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INVESTIGATING THERMAL PERFORMANCE OF PCM PLATES FOR FREE COOLING APPLICATIONS IN SOUTH AFRICA

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ABSTRACT

Free cooling involves using a thermal energy storage medium such as a phase change material (PCM) in order to store the ambient "cold" during the night when ambient air temperatures are lower compared to the indoor building temperatures and release this stored "cold" by using a heat transfer fluid (i.e. air) into the building during the day when higher ambient temperatures are experienced especially during the summer months. This paper assesses the free cooling potential in South Africa by using a set of Rubitherm RT25HC PCM plates. The performance of these PCM plates is assessed by benchmarking the ambient air cooled by the PCM plates during the day against the defined thermal comfort temperatures requirements. The influence of varying the air flow rate on the availability of thermal comfort temperatures at the PCM rig outlet is also studied. The results clearly show the potential of using PCM's as a means of cooling higher ambient air temperature which is experienced in hot summer months to within thermal comfort temperatures for human occupancy in a building.

INTRODUCTION

Efficient energy usage is amongst one of the most important considerations in South Africa and the whole world today. With the high demand for sustainable electricity from both the economic (commercial and industrial) and social (residential) sectors, the need for more efficient energy usage methodologies is very critical. This need is largely motivated by the current energy supply constraints being experienced in South Africa. These constraints have led to various energy usage reduction methodologies being employed in domestic, commercial and industrial sectors in South Africa such as: Solar water heating; Energy efficient lighting; Usage of variable speed drives (in industrial sectors); Low power appliances and electronic equipment; and "Green Building" constructions. Even with these interventions, the disparity between energy supply and demand has remained high. The major reason for this is that Heating, Ventilation, and Air-conditioning (HVAC) systems have remained partially isolated in the reduction of energy consumption. HVAC systems usually account for approximately 55% of the total energy consumption in buildings [1].

The design of HVAC systems for cooling applications comprises of either active or passive cooling techniques. Active cooling techniques include those systems which use energy to provide comfort requirements in buildings. Conversely, passive cooling techniques include those systems which use little or no energy to provide cooling requirements of buildings [2]. Free cooling is one such technology that falls within the passive cooling options. The operation of free cooling technology involves using a thermal storage medium to store the ambient "cold" during the night when ambient temperatures are lower compared to the indoor building temperature and then release this cold into the building during the day when higher ambient temperatures prevail [2], [3].

The concept of thermal energy storage (TES) is one which dates back to early civilization. In the past, early civilizations harvested ice and stored it for later use [4]. With advances in technology and knowledge of various other materials (or substances) that can be used for thermal energy storage purposes, this concept of storing energy for use when required has gained significant interest worldwide. The greater part of this interest lies in its viability for thermal applications such as space heating, water heating, and air conditioning in an effort to create sustainable energy saving systems.

The possibility of using TES systems for cooling applications presents an opportunity to achieve lower energy consumption from HVAC systems. Using a thermal energy storage system for free cooling of buildings is an attractive alternative that may lead to improved energy efficiency and environmental benefits – such as preservation of fossil fuels and consequently lower carbon emissions from energy generating plants. This possibility of using climatic resources (i.e. ambient temperatures) to meet the cooling demand of buildings means that a substantial amount of peak energy will be reduced – also known as peak energy saving. This is particularly advantageous for South Africa considering the current energy supply constraints.

Thermal energy storage can be achieved by either elevating or lowering the temperature of a substance, by changing the phase of a substance or through a combination of both. This involves temporarily storing high or lower temperature energy for later use. Thermal energy storage can be achieved either by: sensible heat storage; latent heat storage; or chemical heat storage [4]. The different classifications of thermal energy storage methods are shown in Figure 1.

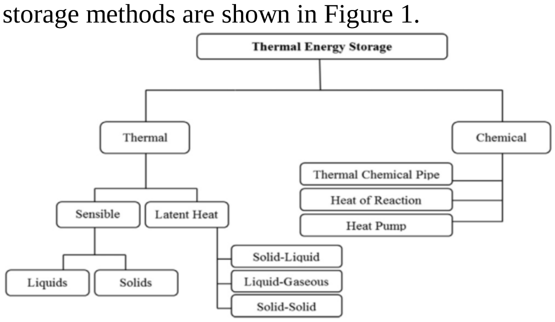

Figure 1: Types of Thermal Energy Storage [5]

Phase change materials (PCMs) form part of the latent heat storage group. In this group, a material is heated or cooled until it experiences a phase change – either from solid to liquid or from liquid to gas. This phase change occurs at a constant temperature – phase change temperature. It is at this temperature where the thermal energy is either stored or released from the material. The key benefit of using latent heat storage materials is that they have higher storage densities and smaller temperature differences are possible as compared to sensible heat storage techniques [6]. This makes PCMs ideal candidates for various thermal applications including passive cooling applications.

In the present work, the thermal performance of PCMs for free cooling applications in South Africa is studied. The thermal energy storage system that will be studied is a Rubitherm RT25HC PCM. In assessing the performance of this PCM, the melting and solidification process of the PCM and the heat carried in the heat transfer fluid (HTF) is studied using an experimental test rig. In the melting process of the PCM, the outlet temperatures from the test rig are evaluated and benchmarked against the defined comfort temperature requirements. The influence of air flow rates on the melting and solidification rates is also evaluated.

THEORETICAL BACKGROUND

Phase Change Materials

Phase Change Materials (PCMs) are a type of latent heat thermal energy storage system, characterized by high thermal energy storage densities and a large phase change enthalpy at nearly constant temperature – a characteristic which is opposite that of sensible heat storage materials [7]. The working principle of PCMs involves the absorption of heat from a heat transfer substance (such as air) which induces melting or vaporization of the PCM. This process is commonly known as the discharging process. This process can be reversed when the PCM changes back from liquid to solid during its heat release process to the heat transfer substance. This reversal process is known as the charging process [1], [4]. The working principle of a PCM during its charging, storing, and discharging processes is illustrated in Figure 2.

