A preliminary experimental study of a novel incorporation of chilled ceiling with phase change materials and transparent membrane cover

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Abstract

This study presents an experimental investigation into a novel incorporation of chilled ceiling with transparent membrane cover and phase-change material (PCM) to form a new type of PCM chilled ceiling panel. The membrane cover is infrared transparent to facilitate radiant cooling, but serves as a barrier of convection to avoid moisture condensation for applications in humid climate regions. As reliable electricity supply is still not accessible to millions of people, especially in sub-Saharan and South Asian countries where these countries also face the combined problems of high cooling demand and inadequate power supply, the use of solar energy would help to overcome these problems. To address such problems, the proposed PCM chilled ceiling can be applied along with a solar photovoltaic (PV) directly driven vapour-compression cooling system. Electricity generated by the photovoltaic (PV) panels drives the variable speed direct current (DC) compressor for cooling production, while excessive cooling is stored in the PCM packs for use at night. The variable speed compressor can adjust to match fluctuation in solar radiation and hence increases the utilization of solar energy. A small-scale experimental setup was prepared using a mini DC compressor refrigeration system. Integration of salt hydrate type PCM in chilled beam and chilled ceiling, respectively, and application of transparent membrane cover in chilled ceiling were tested to verify the proposed design.

Keywords: variable speed DC compressor; PCM; moisture condensation; transparent membrane; convection; radiant cooling; chilled beam; chilled ceiling

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1 INTRODUCTION

Electricity is important for everyday needs such as space cooling. It is reported that in some cities, up to 50% of the supplied electricity during summer months is consumed by air conditioning applications [1]. However, electricity is still not accessible for ∼18% of the world's population [2]. A total of 590 million people did not have access to electricity in sub-Saharan Africa and 240 million in India in 2016. These countries are also facing high temperature and humidity in addition to the problem of access to clean, modern energy services and consequently do not have proper cooling systems either. Thus, use of solar energy for cooling would be an effective way, which comes with many advantages universally considering environmental issues [3]. Among the solar cooling systems, PV-driven systems have advantages in space effectiveness, cost and energy effectiveness [4, 5]. PV-powered refrigeration systems have been investigated considering performance on different factors, such as PV voltage, compressor type and controller methodologies. It is known that in order to connect with PV collectors, the system requires an inverter and battery as PVs generate DC current; however, these components both increase the initial costs and also cause additional energy losses during the operation [6, 7]. Therefore, variable speed DC compressor's efficiency and ability of operation even under low solar radiation make it ideal for application of rural areas. Su *et al.* [8] investigated a PV-powered variable speed DC refrigerator unit that is directly connected to PV cells. They compared fixed speed and variable speed modes and found that variable speed mode increases cooling capacity by 32.76% and PV utilization by 45.69%. Salilih *et al.* [9] modelled PV refrigeration unit with variable speed DC compressor. They found that low solar radiation results in low rotation speeds and it yield higher coefficient of performance value.

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The integration of PCMs as heat or cold storage in building envelope is a popular application as PCM usage can reduce the energy demand and helps to maintain thermal comfort. PCMs are applied to buildings' walls [10], ceilings and floors. As a latent heat storage material, paraffin is the most popular PCM used in buildings (up to 87.5% of the papers used paraffin) and PCM application effect on air temperature reduction was obtained up to 4.2°C [11]. In these applications, melting temperatures of PCMs vary from 19°C to 29°C [11]. Velasco-Carrasco *et al.* [12] experimentally investigated the use of PCM in ceiling tiles for enhancing the building thermal performance. They used hydrated salt PCM with 23°C melting temperature. Their findings indicated that PCMs increase the room temperature by ~5°C.

As seen from the literature, PCMs can heat or cool the buildings passively and regulates the air temperature according to selected PCM specifications and applications. Since the proposed study focuses on cooling the building, radiant cooling studies were reviewed—as they give better comfort [13] and are more efficient [14] compared to standard air conditioners. It has been known that radiant cooling system in buildings can reduce electrical energy consumption up to 40% compared to conventional air conditioning systems [15]. Khan *et al.* [16] conducted a modelling study and they found that the radiant system was 17.5% more efficient than a conventional air system. However, ceiling-mounted radiant cooling panel has condensation risks on its surface when used in humid and hot regions. Therefore, some condensation control strategies were proposed for avoiding condensation on surfaces because the temperature of the radiant cooling panel must be above the dew point of indoor air to avoid surface condensation. These methods include pre-dehumidification process and using different surface materials and other treatments [17].

