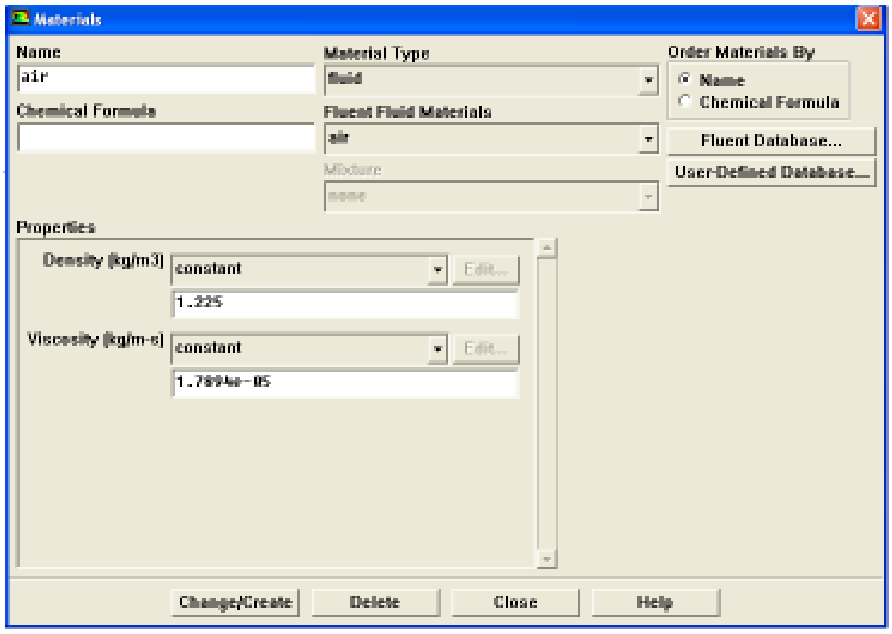


Figure 5.18 Tetrahedral type used for meshing the computational domain

- **Fluent software**

Fluent 6.3 was used in this study. It is worth mentioning that fluent software can be used to simulate air flow under the influence of various parameters such as air velocity, location and size of the opening but in this study it was used only for the purpose of the design verification.

The first step in fluent is to import the case export from gambit as explained earlier. The next step is the definition of fluid properties and the use of boundary condition including the selection of any appropriate solution procedures if options are available (Figure 5.19).



Name: air

Chemical Formula:

Material Type: fluid

Fluent Fluid Materials: air

Mixture: none

Order Materials By: ● Name ○ Chemical Formula

Properties

Density (kg/m3): constant

1.225

Viscosity (kg/m-s): constant

1.7894e-05

Figure 5.19 The definition of working fluid used in the system

Applications vary from one to other, but common options include the definition of the iterative solution method used to find a solution to the flow equations and various other numerical options such as the convergence criteria.

Further iteration did not (result in) produce any significant changes in the solution. The flux report of the calculated net mass flow rate was nearly 0 between inlet and outlet boundaries. This was checked for inlet and outlet in the heat exchanger and the system as whole. Although absolute criteria was set for iteration to stop when residuals are 0.001 [10^{-3}], this criteria was not used to judge the convergence of the solution. The iteration process was stopped once further iterations did not produce any significant changes in the solution.

b- Solving

The solver used for this model consists of different field to specify three aspects: the solution method used in the calculation process, the dimensionality nature of the solution domain and the state of the flow whether it is steady or unsteady. Pressure based solver and steady state calculation has been used on this problem. The velocity formulation was chosen as absolute and the time was based on the steady state during this study. The model is Turbulence. Standard k- epsilon turbulence model with standard wall functions was used in the process; the k-epsilon is two equation model. To compare with lab result the velocity inlet has been set to 2.1 m/s.

- **Definition of the boundary conditions**

Boundary conditions specify different variables on the boundaries of a modelling case. As explained earlier the boundary conditions should be defined in Gambit software first and then the relevant setting can be completed in fluent. For example the inlet air of the wind catcher was defined in Gambit software as supply in and the relevant definition are completed in Fluent, as presented in Figure 5.20 the velocity -inlet boundary condition is used for wind catcher's inlet vents, while pressure -outlet boundary condition has been used for the outlet vents. Interior boundary condition is used on the heat exchanger surface as intermediate layer between the room and the wind catcher.

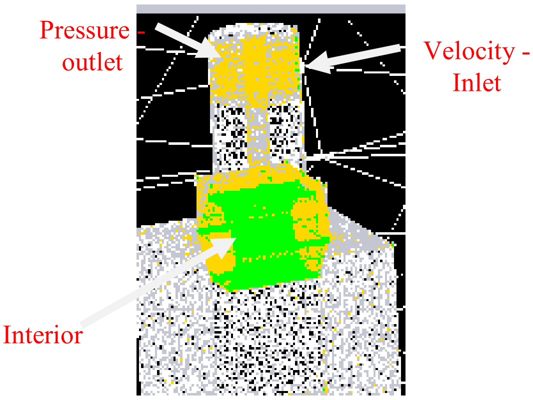


Figure 5.20 Definition of the boundary conditions

- **Residuals monitors**

By completing the relevant setting, fluent start to perform the calculation until a sufficient error tolerance defined by the user is achieved and this means that solution will converge after achievement of that error, while the calculation time depend of the type of the error. Figure 5.21 shows the residual monitoring plot of the converged solution during the modelling of the system.

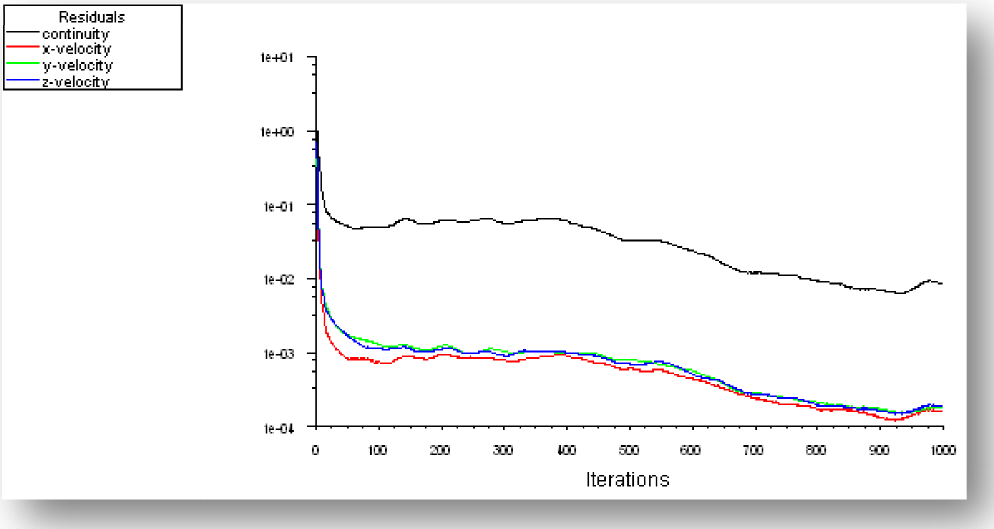


Figure 5.21 Residual monitoring plot of the converge solution during the CFD modelling.

c- Post Processing

Post-processing represents the final stage in the CFD analysis method. Despite the fact that much of the hard work in terms of finding a solution has been completed at the solution stage, many output in different presentation method can be presented, the results from the modelling of the PEC - Wind catcher system are presented using velocity vector and path line where it shown the direction of the air flow in addition to its magnitude. Results of the air flow direction at different point of the system are shown in the Figures 5.22 – 5.26.

The modelling of the system has been carried in stages in order to ensure correct air flow path. First the PEC was modelled and the result in Figure 5.22 has shown that the air coming from the supply in passes through the supply out and the extracted air passes through the extract out channels.

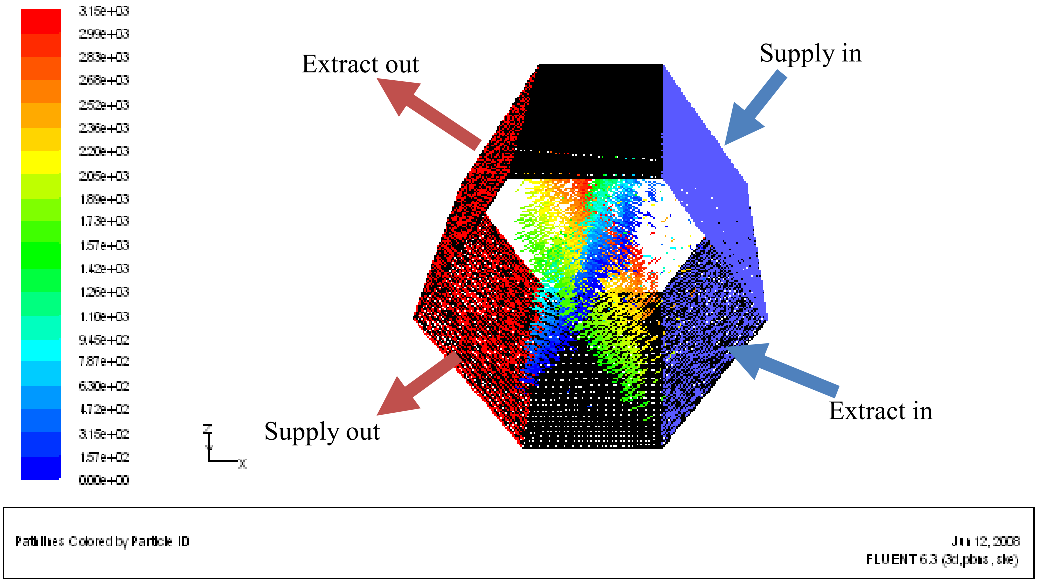


Figure 5.22 The PEC Supply and extract air exchange modelling

5.5.2 Results of the modelling

Figure 5.23, Figure 5.24, show the modelling results of to the PEC and the room. The results show the passage of the Supply and the exhaust air through the PEC to and from the model test room.

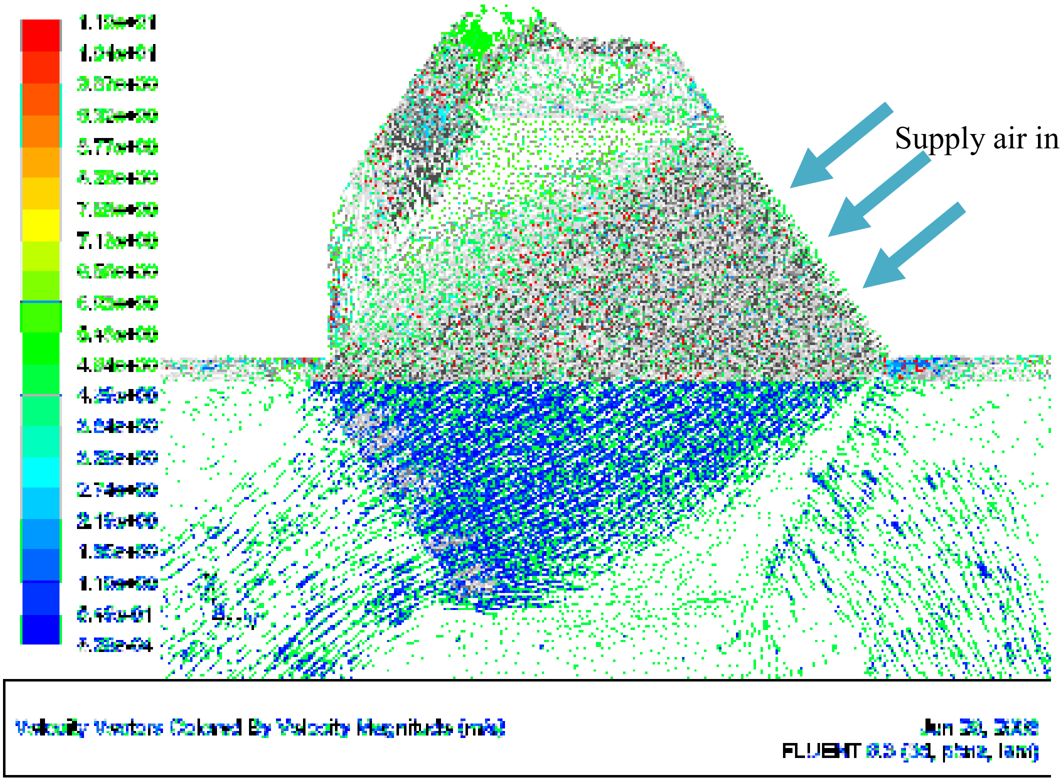


Figure 5.23 CFD modelling showing the passage of the Supply air

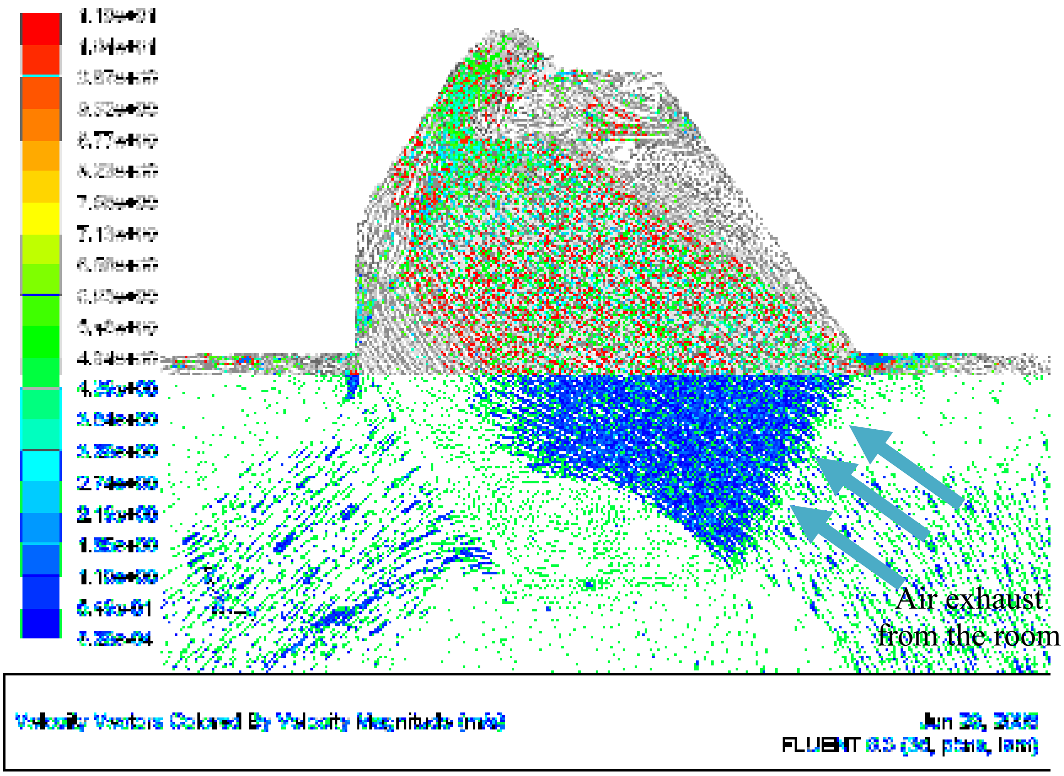


Figure 5.24 CFD modelling showing the passage of the exhaust air

Figure 5.25 show the modelling results of the supply inlet and the middle exhaust duct of the system. The results achieved proof that this part of the system is working properly. The air can pass to the PEC through the supply fan and the exhaust air extracted from the room can also pass through the middle duct as specified in the initial design.

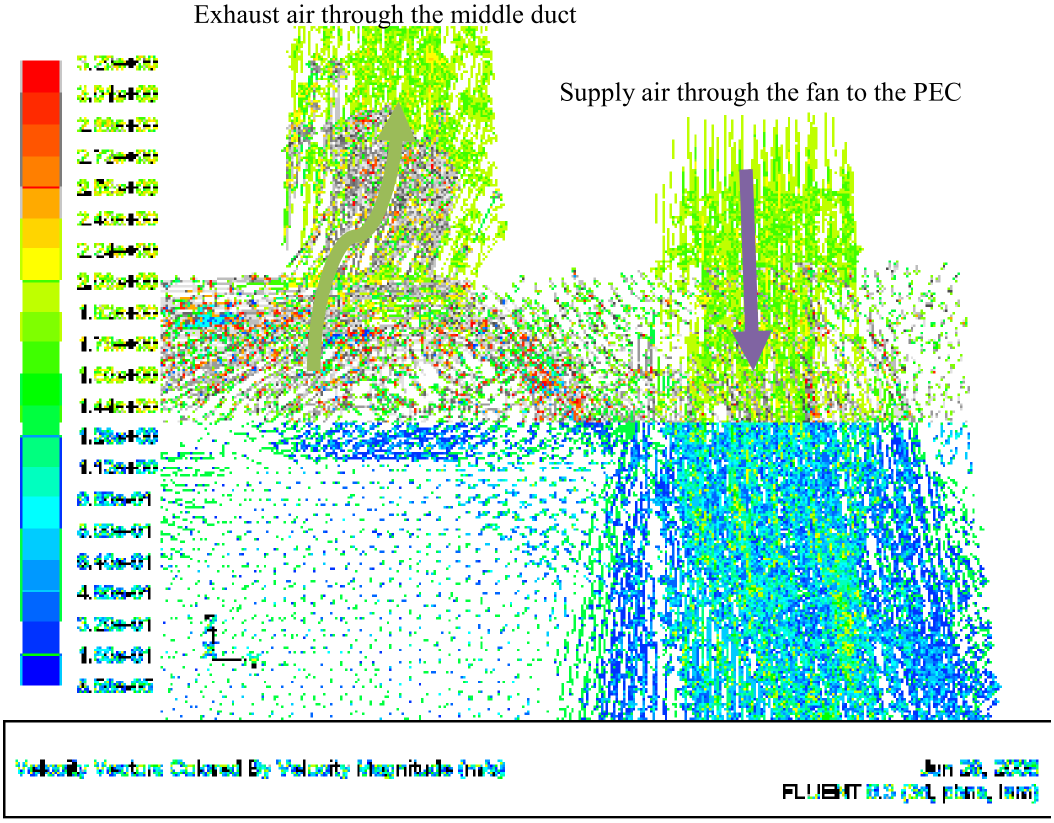


Figure 5.25 Velocity vectors showing the passage of the air through the mid duct

Figure 5.26 present modelling of the entire system with a computational domain. It can be observed that the air gets in the wind catcher inlet and around the middle duct and passes through the PEC to the room. It also show that the exhausted air from the room passes through the PEC to the middle duct and then to the ambient.

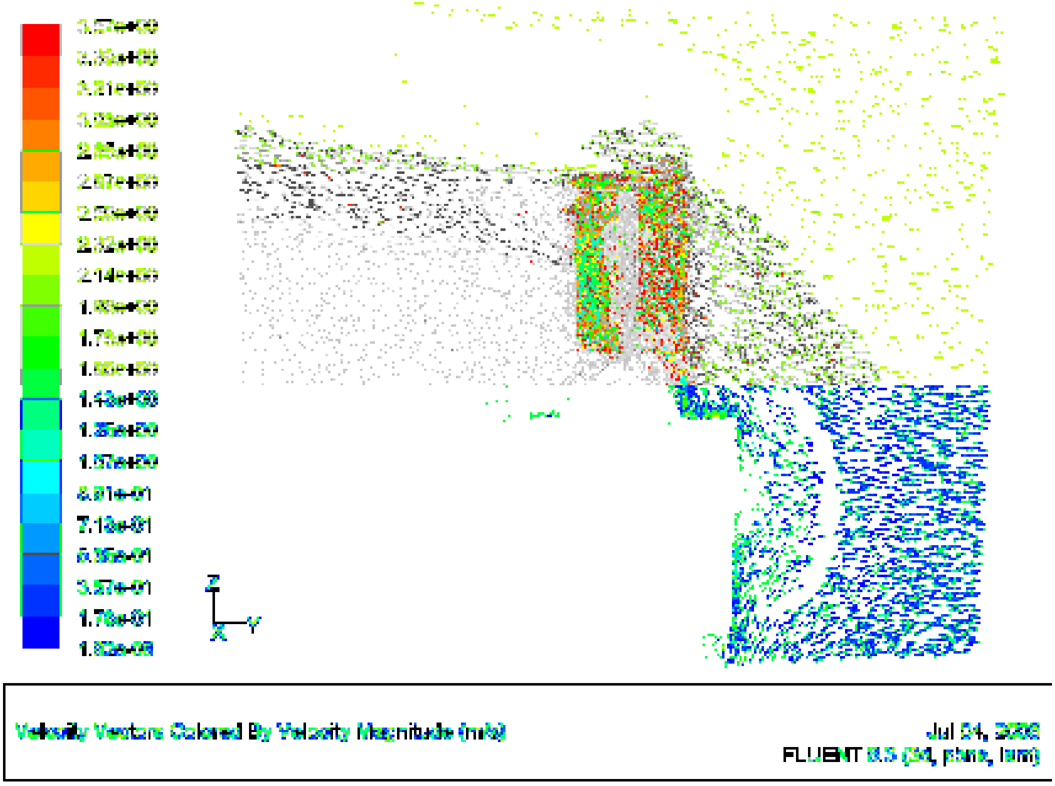


Figure 5.26 Section showing the air coming through the wind catcher inlets

5.6 Conclusions

As stated earlier the use of CFD in this chapter was performed only for the purpose of verification the design to show the air passage in and out through the system.

Design of an evaporation air cooling system comprising a Psycho Energy Core (PEC) cooling unit integrated with wind catcher technology has been developed. Details study of air flow passage has been carried out using the CFD modelling and the results achieved show that the system could be able to operate given the right boundary condition, in this case the inlet air speed.

CHAPTER 6

Experimental Evaluation of the combined PEC wind catcher system

6.0 Introduction

This chapter presents results of an experiment conducted to investigate the performance of the combined PEC wind catcher system. The chapter starts by describing the methodologies used for the tests, rig setups and the measuring transducers. The data obtained from the test were then presented and discussed. Short conclusions of the performance of the combined system under various conditions are given at the end of the chapter.

6.1 Test methodology

The combined system is constructed and prepared for performance evaluation. The tests were carried out indoor using a model test room constructed for the purpose of this study. The room is located inside a laboratory space and a series of tests were conducted using a wind tunnel in order to assess the performance of the system under varying wind speed and ambient temperature. The tests were carried out at ambient air temperature of 23^{o}C then the temperature was increased to 30^{o}C and 38^{o}C using an artificial heating.

The experimental work was carried out at different settings to find out the best combination of wind speed, fan rating and water flow rate that will make the system operate at its optimum performance.

The experiment was carried out under the following conditions

a- Varying wind speed

In practice, the system will be installed on top of the building and so the system will be subject to different wind speeds.

The experiments was run inside a laboratory assisted with wind tunnel to provide varying wind speed between 1.6 to 4.5 m/s at the inlet of the wind catcher, as schematic illustrating the size of the wind tunnel is shown in Figure 6.1. the wind tunnel is constructed on an adjustable from support.

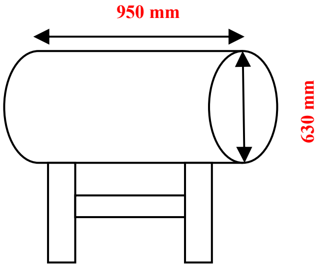


Figure 6.1Schematic of the wind tunnel size

b- Supply and exhaust fan ratings

As mentioned in section 5.2, two low energy fans with power input 12 watt at 12 volts were used in the system to help the system overcome the pressure drop of the air passing through the wind catcher and the PEC core to the room as well as the exhaust duct. These fans has three different speed i.e. low, medium and fast, the air flow rates of these fan has been measured and calculated and found to be (116 m^3/h), (233 m^3/h) and 350 m^3/h respectively. In order to find out how the system would perform under varying wind flow rate the test has been set at different speeds including the fans set off (0 m^3/h).

c- Water flow rates

Water is essential in any evaporation cooling system, as this creates the cooling effect and it has to be controlled using pump controller to optimise the evaporation rate.

The PEC core in this test is wetted continually by spraying water over the PEC core. The tests were carried out under different water flow rates (0.6, 0.8,1, 1.2, 1.4, 1.6 and 2 l/m) in order to find the best water flow rate that could optimise the performance of the core.

d- PEC Core channel size

Three PEC cores with different channel sizes i.e. 4mm, 6mm (tested with 3 different winds speed fan set at maximum only) and 8mm have been examined during the test. The purpose was to determine which channel size of the core will give the best performance at minimum fan power requirement.

6.1.1 Test Rig setup

Figure 6.2 shows a photo of the test rig including the wind tunnel which is used to simulate the ambient wind at different speeds. A variable speed DC pump is used to supply the evaporating water to the PEC at different flow rate. The model test room is well insulated using a 15mm thick insulation made of mineral wool (thermal conductivity= 0.04 W/m/K). Air leakage tests had been performed to ensure that there is no air leakage. Two DC fans were used to assist air flow into and out of the PEC core. Measuring sensors for humidity, temperature and air velocity were connected as shown in Figure 6.3. An electrical heater is used to heat the supply air to 30 and 38 C^o.

The parameters studied were the temperature, relative humidity and the air flow rate outside the system and along the wind catcher. The tests were carried out under different wind speed and different water flow rates.

The small fans have been used in the systems one to enhance the air flow through PEC and the other through the exhaust duct. The purpose of using these fans is to ensure that there is a sufficient airflow through the PEC unit to overcome the pressure drop due to friction in the PEC core channels.

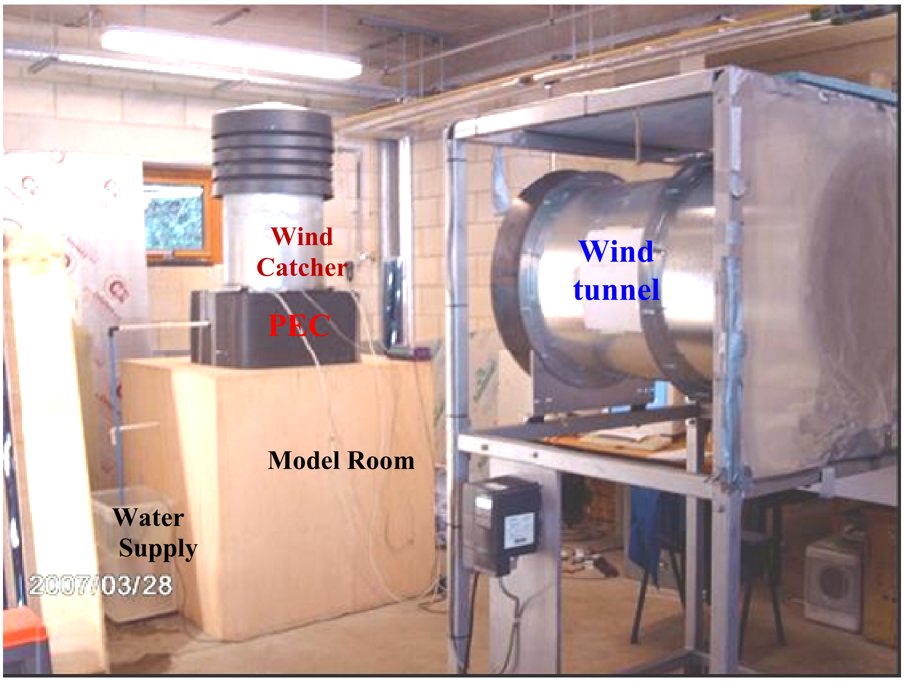


Figure 6.2 A photo showing the test rig and the wind tunnel.

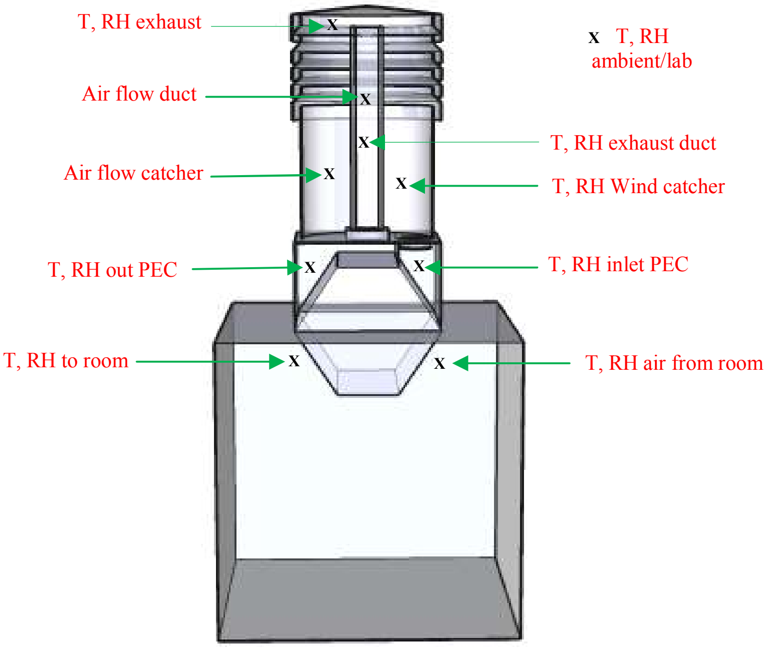


Figure 6.3 Schematic showing the measuring points and sensors positions.