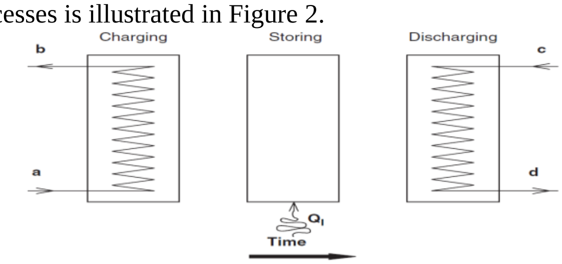

Figure 2: Working principle of a PCM [4]

During the phase change process of a PCM, there is a causal rise/lowering of temperature in the material through the addition/release of heat. In the case of a solid material, heat is added to the material causing the temperature of the material to rise as well in direct proportion of the added heat. This rise in temperature only occurs until the phase change temperature whereby any supply of additional heat to the material will only cause a phase change of the material – particularly from solid to liquid [5]. From this process, it can be established that the stored energy in the PCM combines both sensible and latent energy components. As such, the thermal storage capacity of a PCM can be evaluated using equation 1[5],

$$Q = \int_{T_i}^{T_m} m_{PCM}\, C_p dT + \int_{T_m}^{T_f} m_{PCM}\, C_p dT = m_{PCM}\left[\, C_{sp}(T_m - T_i) + C_{lp}(T_f - T_m)\right] \quad (1)$$

where

Q – quantity of thermal energy stored (kW)
m_{TES} – mass of storage system (kg)
C_p – specific heat storage capacity (kJ/kg-K)
C_{sp} – sensible heat storage capacity (kJ/kg)
C_{lp} – latent heat storage capacity (kJ/kg)
h_m – enthalpy of thermal energy storage material (kJ/kg)
T_i – initial temperature of storage material (°C)
T_f – final temperature of storage material (°C)

T_m – melting temperature of storage material (°C)

The types of PCMs can be classified into three categories, namely: organics; inorganics; and eutectics. PCMs in each of these categories have a certain melting temperature and melting enthalpy based on their material properties. This classification provides a guide into the usability of the PCMs for a specific thermal application. The organic group of PCMs are mainly paraffin and fatty acids, and they have high latent heat but low thermal conductivity. Inorganic based PCMs are primarily metallic and salt hydrates, and they possess higher latent heat than organics as well as a higher thermal conductivity and lower cost. Eutectic based PCMs consist of mainly two or more compounds which can either be inorganic-inorganic, inorganic-organic, or organic-organic combinations [3]. Figure 3 shows the classification of PCMs according to their melting temperatures and melting enthalpy.

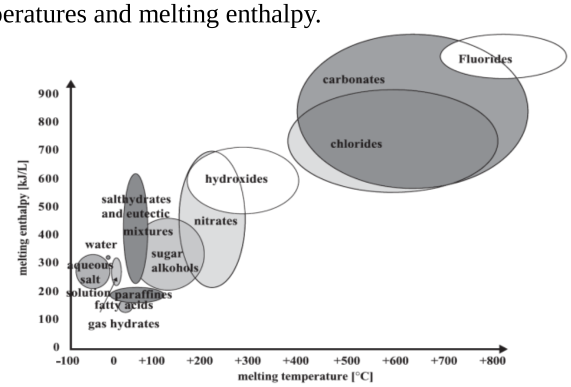

Figure 3: Typical melting temperatures and melting enthalpies of various PCMs [7]

Various PCMs are widely available on the market. However, that does not mean that they satisfy the criteria required for a thermal energy storage system. In any typical thermal application problem, the PCM under consideration should satisfy a set of criteria [4]. These criteria include, but are not limited to:

- High thermal conductivity
- Melting point at the desired operating temperature
- Congruent melting
- Little or no sub cooling
- Noncorrosive behavior to encapsulation materials
- Nontoxic, non-flammable, and non-explosive characteristics
- Commercial availability
- Low cost

The implementation of PCMs for thermal application problems offers some substantial advantages over other conventional methods. Dincer [4], highlighted some benefits to society that PCMs could present. These were:

i. Substantial reduction of peak electrical loads, thereby helping to improve predicted peak-power shortages
ii. Providing an economical means of using climatic energy to meet the growing need for heating and cooling
iii. Providing an alternative means that can lead to increased energy efficiency and environmental benefits such as low carbon emissions from power plants

Thermal Comfort

In determining the thermal comfort temperature, this study adopted adoptive thermal comfort principle which was introduced by Nicol and Humphreys [8] in 2002. In this principle, the comfort temperatures of human beings in buildings are related to the ambient temperature. This principle recognizes that humans have the natural tendency to adapt to their changing environment, and that the comfort temperatures should be defined specific to the selected study area.

The comfort temperature under the adaptive thermal comfort principle is expressed by equation 2 [9], where T_c is the thermal comfort temperature and T_o is the monthly mean outdoor air temperature.

$$T_c = 13.5 + 0.54T_o \quad (2)$$

where,

T_C – comfort temperature (°C)
T_o – monthly mean outdoor air temperature (°C)

The comfort zone within which the temperatures are generally acceptable can be taken to extend roughly 2-3 °C on either side of the thermal comfort temperature. Typically, the range of thermal comfort for human beings is between 21 – 26 °C [10].

Free Cooling

In a typical building that uses the free cooling concept, the cold night air can be used to cool down the PCM hence solidifying it – the charging process. During the day, warm air is blown past the PCM. The warm air is then cooled down through the heat exchange process that occurs between the air and the PCM, thereby melting the PCM. This process of cooling the air is accomplished without any cold production by another piece of equipment that uses electrical energy to function – such as a chiller system. Hence, the only energy consuming item in the free cooling concept is the fan which is used to blow air past the PCM. Considering a conventional HVAC system, it is worth noting that the energy consumption of the chiller is approximately 10 – 20 times that of the fan [11]. This shows that the free cooling concept if applied, can greatly reduce building energy consumption. In addition, fan power can be provided from solar energy resulting in an off-grid system. Figure 4 shows the concept behind free cooling.