In view of the benefit with PCM and the issue of potential condensation on chilled ceiling as reviewed above, this study puts forward the design of a PCM-integrated chilled ceiling panel with a transparent membrane cover, which serves as a barrier of convection to avoid moisture condensation. The first infrared transparent membrane for condensation-free cooling was used in 1963 to isolate the cooling source from the ambient air [18]. Teitelbaum *et al.* [19] experimentally investigated the use of infrared transparent membrane from polyethylene (PE), polypropylene and PE terephthalate. The findings show that there is no condensation when the room temperature was 32°C with 70% relative humidity and cooler surface was 5°C. Ke Du *et al.* [20] adapted a double-skin infrared transparent membrane on radiant cooling unit to obtain condensation free cooling. They found that cooling capacity can be improved by 48% compared to conventional radiant cooling.

Thus, the study proposes to use PCM radiant panel with a transparent membrane cover for cooling application. The chilled ceiling panel may be connected with a solar PV directly driven vapour-compression cooling system particularly suitable for stand-alone applications. In small-scale experiments, the cooling performance characteristics for different design parameters were measured and analysed to evaluate the proposed design.

2 THE OPERATION PRINCIPLE OF THE SYSTEM

In this study, PV-driven variable speed DC compressor refrigeration unit is adopted to actualize the cooling of a room and cold storage in the PCM ceiling by circulated heat transfer fluid (HTF). The system is divided into two main parts: one is the cooling unit for producing cooling during the solar time and the second one is the PCM-integrated chilled ceiling panel inside the room. Figure 1 shows the schematic view of the system.

PV panels generate DC current to run a variable speed compressor. The vapour compression unit operates like a conventional cooling/refrigerator unit that uses efficient and compact heat exchangers and compressor unit. The refrigerant is circulated around the cycle by the compressor. The low-pressure vapour leaving the evaporator enters the compressor and leaves the compressor as high-pressure, high-temperature superheated vapour. That vapour is condensed to liquid in the condenser. Finally, the high-pressure liquid refrigerant leaving the condenser goes into the expansion valve, which creates low-pressure, low-temperature refrigerant. The refrigerant is evaporated in the heat exchanger where it allows heat transfer from the HTF fluid to the refrigerant. Chilled HTF is circulated through the evaporator unit, and the liquid is then pumped through the PCM packs.

Chilled HTF is pumped to PCM packs, which are installed in the ceiling and cold liquid absorbs heat from the PCM packs with the help of coils. In the daytime, when there is sufficient sunlight, the solar PV driven variable speed compression cooling system works to generate cool energy and thanks to latent heat capacity of the PCM, the extra cooling can be stored in the PCM packs. When the cooling energy is required in the night, low-temperature PCMs supply radiant cooling to the room. PCM cooling storage materials have high thermal energy storage capacity, which allows for more energy to be stored in a limited space. The processes of heat storing and releasing take place at relatively constant temperatures without supercooling effect. Figure 2 shows the radiant panel used on the ceiling. Cold HTF circulates through the finned tube heat exchanger PCMs, which are placed on the heat exchanger charged during the day time. When PCMs are in phase-changing stage, the metal plate is exposed to heat loss to the PCM side and heat gain from the radiant cooling side. The front of the panel is covered with a membrane that is transparent to thermal radiation. In this way, cold surface is separated from the room air to obstruct condensation. The cooling capacity of the PCM radiant panel with a transparent membrane cover system consists of two parts, radiant flux and convective flux. Radiant heat transfer occurs between the surfaces of the cold metal plates with cooling surfaces in the room. As the membrane has an air contact surface on both sides thus, convective heat transfer occurs between the transparent membrane and room air and between the membrane and air trapped inside the PCM radiant panel. A desiccant bag is also placed between the metal plate and the transparent membrane to absorb humidity and prevent condensation inside the panel.