6.2 Tests results and discussion

As mention in section 5.5, PEC with different channel width (4mm, 6mm and 8mm) have been fabricated for the purpose of this test. The parameters which have been studied were the temperature, relative humidity and the air flow of the system. Measurements of the above parameters were carried out using measuring sensors connected to a data logger and a PC (Figure 6.4). First the system was operated until the setting conditions were maintained. The cooling system is then switched on and measurements were taken until steady state is achieved. The time for this varied for the different PECs, with an average of one hour. The humidity and the temperatures are measured using humidity and temperature probes and the air flow rate was measured using a hot wire anemometer. The tests were carried out under different wind speeds, different exhaust and supply fan rated power and different water flow rates.

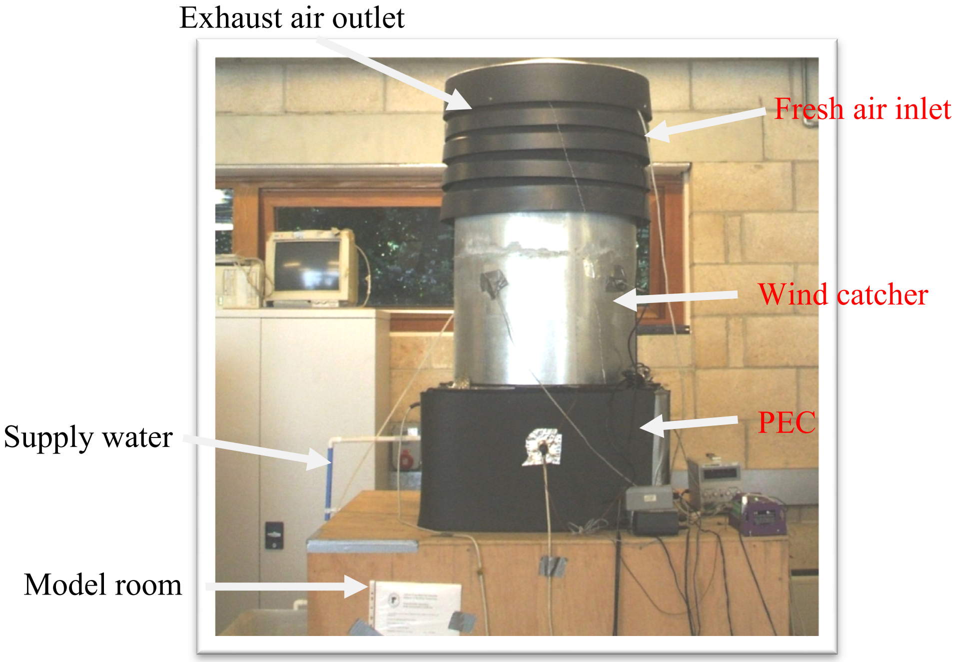


Figure 6.4 A photo showing the test rig and the measurement setups

6.2.1 System air pressure drop

Pressure test have been carried out on the system at different wind speeds using a differential pressure metre connected with a tube at different points in the test room and in the wind catcher to establish some information about the effect of using the PEC on the pressure drop. Theoretically the pressure different should be between 60 Pa to 70 Pa if there is no heat exchanger at wind speed around 3 m/s, [53]. The measurements were taken with the two internal fans set on and off. The result of measurement with fan off showed that the pressure drop at all wind speeds when using the PEC is still lower than the standard when the fans are on. This drop is caused by resistance of the PEC unit.

6.2.2 Effect of the internal fans on the temperature, relative humidity and the air flow at a given wind speed and ambient temperature.

A series of tests were carried out with supply and exhaust fans set on and off at different water flow rates with wind speed 2.1m/s. The core unit channel size was 4 mm. The purpose was to evaluate the effect of the supply and exhaust fans on the temperature, relative's humidity and the air flow rates of the air in the wind catcher through the PEC.

Figure 6.5 and Figure 6.6 shows the variation of the incoming and exhaust air temperatures with water flow rate when the internal fans are set on. The wind speed in this case was 2.1 m/s and the ambient temperature (lab temperature) was set 23°C. The room temperature was cooled to 17°C i.e. 6 degree cooler than the ambient. It can be observed that the temperature has dropped at the supply fan point before passing through the PEC. The room temperature dropped by 4 degree to 19°C from 23°C, this is caused by the heat exchange between supply and exhaust air. The temperature at the exhaust outlet has increased to 22.5°C. It could be observed that heat exchange has also taken place within the wind catcher between incoming air and the leaving air. This is evident from the fact that the air temperature increased in the exhaust, it was 20°C at the duct and dropped to 19°C in the wind catcher. There was slight change in the ambient air temperature and therefore all other temperatures have varied as shown in Figure 6.5 and 6.6.

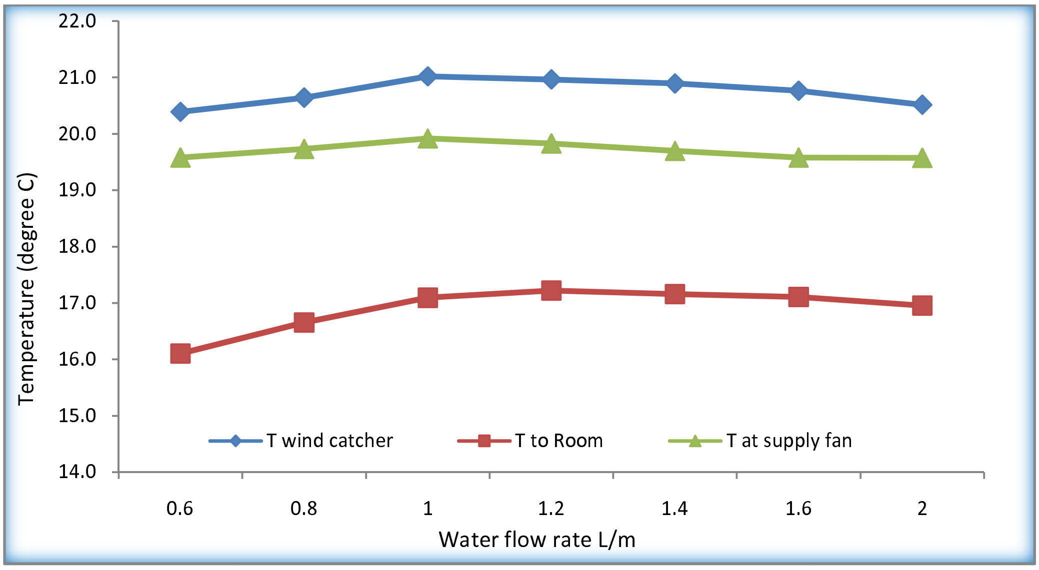


Figure 6.5 Variations of incoming air temperature when the internal fans are set on.

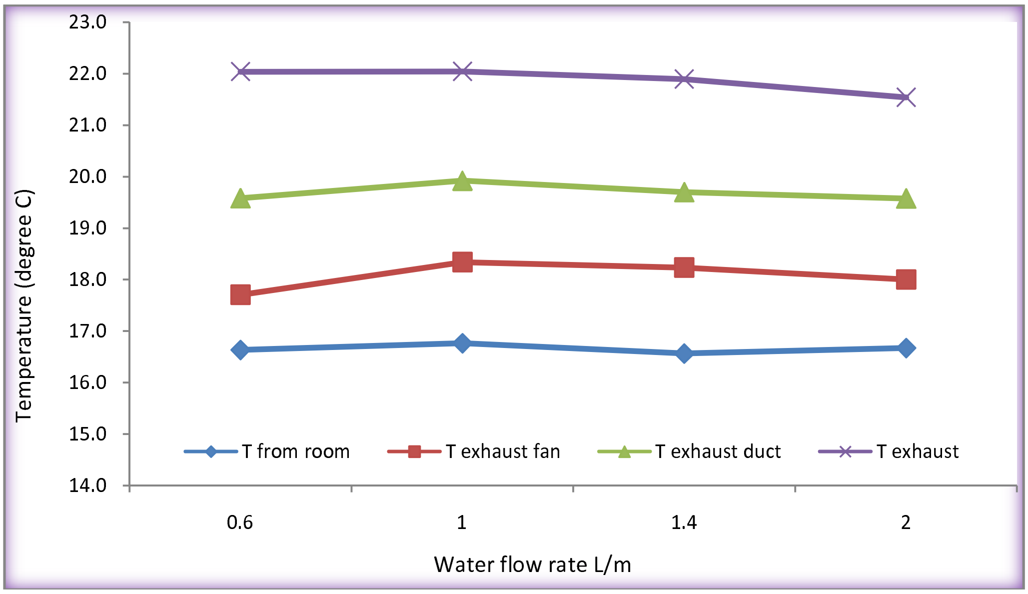


Figure 6.6 Variations of the air temperature leaving the room when the internal fans are set on.

6.2.2.1 The effect on temperatures when supply and the exhaust fan is set off

Figure 6.7 and Figure 6.8 show the variation in the incoming and the leaving air temperature with the water flow rate with the internal fan set off. In this case the test room temperature was 17°C i.e. 6 degrees lower than the ambient (lab) temperature. It can be observed that the heat exchange inside the wind catcher is not as significant as in the case of fan on. The temperature of the incoming air dropped by about one degree only, that of the leaving air increased by about one degree as well.

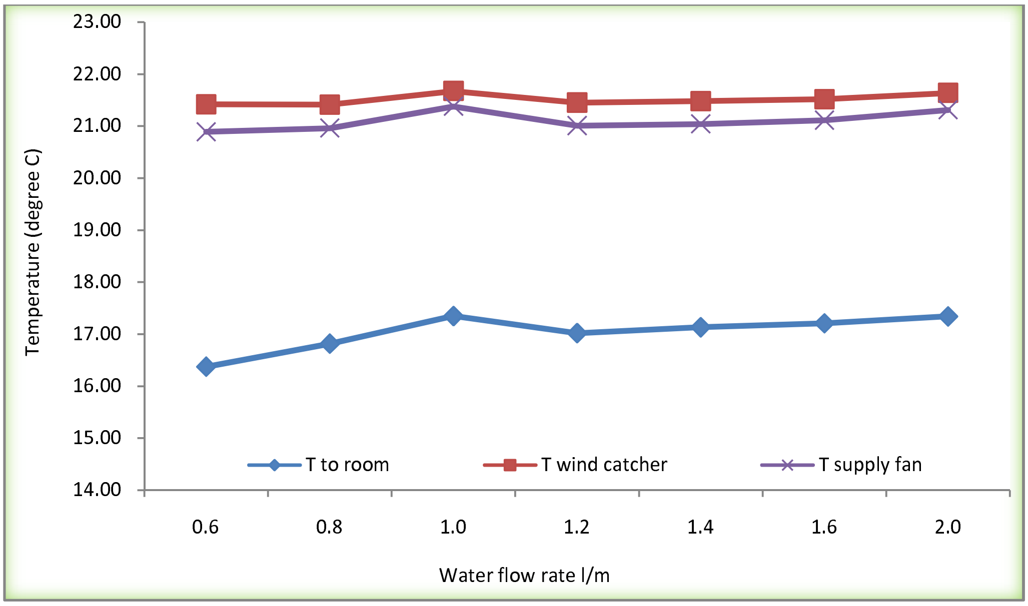


Figure 6.7 Variations of the Incoming air temperatures when internal fans set at off.

The changed when the water was 1.0 l/m to all temperature caused by the change in ambient air temperature

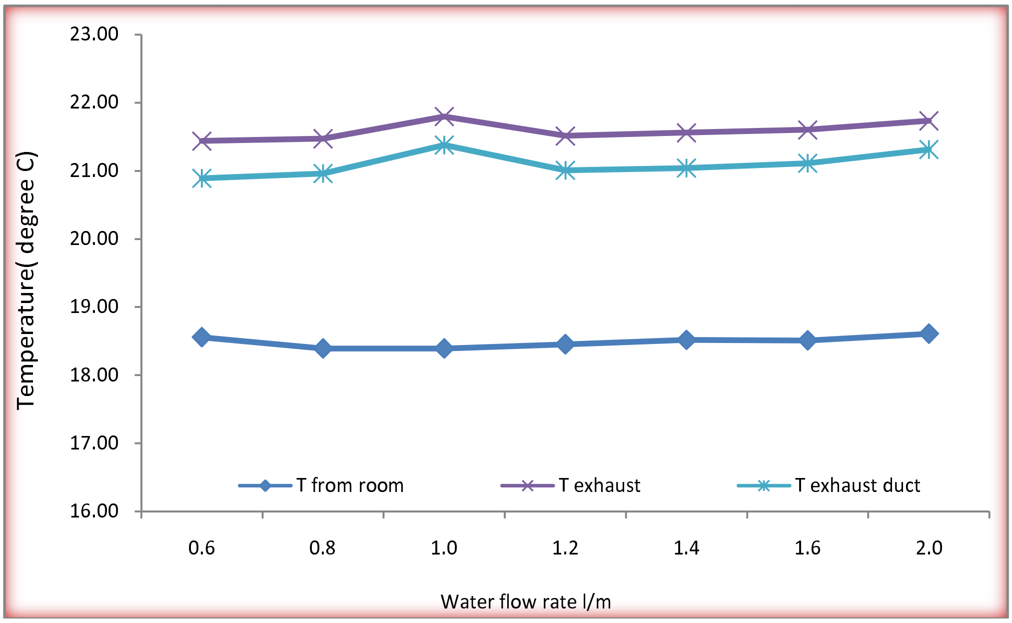


Figure 6.8 Variation of the air temperatures leaving the room when internal fans set off.

6.2.2.2 The effect of fans and water flow rate

Figure 6.9 and Figure 6.10 show the variation of the air relative humidity with water flow rate with fan set on and off respectively. First it can be observed that the rate of water in this case has little effect on the relative humidity at the test room except when the fans are set on, where there is a slight variation in the room RH. In Figure 6.9 it can be seen that this change may have caused by the variation in the supply air relative humidity. However, the state of the fan i.e. air flow rate has effect on the RH of the air into the room, though the supply air RH was 55% in both cases, the RH of the room increased to 65% with fan set on and only to 55% when the fans were set off. When the fans are on, the exhaust air rose to only 70%, while it rose to 80% when fans are set off as shown in Figure 6.10. It could also observed from Figure 6.9 and Figure 6.10 that the air RH to the room is slightly higher than from the room when the fans are on, while these are equal when the fans are set off.

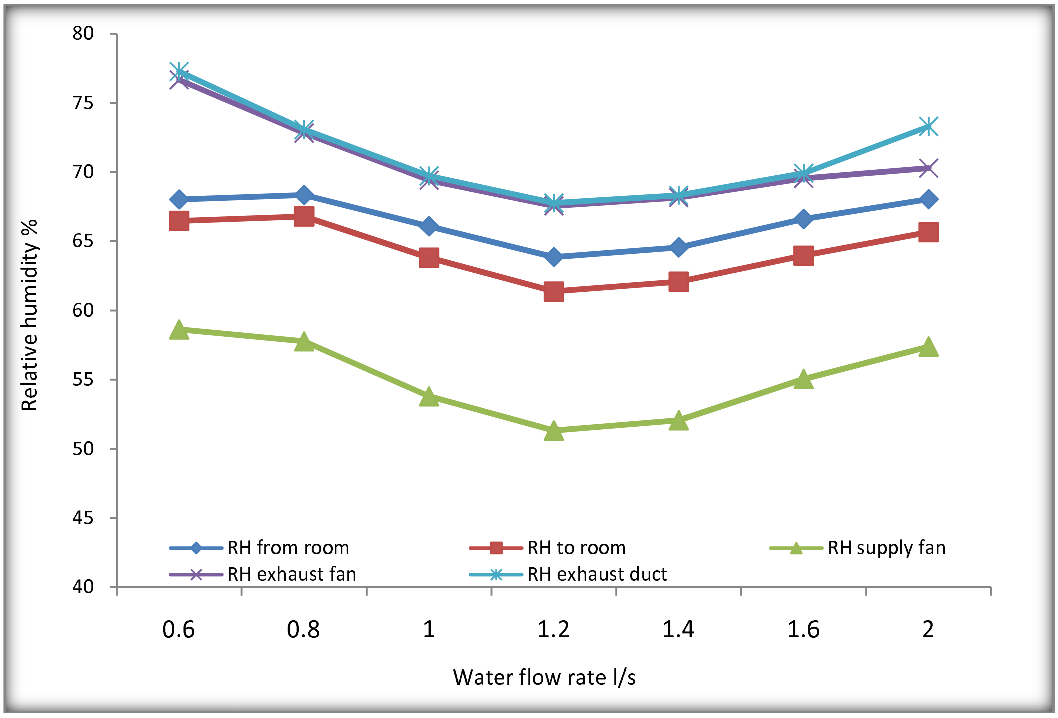


Figure 6.9 Variation of the air humidity with water flow rate when fans are set on at maximum speed.

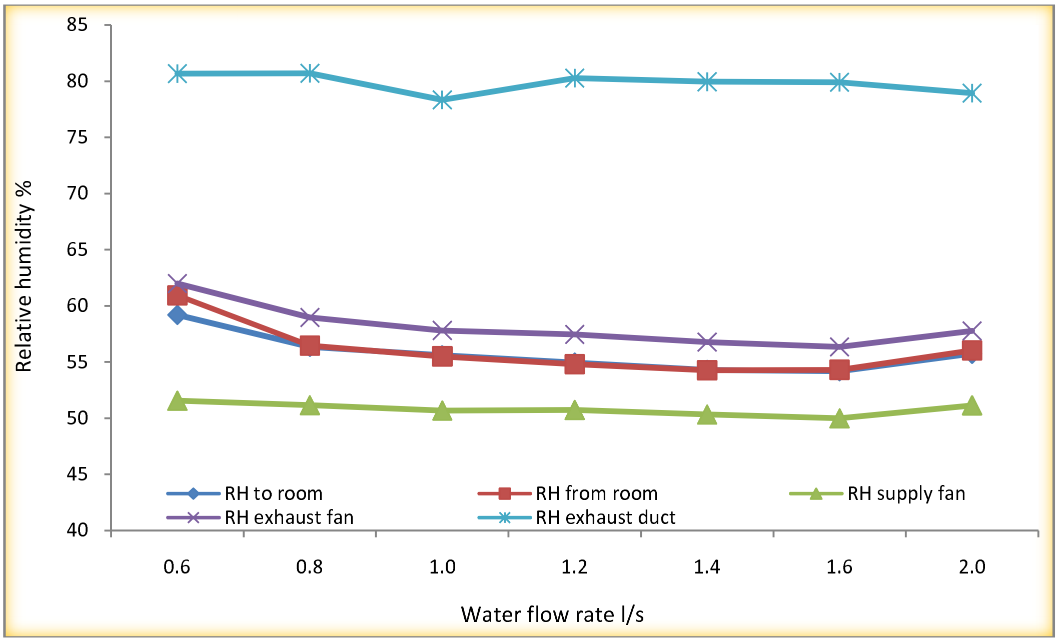


Figure 6.10 Variation of the air humidity with water flow rate when fans are off.

6.2.3 Impact of the ambient temperature, air flow rate and water flow rate on evaporative rate.

The effect of the ambient temperature, air flow rate and water flow rate on the cooling effect of the system was assessed by varying these parameters. First test was carried out at average ambient temperature of 23 ^{0}C, where 5.5 ^{0}C to 6 ^{0}C temperature difference between the room and ambient temperature were achieved. In the following tests the ambient air temperature has been increased to 30^0 C and then to 38^0 C using an electrical heater, Figure 6.11 shows the comparison of the room temperatures at three different ambient temperature test conditions. The temperature different between the room and the ambient in these cases was higher at 6.86 ^{0}C and 9.6 ^{0}C respectively.

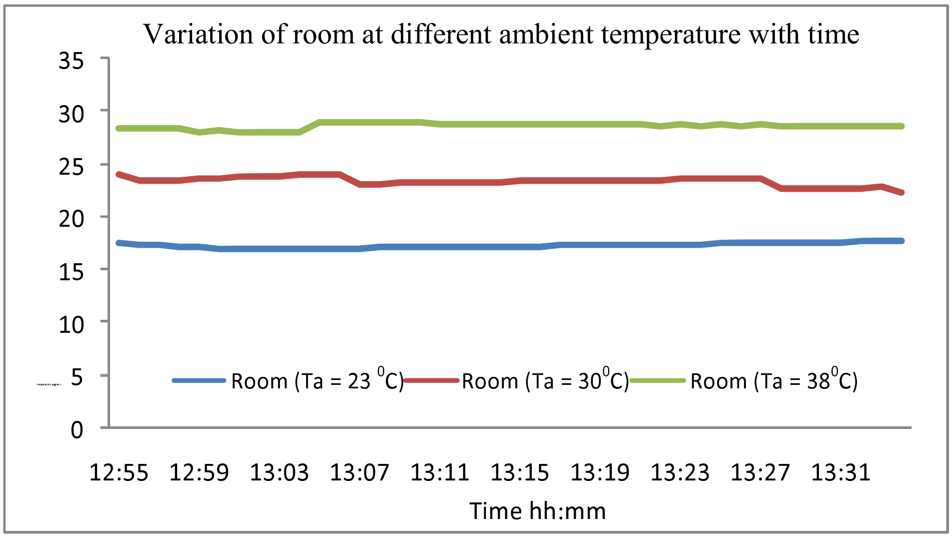


Figure 6.11 Variation of room temperature at different ambient air temperature

The relative humidity of the ambient air has also been varied to assess its effect on the cooling rate of the system. Figure 6.12 shows the variation in the relative humidity of the air inside the room when the ambient relative humidity was set at 30%, 35% and 40%. It can be seen that the relative humidity of the room have increased by 22 %, 21 % and 20 % respectively at the end of the test.

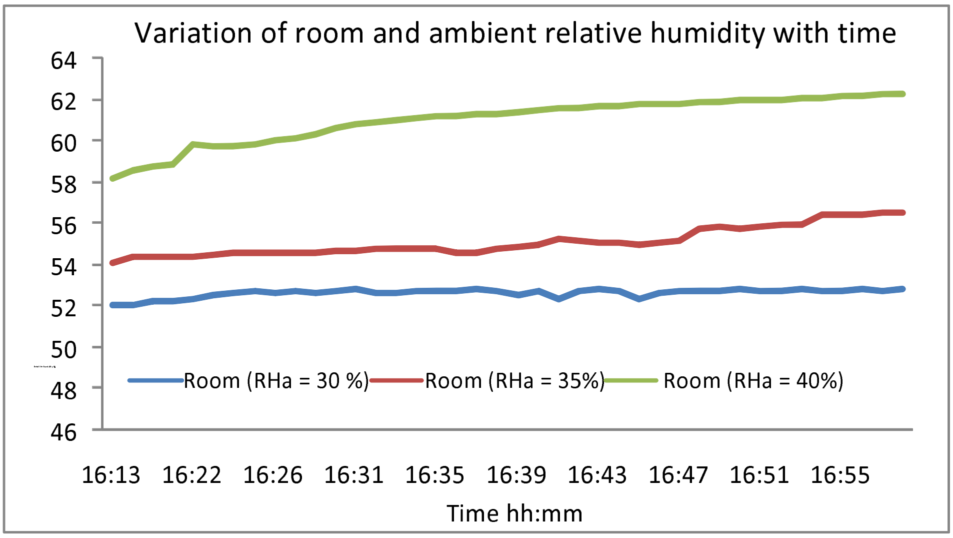


Figure 6.12 Variation of room RH at different values of ambient RH

Figure 6.13 and Figure 6.14 show the variation of room temperature and the room relative humidity with the water flow rate. Air flow rate was varied at 0.6 m/sec, 0.9 m/sec and 1.2 m/sec and water flow rate was varied between 0.6 l/m to 2 l/m. The results indicate that the room temperature increases with the increase of the air flow rate. The results also shows that the variation in water flow rate have a very little effect on the cooling effect of the system as shown in Figure 6.13. However increase in the water flow rate does affect the room relative humidity, as shown in Figure 6.14.

As can be observed there is a continuous increase in the room RH with the increase of the water flow rate at the variation air flow rate.

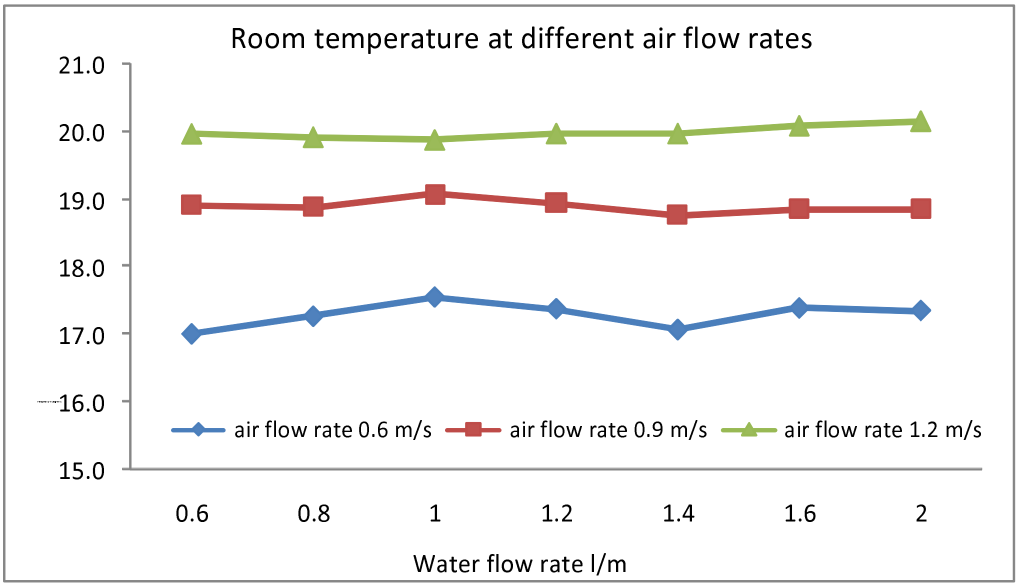


Figure 6.13 Variation of room temperature with air and water flow rates

As the water supply increases the evaporation rate decreases and hence the cooling is also decreases.

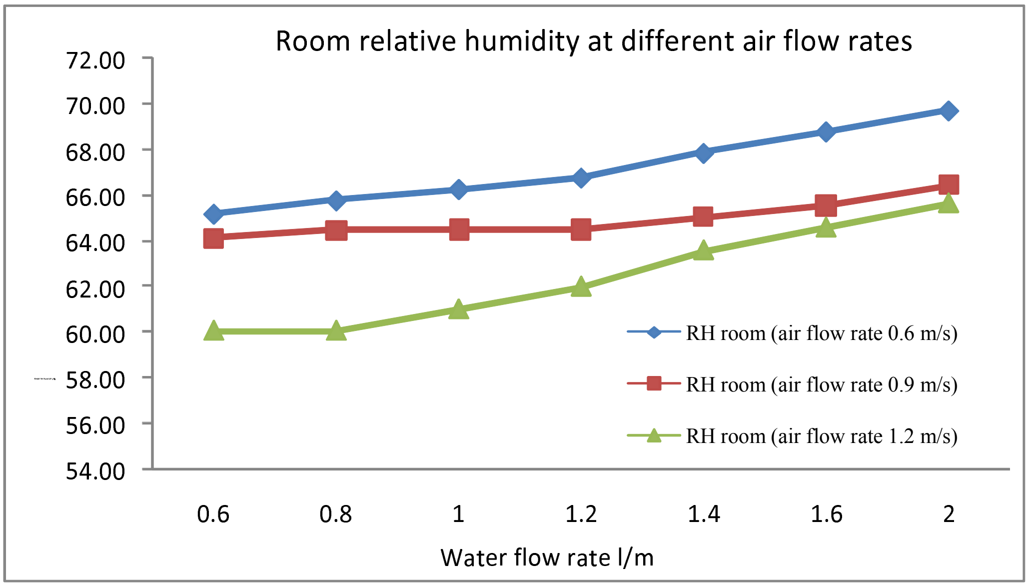


Figure 6.14 Variation of room relative humidity with air and water flow rates

The RH increase with the increase of water supply, and this is the reason why the cooling is reduced by water supply. 0.9 m/sec look to be better (optimum) air flow where the increase in temperature and the RH was not high with water supply. (The air saturation causes drop in the evaporation rate at high water supply).

6.2.4 The effect of PEC channel width size

As mentioned in section 6.1 different PEC have been tested. Results presented in this section are obtained by testing a PEC of 6mm and 8mm channel size at the same conditions used above i.e.; different water flow rate (0.6 – 2l/min), different wind speed and different system fan ratings.

Figure 6.15, 6.16 and 6.17 present the variation in room temperature using PEC channel width 6mm. the results show that the lowest room temperature is achieved when the fans are at high speed regardless of the external wind speed and water flow rate. The results also show that there is no much different in the room temperature when fan is off or operated at low speed. With the PEC of 6mm channel width it is also observed that the changes in the room temperature at the different fan ratings is much higher than that of the 4mm channel width PEC unit.