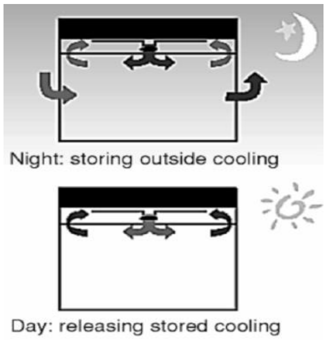

Figure 4: Free cooling concept [11]

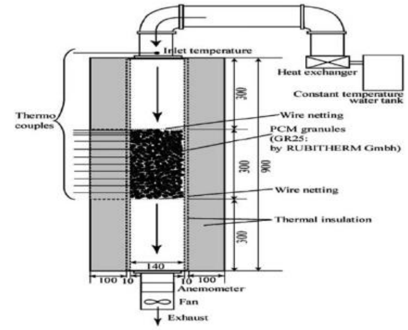

Figure 5: Experimental setup constructed by Takeda [13]

The major influencing factor on the effectiveness of a free cooling system is the phase change temperature of the PCM. An incorrect selection of the PCM will therefore result in insufficient cooling. Rastogi et al. [12] conducted a study on the selection of suitable PCMs for air-conditioning applications. The selection process was based on a TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution) by evaluating and ranking various commercially available PCMs on their relative performance in maintaining human comfort temperature. This was done by utilizing a simulation software called PCM Express. The results showed that the suitable PCMs to achieve the thermal comfort requirements had a phase change temperature ranging from 17 – 25 °C. Furthermore, the selected phase change temperature of the PCM should be within 3 – 5 °C lower than the monthly average daytime ambient temperature to ensure that the air will be cooled to within thermal comfort requirements.

Takeda et al. [13] developed a ventilation system that used PCM granules for direct heat exchange with the air. A PCM packed bed was installed vertically in a ventilation duct system with T-type thermocouples to measure the temperature of the PCM packed bed. The PCM used was Rubitherm GR25 granules with a phase change temperature ranging between 23.5 - 24.9 °C and a latent heat of 41.9 kJ/kg. The experimental setup used in this study is shown in Figure 5. Air was pulled through the duct in a downward direction at a rate of 48 m^3/h by an exhaust fan installed at the outlet of the duct. In order to simulate varying outdoor air temperature, the air inlet temperatures were varied between 21.5 °C and 28 °C by using a heater. The outlet air temperatures were then measured to evaluate the degree of cooling that occurred. The results obtained from the study showed that the outlet air temperature was stabilized within the range of phase change of the PCM packed bed.

Zalba et al. [3] in 2004 studied the application of phase change materials in free cooling systems. The objective of the study was to design, construct and test an experimental rig to study the performance of PCMs with a melting temperature of around 20 – 25 °C. The experimental test rig used was a closed circuit comprising of a fan, a heating and cooling device (to simulate PCM discharging and charging process) and a thermal energy storage unit. The study considered some influential factors which could affect the performance of the chosen PCM. These factors were: thickness of the PCM encapsulation; temperature of air; and air flow rate. In the experiments, these factors were varied with one another. For the solidification process, an increase in the air flow rate decreased the time of the solidification process. An increase of both air temperature and encapsulate thickness increased the duration of the solidification process. However, the effects of varying the air temperature were more profound than those of varying the encapsulate thickness. For the melting process, an increase in the air flow rate reduced the melting time. In this process, an increase in the encapsulation thickness at lower temperatures had a more profound effect on the melting time whereas an increase in air temperature would have a larger effect with a higher thickness of the encapsulate. In further assessing the influence of air flow rates on the performance of a PCM, Mosaffa et al. [14] performed a numerical investigation of the optimization of free cooling system by using multiple PCMs integrated in a thermal energy storage unit. They varied the air flow rate of air entering the storage unit – the temperature of the incoming air was kept constant at 29 °C. They found that an increase in air flow rate resulted in higher outlet temperatures for both the melting and solidification processes. This was primarily due to the short residence times of the air in contact with the storage unit. This meant that the effectiveness of the PCM storage unit was reduced at higher air flow rates.

Turnpenny et al. [15] in 1999 designed and tested a latent heat storage unit incorporating heat pipes embedded in a phase change material. The intent of the design was to reduce air conditioning usage in buildings and to verify the PCM's potential for passive cooling. The hypothesis was that during the day, heat would be transferred from the room air to the PCM hence inducing melting of the PCM which would in turn reduce the temperature in the room. At night, the cool outside air would be passed through the heat pipes to reverse the heat transfer process which occurred during the day – this would solidify the PCM back to its original state. The results of the experiment showed that the PCMs were able to cold store and release heat between the air and the PCM storage unit.

In any free cooling system, efficient heat transfer between the PCM and the air is important to ensure adequate solidification and melting for the storage and release of thermal energy. The common challenge amongst most PCMs is that they have relatively low thermal conductivities – a characteristic such as this is not ideal for a free cooling system due to the low surface heat transfer with air. Such challenges can potentially affect the performance of the free cooling system resulting in insufficient charging and discharging [16]. Various researchers [14], [17]–[19] have suggested methods to overcome the low thermal conductivity problem. This involved enhancing the heat transfer mechanism by including finned tubes, inserting metal matrices in the PCM, using PCM embedded with high conductivity particles (such as porous silica or activated carbon), and using multiple PCMs of varying melting points [1], [17]. Other heat transfer enhancement methods have considered the material of encapsulation – such as using aluminum panels to contain the PCM. The various encapsulation methods are shown in Figure 6.