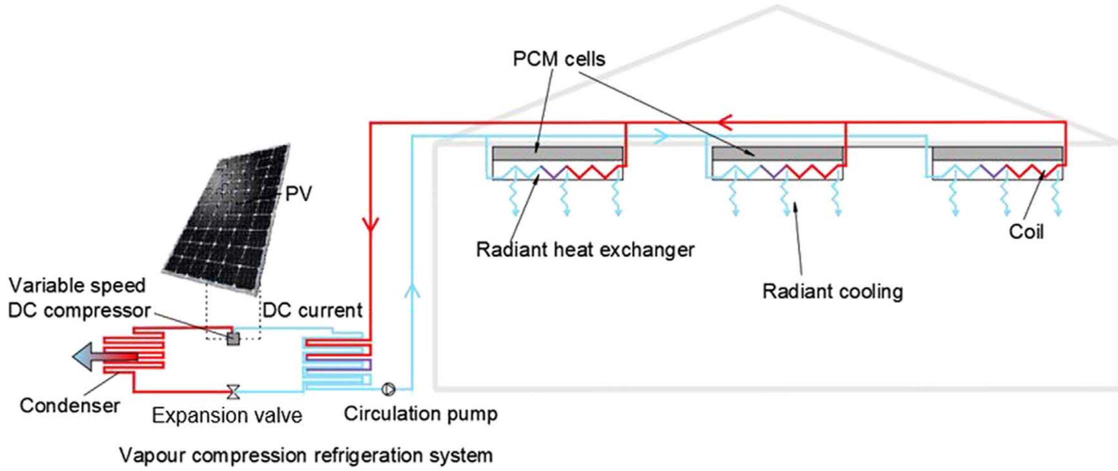

Figure 1. *Schematic of a solar PV driven vapour compression cooling system with PCM-integrated chilled ceiling panel.*

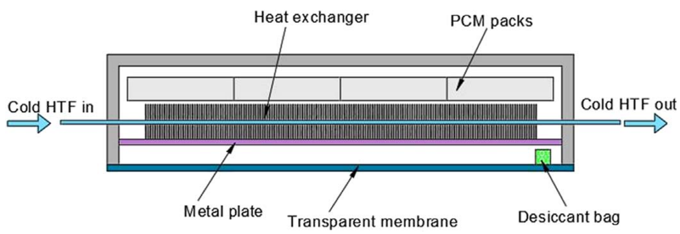

Figure 2. *PCM Radiant Panel with a transparent membrane cover.*

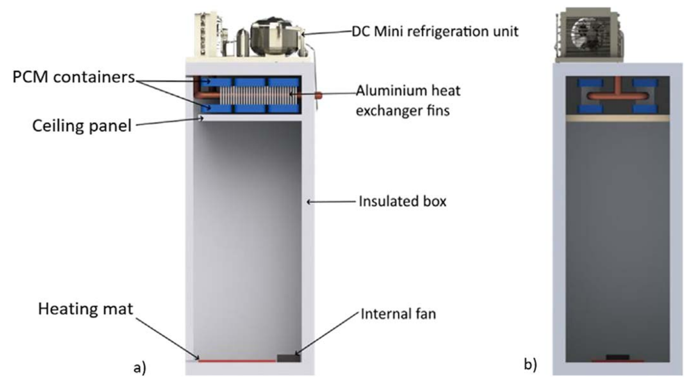

Figure 3. *Assembly and setup of the testing rig front view(a) and side view (b).*

3 EXPERIMENTAL APPARATUS AND PROCEDURE

As shown in Figure 3, the experiment unit mainly consists of a mini-DC compressor refrigeration unit, insulated box, aluminium finned tube heat exchanger, circulation pump for HTF, PCM containers, fan, and so forth. The experiment was conducted in a testing room at The University of Nottingham. The cabinet was constructed inside of which the air is cooled, and the temperature sensors would be placed during the experiments. The box was built with a 50-mm thick foam board insulation contained in a wooden structure to give it a support. This type of thermal insulation was selected to avoid heat losses as much as possible. The edges are sealed with silicone sealant to prevent air leakage. The outside of the cabinet was covered with a 3-mm MDF board.