From Figure 6.18, 6.19 and 6.20 which show the variation of the room relative humidity with water flow rate and fans rating, the room relative humidity increase slight with water flow rate during the tests. The relative humidity has also increased with the fan rating, the highest at the maximum fan rating.

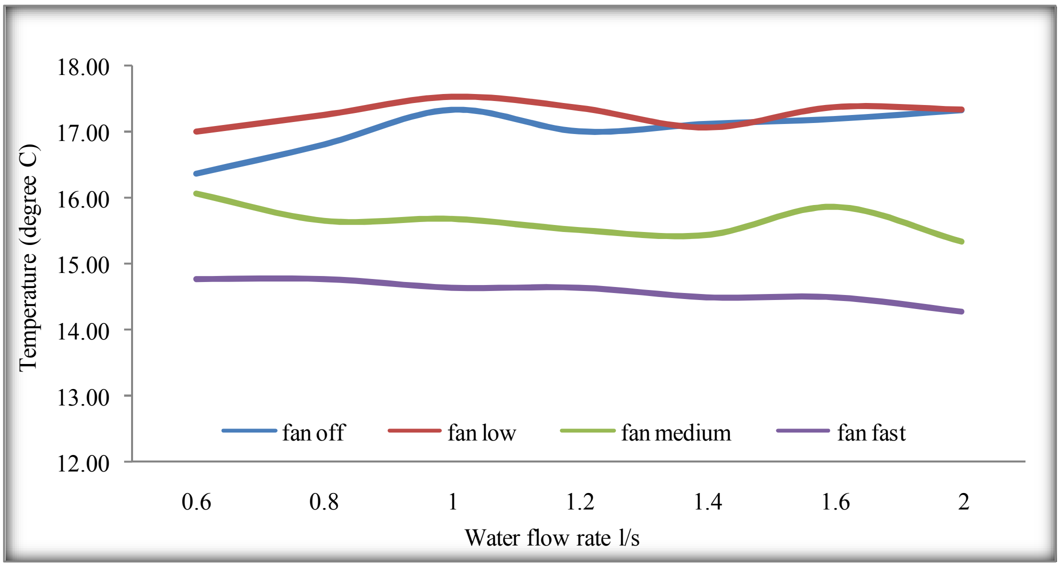


Figure 6.15 Room temperature at wind speed 2.1 m/s for PEC of 6mm channel

It is evidence that both the temperature and the relative humidity of the room increases gradually with the water flow rate. This indicated that as the water flow rate increases the rate of cooling decreases as a result of air saturation. Generally these results have shown that the air flow rate needs to be increased with the water flow rate to keep the ration at optimum value for effective evaporation.

At high air speed, the amount of air is sufficient to avoid air saturation and so the rate of evaporation is relatively high and hence better cooling.

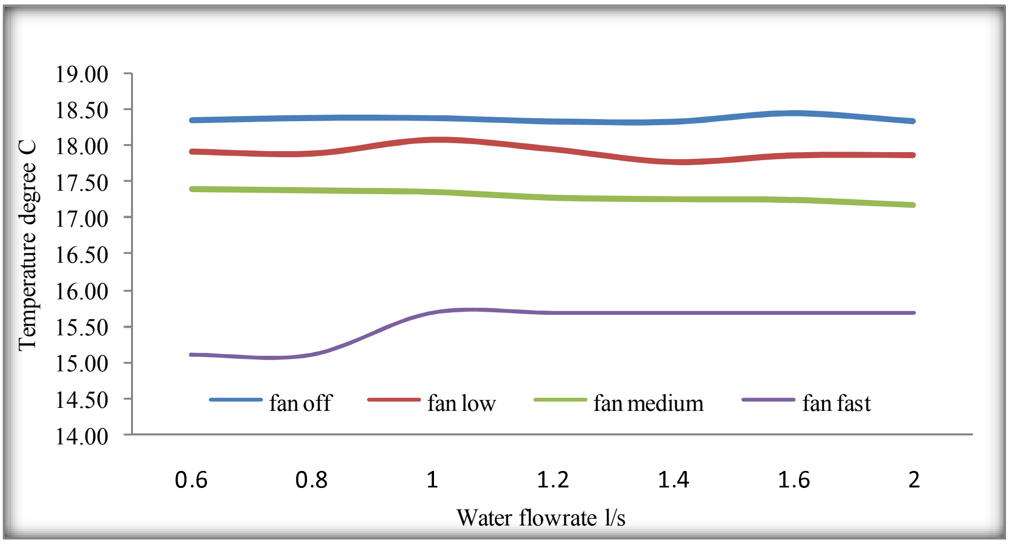


Figure 6.16 Room temperature at wind speed 3.3 m/s for PEC of 6mm

The rise in the room temperature when system fan was operating at fast speed and water flow at 0.6 and 0.8 was due to change in ambient temperature.

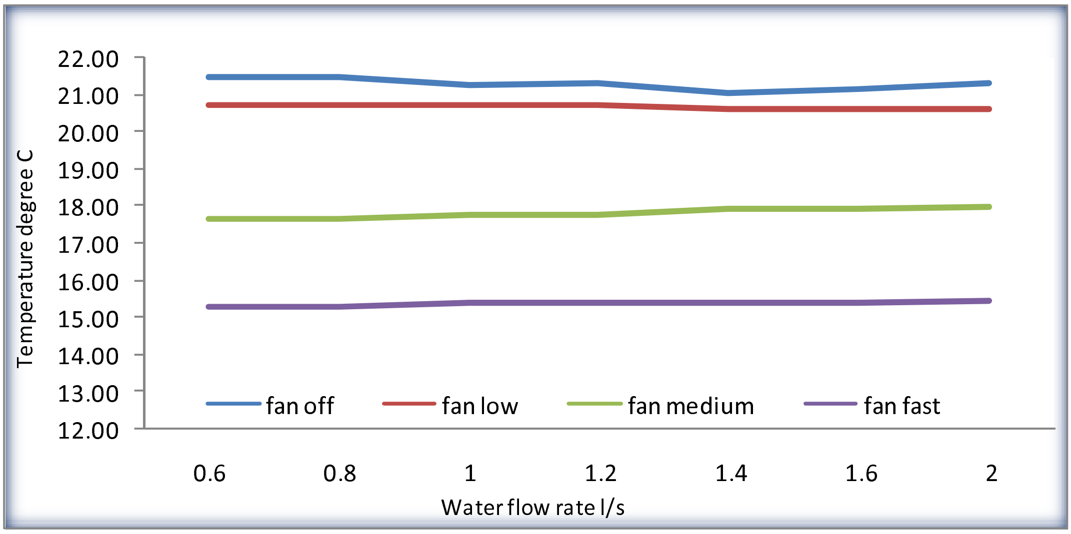


Figure 6.17 Room temperature at wind speed 4.5 m/s for PEC of 6mm

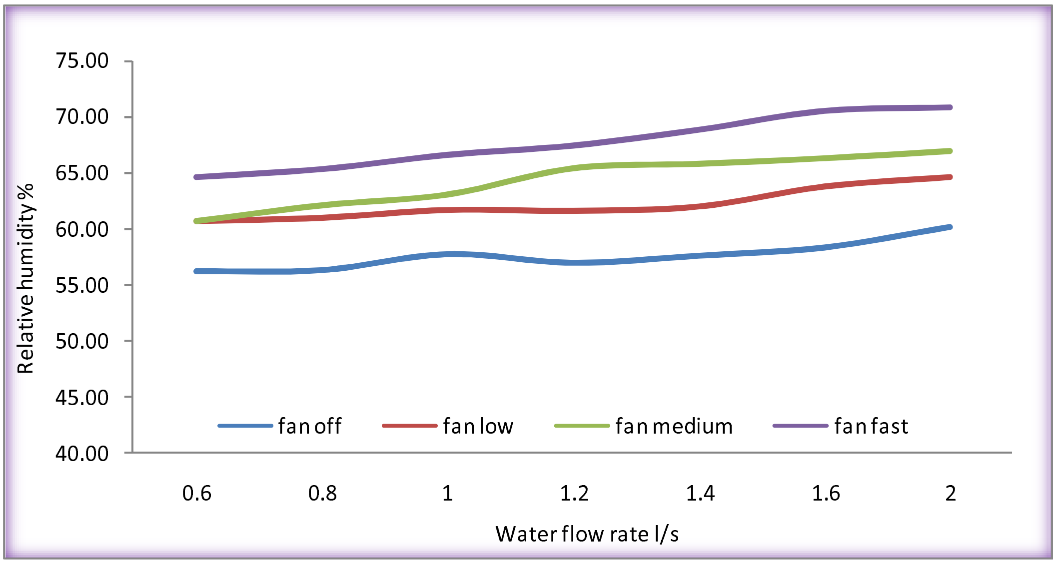


Figure 6.18 Room relative humidity at wind speed 2.1 m/s for PEC of 6mm

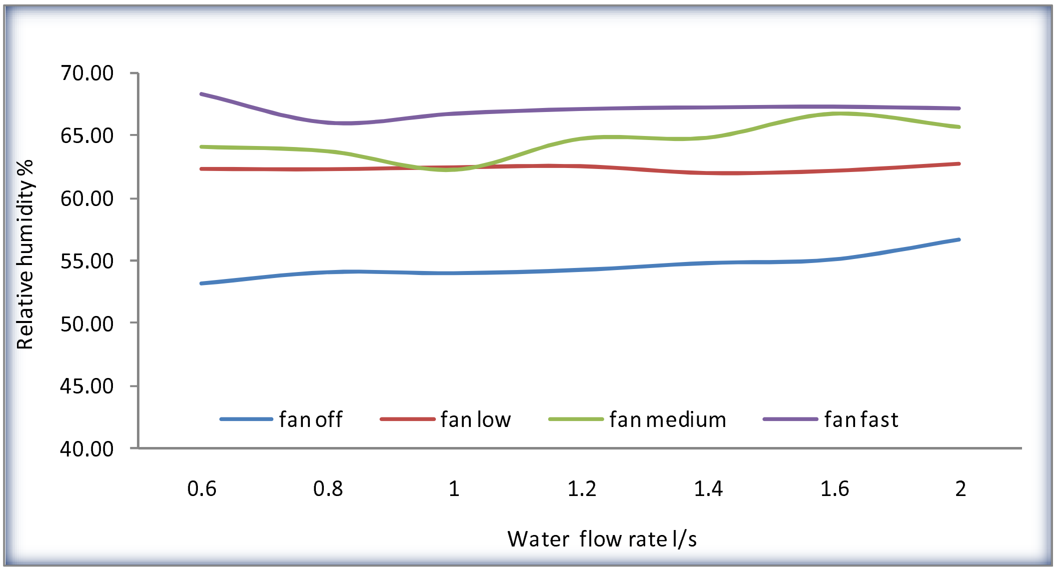


Figure 6.19 Room relative humidity at wind speed 3.3 m/s for PEC 6mm

RH increased with the water flow rate and also increased with the fan speed, at all wind speed values.

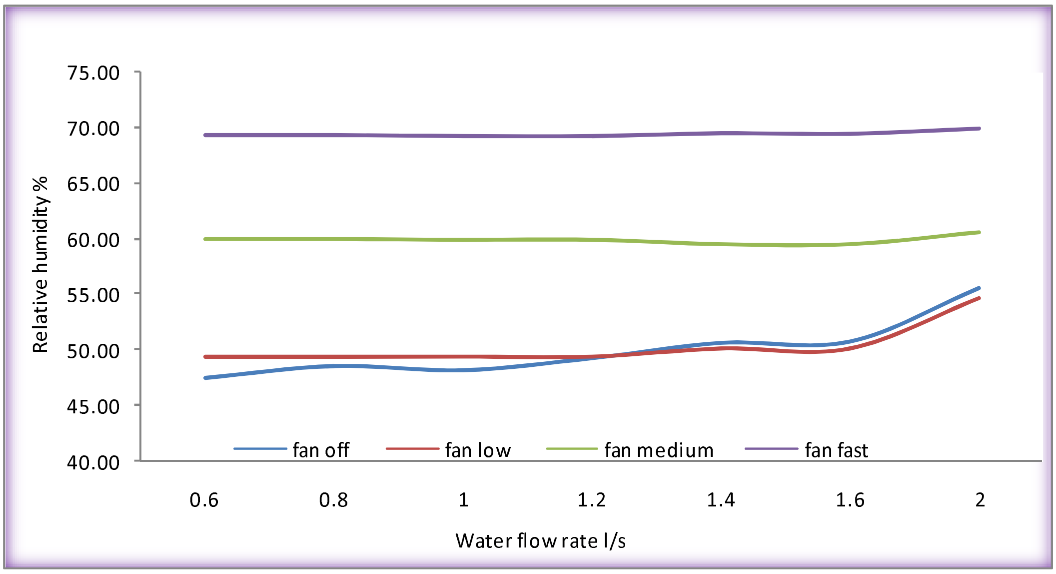


Figure 6.20 Room relative humidity at wind speed 4.5 m/s for PEC 6mm

The tests are repeated for the system using PEC with channel width 8 mm at ambient temperature 23 ^{o} C and with the same wind speed, water flow rate and fan setting. The results of room temperature variation are presented in Figure 6.21, Figure 6.22 and Figure 6.23. It can observe that, as before the cooling effectiveness decreases with the water flow rate, which increase with fan speed i.e. air flow rate.

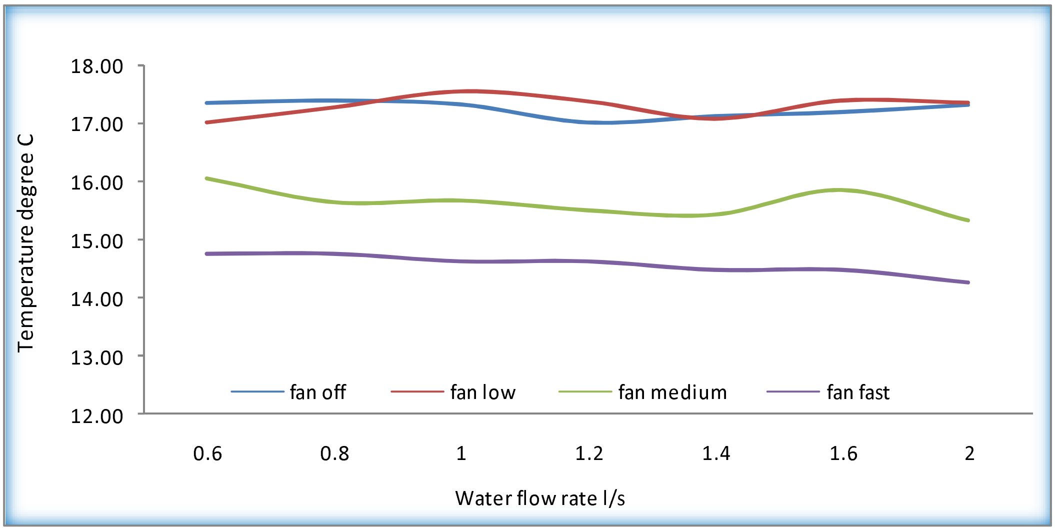


Figure 6.21 Room temperature at wind speed 2.1 m/s for PEC of 8mm

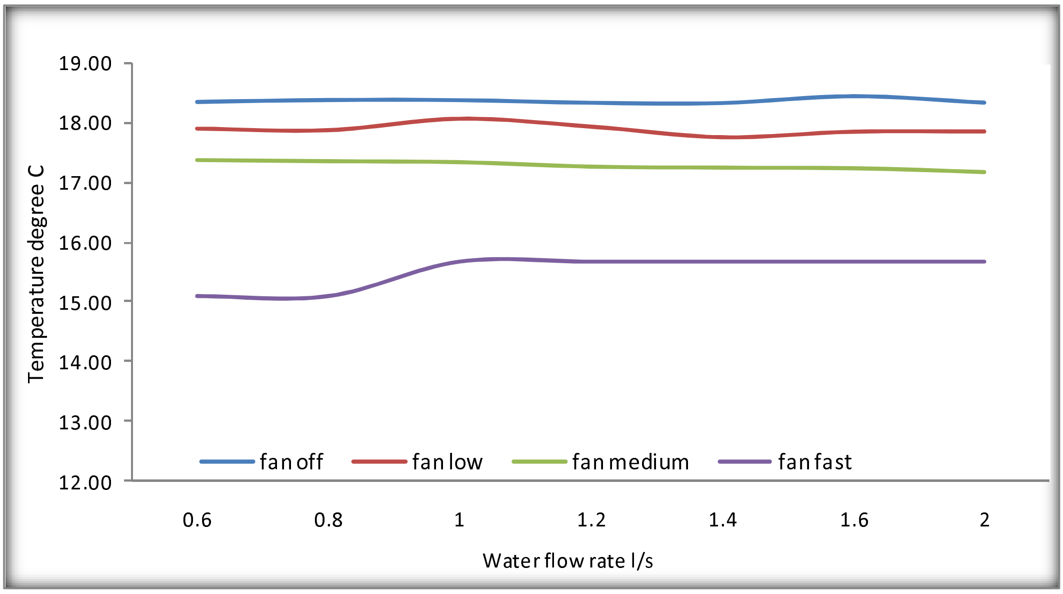


Figure 6.22 Room temperature at wind speed 3.3 m/s for a PEC 8mm

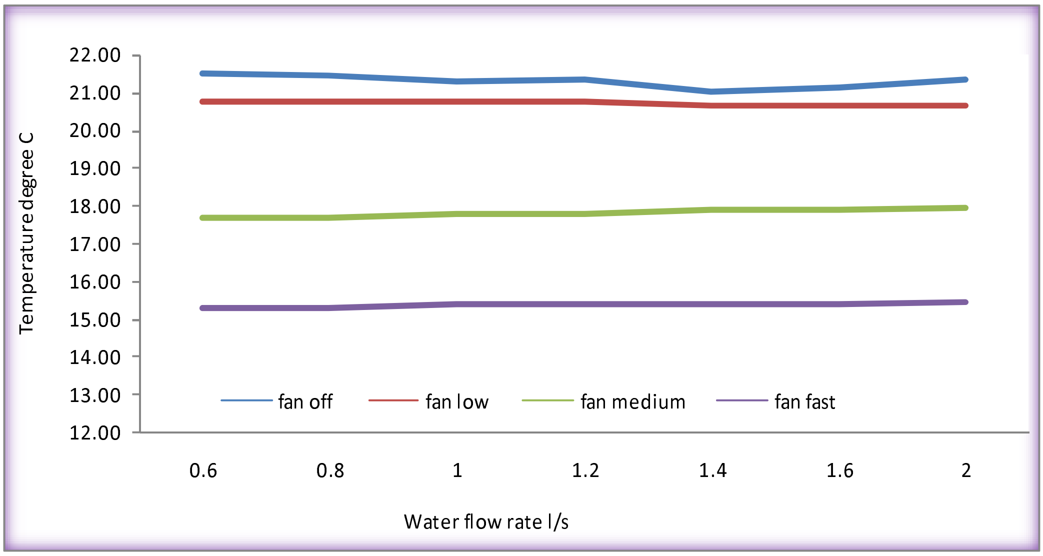


Figure 6.23 Room temperature at wind speed 4.5 m/s for PEC 8mm

The room relative humidity has also been assessed during the test, and it was found that it increases with the water flow and with the fan speed. The RH approached 70% at the end of the test under all test conditions. The results of room Relative humidity variation are presented in Figure 6.24, Figure 6.25 and Figure 6.26.

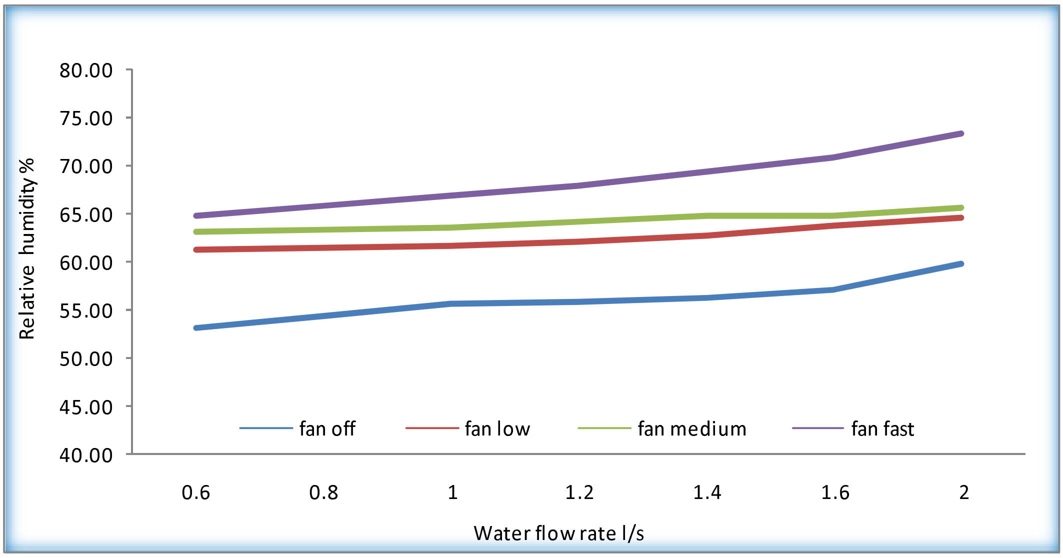


Figure 6.24 Room relative humidity at wind speed 2.1m/s for PEC of 8mm.

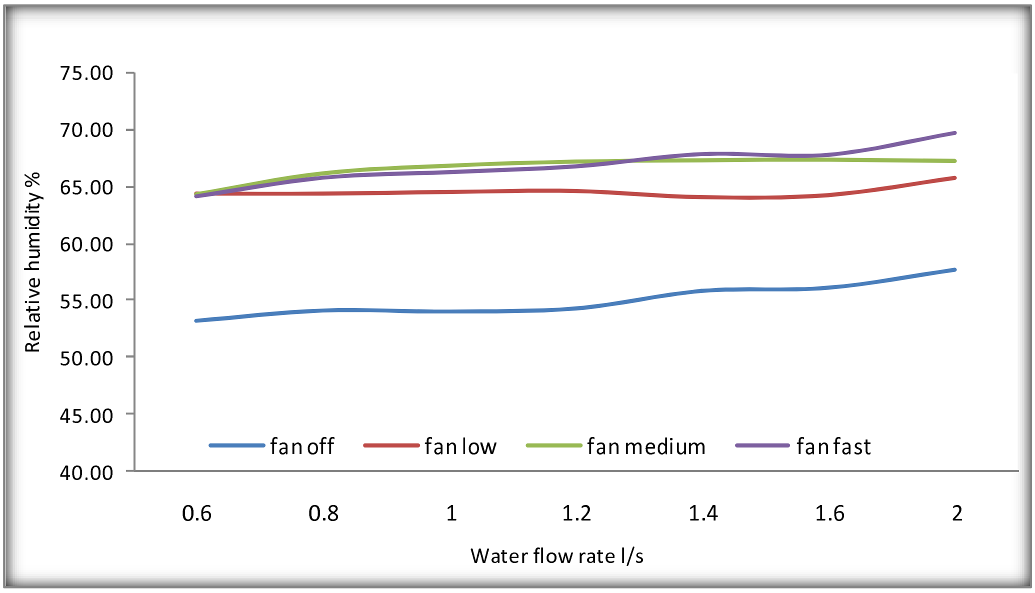


Figure 6.25 Room relative humidity at wind speed 3.3 m/s for PEC of 8mm.

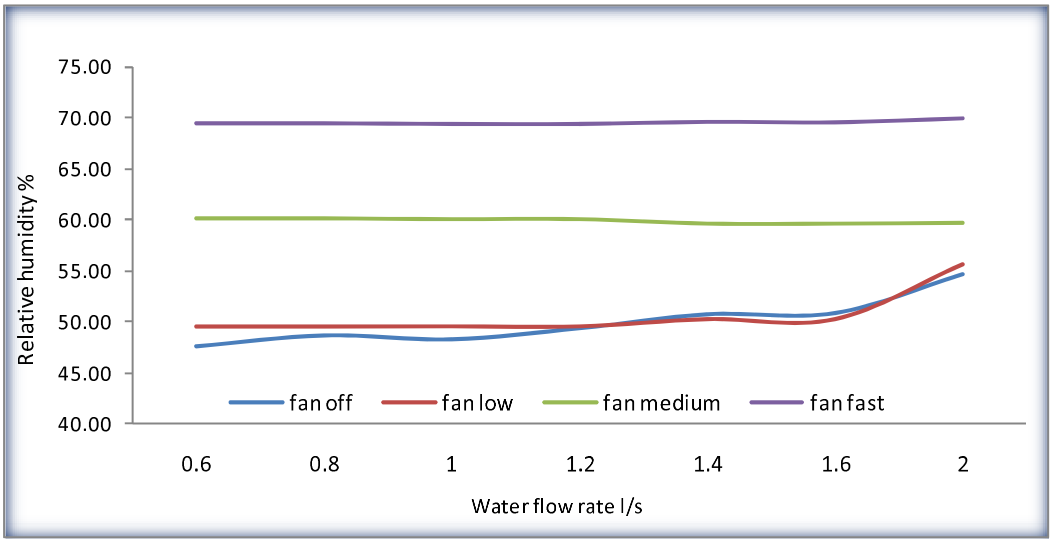


Figure 6.26 Room relative humidity at wind speed 4.5 m/s for PEC of 8mm.

6.3 Cooling load & COP

The air inside the building receives heat from a number of sources during the cooling season. If the temperature and humidity of the air are to be maintained at a comfortable level, this heat (cooling load) must be removed. The load depends on the thermal characteristics of the building`s envelope and the difference between the outside and inside conditions [54].

The cooling load calculations are usually based on the inside and the outdoor design conditions of temperature and humidity. The inside conditions are those that are required to provide satisfactory comfort.

System cooling load has been calculated at different temperature and relative humidity, the corresponding enthalpy has been calculated using Engineering Equation Solver (EES) software.

The cooling capacity (PEC / Catcher) (Q_C) has been calculated using the following expression:

$$Q_C = \dot{M}(h_{in} - h_{out}) \qquad 6.1$$

Where:

Qc= cooling capacity (kilowatts)

$\dot{m}$*= mass flow rate (kg/s)*

h_{in} *= Enthalpy at inlet (kJ/kg)*

h_{out}*= Enthalpy at outlet (kJ/kg)*

The mass flow rate is estimated as follows:

$$\dot{m} = V_1 A_1 \rho_1 \qquad 6.2$$

Where:

V=air velocity (m/s)

A= cross sectional area of the duct *(m^2)*

ρ *= Density of the air* *(kg/m^3)* *at ambient temperature.*

Maximum cooling capacity of 1.75 kW has been achieved for the 4mm channel width PEC. The system power consumption is estimated at 39 watt (24 watt fans + 15 watt pump). Table 5.1 presents the System cooling load and the COP at different air (ambient) conditions.

Test no.	RH_1 %	T_1 ºC	RH_2 %	T_2 ºC	h_{in}(kJ/kg)	h_{out}(kJ/kg)	Cooling capacity(kW)	COP
1	30	23	52.7	17.7	38.66	32.6	9.5466	24.4
2	35	30	55.7	23.14	53.42	46.34	11.1534	28.5
3	40	38	61.7	28.4	77.07	65.94	17.5336	44.9

Table 6.1 Summary of the system cooling load and COP for the 4mm channel width PEC unit.

6.4 Discussion of the results

Tests results show that the water flow rate have a little effect on the cooling effect of the system, however it does affect the room relative humidity. The relative humidity has been found to increase with water flow rate for the PEC tested under all conditions maintained in these tests.

the maximum velocity of air entering the room is close to the external wind speed and in principles the the combined PEC windcatcher system is found to be an effective way to channel fresh air into the room. The results also show that the airflow rate of the air entering the room increases with wind speed and with the PEC channels size.

The results demonstrate that the PEC windcatcher cooling performance is greatly influenced by the external wind speed. Figures 6.27 to Figure 6.32 show a comparison of room tempeature and relative humidity when the system is operated with different PEC size and at different wind speed. It can be seen that the lowest room temperature achieved using PEC size of 8 mm channel width.

Figure 6.27 presents the results obtained using different PEC channel. It can be seen that the relative humidity increased with the PEC channel size. This design shows that the room temperature decrease with the water mass flow rate regarding of the PEC channel size (the cooling is better, Figure 6.26).