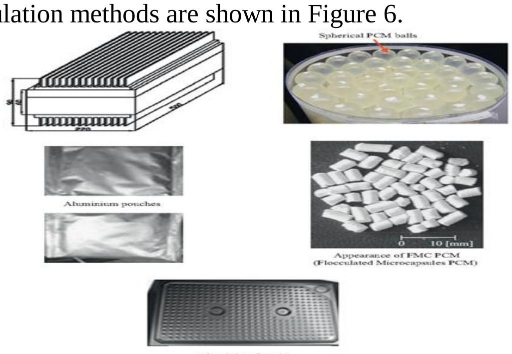

Figure 6: PCM encapsulation methods [2]

EXPERIMENTAL DESIGN

Selection of a suitable PCM for a free cooling system is critical to ensure that the system functions effectively. The selection of the PCM considered the climatic conditions in Johannesburg, South Africa, where the experiment was carried out. Other considerations in the selection of the PCM were: phase change temperature; heat storage capacity; and density. The daily average temperatures for Johannesburg during the summer months were obtained using weather data from www.accuweather.com [20]. The average daily temperatures are shown in Figure 7. From these temperatures, it was established that a PCM with a phase change temperature ranging between 25 – 26 °C would be suitable.

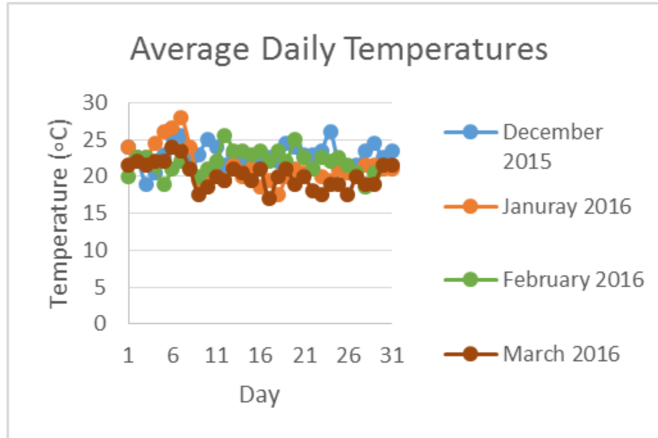

Figure 7: Average daily temperatures in Johannesburg [20]

The selected latent heat storage system selected was a paraffin based PCM, namely Rubitherm ® RT25HC. This PCM consists of granules embedded in an aluminum casing resembling a rectangular plate – the aluminum casing promotes heat transfer between the PCM material and the heat transfer fluid (i.e. air). The technical specifications of this PCM are shown in Table 1.

Table 1: Technical specification of Rubitherm RT25HC PCM

Property	Unit	Value
Melting Point	°C	22 - 26
Congealing Point	°C	22 - 26
Heat Storage Capacity	kJ/kg	230
Heat Conductivity	W/m.K	0.2
Density	kg/m³	880 (solid) – 770 (liquid)
Max. Operating Temperature	°C	65

Figure 8 shows the PCM plate used in the experiment. The dimensions are in mm.

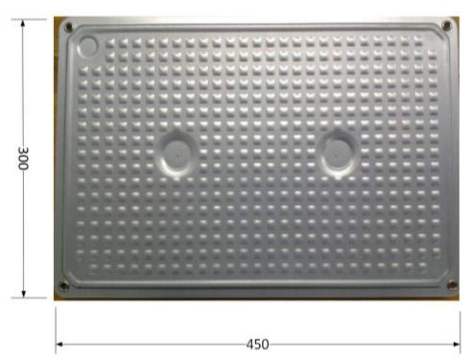

Figure 8: Rubitherm ® RT25HC PCM plate

An experimental test rig was designed to investigate the performance of the PCM plates for free cooling applications. The design of the test rig adopted the multiple PCM approach in the design of the storage box – a total of 3 PCM plates were used. The test rig consisted of three (4) major components, namely: inlet duct; storage box; outlet duct; variable speed fan.

The inlet duct consisted of a circular duct section constructed from 0.5 mm thick galvanized sheet metal of 102 mm diameter and 500 mm long. A square to round transition was also designed to form the completed piece of the inlet duct – the transition duct was required to evenly distribute the air flow into the storage box. The design of the outlet duct was an exact replication of the inlet duct. Both ducts were lagged with foil backed rockwool insulation to minimize the thermal losses/gains.

A 340 x 123 x 550 mm storage box was designed and constructed using 4 sheets of Plexiglas. The inner sides of the storage box were machined to form three (3) slots which would hold the PCM plates. The assembled 3-D model of the experimental test rig is shown in Figure 9.

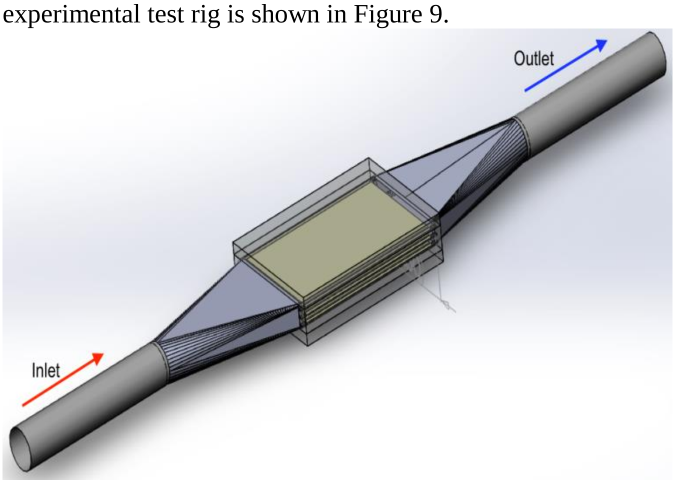

Figure 9: 3-D model of experimental test rig

EXPERIMENTAL SETUP

An overall schematic of the experimental setup is shown in Figure 10. The dimensions of the components are in mm. The setup consisted of: test rig; 3 PCM plates; seventeen (17) K-type thermocouples; National Instruments NI cDAQ-9178 data logger; laptop computer; variable speed fan; and a pitot tube flowmeter.