A compact cooling system (model FSCH019Z12B), also known as mini refrigeration unit, was used to cool the inside of the cabinet. This device uses a miniature compressor refrigeration system using R134a and it delivers 100–300 W cooling capacity. The circuit control board has built-in temperature settings and adjusts the compressor speed to find the balance between the chiller and heat component. In the tests, chiller was used in its maximum cooling capacity to cool the cabinet and charge the PCMs. A summary of the product specifications is given in Table 1.

HTF was connected to an external pump that circulates it through a heat exchanger inside the box. A finned tube heat exchanger has been manufactured to benefit from a large fin surface area, which increases the heat transfer rate. The pump used for HTF circulation is a 12 V DC, 60 W water pump. The chilled HTF circulates through 1/2″ copper pipes inside the cabinet. A silicone heater mat (240 V, 533 W) was used in some experiments to simulate a heat load. It was controlled by a thermostat to keep it at the desired temperature. A 16-channel data logger brand Grant model was used to record the temperature readings using 7 K-type thermocouples. Thermocouples are placed to measure room temperature, panel temperature, heat exchanger temperature, cabinet centre temperature, top and bottom of the cabinet and PCM temperature when PCM is used. Thermocouples have an accuracy of 0.05% according to the manufacturer.

As the study aims to investigate PCM-integrated chilled beam unit and the PCM-integrated chilled ceiling panel, the test rig was prepared for both cases. Moreover, additional tests were carried out in order to compare the cases with and without PCM. For a normal chilled beam test, only a finned tube heat exchanger is placed on the top of the box and with and without

Table 1. *Datasheet of the mini chiller.*

Refrigerant	R134a	Condenser	Finned tube
Rated voltage	12 V	Fan voltage	12 V@3200 rpm
Voltage range	9–16 V	Noise	≤48Db(A)
Temperature range (evap)	−18°Cto 30°C	Vibration	≤0.65 m/s^2
Work current range	1-9A	Net weight	3 kg
Cooling capacity	100–300 W	Motor speed	2000–4500 rpm
Evaporator	Stainless steel plate	Driver board	Variable frequency controller