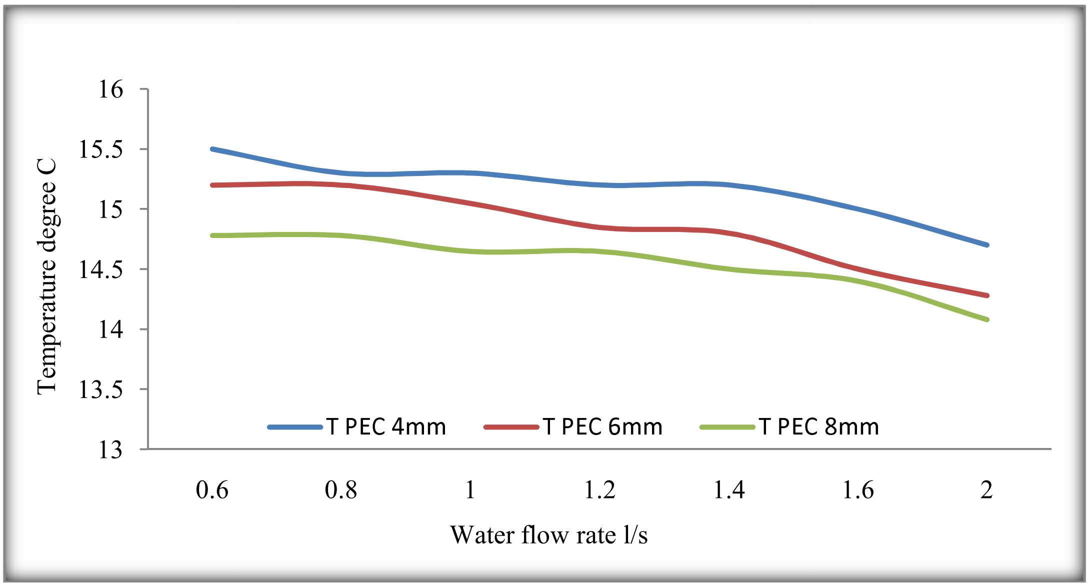


Figure 6.27 Comparison of room temperature with different PEC channel size with fan set at fast speed.

However, the relative humidity increases with water flow. At lower water flow rate the different in RH is small and this increases with the water flow rate reaching up to 4% at 2 l/m water flow rate as shown in Figure 6.28.

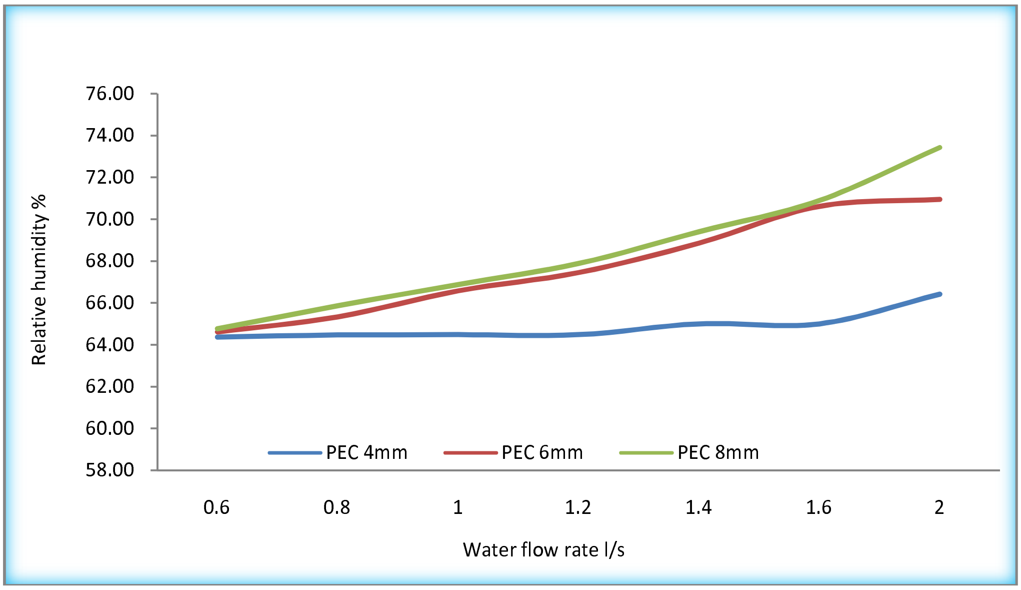


Figure 6.28 Comparison of room relative humidity with different PEC channel size with fans set at fast speed and wind speed 2.1m/s.

Figure 6.29 shows that as the wind speed increase the cooling effect is independent of the water mass flow (almost constant).

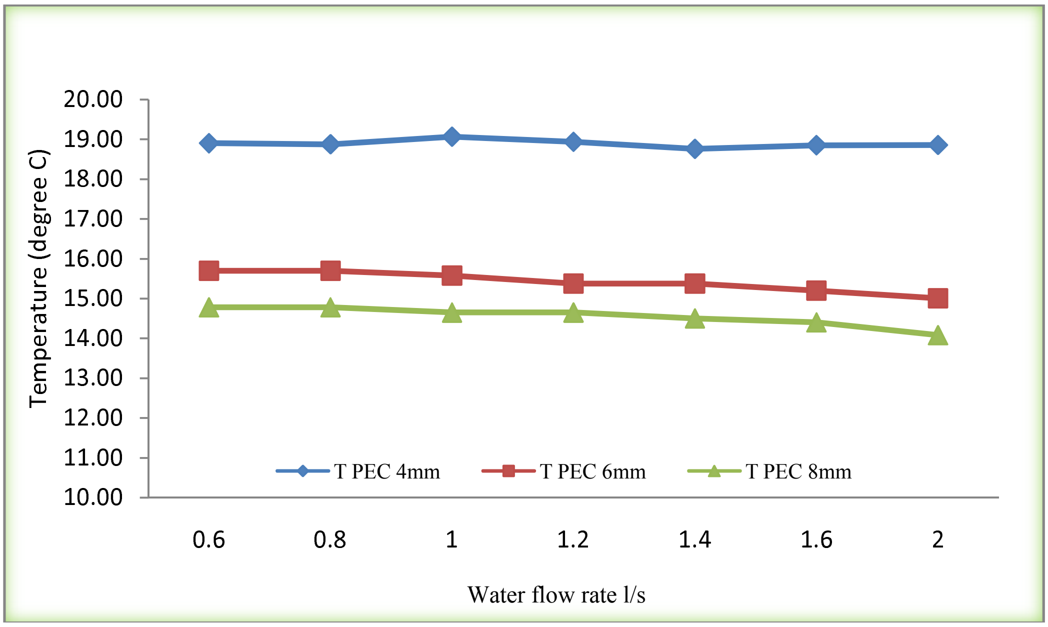


Figure 6.29 Comparison of room temperature with different PEC channel size with fan set at fast speed and wind speed 3.3m/s.

The RH however still increases with the water flow rate, but at a lower rate (Figure 6.30).

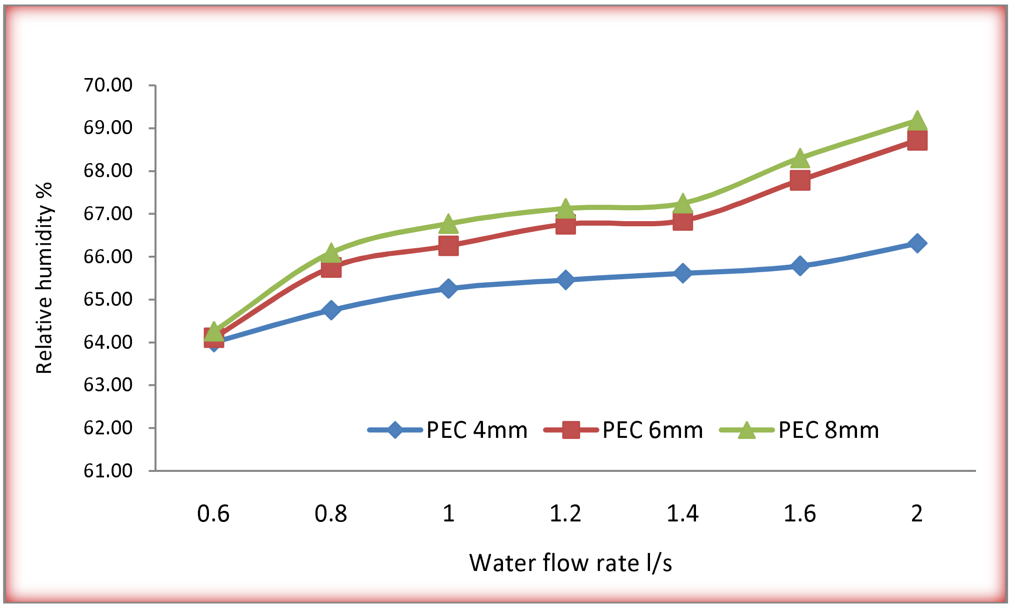


Figure 6.30 Comparison of room relative humidity with different PEC channel size with fans set at fast speed and wind speed 3.3 m/s.

As shown in Figure 6.31, at wind speed 4.5 m/sec the temperature for 4mm PEC size decreases slightly for larger channel width with the water flow rate and in Figure 6.32 at wind speed 4.5m/sec the relative humidity increase with increase of water flow.

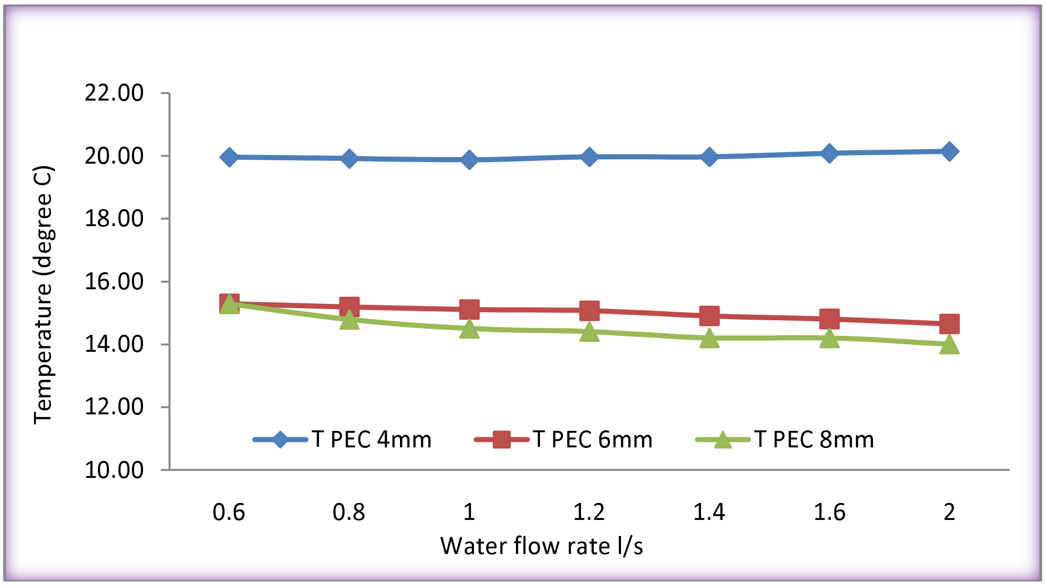


Figure 6.31 Comparison of room temperature with different PEC channel size with fan set at fast speed and wind speed 4.5 m/s.

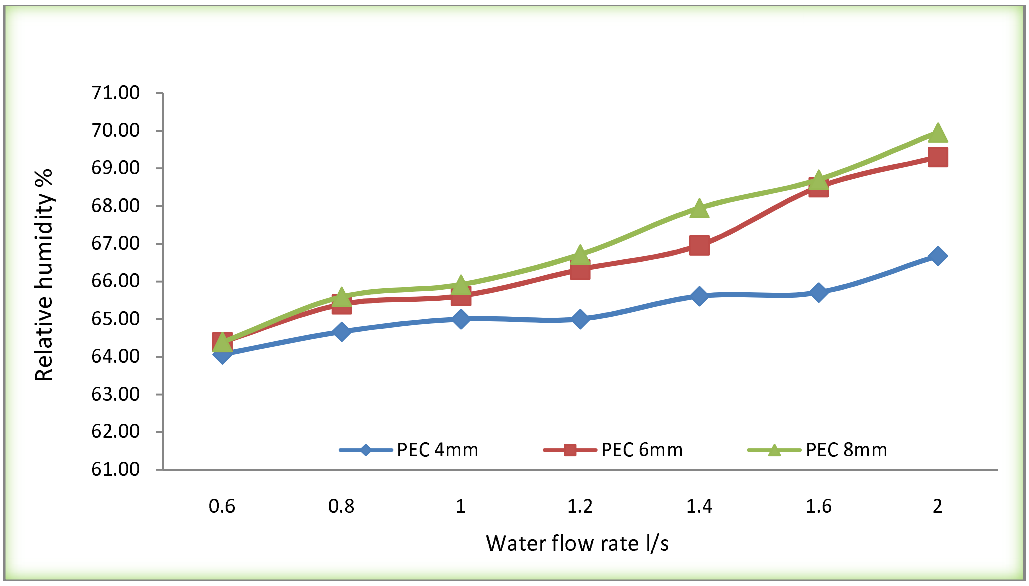


Figure 6.32 Comparison of room relative humidity with different PEC channel size with fans set at fast speed and wind speed 4.5 m/s.

6.5 Conclusions

The results obtained in these tests show that the system has potential of operation passively without a support of fan under certain wind speeds, and a fan would be required at a very low wind speed to overcome the pressure drop within the PEC core channels. The tests results also show that, the system has ability to provide cooling effectively even at high relative humidity conditions of ambient air.

The system offer good cooling performance which could claim to be one of the preferred methods of roof evaporative cooling system. The system has no compressor, no refrigerant and water is the only cooling media used, therefore, it is environmental friendly. The system consumed only the necessary electrical energy for the operation of air fans and the small water pumps, this is far less than the electricity required for the operation of conventional air conditioners; this could even be met by using solar energy such as PV as presented in Figure 6.33.

The results shows that the PEC windcatcher performance is greatly influenced by the external wind speed and as the wind speed increase the cooling effect is independent of the water mass flow.

The airflow rate of the air entering the room increases with wind speed and with the PEC channels size, also the relative humidity increased with the PEC channel size and with the increase of the water flow, and the cooling is also better with larger channel size.

Figure 3.33 Operation of the system using solar power

Chapter 7

GENERAL DISCUSSION AND CONCLUSIONS

7.1 General discussions

As stated in section 1.3 the objectives of the research are to investigate a wind catcher assisted indirect evaporative cooling systems for buildings applications. The systems comprise an indirect evaporative cooling unit utilizing a Psychrometric energy core (PEC) unit and a wind catcher.

The performance of the system is investigated through laboratory testing and use of computational fluid dynamics (CFD) analysis which enabled assessment of the air flow in and around the integrated PEC wind catcher system to be performed.

In achieving these objectives as reported in chapter 4, investigations were first carried out into three different pre - design sizes 1kW, 2kW and 3kW of PEC units in order to optimize the parameters that affect their performance. Some modifications were carried out and testing was conducted to the 2 kW PEC unit which has been fabricated and further evaluated.

A newly evaporation air cooling system comprising a Psychometric Energy Core (PEC) cooling unit integrated into a wind catcher technology has been designed and pattern of air flow passage through the system have been assessed using CFD modelling.

The system is experimentally tested, and the effects of parameters that may influence its performance were investigated. These included, the ambient air condition, air speed through the system, the indirect evaporating water flow rates and the size of PEC chanells.

7.1.1 Performance of a three pre-prototype PEC

A progressive evaluation and optimisation of the air flow passage and PEC pads wetting water flow rate have been carried out using three pre-prototype PEC units in order to optimise the parameters that affect the performance of the system.

Experimental results with the three different sizes of PEC have shown that the performance of the system can be maximised by optimizing the PEC pads wetting water flow rate and the air flow rate through the core.

Based on the results the system design was optimised and performance of the optimised system in terms of cooling capacity was found to be higher than 80%. The unit was able to produce about 2.4kW cooling capacity and achieved a COP of 33.56 under controlled operation conditions.

It has been found that the evaporative cooling works better at a high air temperature and low relative humidity. Ambient air flow rate, air temperature and relative humidity have found to have an effect on the performance of the system. Within the range used in these test, water flow was found to have little effect on the cooling performance, though it does affect the supply air relative humidity.

7.1.2 Combined PEC wind catcher system, design and experimental evaluation

Chapters 5 presents the design of the evaporation air cooling system which comprises a Psychometric Energy Core (PEC) cooling unit integrated into a wind catcher technology. Computational Fluid Dynamic (CFD) modelling has been performed to assess the flow pattern throughout the system in order to verify the complete circulation of the ventilation flow. The results of air flow passage resulted from the modelling for the entire system have show that the air flow pattern is as required under conditions used in the model.

The experimental work was carried out at different settings to find out the best combination of wind speed and water flow rate that will make the system operate at its optimum performance.

The effect of the supply and exhaust fans on the incoming and exhaust air temperatures, relative's humidity and the air flow rates have been evaluated. The purpose of these experiments was to test the requirement of fans to assist the air flow through the system, particular to overcome pressure losses due to PEC pressure.

The tests results have shown that the water flow rate has a negative effect on the cooling unless the air flow rate is increased. Also it was found that the relative humidity has increased with the water flow rate and also increased with the fan speed, at all wind speed values during the tests. The system cooling load has been calculated at different temperature and relative humidity, cooling capacity of 1.75 kW and COP of 44.9 has been achieved for the 4mm channel width PEC.

The results demonstrate that the PEC Wind catcher performance is greatly influenced by the external wind speed but the system could operate passively without a support of fan under certain wind speeds.

Obviously the evaporative cooler requires water to keep pads wet, in the combined PEC wind catcher system the supply water tank was fixed in this position outside the room for the purpose of the test only, in practice the water system could connected directly from the main and adjusted using valves.

7.2 Recommendation for further research

High humidity in air may cause condensation as well as other series problems. Therefore use of the liquid desiccant system to dehumidify the supply air could be proposed. This could be incorporated in the the PEC unit to overcome the high humidity problem that may result from the system under humid air conditions.

Evaporative coolers require a constant supply of water to wet the pads. Water high in mineral content will leave mineral deposits on the pads and interior of the cooler. Water softeners, bleed-off, and refill systems may reduce this problem.

Regardless of system type, water quality often does have an impact on cooling system maintenance requirements. Improving water quality when possible will reduce cooling system maintenance.

Various factors that affect and improve the performance of the Wind catcher indirect evaporative cooling system have been investigated in this research study and as a result a system integrating PEC was successfully designed. However, PEC wind catcher conversion is of a multi-discipline nature that involved physics and many of the engineering fields, thus further studies are required based on some of the observations and results obtained in the course of the research; in particular the following issues needed further investigation.

Further work could be done to help solving the pressure drop problems inside the wind catcher and to enhance the system performance by restoring the wind catcher original internal parts(the traditional mondraugt four quardants) to be adapted with the exhaust duct, the photos in Figure 7.1 shows system modification stages carried out by the author and can be considered to achieve that.

Figure 7.1 Stages of modification of the internal parts of the wind catcher

Economic analysis in term of initial and operating cost of the system could be considered in the future work.

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APPENDIX I: Natural ventilation and human thermal comfort

There are many definitions for Human thermal comfort; ASHRAE defined it as the state of mind that expresses satisfaction with the surrounding environment. ISO 1994 also refers to it as 'a condition of mind which expresses satisfaction with the thermal environment'.

British Standard BS EN ISO 7730. gave the same definition to the Thermal comfort as: *'that condition of mind which expresses satisfaction with the thermal environment.'* So the term 'thermal comfort' describes a person's psychological state of mind and is usually referred to in terms of whether someone is feeling too hot or too cold.

Thermal comfort can be difficult to define parametrically because a range of environmental and human factors need to be considered in order to determine what will make people feel comfortable. These factors make up what is known as the 'human thermal environment'.

The most commonly used indicator of thermal comfort is air temperature – it is easy to use and most people can relate to it. But although it is an important indicator to take into account, air temperature alone is neither a valid nor an accurate indicator of thermal comfort or thermal stress. Air temperature should always be considered in relation to other environmental and personal factors.

Figure I1 illustrate the six factors affecting thermal comfort which are both environmental and personal. These factors may be independent of each other, but together contribute to the human thermal comfort.

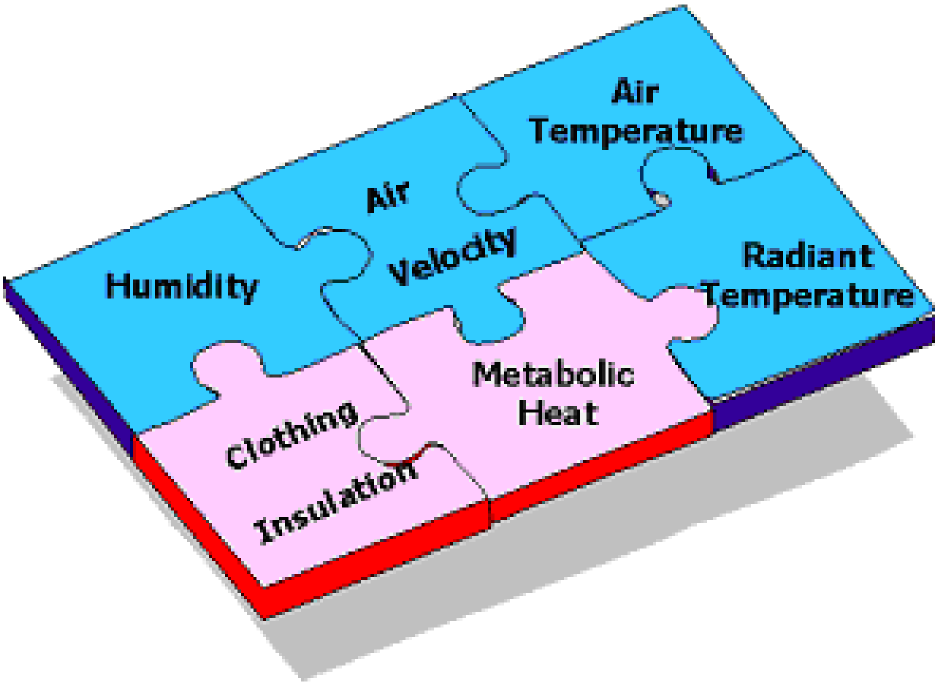


Figure I1: Factors affecting thermal comfort

Source (http://www.hse.gov.uk)

❖ Environmental factors

The environmental factors affect the thermal comforts as shown with blue colour in the Figure above are:

- Air temperature & Operative temperature
- Radiant temperature
- Air velocity
- Humidity

1- Air temperature - Operative temperature

Operative temperature is the uniform temperature of an imaginary black enclosure, in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment. In the absence of radiant heating/cooling panels, heat generating equipment, envelope insulation and large window solar heat gain (as specified in ASHRAE, 2004), the assumption that operative temperature equals air temperature is acceptable. The operative air temperature for buildings recommended by ISO (1994) between 20 °C and 24 °C (22 °C ± 2 °C) for winter conditions and between 23 °C and 26 °C (24.5 °C ± 1.5 °C) for summer conditions.

2- Radiant temperature

Mean radiant temperature: the uniform surface temperature of an imaginary black enclosure, in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space.

Thermal radiation is the heat that radiates from a warm object. Radiant heat may be present if there are heat sources in an environment. Radiant temperature has a greater influence than air temperature on how we lose or gain heat to the environment. Examples of radiant heat sources include: the sun; fire; electric fires; furnaces; steam rollers; ovens; cookers; dryers; hot surfaces and machinery, molten metal's etc.

3- Air velocity

Air velocity is an important factor in thermal comfort and an increased air speed can be useful in warm climates as a means for decreasing body temperature. Indoor air spaces have been found to have air speeds between 0.05 and 0.3 m/s. ISO 1994 recommended that the mean air speed be less than 0.1 m/s, while ASHRAE (1992) recommended an air speed of less than 0.2 m/s for summer conditions. On this basis, it is recommended that air velocity should be targeted within the range of 0.05--0.2 m/s.

ASHRAE 2004 specified that air speed may be increased above 0.2 m/s to increase the maximum temperature for acceptability, if occupants are able to control the air speed. This offset using increased air speed is allowed, but not by more than 3 °C and with air speed no higher than 0.8 m/s.

Another aspect of air speed is draughts. ASHRAE 2004 specified a requirement based on the sensitivity of the head to a draught from behind. The requirement is based on an 80% acceptance of various draught-temperature profiles for different levels of air turbulence. In typical office air turbulence conditions, acceptable draught air-speed levels range from 0.15 to 0.3 m/s.

Still or stagnant air in indoor environments that are artificially heated may cause people to feel stuffy and also it may lead to a build-up of odour. Moving air in warm or humid conditions can increase heat loss through convection without any change in air temperature. If the air temperature is less than skin temperature it will significantly increase convective heat loss.

4- Humidity

Relative humidity that is too high or too low can lead to skin, eye and respiratory irritation (ASHRAE, 1992). ISO (1994) recommended that the relative humidity should be 30% to 70% for summer and winter conditions. ASHRAE 2004 considered that there was no lower humidity limit for thermal comfort, but noted that there were non-thermal comfort factors to consider: skin drying, dry eyes, mucosal irritation and static electricity generation. The ISO lower limit (30%) is considered appropriate to limit these factors.

ASHRAE 2004 specified an upper humidity limit of a humidity ratio of 0.012 (water vapour pressure of 1.91 kPa or dew-point Temperature of 16.8 °C). This corresponds to upper RHs of 55--85% for acceptable thermal comfort, depending on operative T and clothing. However, it is important to consider that relative humidity above approximately 70% can cause micro-organism growth and damage to surfaces within buildings, especially when condensation on surfaces occurs. Therefore, it is recommended that relative humidity in buildings should not exceed 70%.

❖ Personal factors

Thermal comfort can also be affected by some personal or occupant activities such as:

- Clothing Insulation
- Metabolic heat

- Clothing insulation

Clothing, by its very nature, interferes with our ability to lose heat to the environment. Thermal comfort is very much dependent on the insulating effect of clothing on the wearer. Wearing too much clothing or personal protective equipment (PPE) may be a primary cause of heat stress even if the environment is not considered warm or hot. If clothing does not provide enough insulation, the wearer may be at risk from cold injuries such as frost bite or hypothermia in cold conditions.

Clothing is both a potential cause of thermal discomfort as well as a control for it as we adapt to the climate in which we live and play. You may add layers of clothing if you feel cold, or remove layers of clothing if you feel warm. Table I.1 present some data for different clothing combinations.

Clothing combination	I_{cl} *	f_{cl} *
Shorts	0.1	1.0
Light summer clothing	0.5	1.1
Typical business suite	1.0	1.15
Heavy wool pile ensemble	3 - 4	1.3 – 1.5

* I_{cl} Clothing insulation *f_{cl} Clothing factor

Table I.1 Different clothing combination values for thermal comfort calculation

- Work rate/metabolic heat

The work or metabolic rate is essential for a thermal risk assessment. It describes the heat that we produce inside our bodies as we carry out physical activity. The more physical work we do the more heat we produce. The more heat we produce, the more heat needs to be lost so we don't overheat. The impact of metabolic rate on thermal comfort is critical.

When considering these factors, it is also essential to consider a person's own physical characteristics. A person's physical characteristic should always be considered when assessing their thermal comfort, as factors such as their size and weight, age, fitness level and sex can all have an impact on how they feel, even if other factors such as air temperature, humidity and air velocity are all constant. Table I.2 presents some data for different activities of human body.

Activity	Metabolic rate	Mechanical efficiency	Relative velocity
Sleeping	35	0	0
Seated	50	0	0
Standing	60	0	0
Heavy work	300	0.2	0.5
Domestic work	100 - 170	0 – 0.1	0.1 – 0.3

Table I.2 Human body heat emission against activities, Source (passive cooling of building by M. Santamouris and D. Asimakopoulos)

❖ Bodily heat transfer mechanism

Humans in general, are usually in a thermal steady state with respect to their surroundings.

The body thermal equilibrium is a dynamic balance between heat production (as a result of human metabolic rate) and body heat transfer to the environment through several mechanisms: convection, conduction, radiation and evaporation to or from the environment as illustrated in Figure I.2.

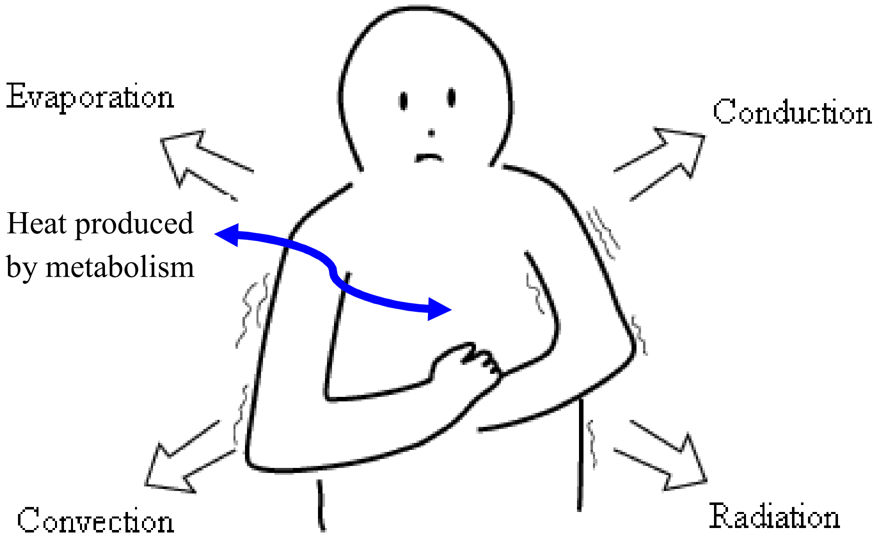


Figure I.2 interaction of the human body with the environment

Source (hyperphysics.phy-astr.gsu.edu) Reproduced by the author

The thermal balance equation between the human body and the environment can be expressed as follow:

$$Q_M - Q_{dif} - Q_{evap} - Q_{resp} = Q_r + Q_c$$

Where

Q_M = body's heat production due to metabolic rate (metabolism),

Q_{dif} = vapour diffusion through the skin,

Q_{evap} = sweat evaporation,

Q_{resp} = latent heat from sweating,

Q_r = radiative heat loss from the outer surface of a clothed person to the environment,

Q_c = convective heat transfer to the environment.