A 6-speed variable speed fan was used to draw in air into the test rig. Testing was done at each fan speed setting of which the air speeds were measured by the Pitot tube flowmeter to an accuracy of ± 0.1 m/s. The temperature drop in the test rig effected by the PCM storage box was measured using K-type thermocouples to an accuracy of ±1°C. The thermocouples were connected to a National Instruments NI cDAQ-9178 data logger, programmed from a laptop computer.

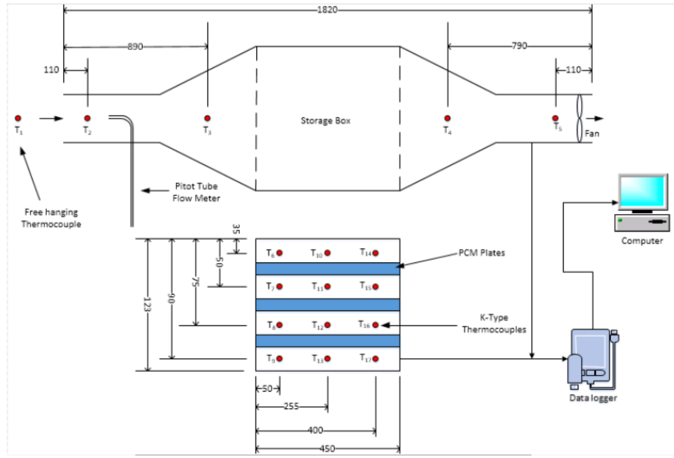

Figure 10: Experimental setup

The assembled test rig is shown in Figure 11.

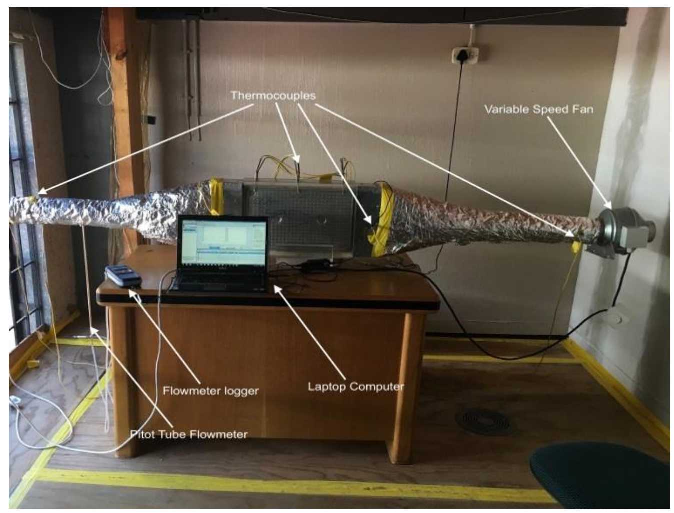

Figure 11: Assembly of test rig

To test the thermal performance of the PCM plates, the inlet and outlet temperatures in the test rig were closely monitored. These temperatures were also observed to establish the charging and discharging effectiveness of the PCM plates. The influence of varying the air flow rate (air speeds) was also monitored to evaluate the impact on the charging and discharging characteristics of the PCM plates.

RESULTS AND DISCUSSION

Ambient air cooling was assessed by determining the outlet air temperatures and compared them against the thermal comfort requirements determined for the Adaptive Thermal Comfort principle. The climatic temperature variations experienced in December 2015 were used to calculate the thermal comfort temperature range as they were indicative of the worst case. During that month, the monthly average minimum and maximum temperatures were 16.29 °C and 29.45 °C respectively. The monthly mean outdoor temperature was calculated from:

$$T_o = \frac{T_{min} + T_{max}}{2} = \frac{16.29 + 29.45}{2} = 22.87 \text{ °C}$$

Therefore, by using (2), the thermal comfort temperature is calculated as:

$$T_c = 13.5 + 0.54T_o = 13.5 + 0.54(22.87) = 25.85 \text{ °C}$$

The thermal comfort zone (which ranges 2 – 3 °C on either side of the thermal comfort temperature) ranges between 23.85 and 27.85 °C.

The effectiveness of ambient air cooling showed that the outlet air temperatures exiting the test rig fell within the defined range of thermal comfort – this result was true for all the flow rates which were tested. Typically, the average hours required for cooling was 5 hours. This was between 10:00 hrs when the ambient air temperatures were above the thermal comfort temperatures till about 15:00 hrs. The effectiveness of ambient air cooling at the various mass flow rates is shown in Figures 12 – 17. At higher mass flow rates, heat transfer can occur much faster due to higher Reynolds numbers and consequently higher Nusselt numbers therefore a higher convective heat transfer coefficient. This however, only suggests that the rate at which heat transfer between the PCM and the air will be faster than at lower mass flow rates. It does not suggest lower outlet air temperatures will be obtained. This is evident from Figure 12, 15 and 17. The inlet ambient conditions (initial) presented by those figures are somewhat comparable ranging between 36-38 °C. The outlet air temperatures showed that lower outlet air temperatures were achievable at lower mass flow rates. This means that the residence time of the air with the PCM plates has a significant impact on the degree to which ambient air can be cooled.