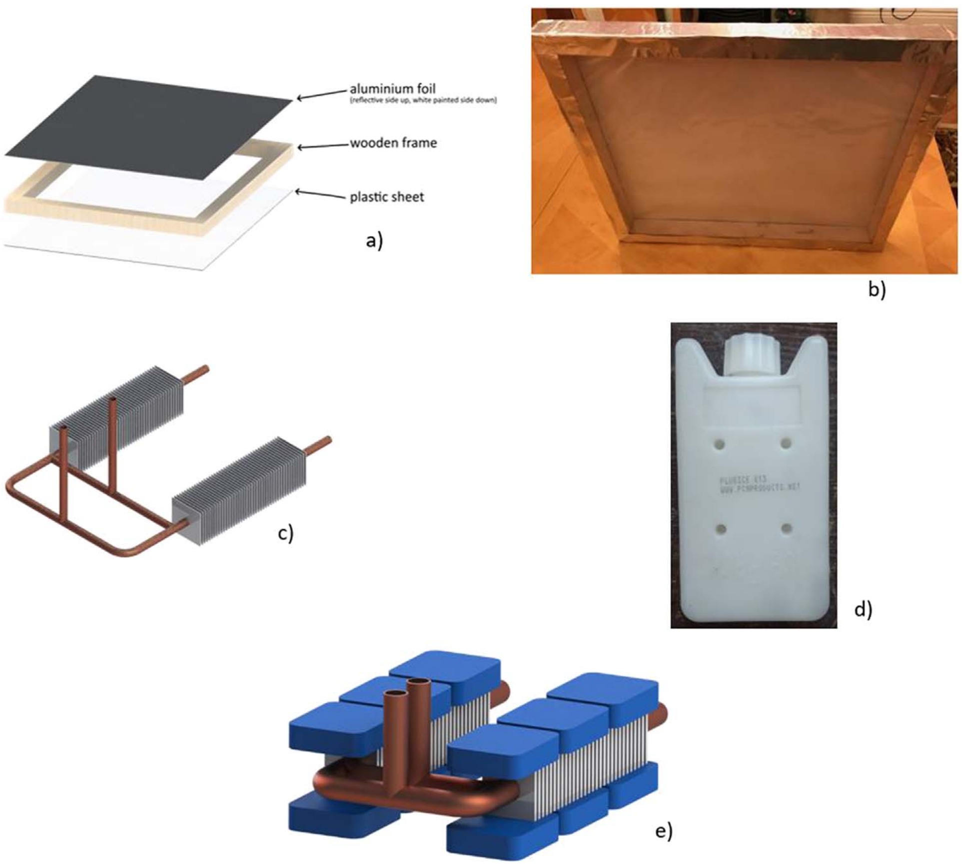

Figure 4. *Components of the cover for the chilled ceiling panel (a), picture of the assembled cover (b), finned tube heat exchanger (c) PCM pack (d) and PCM arrangement (e).*

PCM tests were carried out. In order to carry out radiant cooling tests, a special panel was installed inside the cabinet that separates the area where the heat exchanger is located from the rest of the cabinet. The purpose of this panel was to induce radiant cooling. The panel consists of a wooden frame that on one side has a thin aluminium sheet, with the reflective side bonded with heat-conductive glue to the heat exchanger fins and the other side, painted white, facing the inside of the cabinet. The other side of the panel is covered by an infrared transparent plastic sheet. All of the above is illustrated in Figure 4. The arrangement of the PCM containers (blue) inside the fridge is given in Figure 4e. The PCM pack dimensions are 120 × 100 × 30 mm. They were arranged three above and three below both heat exchangers. Twelve PCM containers were inserted in total.

The used PCM was PlusICE S13 Hydrated Salt produced by PCM Products Ltd with a melting temperature of 13°C, the thermal properties are given in Table 2. The capsule material is in a rectangular plastic container, which will be placed on the finned tube heat exchanger.

4 RESULTS AND DISCUSSIONS

The experiments were carried out at the University of Nottingham. Cooling performance was tested in two different setups.

Table 2. *Thermophysical properties of PlusICE S13* [21].

Specific heat	1.9 kJ/kgK	Latent heat capacity	150 kJ/kg
Density	1515 kg/m^3	Thermal conductivity	0.43 W/mK

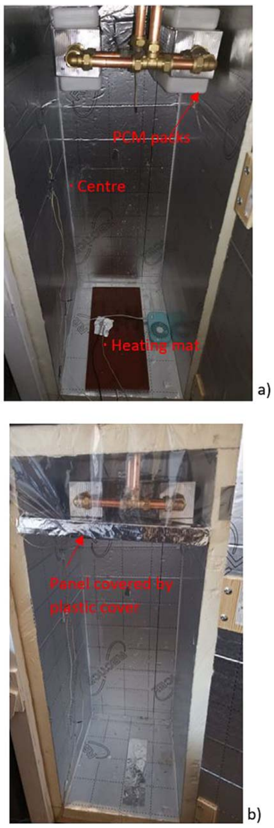

Figure 5. *Two test setups: (a) PCM-integrated chilled beam unit, (b) PCM-integrated chilled ceiling panel with a transparent membrane cover.*

One is for the test of the PCM-integrated chilled ceiling panel and the other one is for the PCM-integrated chilled ceiling panel with a transparent membrane cover to avoid condensation on the panel for high humidity regions. The tests were carried out in a temperature-controlled laboratory environment. The room temperature was set to 20°*C*. Figure 5 shows two prepared testing setups. A finned tube heat exchanger was assembled to the top of the box and connected to the refrigerator via circulating HTF. Heat gain was simulated with an electric resistance heating mat by this configuration, radiant cooling can occur directly with the heating mat and the wall surfaces.