- **Radiation**

Radiation is heat transfer by the emission of electromagnetic waves which carry energy away from the emitting object. Radiation rates depend on material properties and temperature. Human skin loses heat by radiation depending on the mean radiant temperature value of surrounding objects and the distance between the human body and the object.

- **Convection**

Convection is heat transfer by mass motion of a fluid such as air or water when the heated fluid is caused to move away from the source of heat, carrying energy with it. Convection heat transfer rate is in proportion with the temperature difference between skin and ambient air, the human skin loses heat by convection when cold air passes over it and also through breathing as well.

- **Conduction**

Conduction is the transfer and distribution of heat energy from atom to atom within a substance without any motion of the material as a whole. Conduction occurs when a human body gets in direct contact with another material. Conduction is less important in terms of thermal human comfort determination when compared to the other factors i.e. radiation, convection and evaporation.

- **Evaporation**

If part of a liquid evaporates, it cools the remaining liquid because it must extract the necessary heat of vaporization from that liquid in order to make the phase change to the gaseous state. It is therefore an important means of heat transfer in certain circumstances, such as the cooling of the human body when it is subjected to ambient temperatures above the normal body temperature.

❖ Relations between natural ventilation and factors affecting thermal comfort

As already discussed, the main objectives of natural ventilation is to encourage heat transfer between human body and it`s ambient environment. The effect of natural ventilation on the environment factors related to human thermal comfort can be expressed as follows:

1- Effect of air velocity on air temperature and mean radiant temperature (MRT)

Air movement around the human body can also influence thermal comfort. It determines the convective heat exchange of the body and the evaporative capacity of the air. Convective losses are directly proportional to a power of the air velocity and the temperature difference between the skin and the air temperature. Higher air velocities increase evaporation rates and consequently enhance the cooling sensation and reduce the negative effect of high humidity. During the summer, natural ventilation or the use of ceiling fans to enhance or control the indoor air movement can shift the thermal comfort area to higher air temperature.

2- Effect of air velocity on relative humidity

Humidity is another determinant factor of thermal comfort. It does not affect the thermal load from the environment on the body, but it determines the evaporative capacity of the air. Low relative humidity of ambient air aids the evaporation of perspiration from the human body, which in turn enhances the cooling sensation.

❖ Conclusions

Natural ventilation is an energy efficient alternative for reducing the energy use in buildings, achieving thermal comfort, and maintaining a healthy indoor environment. Typically, the energy cost of a naturally ventilated building is 40% less than that of an air-conditioned building. Natural ventilation, therefore, contributes to a sustainable environment by reducing energy use in buildings. Natural ventilation has become a new trend in building design in the architectural community and has been used in many types of buildings, even in highly indoor climate controlled hospitals. However, it should be pointed out that natural ventilation can only be applied to certain climates and it has many limitations.

Even local noise and pollution levels would limit the applications of natural ventilation.

The key to a successful natural ventilation approach is that it should be an integral part of the building design. Buildings ventilated with natural ventilation strategies can considerably reduce energy consumption, making a significant contribution to sustainable building design.

Thermal comfort can be achieved by adjusting one of the influencing parameters. It is preferable, in order to achieve the desirable end effect, to give priority to the parameter which has a low energy requirements, or even no energy requirements at all. Clothing is one of the easiest parameters that an individual can adjust in order to achieve thermal comfort in an environment with given conditions.

❖ Cooling load and Energy conservation

• Cooling load

The air inside a building receives heat from a number of sources during the cooling season. If the temperature and humidity of the air are to be maintained at a comfortable level, this heat must be removed. The amount of heat that must be removed from a building in order to maintain a desirable indoor temperature and humidity condition is called the cooling load. The load depends on the thermal characteristics of the building`s envelope and the difference between the outside and inside conditions. The cooling load must be determined because it is the basis for selection of the proper size air cooling equipment and distribution system. It is also used to analyze energy use and conservation.

The cooling load calculations are usually based on inside and outdoor design conditions of temperature and humidity. The inside conditions are those that provide satisfactory comfort.

There are two types of cooling loads:

- sensible cooling load
- latent cooling load

The sensible cooling load refers to the dry bulb temperature of the building and the latent cooling load refers to the wet bulb temperature of the building. In the summer, humidity influence the selection of the cooling equipment and the latent load as well as the sensible load must be calculated.

- **Sensible Heat**

Sensible Heat is defined as the heat energy stored in a substance as a result of an increase in its temperature. The sensible heat in a heating or cooling process of air can be expressed as

$$hs = 1.08\ q\ dt$$

Where

hs = sensible heat (btu/hr)

q = air volume flow (cfm, cubic feet per minute)

dt = temperature difference (^{o}F)

- **Latent Heat**

Latent Heat is defined as the heat which flows to or from a material without a change to temperature. The heat will only change the structure or phase of the material. e.g. melting or boiling of pure materials.

The latent heat due to moisture in the air can be expressed as:

$hl = 0.68\ q\ dwgr$

or

$hl = 4{,}840\ q\ dwlb$

Where

hl= latent heat (btu/hr)

q = air volume flow (cfm, cubic feet per minute)

$dwgr$ = humidity ratio difference (gram water/lb dry air)

$dwlb$ = humidity ratio difference (lb water/lb dry air)

- **Total Heat (Latent and Sensible Heat)**

Total heat due to both temperature and moisture can be expressed as:

$ht = 4.5\ q\ dh$

Where

ht= total heat (btu/hr)

q = air volume flow (cfm, cubic feet per minute)

dh = enthalpy difference (btu/lb dry air)

Total heat can also be expressed as:

$ht = hs + hl$

$= 1.08\ q\ dt + 0.68\ q\ dwgr$

❖ Factors influence the sensible and latent cooling loads

The factors that influence the sensible cooling loads are:

- use of glass windows or doors
- Sunlight striking windows, skylights, or glass doors and heating the room
- Exterior walls.
- Partitions (that separate spaces of different temperatures)
- Ceilings under an attic
- Roofs
- Floors over an open crawl space
- Air infiltration through cracks in the building, doors, and windows
- People in the building
- Equipment and appliances operated in the summer
- Lights

Notice that below grade walls, below grade floors, and floors on concrete slabs do not increase the cooling load on the structure and are therefore ignored. Other sensible heat gains are taken care of by the HVAC equipment before the air reaches the rooms (system gains). Two items that require additional sensible cooling capacity from the HVAC equipment are:

- Ductwork located in an unconditioned space
- Ventilation air (air that is mechanically introduced into the building)

The factors that influence the latent cooling load are the moisture which is introduced into a structure through either People or Equipment and appliances; also main factor is the Air infiltration through cracks in the building, doors, and windows.

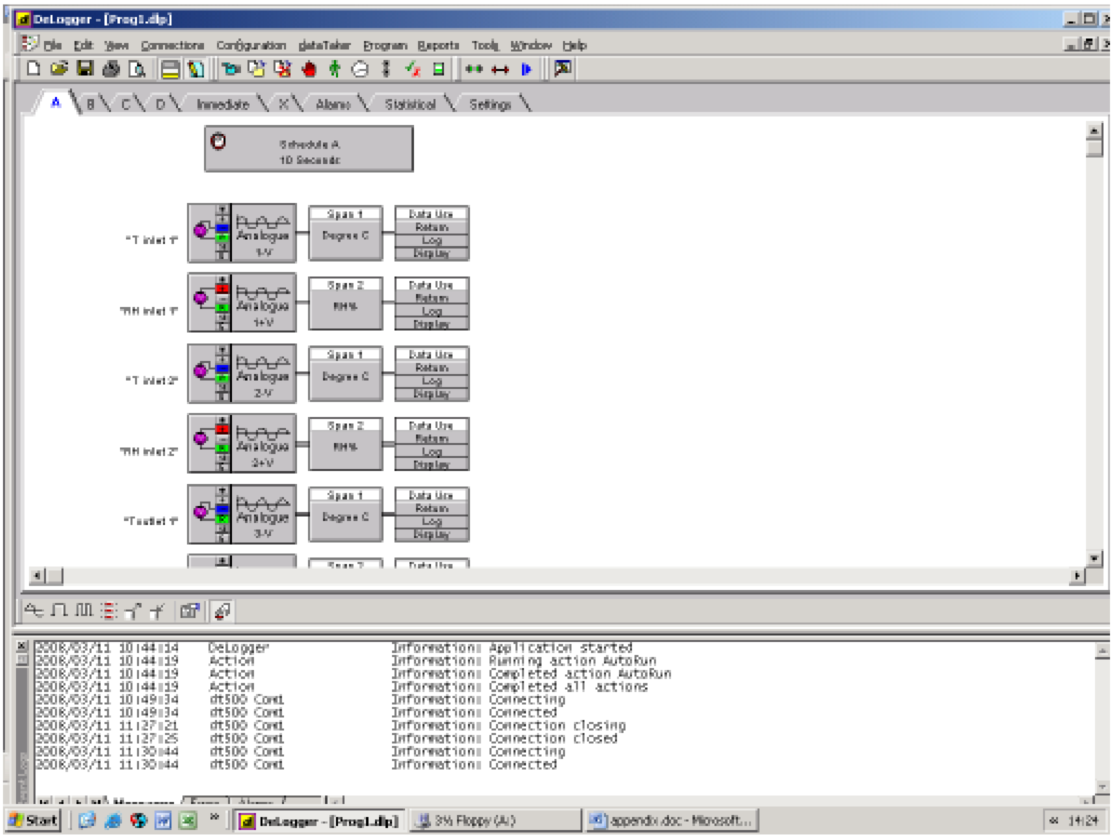
❖ Energy conservation

Reducing the building cooling load provides a major opportunity for energy conservation. Some ways this can be achieved are:

1. Use high R-value insulation throughout the building fabric.
2. Consider use of heat – absorbing glass.
3. Provide effective interior shading strategies.
4. Minimize use of glass in a building unless used on the south side for receiving solar heat in the winter.
5. Consider outside construction features that provide shading of glass.
6. Orientate the building so that solar radiation in summer is minimum on sides with large glass areas.
7. Avoid unnecessary excessive lighting levels.
8. Use types of lighting that convert electrical energy more efficiently into light.
9. Above all, use proper calculation procedures that account for heat storage and time lag.

APPENDIX II: Data logger setups and operation

The Data taker used for recording the test results in this thesis is DT 500 series 2, the figures below shows the stages of setting a program and recording the data.



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2008/03/11 10:49:34   dt500 Conn      Information: Connected
2008/03/11 11:27:21   dt500 Conn      Information: Connection closing
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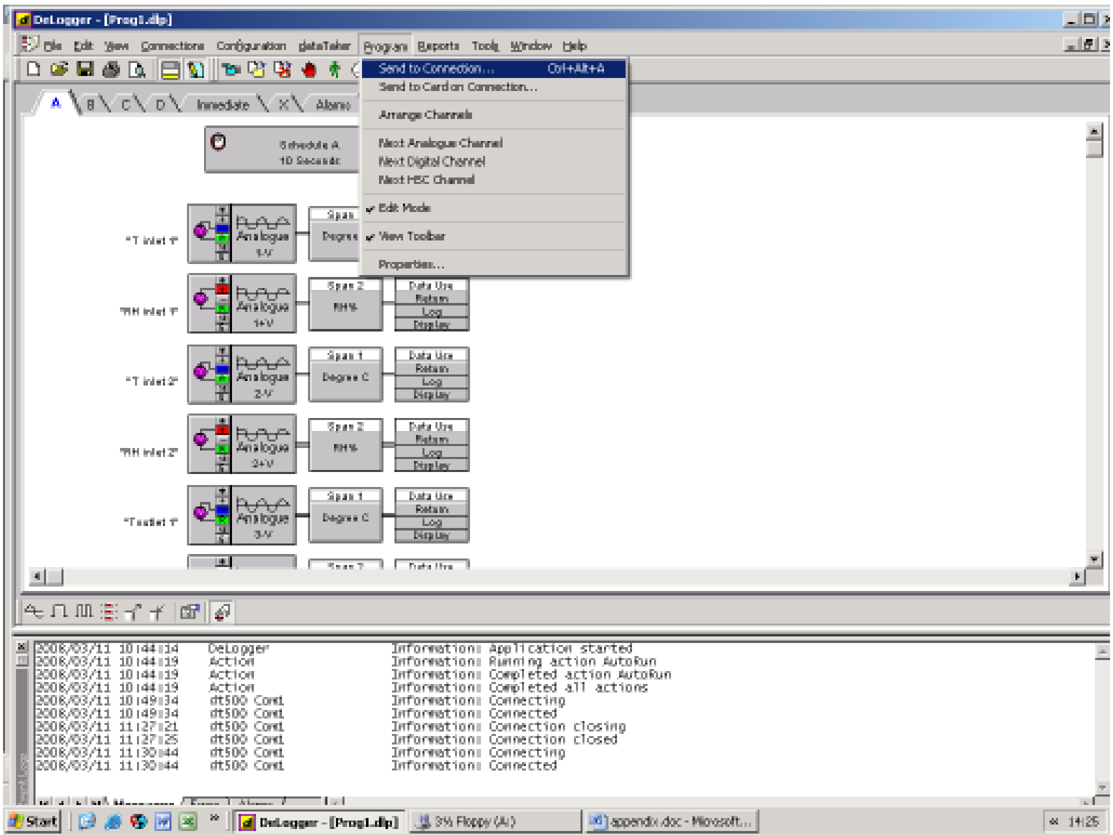

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2008/03/11 10:49:34   dt500 Con1      Information: Connected
2008/03/11 11:27:21   dt500 Con1      Information: Connection closing
2008/03/11 11:27:25   dt500 Con1      Information: Connection closed
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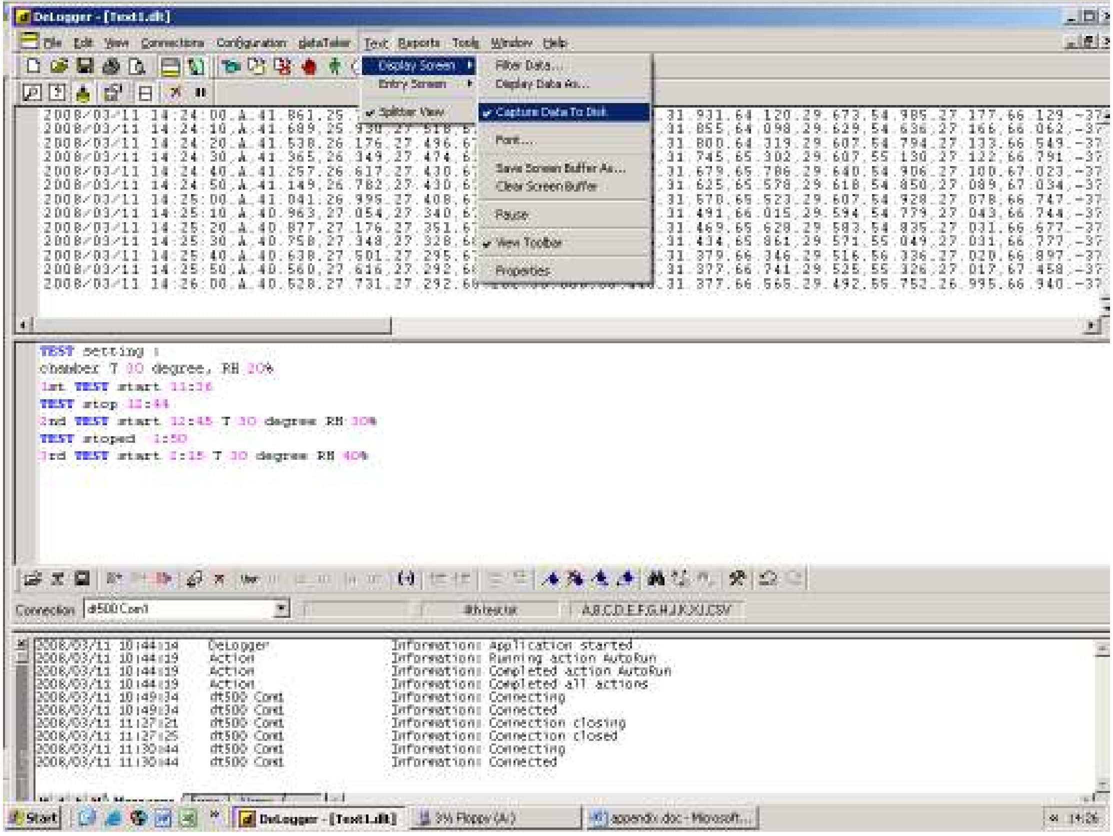

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```
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1st TEST start 11:36
TEST stop 12:44
2nd TEST start 12:45 T 30 degree RH 30%
TEST stoped  1:50
3rd TEST start 2:15 T 30 degree RH 40%
```

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2008/03/11 10:44:19   Action          Information: Completed all actions
2008/03/11 10:49:34   dt500 Con1      Information: Connecting
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2008/03/11 11:27:21   dt500 Con1      Information: Connection closing
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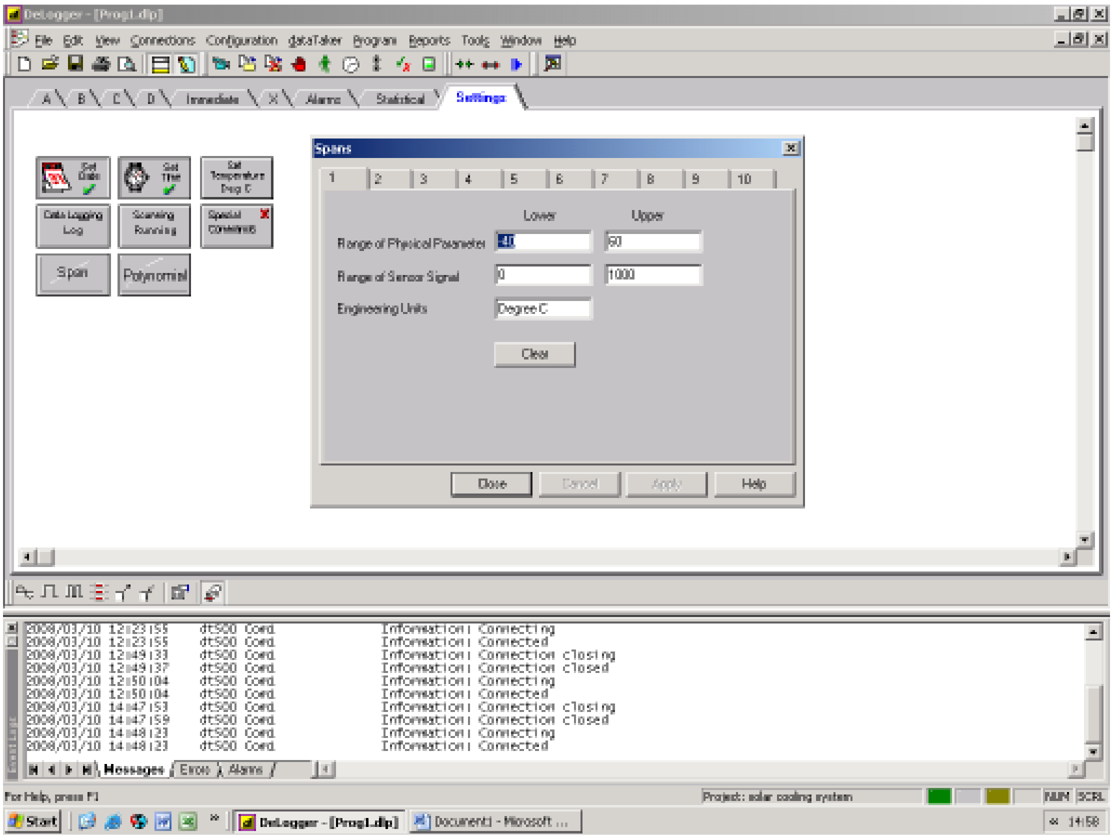

	Lower	Upper
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Range of Sensor Signal	0	1000
Engineering Units	Degree C	

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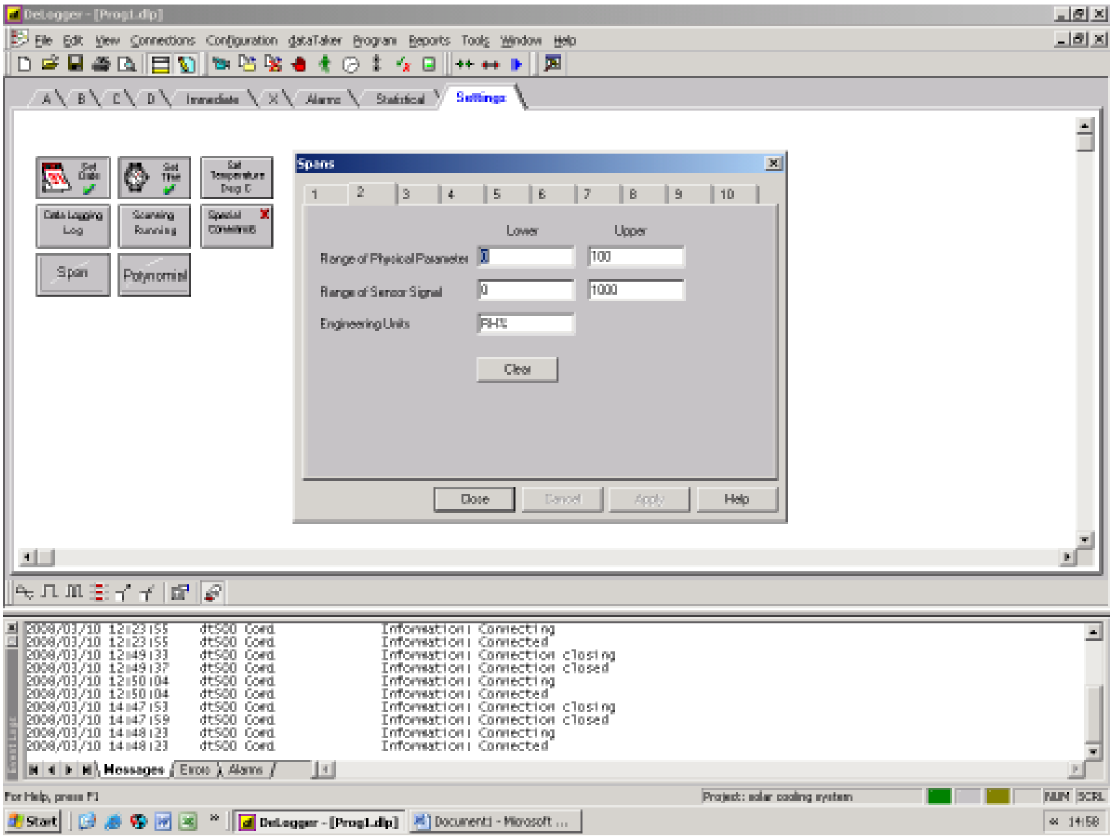

	Lower	Upper
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Range of Sensor Signal	0	1000
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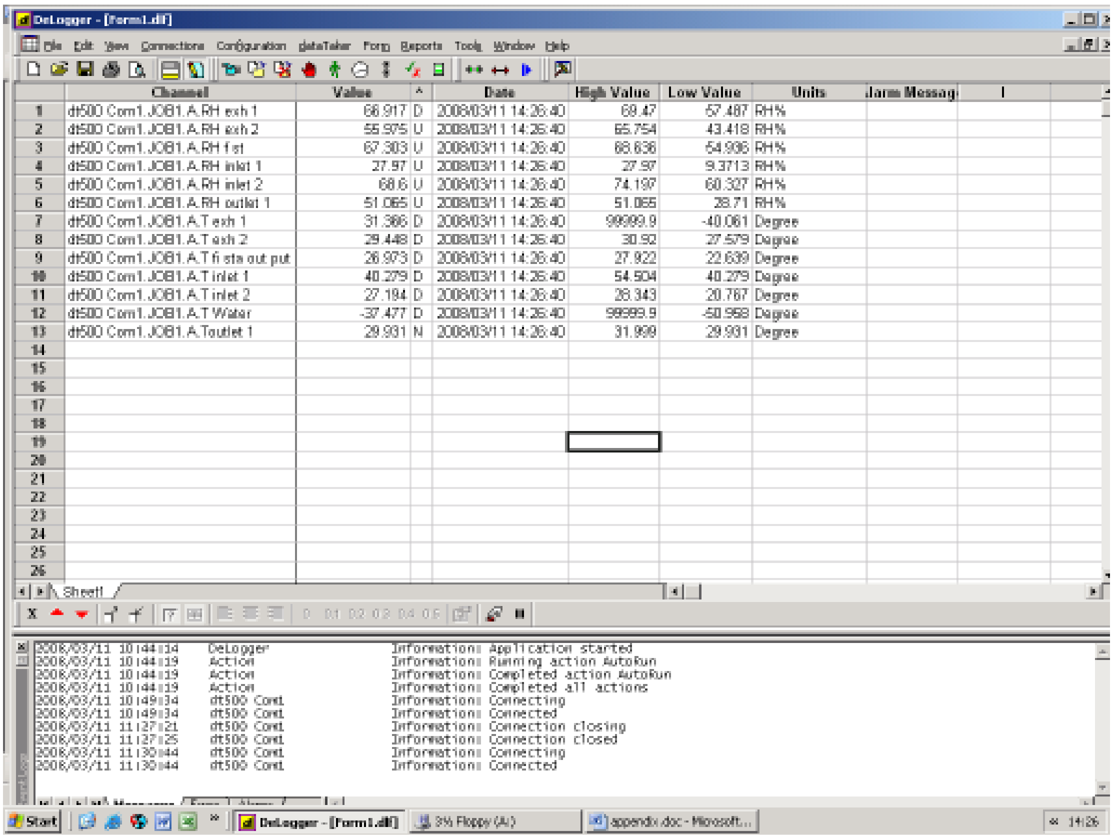

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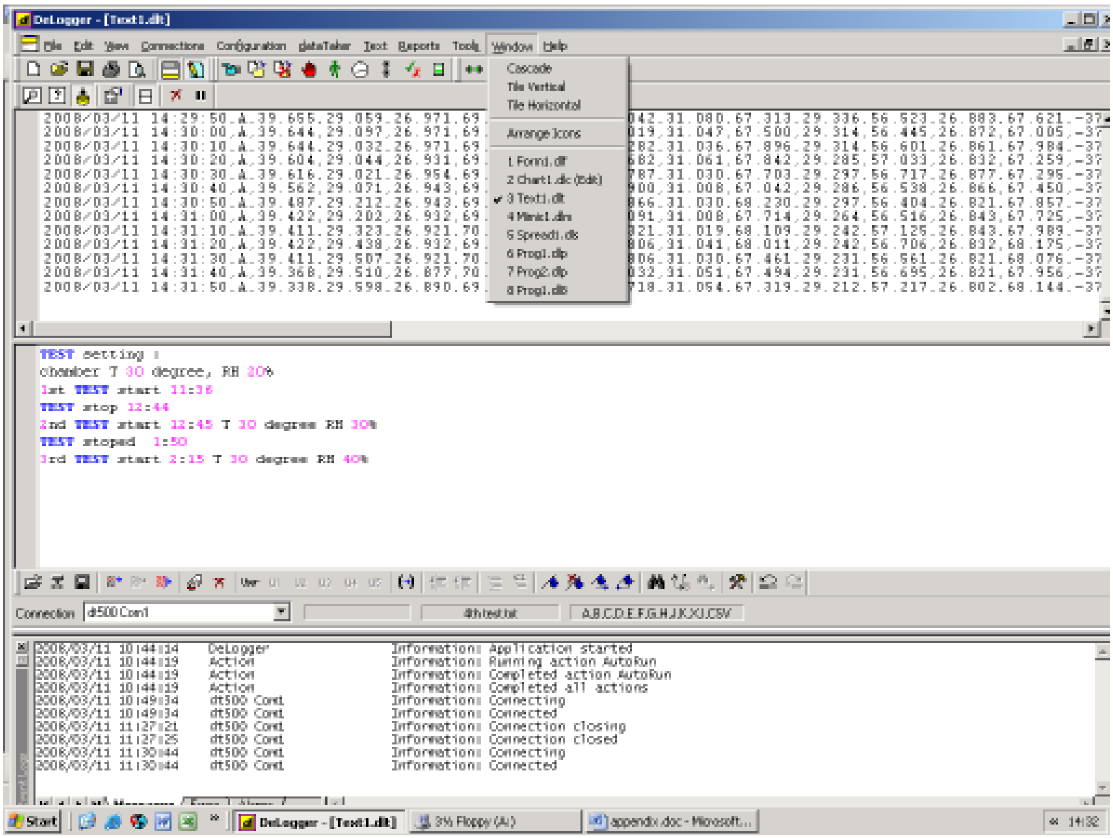
3	dt500 Com1.JOB1.A.RH f st	67.303	U	2008/03/11 14:26:40	68.636	54.936	RH%	
4	dt500 Com1.JOB1.A.RH inlet 1	27.97	U	2008/03/11 14:26:40	27.97	9.3713	RH%	
5	dt500 Com1.JOB1.A.RH inlet 2	68.6	U	2008/03/11 14:26:40	74.197	60.327	RH%	
6	dt500 Com1.JOB1.A.RH outlet 1	51.065	U	2008/03/11 14:26:40	51.065	28.71	RH%	
7	dt500 Com1.JOB1.A.T exh 1	31.386	D	2008/03/11 14:26:40	99999.9	-40.061	Degree	
8	dt500 Com1.JOB1.A.T exh 2	29.448	D	2008/03/11 14:26:40	30.92	27.579	Degree	
9	dt500 Com1.JOB1.A.T fi sta out put	26.973	D	2008/03/11 14:26:40	27.922	22.639	Degree	
10	dt500 Com1.JOB1.A.T inlet 1	40.279	D	2008/03/11 14:26:40	54.504	40.279	Degree	
11	dt500 Com1.JOB1.A.T inlet 2	27.194	D	2008/03/11 14:26:40	28.343	20.767	Degree	
12	dt500 Com1.JOB1.A.T Water	-37.477	D	2008/03/11 14:26:40	99999.9	-50.968	Degree	
13	dt500 Com1.JOB1.A.Toutlet 1	29.931	N	2008/03/11 14:26:40	31.999	29.931	Degree	
14								
15								
16								
17								
18								
19								
20								
21								
22								
23								
24								
25								
26								