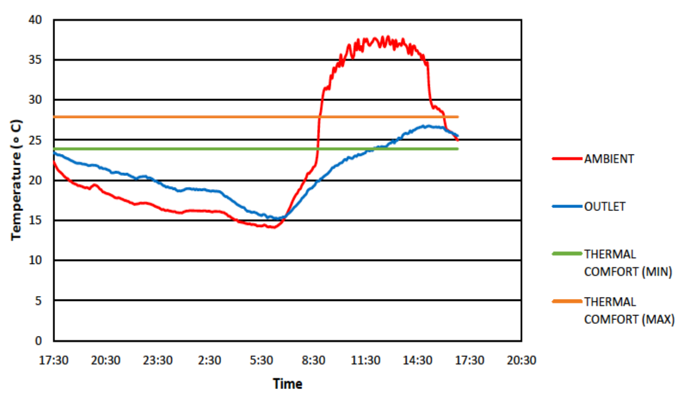

Figure 12: Temperature vs. Time measurements at 0.0077kg/s

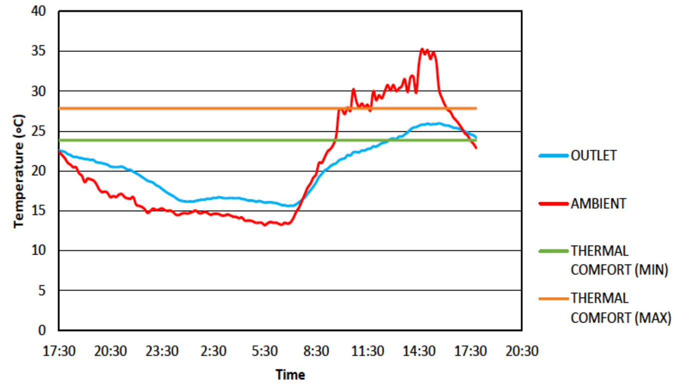

Figure 13: Temperature vs. Time measurements at 0.0154kg/s

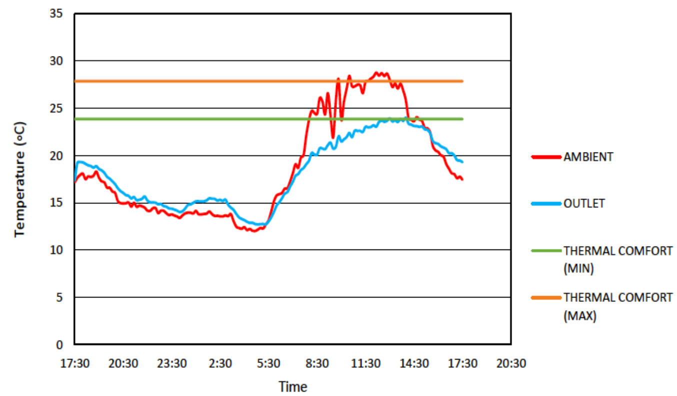

Figure 14: Temperature vs. Time measurements at 0.027kg/s

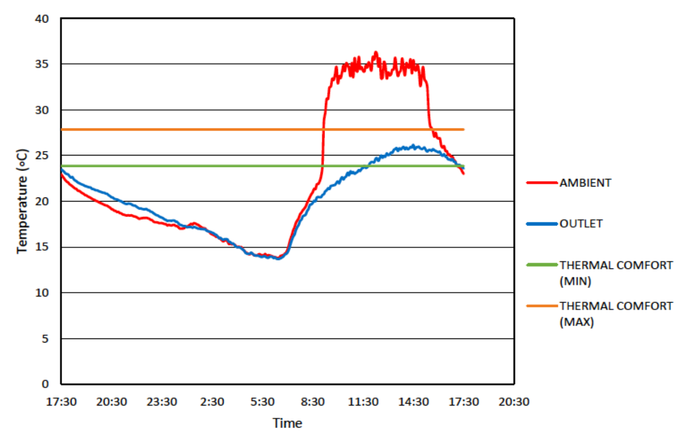

Figure 15: Temperature vs. Time measurements at 0.0308kg/s

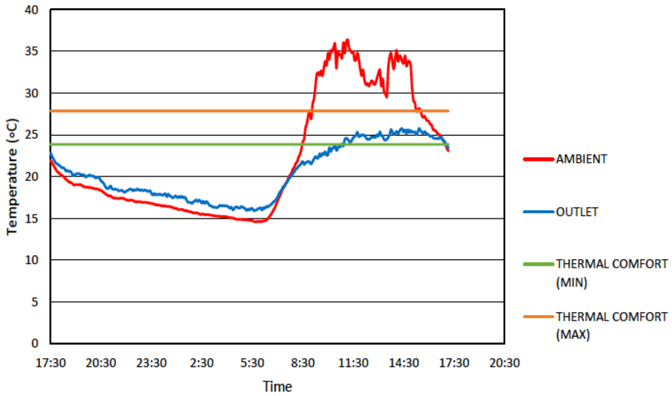

Figure 16: Temperature vs. Time measurements at 0.0385kg/s

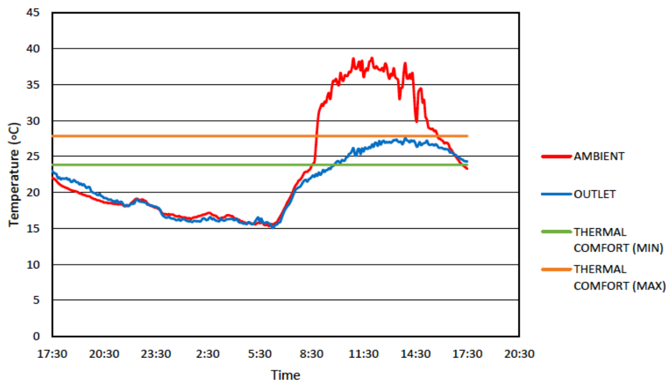

Figure 17: Temperature vs. Time measurements at 0.0424kg/s

The effect of varying air flow rates on the outlet temperatures is shown in Figure 18. The outlet temperatures shown are those from Figure 12, 15 and 17 as the ambient conditions were similar. It is almost noticeable that the lower mass flow rates result in lower outlet air temperatures. The effect of varying the mass flow rates is however partially conclusive, largely due to the fact that the testing conditions varied from one another when the experimental work was carried out.