4.1 Cooling of the cabinet by a PCM-integrated chilled beam unit

The first test was carried out to show the effect of the PCM integrated in the chilled beam unit. The heating mat temperature was set at 30°C and a fan is placed inside the cabinet to represent air

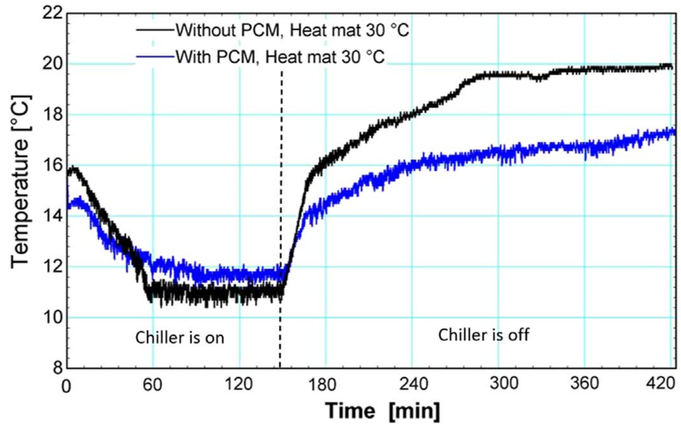

Figure 6. *The cabinet centre temperatures for the cases with and without PCM, respectively (heating mats and fans are always on).*

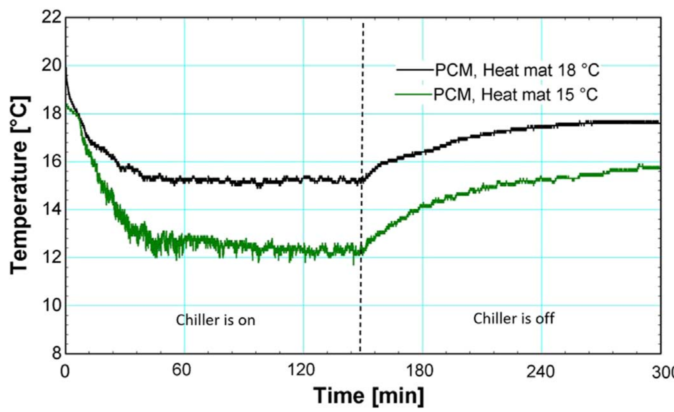

Figure 7. *Effect of heat mat on cabinet centre temperatures. (Heating mats are always on).*

movement in both cases. The test was started when the heater and refrigerator were turned on and maintained a steady temperature for 2.5 hours. The refrigerator was turned off and measurement continued for further 4.5 hours. During a total of 7 hours of testing, the heating mat temperature was controlled for operating at 30°C. Figure 6 shows measured temperatures at the centre of the cabinet for the cases with and without PCM, respectively. During the cooling period, centre temperature decreases in both cases. However, when the temperatures are stable at the end of the cooling period, without PCM test temperature is 0.5°C lower than with PCM case as the PCM also loses heat, cold storage and maintains slightly higher air temperature in the box. During the refrigerator turned off period, the temperature of the centre without PCM increases to 20°C from 11°C in 4.5 hours. However, the temperature of the test with PCM increases to 17.5°C because PCM cold storage absorbs the heat in the cabinet during refrigerator off period and prevents to increase its temperature.

After presenting the influence of PCM usage on the chilled beam unit, the following analyses are focused on a PCM-integrated chilled beam unit. Figure 7 shows the effect of different

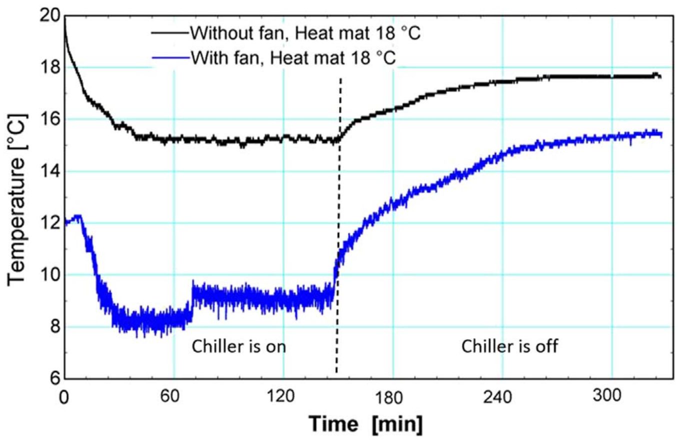

Figure 8. *Effect of air circulation fan on cabinet centre temperatures (heating mats are always on).*