```
2008/03/11 10:44:14    DeLogger                          Information: Application started
2008/03/11 10:44:19    Action                            Information: Running action AutoRun
2008/03/11 10:44:19    Action                            Information: Completed action AutoRun
2008/03/11 10:44:19    Action                            Information: Completed all actions
2008/03/11 10:49:34    dt500 Com1                        Information: Connecting
2008/03/11 10:49:34    dt500 Com1                        Information: Connected
2008/03/11 11:27:21    dt500 Com1                        Information: Connection closing
2008/03/11 11:27:25    dt500 Com1                        Information: Connection closed
2008/03/11 11:30:44    dt500 Com1                        Information: Connecting
2008/03/11 11:30:44    dt500 Com1                        Information: Connected
```

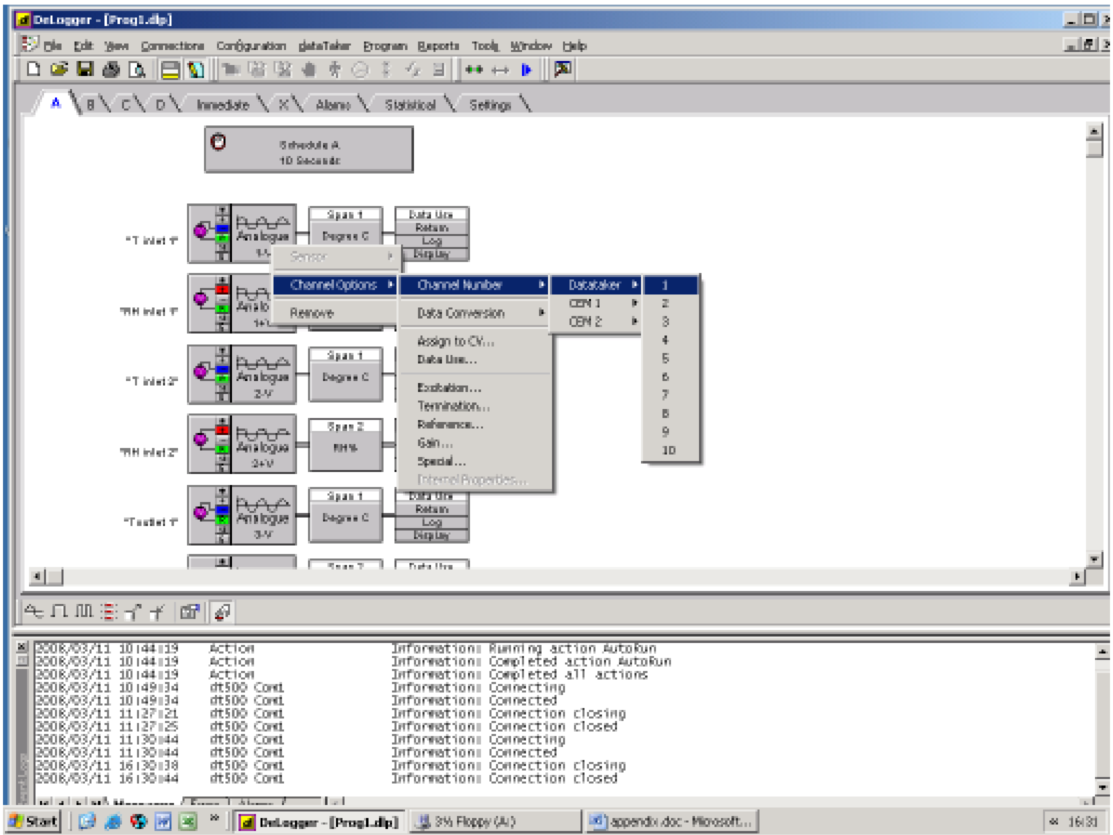


```
2008/03/11 14:29:50,A,39.655,29.059,26.971,69.          042,31.080,67.313,29.336,56.523,26.883,67.621,-37
2008/03/11 14:30:00,A,39.644,29.097,26.971,69.          019,31.047,67.500,29.314,56.445,26.872,67.005,-37
2008/03/11 14:30:10,A,39.644,29.032,26.971,69.          282,31.036,67.896,29.314,56.601,26.861,67.984,-37
2008/03/11 14:30:20,A,39.604,29.044,26.931,69.          682,31.061,67.842,29.285,57.033,26.832,67.259,-37
2008/03/11 14:30:30,A,39.616,29.021,26.954,69.          787,31.030,67.703,29.297,56.717,26.877,67.295,-37
2008/03/11 14:30:40,A,39.562,29.071,26.943,69.          900,31.008,67.042,29.286,56.538,26.866,67.450,-37
2008/03/11 14:30:50,A,39.487,29.212,26.943,69.          866,31.030,68.230,29.297,56.404,26.821,67.857,-37
2008/03/11 14:31:00,A,39.422,29.202,26.932,69.          091,31.008,67.714,29.264,56.516,26.843,67.725,-37
2008/03/11 14:31:10,A,39.411,29.323,26.921,70.          821,31.019,68.109,29.242,57.125,26.843,67.989,-37
2008/03/11 14:31:20,A,39.422,29.438,26.932,69.          806,31.041,68.011,29.242,56.706,26.832,68.175,-37
2008/03/11 14:31:30,A,39.411,29.507,26.921,70.          806,31.030,67.461,29.231,56.561,26.821,68.076,-37
2008/03/11 14:31:40,A,39.368,29.510,26.877,70.          032,31.051,67.494,29.231,56.695,26.821,67.956,-37
2008/03/11 14:31:50,A,39.338,29.598,26.890,69.          718,31.054,67.319,29.212,57.217,26.802,68.144,-37
```

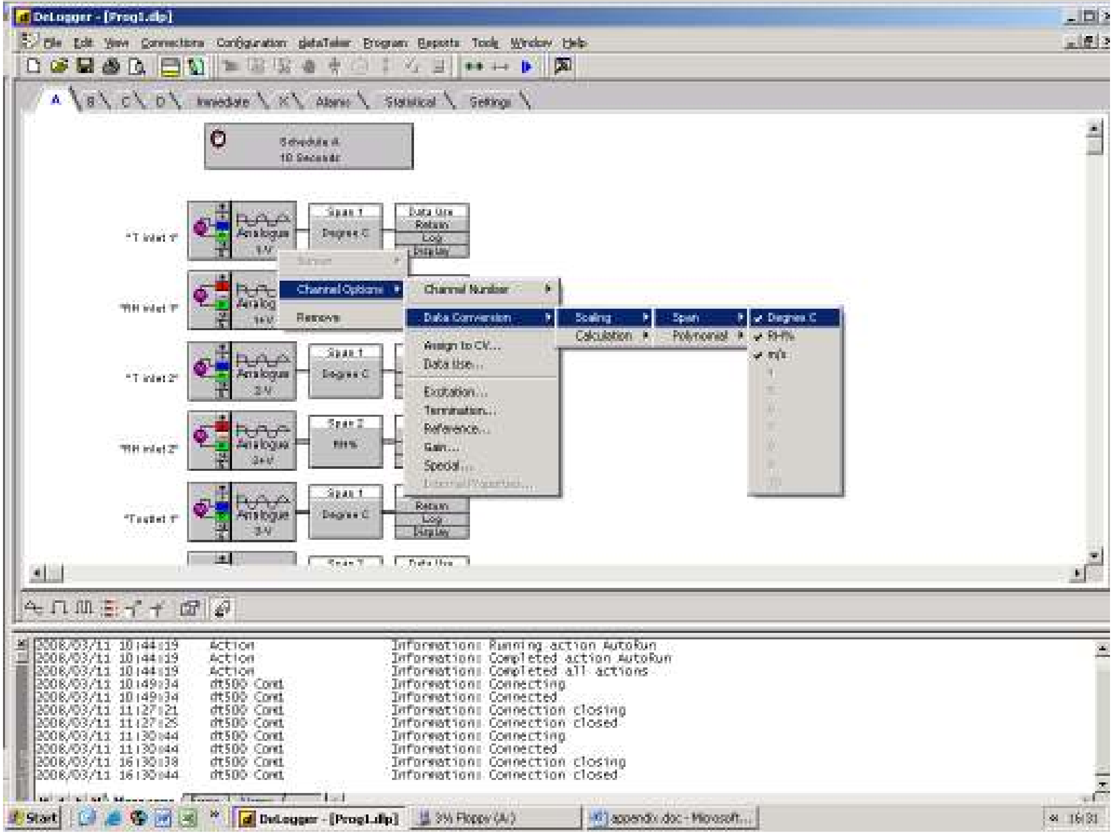
```
TEST setting :
chamber T 30 degree, RH 20%
1st TEST start 11:36
TEST stop 12:44
2nd TEST start 12:45 T 30 degree RH 30%
TEST stoped  1:50
3rd TEST start 2:15 T 30 degree RH 40%
```

Connection: dt500 Com1 | 4thtest.txt | A,B,C,D,E,F,G,H,J,K,X,J,CSV

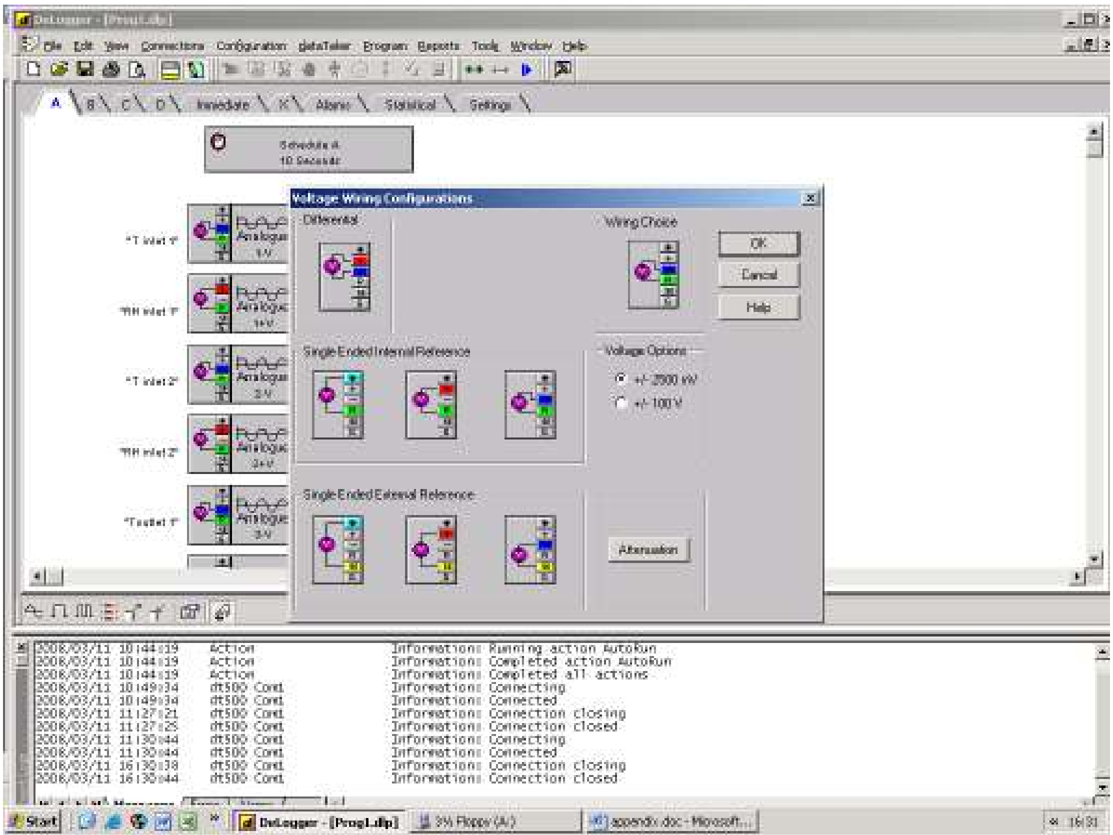
```
2008/03/11 10:44:14    DeLogger                          Information: Application started
2008/03/11 10:44:19    Action                            Information: Running action AutoRun
2008/03/11 10:44:19    Action                            Information: Completed action AutoRun
2008/03/11 10:44:19    Action                            Information: Completed all actions
2008/03/11 10:49:34    dt500 Com1                        Information: Connecting
2008/03/11 10:49:34    dt500 Com1                        Information: Connected
2008/03/11 11:27:21    dt500 Com1                        Information: Connection closing
2008/03/11 11:27:25    dt500 Com1                        Information: Connection closed
2008/03/11 11:30:44    dt500 Com1                        Information: Connecting
2008/03/11 11:30:44    dt500 Com1                        Information: Connected
```



```
2008/03/11 10:44:19   Action            Information: Running action AutoRun
2008/03/11 10:44:19   Action            Information: Completed action AutoRun
2008/03/11 10:44:19   Action            Information: Completed all actions
2008/03/11 10:49:34   dt500 Com1        Information: Connecting
2008/03/11 10:49:34   dt500 Com1        Information: Connected
2008/03/11 11:27:21   dt500 Com1        Information: Connection closing
2008/03/11 11:27:25   dt500 Com1        Information: Connection closed
2008/03/11 11:30:44   dt500 Com1        Information: Connecting
2008/03/11 11:30:44   dt500 Com1        Information: Connected
2008/03/11 16:30:38   dt500 Com1        Information: Connection closing
2008/03/11 16:30:44   dt500 Com1        Information: Connection closed
```

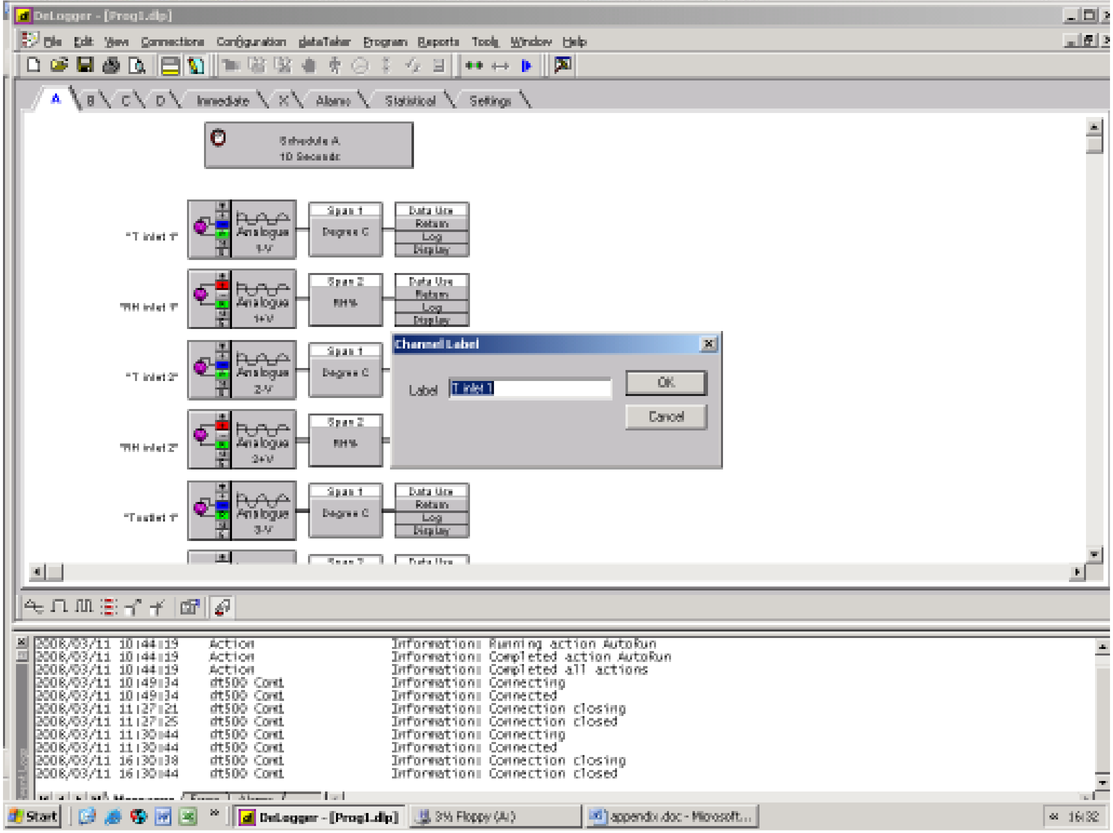


```
2008/03/11 10:44:19   Action            Information: Running action AutoRun
2008/03/11 10:44:19   Action            Information: Completed action AutoRun
2008/03/11 10:44:19   Action            Information: Completed all actions
2008/03/11 10:49:34   dt500 Com1        Information: Connecting
2008/03/11 10:49:34   dt500 Com1        Information: Connected
2008/03/11 11:27:21   dt500 Com1        Information: Connection closing
2008/03/11 11:27:25   dt500 Com1        Information: Connection closed
2008/03/11 11:30:44   dt500 Com1        Information: Connecting
2008/03/11 11:30:44   dt500 Com1        Information: Connected
2008/03/11 16:30:38   dt500 Com1        Information: Connection closing
2008/03/11 16:30:44   dt500 Com1        Information: Connection closed
```



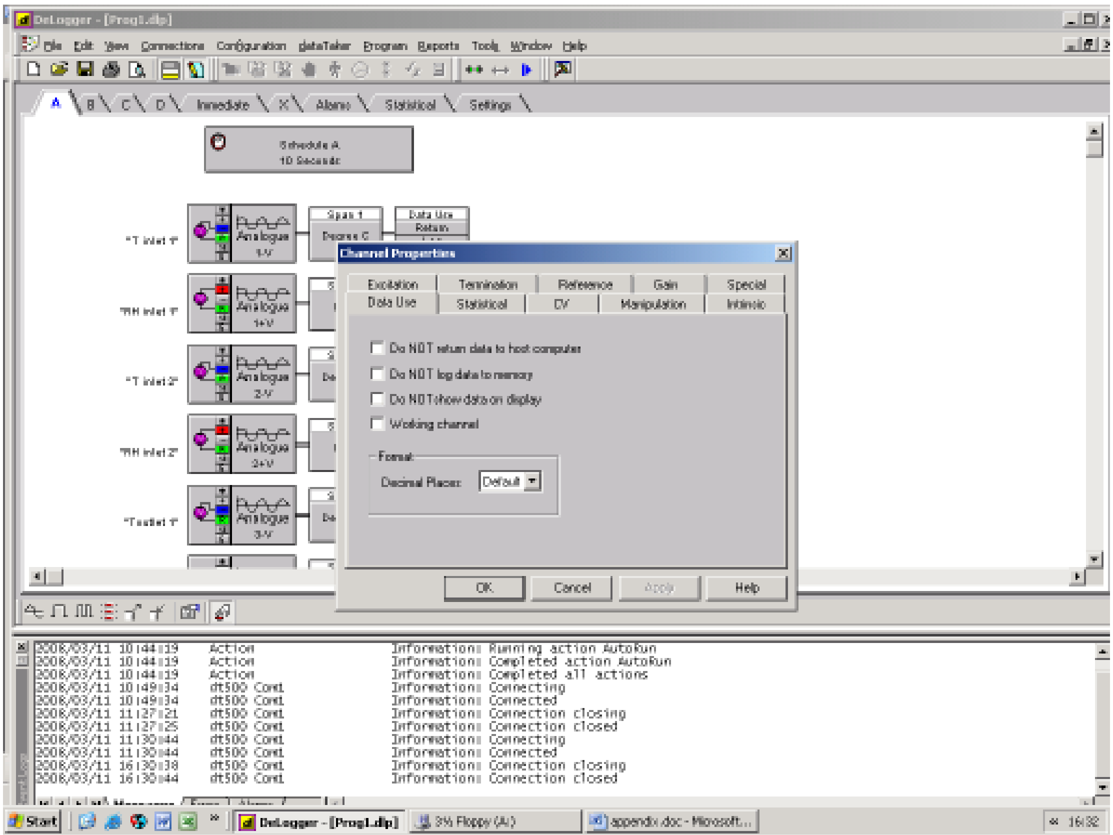
Voltage Options
● +/- 2500 mV
○ +/- 100 V

```
2008/03/11 10:44:19    Action          Information: Running action AutoRun
2008/03/11 10:44:19    Action          Information: Completed action AutoRun
2008/03/11 10:44:19    Action          Information: Completed all actions
2008/03/11 10:49:34    dt500 Com1      Information: Connecting
2008/03/11 10:49:34    dt500 Com1      Information: Connected
2008/03/11 11:27:21    dt500 Com1      Information: Connection closing
2008/03/11 11:27:25    dt500 Com1      Information: Connection closed
2008/03/11 11:30:44    dt500 Com1      Information: Connecting
2008/03/11 11:30:44    dt500 Com1      Information: Connected
2008/03/11 16:30:38    dt500 Com1      Information: Connection closing
2008/03/11 16:30:44    dt500 Com1      Information: Connection closed
```



Label: T inlet 1

```
2008/03/11 10:44:19    Action          Information: Running action AutoRun
2008/03/11 10:44:19    Action          Information: Completed action AutoRun
2008/03/11 10:44:19    Action          Information: Completed all actions
2008/03/11 10:49:34    dt500 Com1      Information: Connecting
2008/03/11 10:49:34    dt500 Com1      Information: Connected
2008/03/11 11:27:21    dt500 Com1      Information: Connection closing
2008/03/11 11:27:25    dt500 Com1      Information: Connection closed
2008/03/11 11:30:44    dt500 Com1      Information: Connecting
2008/03/11 11:30:44    dt500 Com1      Information: Connected
2008/03/11 16:30:38    dt500 Com1      Information: Connection closing
2008/03/11 16:30:44    dt500 Com1      Information: Connection closed
```



☐ Do NOT return data to host computer

☐ Do NOT log data to memory

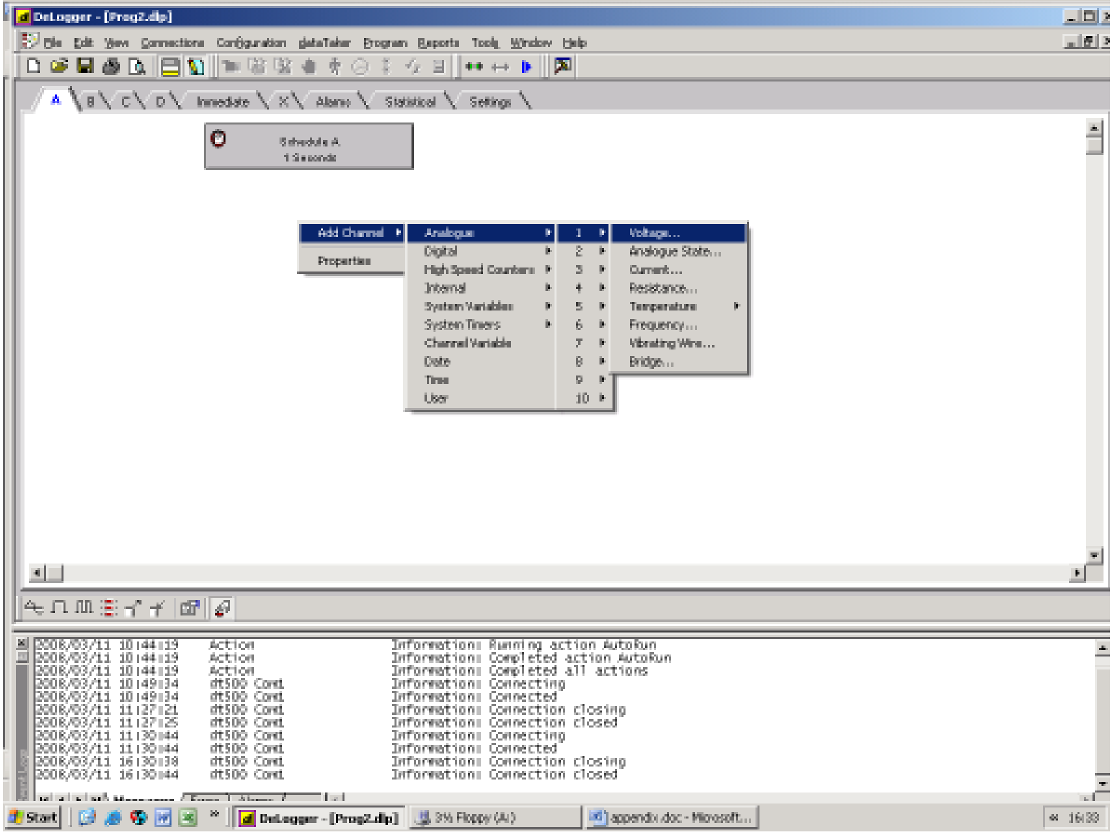
☐ Do NOT show data on display

☐ Working channel

Format

Decimal Places: Default

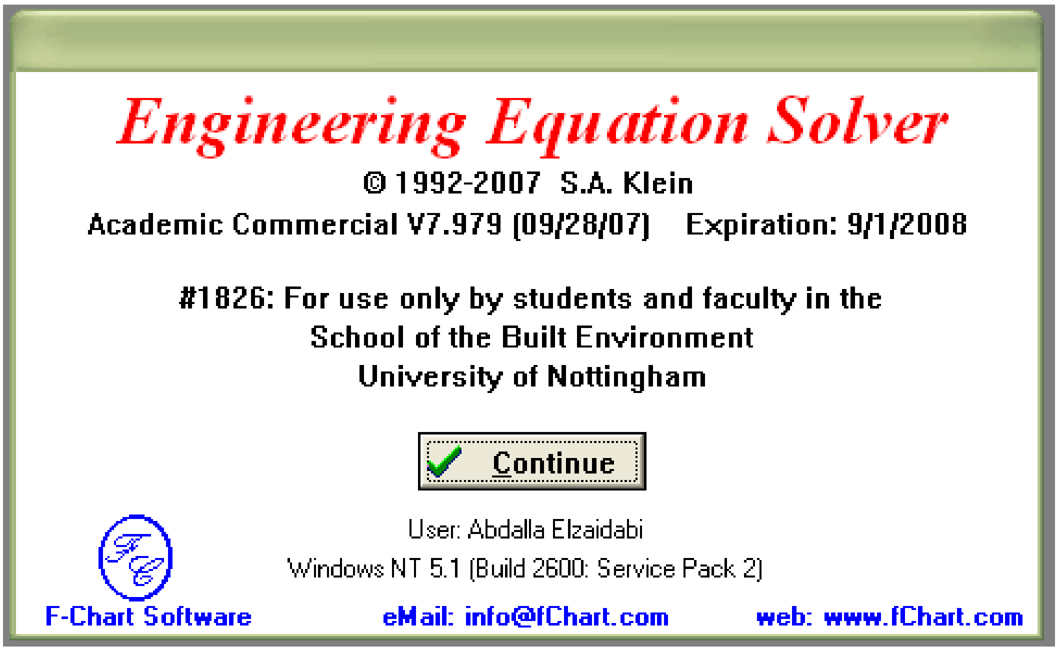
```
2008/03/11 10:44:19   Action          Information: Running action AutoRun
2008/03/11 10:44:19   Action          Information: Completed action AutoRun
2008/03/11 10:44:19   Action          Information: Completed all actions
2008/03/11 10:49:34   dt500 Conn      Information: Connecting
2008/03/11 10:49:34   dt500 Conn      Information: Connected
2008/03/11 11:27:21   dt500 Conn      Information: Connection closing
2008/03/11 11:27:25   dt500 Conn      Information: Connection closed
2008/03/11 11:30:44   dt500 Conn      Information: Connecting
2008/03/11 11:30:44   dt500 Conn      Information: Connected
2008/03/11 16:30:38   dt500 Conn      Information: Connection closing
2008/03/11 16:30:44   dt500 Conn      Information: Connection closed
```