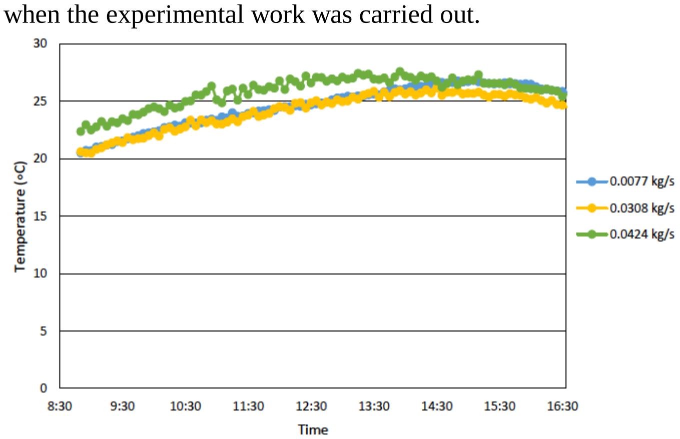

Figure 18: Effect of air flow rate on the outlet air temperature

The heat transfer during the discharging process for the various mass flow rates is shown in Figure 19. This graph presents the total heat/energy extracted from the PCM during the day.

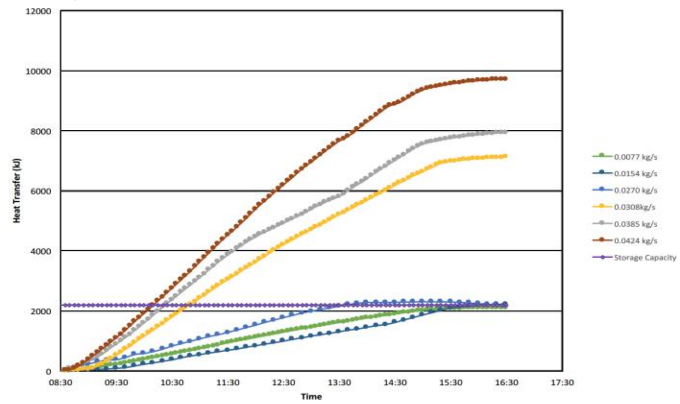

Figure 19: Cumulative heat transfer during discharging experiments

The storage capacity was calculated using the data shown in Table 1 as well as the physical dimensions of the PCM plate to approximate the volume occupied by the PCM within the plate. This storage capacity was calculated to be approximately 2193kJ. This represents the latent heat available for cooling the warm ambient air to within the thermal comfort temperatures. For the first three (3) mass flow rates (i.e. 0.0077, 0.0154 and 0.0270 kg/s), it can be seen that complete discharging of the PCM plates is achieved within the hours when cooling is required. This is between 10:00 - 15:00 hrs. The energy extracted from the PCM gradually rises during the course of the day up to a point when complete discharging is achieved at about 15:30 hrs. For the remaining mass flow rates (i.e. 0.0308, 0.0385 and 0.0424kg/s), discharging of the PCM plates is accelerated in such a manner that the PCM plate is completely discharged within the first 2 hours when discharging commences (from 8:30 - 10:30 hrs). Such accelerated discharging can be attributed to high ambient temperatures experienced in the morning as can be seen from Figure 15-17. Furthermore, it is suspected that poor charging from the previous cycle may have resulted in less latent heat energy available for the latter discharging experiment at the higher mass flow rates. The influence of the mass flow rates on the discharging process is not easily determined from Figure 19 due to the varying ambient conditions (temperature) experienced at those mass flow rates. What is apparent is that the ambient conditions play a major role in the performance of a free cooling system, hence the importance of selecting the appropriate PCM for the working environment.

During the charging experiments, it was evident that the temperature of the PCM plates is within the phase change temperature range from 17:30 to show that the solidification had started. This is seen in Figures 20-25. This temperature was approximately 24°C. The temperature of the PCM plates reduces to less than the phase change temperature within the first 120 minutes (19:30) quite aggressively as shown in the figures. Below the phase change temperature range, the decrease in temperature of the PCMs happens quite gradually until a stable temperature of 15°C is reached. This gradual decrease in temperature until stabilization shows that the majority of the latent heat stored by the PCM lies in the phase change temperature range (22-26°C). At this point of stabilization, the temperature difference between the ambient air and the outlet side of the PCM plates is very minimal hence showing that the instantaneous heat transfer between the ambient air and PCM plates becomes insignificant – this means that the difference between the ambient air and the outlet temperatures in the duct will be small. This is an indication that complete solidification of the PCM plates would have been achieved by this time. The only heat transfer that takes place at this point is sensible heat.