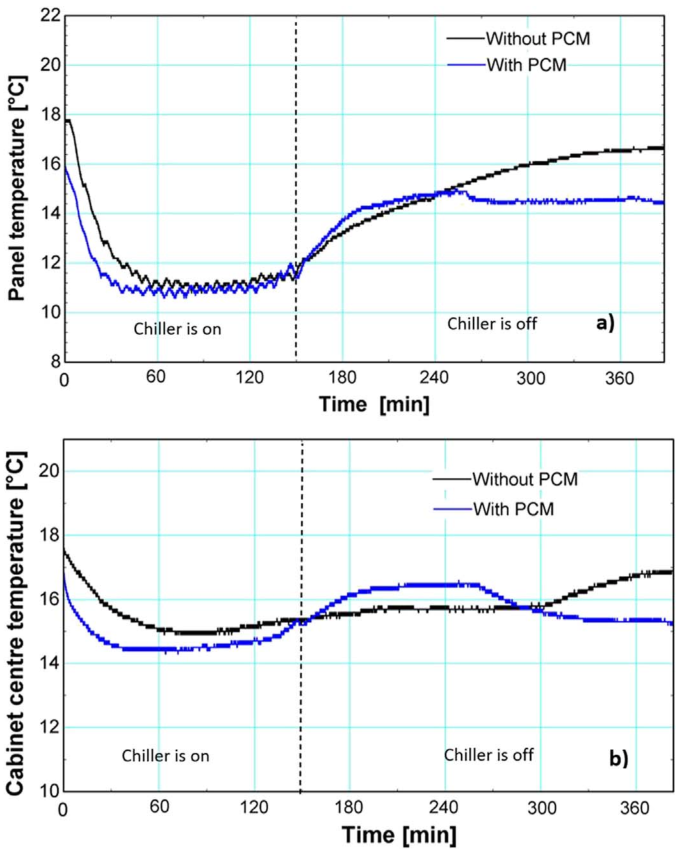

Figure 9. *The panel temperature (a) and the cabinet centre temperatures (b) for the cases with and without PCM.*

temperature settings of the heat mat on room temperature, which represents different thermal loads. Two temperature settings were used as 18°C and 15°C. During the cooling period, 15°C and 18°C setting tests resulted in stable temperatures in the centre of the cabinet of 12.2°C and 15.4°C, respectively. As expected, higher temperature heat mat generates a higher amount of heat to the cabinet; thus, without any forced air movement, the cooling load

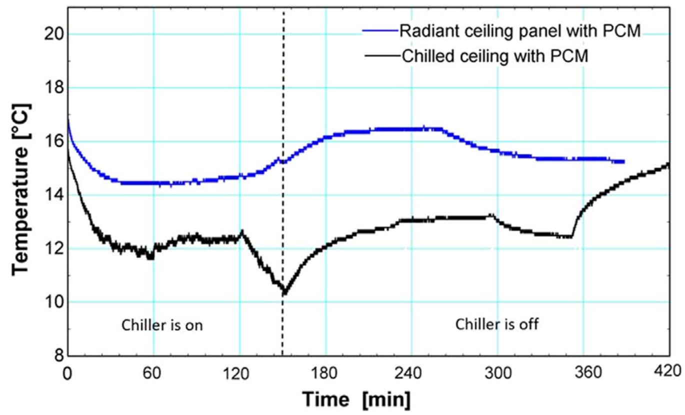

Figure 10. *The cabinet centre temperatures for the cases of the PCM-integrated chilled beam unit and the PCM-integrated chilled ceiling panel with a transparent membrane cover.*

cannot compensate for the heating and the cabinet temperature increases because air flow happens in natural convection.