```
2008/03/11 10:44:19   Action          Information: Running action AutoRun
2008/03/11 10:44:19   Action          Information: Completed action AutoRun
2008/03/11 10:44:19   Action          Information: Completed all actions
2008/03/11 10:49:34   dt500 Conn      Information: Connecting
2008/03/11 10:49:34   dt500 Conn      Information: Connected
2008/03/11 11:27:21   dt500 Conn      Information: Connection closing
2008/03/11 11:27:25   dt500 Conn      Information: Connection closed
2008/03/11 11:30:44   dt500 Conn      Information: Connecting
2008/03/11 11:30:44   dt500 Conn      Information: Connected
2008/03/11 16:30:38   dt500 Conn      Information: Connection closing
2008/03/11 16:30:44   dt500 Conn      Information: Connection closed
```

APPENDIX III: EES software calculation procedure

The figures below show how to calculate the properties of the air using the Engineering Equation Solver (EES) software.



Engineering Equation Solver

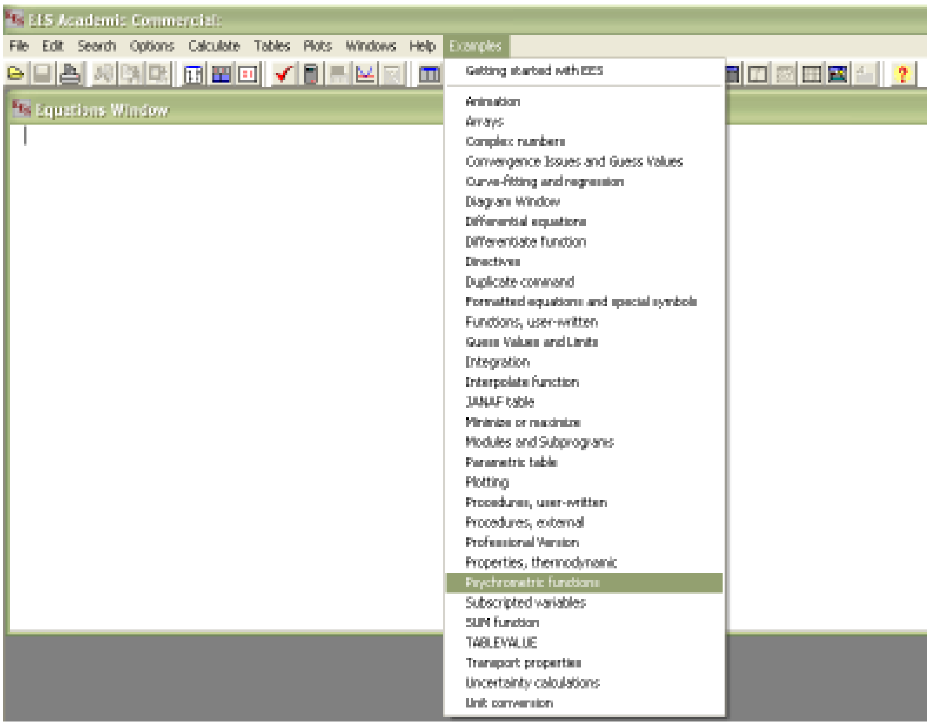
© 1992-2007 S.A. Klein

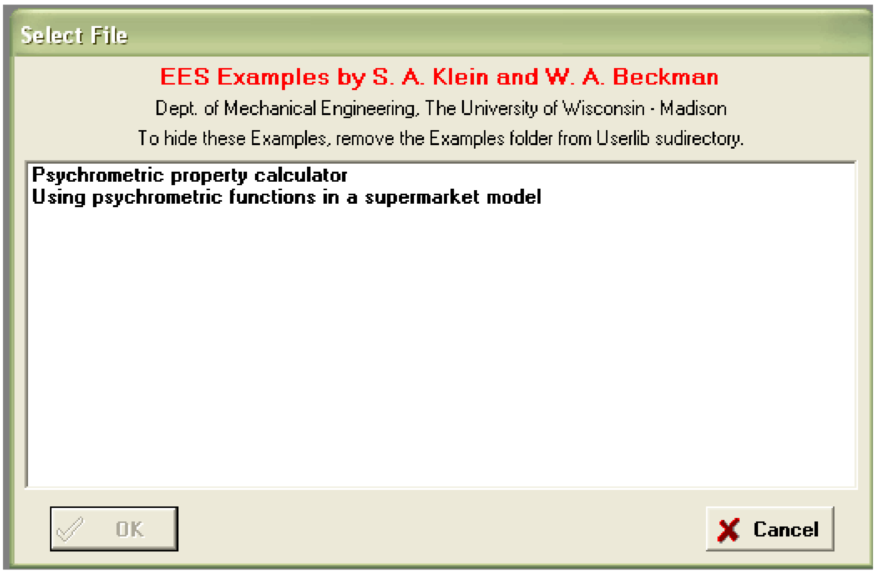
Academic Commercial V7.979 (09/28/07) Expiration: 9/1/2008

#1826: For use only by students and faculty in the
School of the Built Environment
University of Nottingham

User: Abdalla Elzaidabi
Windows NT 5.1 (Build 2600: Service Pack 2)

F-Chart Software eMail: info@fChart.com web: www.fChart.com



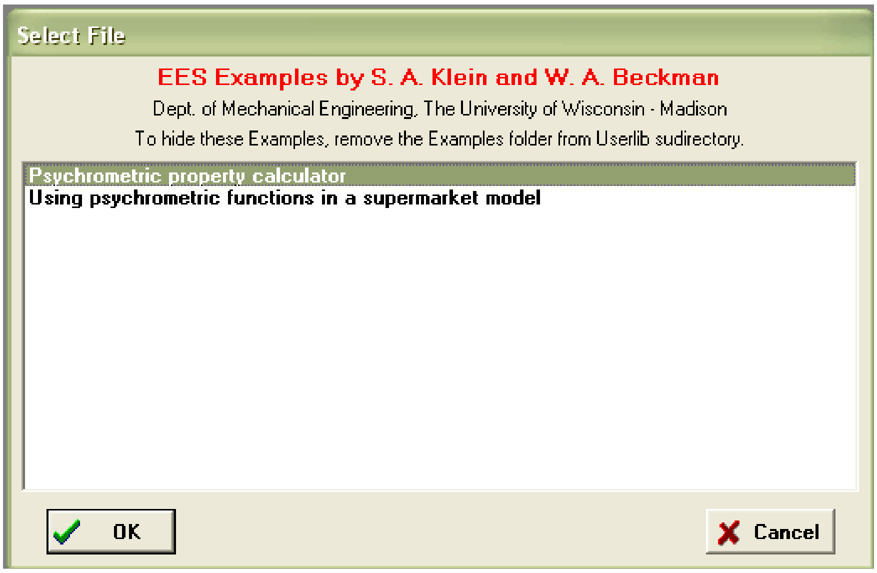


EES Examples by S. A. Klein and W. A. Beckman

Dept. of Mechanical Engineering, The University of Wisconsin - Madison

To hide these Examples, remove the Examples folder from Userlib sudirectory.

Psychrometric property calculator
Using psychrometric functions in a supermarket model

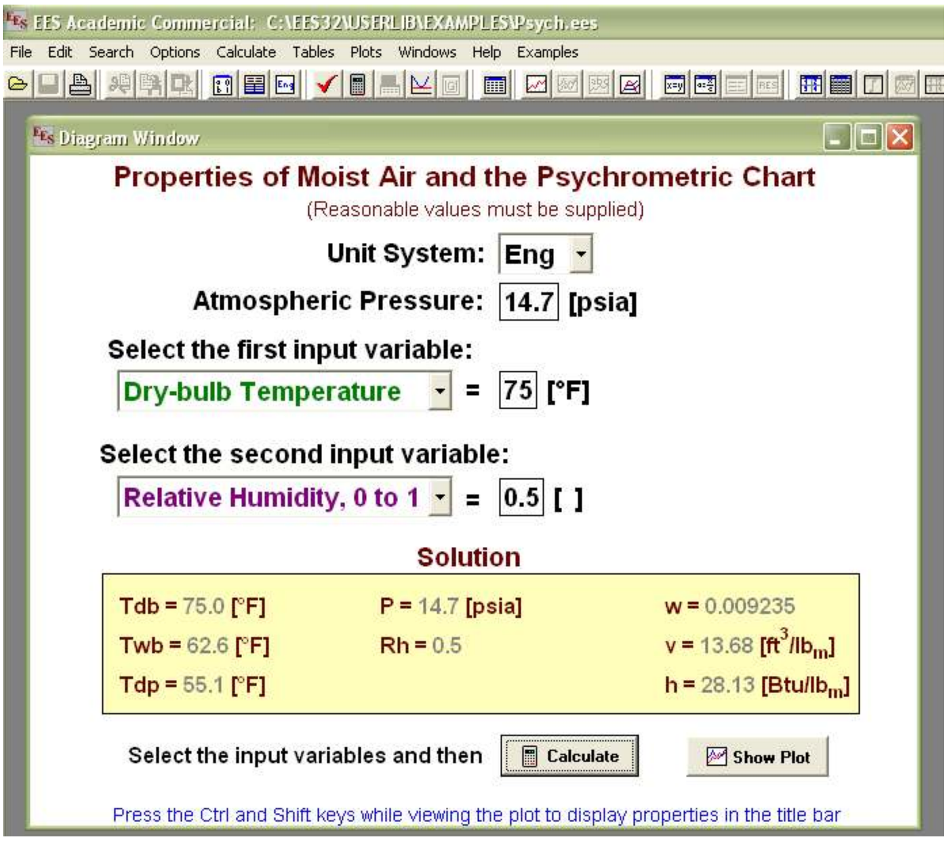


EES Examples by S. A. Klein and W. A. Beckman

Dept. of Mechanical Engineering, The University of Wisconsin - Madison

To hide these Examples, remove the Examples folder from Userlib sudirectory.

Psychrometric property calculator
Using psychrometric functions in a supermarket model



Properties of Moist Air and the Psychrometric Chart

(Reasonable values must be supplied)

Unit System: Eng

Atmospheric Pressure: 14.7 [psia]

Select the first input variable:

Dry-bulb Temperature = 75 [°F]

Select the second input variable:

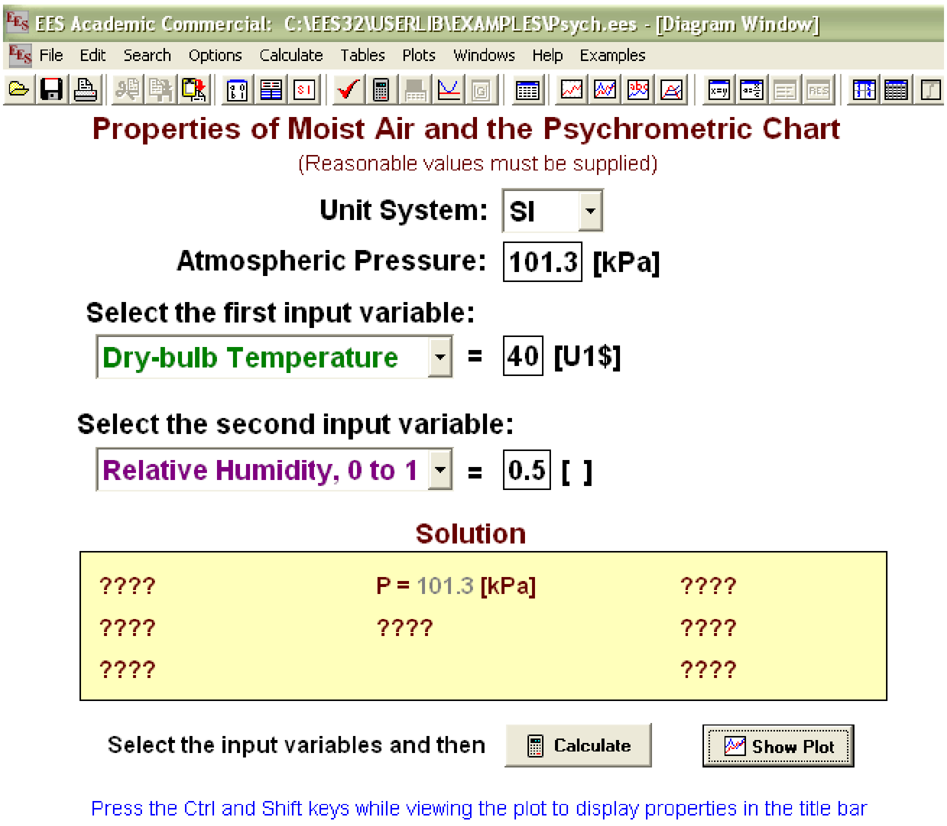
Relative Humidity, 0 to 1 = 0.5 [ ]

Solution

Tdb = 75.0 [°F]
Twb = 62.6 [°F]
Tdp = 55.1 [°F]
P = 14.7 [psia]
Rh = 0.5
w = 0.009235
v = 13.68 [ft^3/lb_m]
h = 28.13 [Btu/lb_m]

Select the input variables and then

Press the Ctrl and Shift keys while viewing the plot to display properties in the title bar



Properties of Moist Air and the Psychrometric Chart

(Reasonable values must be supplied)

Unit System: SI

Atmospheric Pressure: 101.3 [kPa]

Select the first input variable:

Dry-bulb Temperature = 40 [U1$]

Select the second input variable:

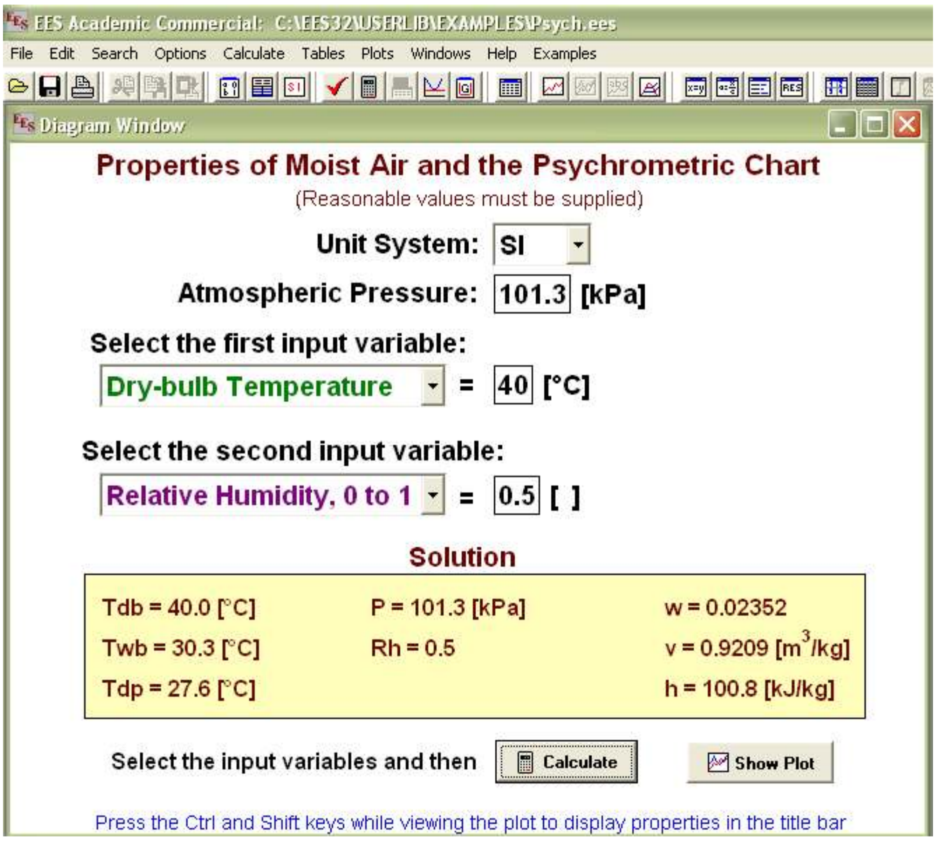
Relative Humidity, 0 to 1 = 0.5 [ ]

Solution

????
????
????
P = 101.3 [kPa]
????
????
????
????

Select the input variables and then

Press the Ctrl and Shift keys while viewing the plot to display properties in the title bar



Properties of Moist Air and the Psychrometric Chart

(Reasonable values must be supplied)

Unit System: SI

Atmospheric Pressure: 101.3 [kPa]

Select the first input variable:

Dry-bulb Temperature = 40 [°C]

Select the second input variable:

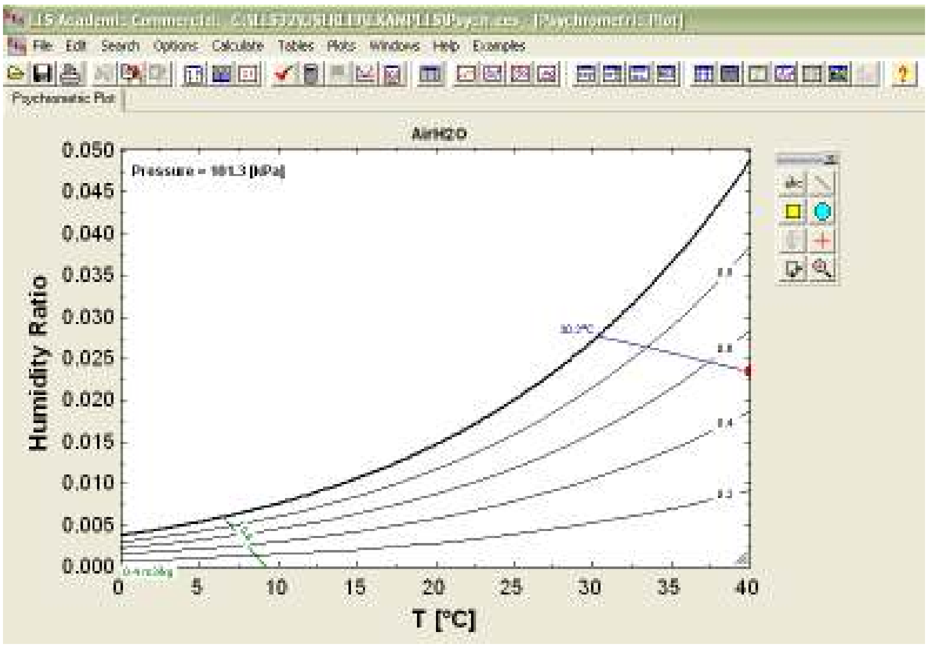
Relative Humidity, 0 to 1 = 0.5 [ ]

Solution

Tdb = 40.0 [°C]	P = 101.3 [kPa]	w = 0.02352
Twb = 30.3 [°C]	Rh = 0.5	v = 0.9209 [m^3/kg]
Tdp = 27.6 [°C]		h = 100.8 [kJ/kg]

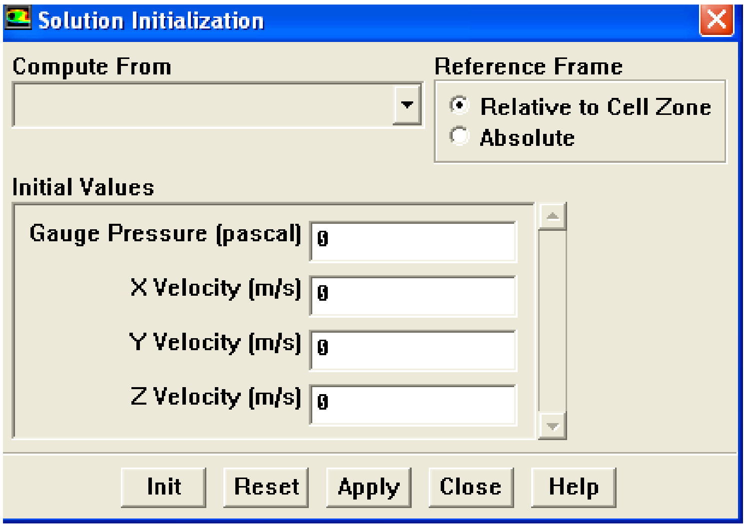
Select the input variables and then

Press the Ctrl and Shift keys while viewing the plot to display properties in the title bar



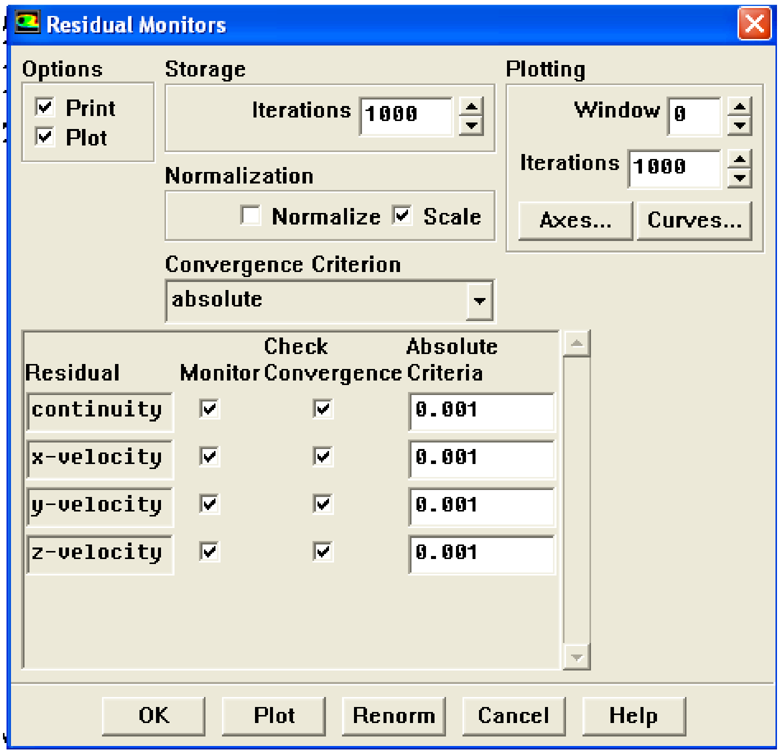
APPENDIX IV: Computitional Fluid Dynamic (CFD)

The figures below shows the stages of performing and displaying the CFD results.



Reference Frame
● Relative to Cell Zone
○ Absolute

Initial Values
Gauge Pressure (pascal) 0
X Velocity (m/s) 0
Y Velocity (m/s) 0
Z Velocity (m/s) 0



Options
☑ Print
☑ Plot

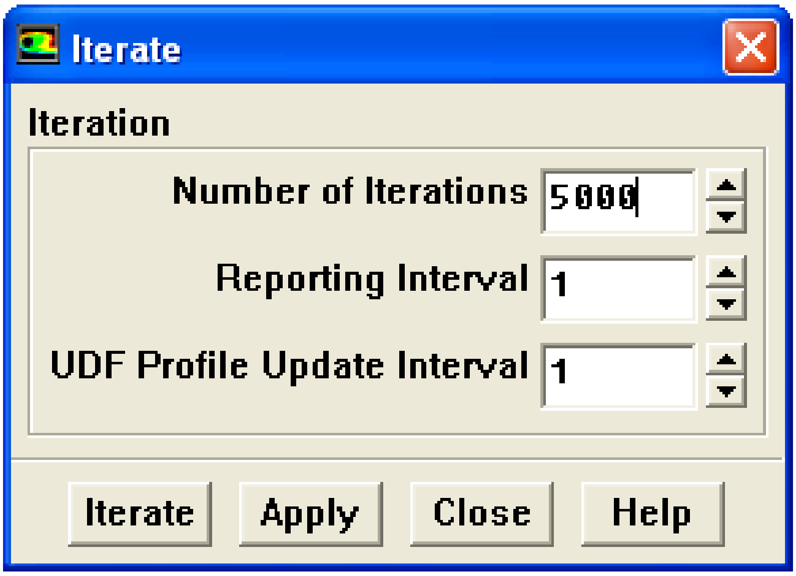
Storage
Iterations 1000

Normalization
☐ Normalize ☑ Scale

Convergence Criterion
absolute

Plotting
Window 0
Iterations 1000