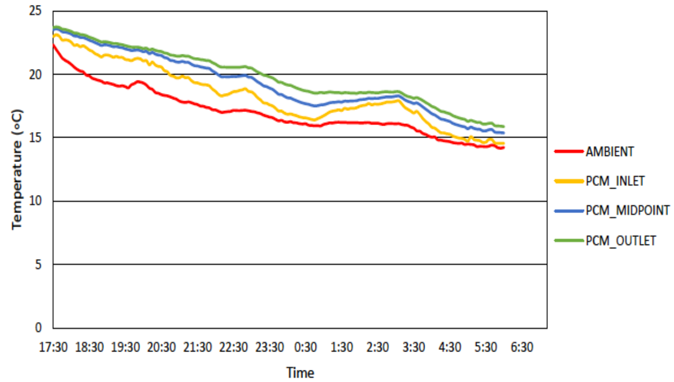

Figure 20: Charging process at 0.0077kg/s

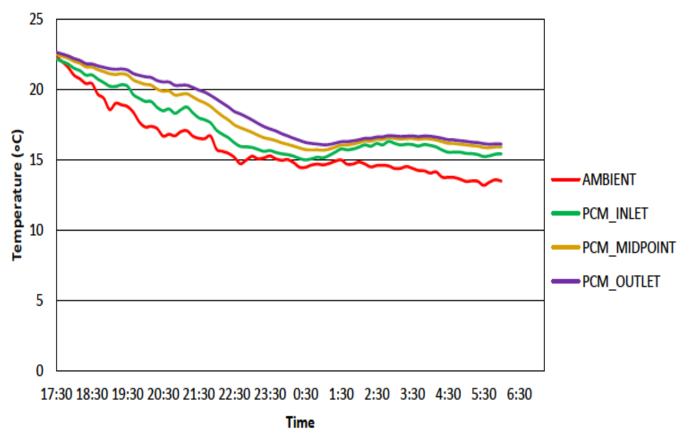

Figure 21: Charging process at 0.0154kg/s

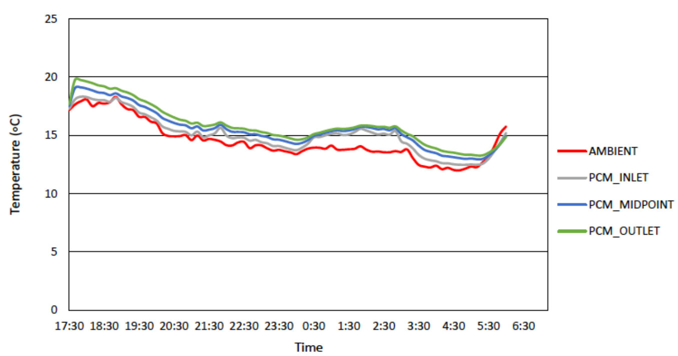

Figure 22: Charging process at 0.027kg/s

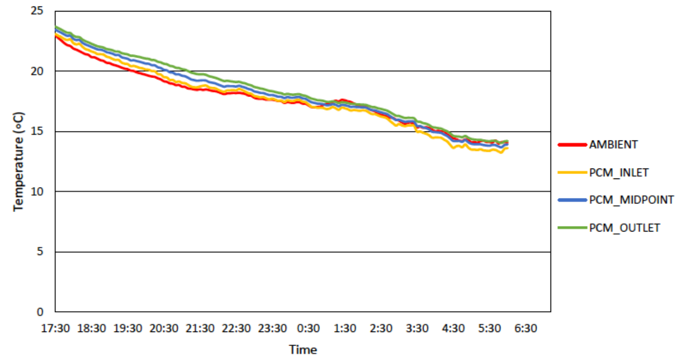

Figure 23: Charging process at 0.0308kg/s

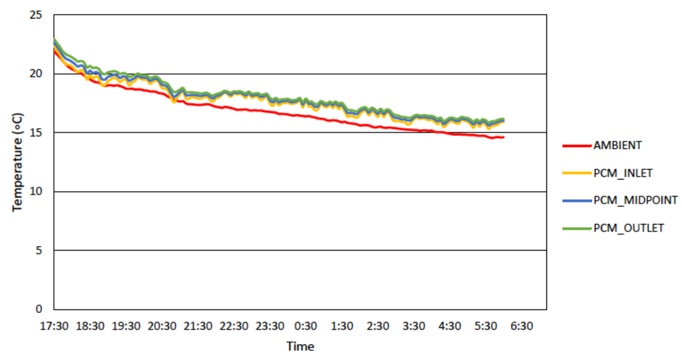

Figure 24: Charging process at 0.0385kg/s

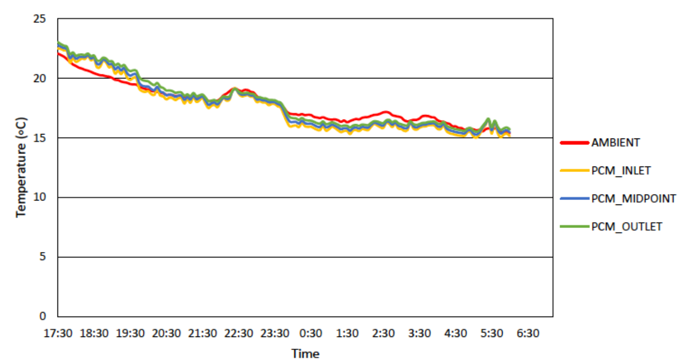

Figure 25: Charging process at 0.042kg/s

The effect of air flow rates on the solidification of phase change materials has been known to have shortened the solidification time at high air flow rates. This means that higher air flow rates would be required to achieve complete charging of a PCM in the shortest possible time to ensure that daytime cooling of ambient air can be achieved. In the current investigation, the effect of the air flow rates on the solidification rate of the PCM plates cannot be ascertained. This is largely due to the fact that the ambient temperatures during the testing at the various air flow rates varies greatly. It would be preferable for the ambient air temperature not to vary widely during the experimental tests so that the effect of air flow rates can be ascertained with confidence.

CONCLUSIONS

The storage box of the experimental test rig was able to cool down the warm ambient air temperature to temperatures within the thermal comfort range determined from the adaptive thermal comfort principle. The thermal comfort temperatures ranged between 23.8°C and 27.8°C. Lower outlet temperatures can be achieved by increasing the residence time of the air in contact with the PCM plates. This phenomenon was seen at mass flow rates of 0.0077, 0.0308 and 0.0424 kg/s whereby the ambient air conditions where comparable. The ambient air temperature however has a more profound impact on the heat that can be extracted from the PCM plates during the discharging period. The effect of the air flow rate on the discharging process would be more conclusive if the experimental work was done under a controlled environment which can simulate a constant ambient temperature for all the air flow rates.

During the solidification experiments, the initial temperature of the PCM plates reduces to less than the phase change temperature within the first 120 minutes (19:30) quite aggressively. This is followed by further ambient air temperature decrease until a stabilization temperature of 15°C is reached. This results in complete solidification of the plate as the latent heat in the PCM plates has been recovered. The remainder of the heat transfer that occurs at this stabilized temperature is only sensible heat.

The effect of air flow rates on the charging experiments (solidification) was not conclusive to justify that higher flow rates shorten the solidification time. This was largely due to the fact that the charging temperatures varied quite significantly during testing at the various air flow rates. It would be ideal to have similar test conditions, particularly those of charging ambient air temperatures to ascertain the effect of varying the air flow rate on the charging duration. The most influential parameter on the charging duration was found to be the ambient air temperature entering the storage box.

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ANNEX A

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