In order to show the influence of forced convection on cooling performance of PCM ceiling, new test was set up. A mini portable fan with 5 W output is located inside the cabinet. Figure 8 shows results of with and without fan used tests. The figure indicates centre of the cabinet temperature variation when the heating mat is set for 18°C. Since the fan gives velocity to the air, the heat transfer coefficient is improved and heat transfer increases. Thus, the temperature of the fan used test decreases to 9°C but, the test without fan remains at 15°C, showing the effect of the higher heat transfer coefficient in the cabinet. Measured 6°C difference in cooling periods yields 2°C lower air temperature after 4.5 hours of without cooling.

4.2 Cooling of the cabinet by a PCM-integrated chilled ceiling panel with a transparent membrane cover

In order to test the radiant panel performance, two sets of tests were carried out. In the first test, the radiant panel was placed on the finned tube heat exchanger without PCMs. In the second test, PCM packs were added to the finned tube heat exchanger to increase cooling capacity after the refrigerator is turned off. The tests were started when the refrigerator was turned on and maintained a steady temperature for 2.5 hours. Then, the refrigerator was turned off and the temperatures are measured for further 4 hours.

Figure 9a shows the measured panel temperatures. After the refrigerator is turned off, the temperature of the panels increases as heat gain from the ambient. Among the tests, PCM used panel temperature is the lowest after 270 minutes. Although the temperatures of no-PCM test increase over time, the PCM-used test temperature remains stable because of the latent heat capacity of the PCM. At the end of the 6.5 hours of measurement, the PCM used panel temperature is 2°C lower than the without PCM cases. Figure 9b shows the temperature variation of the cabinet centre. Similar to the panel temperatures, the use of PCM results in a lower temperature in the cabinet when active cooling is existing. Measurements were recorded for 6.5 hours, the PCM used panel keeps the air temperature 2 °C lower compared to the panel without PCMs.

Figure 10 shows a comparison of the cabinet centre temperatures between two cases, the PCM-integrated chilled beam unit (chilled ceiling panel with PCM) and the PCM-integrated chilled ceiling panel with a transparent membrane cover (radiant ceiling panel with PCM). Both tests have the same number of PCM containers and there was no heating mat and the fan. When the chiller is on, the PCM-integrated chilled beam unit cools the cabinet to a lower temperature as convection in this case is stronger than the case for the PCM-integrated chilled ceiling panel. As the fins have direct contact with the air in the test of the PCM-integrated chilled beam unit, higher cooling load is delivered to the air side, thus, PCM packs are less charged and possess a lower cold storage compared with the PCM-integrated chilled ceiling panel. Therefore, air temperature increases sharply after 350 minutes in the case of the PCM-integrated chilled beam unit; while air temperature is remaining stable even after 390 minutes in the case for the PCM-integrated chilled ceiling panel.

5 CONCLUSIONS

This preliminary experimental study has demonstrated the cooling performance of PCM-integrated chilled ceiling panel with a transparent membrane cover for applications in humid climate. The proposed PCM-integrated chilled ceiling panel can be applied along with a PV directly driven variable speed DC compressor cooling system for stand-alone application in off-grid regions. An experimental comparison has also been made between the PCM-integrated chilled beam unit and the PCM-integrated chilled ceiling panel. In order to avoid condensation on the chilled ceiling in humid regions, an infrared transparent membrane cover was used between the conditioned space and the radiant cooling panel. A hydrated salt-based PCM with melting temperature at 13°C was used and promising results were obtained regarding cold storage. Some influence parameters have been tested in both cases. Some findings from this preliminary experimental study are summarized as follows:

- In both the chilled beam unit and the chilled ceiling panel, integration of PCM packs has maintained the cabinet temperature lower by 2– 2.5°C than the case without PCM up to 4.5 hours after the chiller is switched off.
- In the case of using the PCM-integrated chilled beam unit, a better cooling performance was obtained by using a fan to enhance air convection.
- The use of a transparent membrane cover in the chilled ceiling panel can restrict convection to avoid condensation, so a lower cooling capacity has been evident. However, this can be an improvement in the next stage of investigation by optimizing design configurations.

SUPPLEMENTARY DATA

Supplementary material is available at *International Journal of Low Carbon Technologies* online.

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