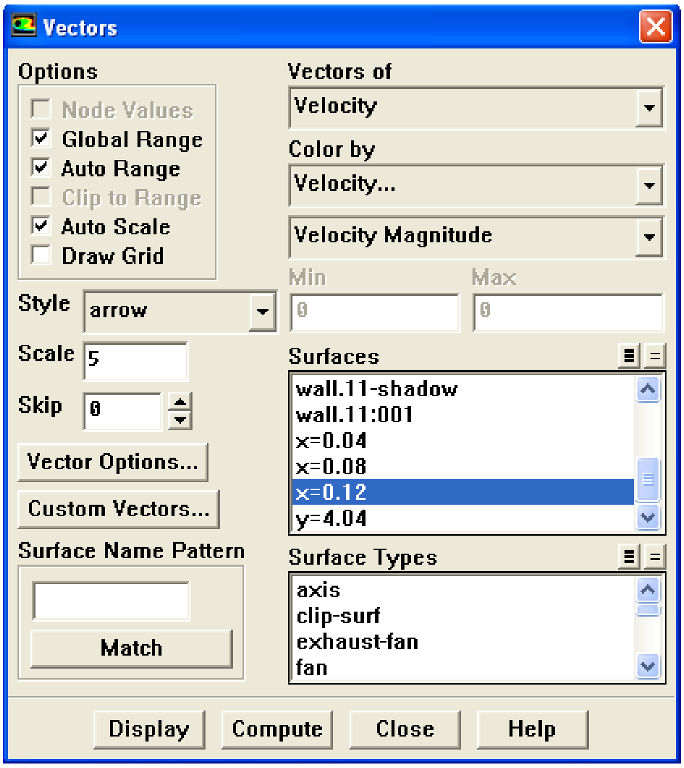
Residual	Monitor	Check Convergence	Absolute Criteria
continuity	☑	☑	0.001
x-velocity	☑	☑	0.001
y-velocity	☑	☑	0.001
z-velocity	☑	☑	0.001



Number of Iterations 5000

Reporting Interval 1

UDF Profile Update Interval 1



Options

☐ Node Values
☑ Global Range
☑ Auto Range
☐ Clip to Range
☑ Auto Scale
☐ Draw Grid

Style arrow

Scale 5

Skip 0

Vectors of Velocity

Color by Velocity...

Velocity Magnitude

Min 0

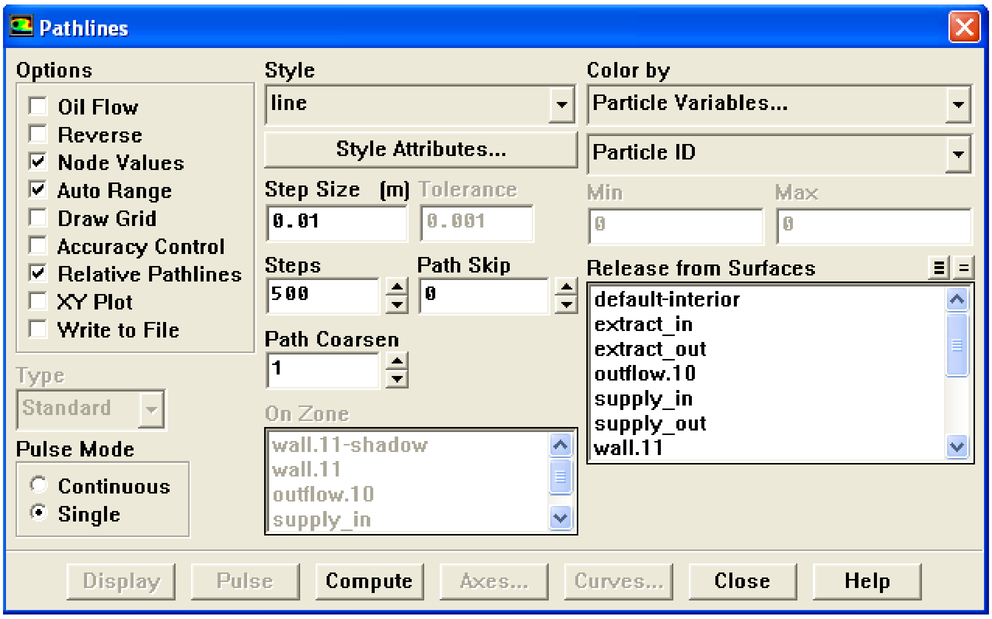
Max 0

Surfaces

wall.11-shadow
wall.11:001
x=0.04
x=0.08
x=0.12
y=4.04

Surface Types

axis
clip-surf
exhaust-fan
fan



Options
☐ Oil Flow
☐ Reverse
☑ Node Values
☑ Auto Range
☐ Draw Grid
☐ Accuracy Control
☑ Relative Pathlines
☐ XY Plot
☐ Write to File

Type: Standard

Pulse Mode
○ Continuous
● Single

Style: line

Step Size (m): 0.01
Tolerance: 0.001
Steps: 500
Path Skip: 0
Path Coarsen: 1

On Zone
wall.11-shadow
wall.11
outflow.10
supply_in

Color by: Particle Variables...
Particle ID
Min: 0
Max: 0

Release from Surfaces
default-interior
extract_in
extract_out
outflow.10
supply_in
supply_out
wall.11

❖ Governing Equations

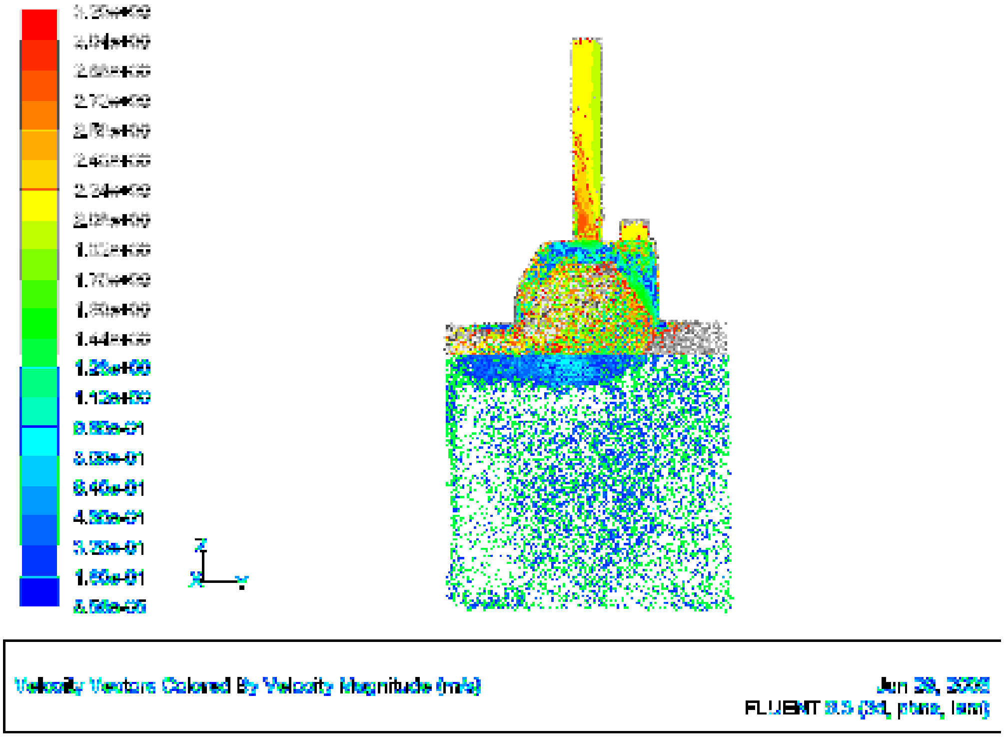
For the purposes of a general understanding of the CFD process a number fundamental laws must be applied and resulting equations derived that govern fluid flow. There are three core equations common to all CFD analyses

-The Continuity Equation

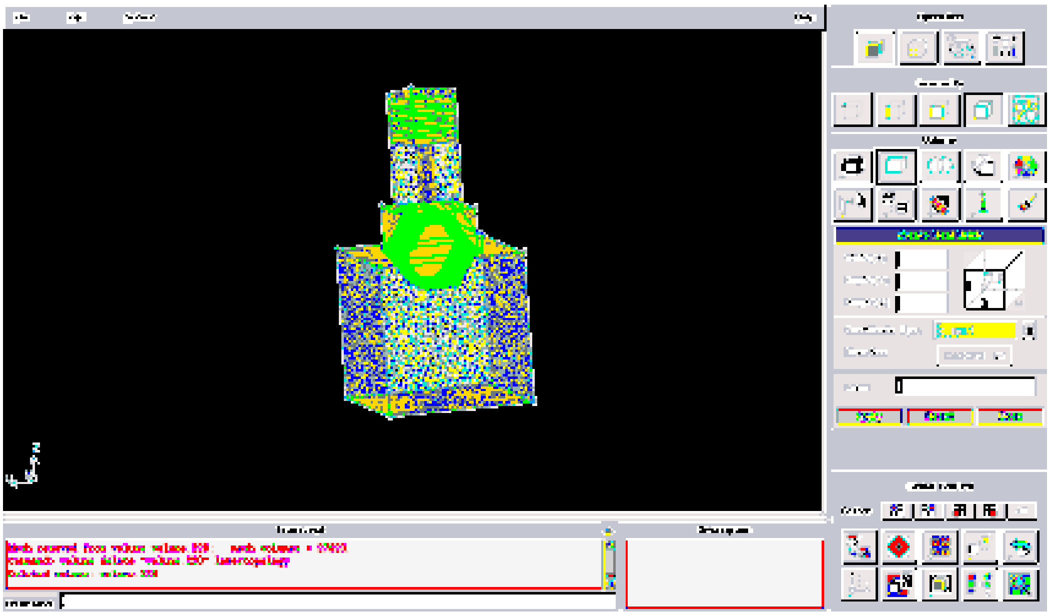
-The Momentum Equation

-The Energy Equation

The *energy equation* is the final of the governing equations required for a fundamental mathematical expression of fluid flow.

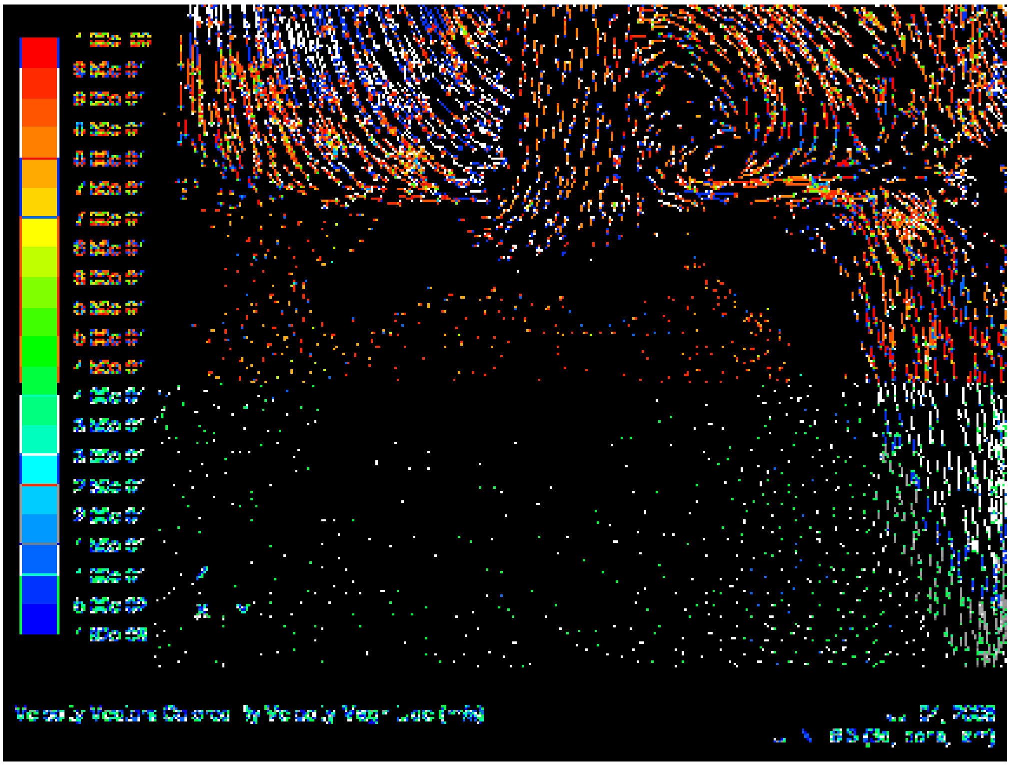


- ❖ Modelling the heat exchanger and the mid duct

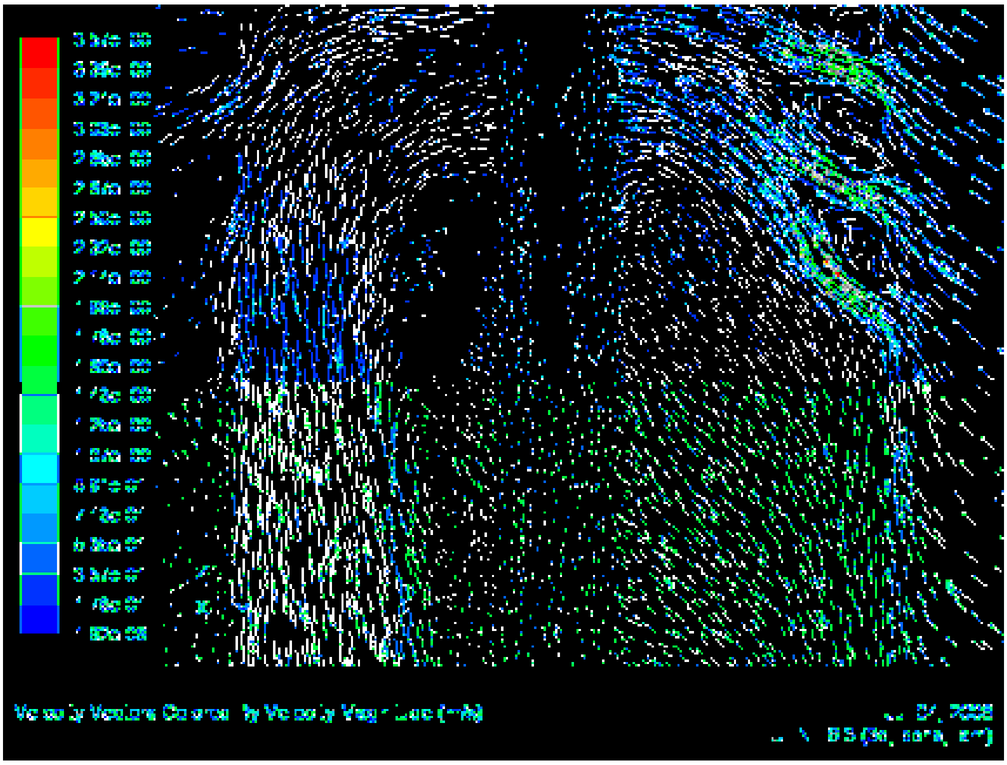


- ❖ Generating mesh for the whole system

- Air in through the outer duct and out through the middle duct



- Air circulate around the middle duct



Appendix V: Components of the Prototype system

2 DC Fans has been used in the system and their specification as follow:

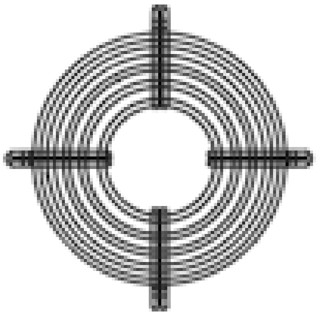
- Flow rate: 550cu.ft/min.
- Power consumption: 29W
- Voltage, supply DC: 24V
- Diameter, External: 254mm.

A Hozelock Cascade 700 DC Pump has been used in the system; it has excellent performance - higher head than most equivalent flow pumps. This pump is a low voltage pump and offers identical performance to the mains version. The power supply is only 24 volts and the power consumption is only 11 watt.

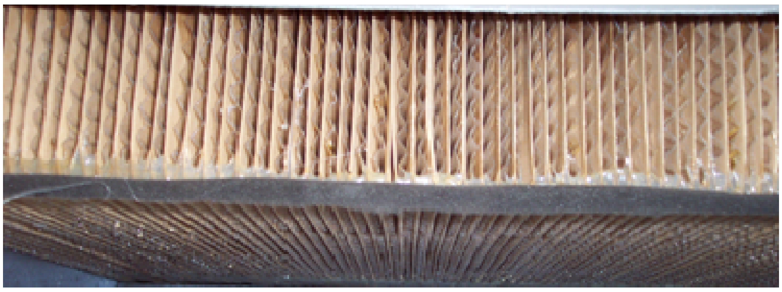
The system water pump

Shutter 250mm, has been used in the air outlet and air exhaust let; it consists of a light weight blades and squire opening to provide maximum free area when the fan is operating. The shutter size is 26mm Depth, 294mm Height and 294mm Width.

Finger guard, 254mm Height: 254mm Width, external: 254mm has been used for the both fans.



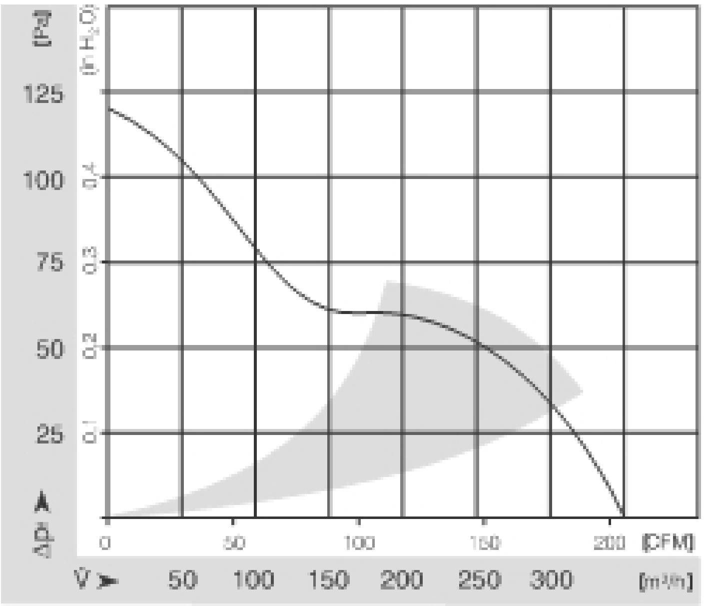
PEC of 500mm Width, 200 mm Length and 350 mm depth has been used as one of the main parts of the system.



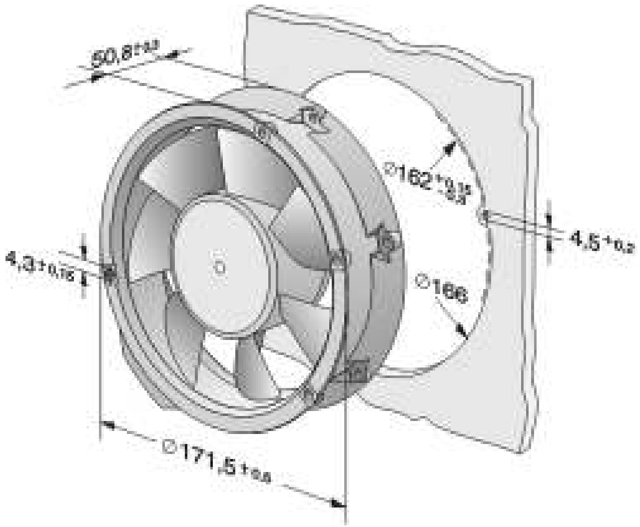
The system PEC core

Water spraying pipe: 1000 mm water spraying pipe has been used to distribute the water to the system.

❖ Details of the sytem fan

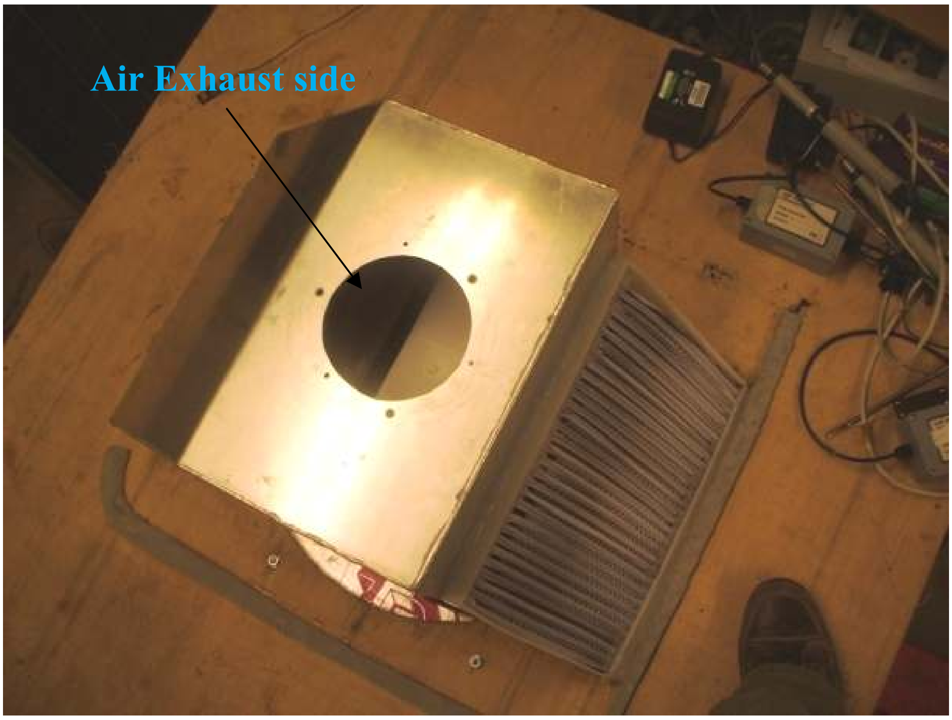


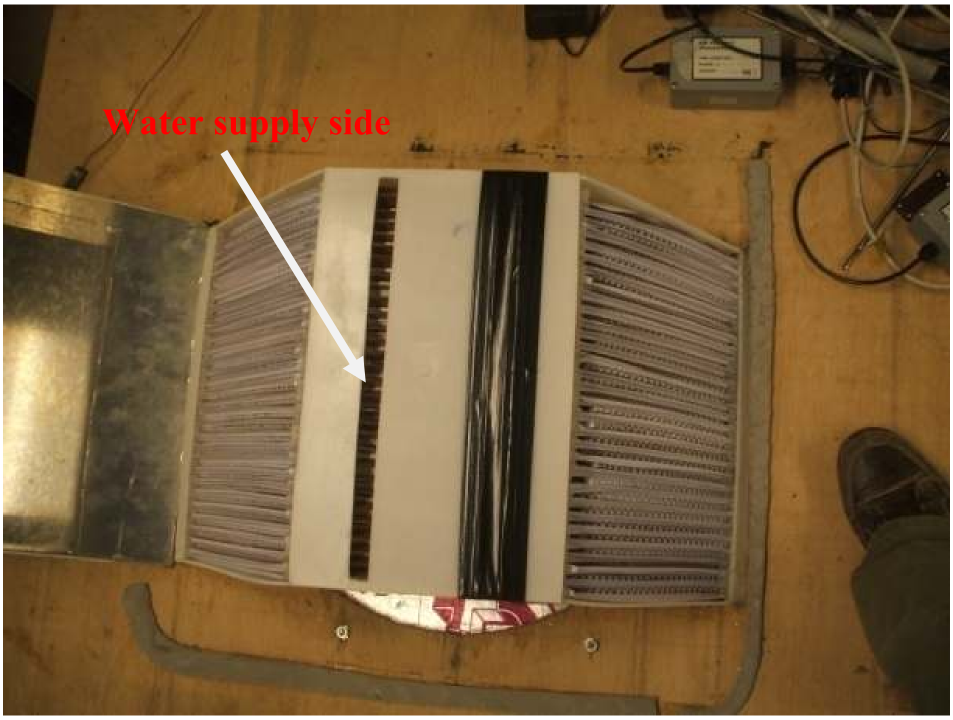
- Pressure V/S air flow



- Dimensions of the fan

Appendix VI: PEC Wind Catcher System setups and other results




Water supply side

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4 mm

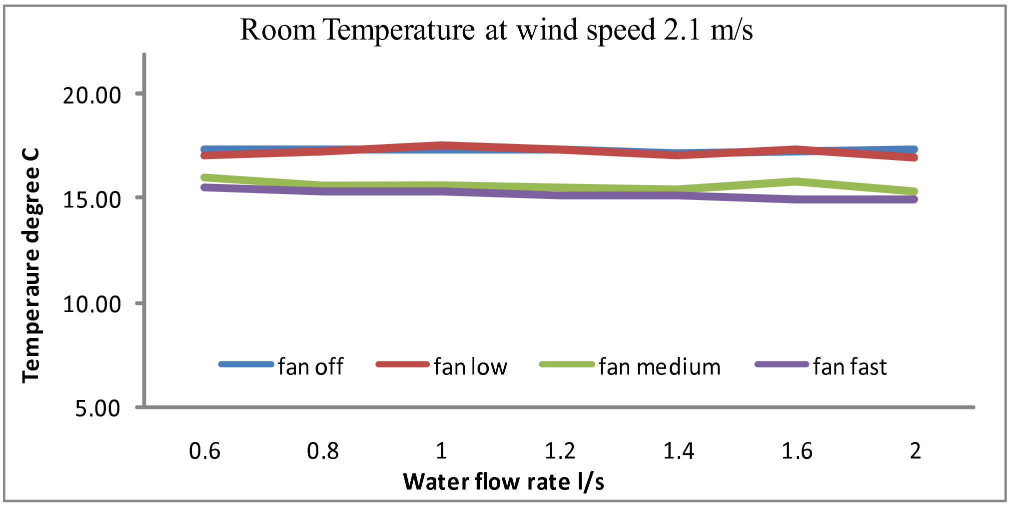
PEC- wind catcher system

- PV could be used to power the system

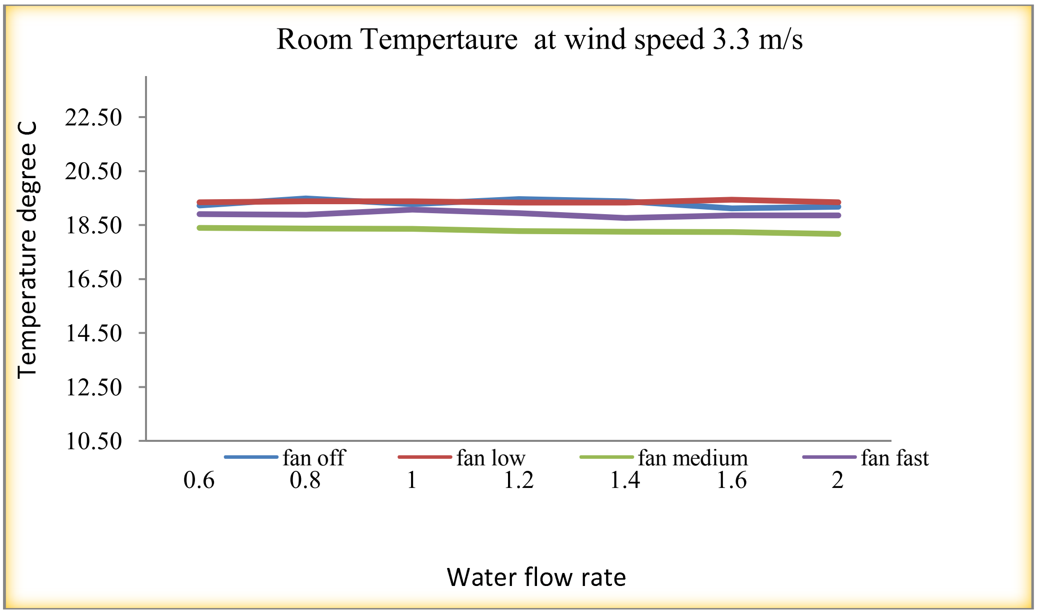
- Performing a test to the system

Other Results of the PEC-Windcatcher system

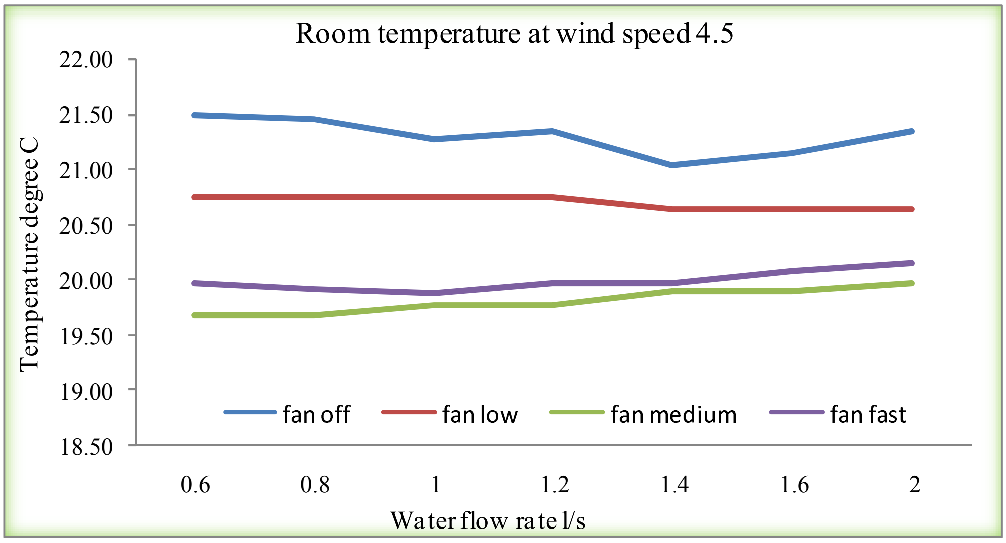
- Room temperature at wind speed 2.1 m/s and different fans ratings



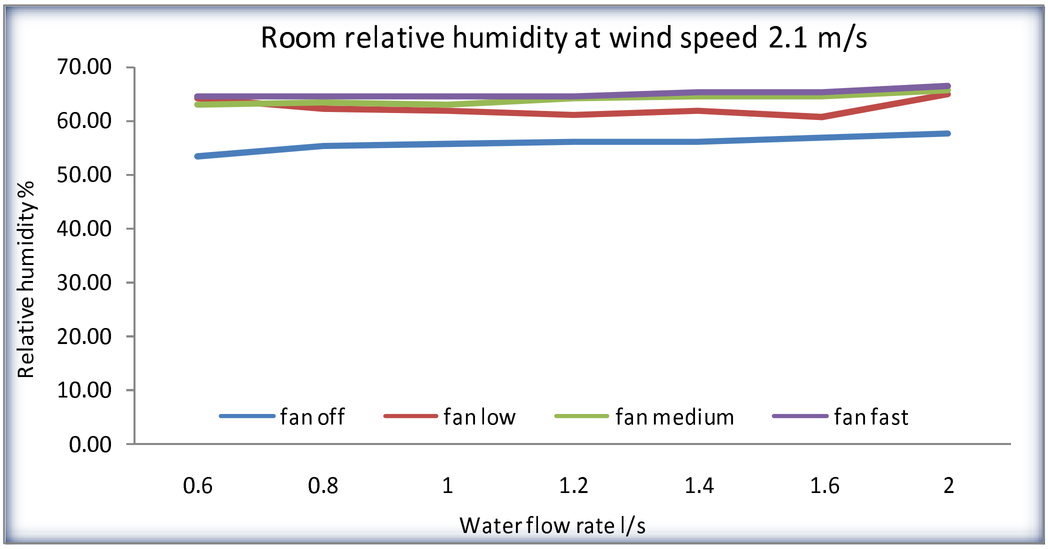
- Room temperature at wind speed 3.3 m/s and different fans ratings



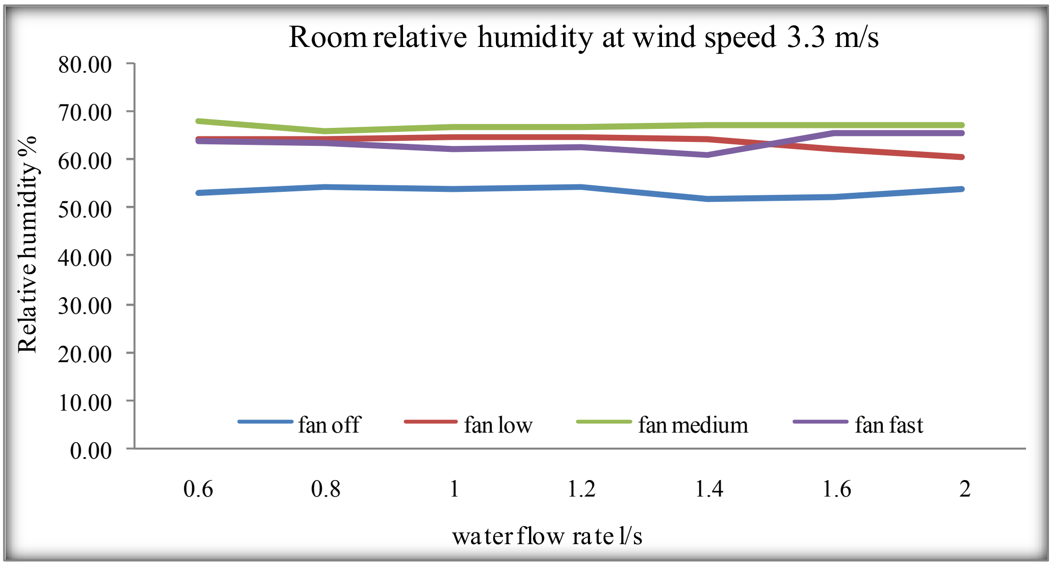
- Room temperature at wind speed 4.5 m/s and different fans ratings



- Room relative humidity at wind speed 2.1 and different fans ratings



- Room relative humidity at wind speed 3.3 and different fans ratings



- Room relative humidity at wind speed 4.5 and different fans ratings