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Lessons learned from PCM embedded radiant chilled ceiling experiments in Melbourne

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Abstract

Buildings are responsible for over a third of energy consumption worldwide, particularly due to the increasing demand for air-conditioners in response to the more extreme heat around the globe. It is imperative to move towards more energy-efficient space cooling alternatives. The integration of phase change material (PCM) with radiant chilled ceilings (RCC) is a promising technology due to its benefits regarding energy efficiency and indoor environmental quality. This article presents a field study conducted on a newly-developed PCM embedded radiant chilled ceiling (PCM-RCC) installed in a stand-alone cabin located in Melbourne. The study evaluates the thermal and energy performance of the system through investigations of the transient thermal behaviour of PCM panels in charging-discharging cycles, the indoor comfort conditions, and the electricity peak demand. It was observed that the proposed PCM-RCC can provide satisfactory comfort conditions and contribute to load shifting if a refined operating strategy is applied. The efficiency of PCM recharge overnight depends on several factors that need to be carefully considered in design. The challenges related to the implementation of optimal operating dynamic schedules in response to the thermal behaviour of PCM-RCC, and accurate weather forecasting should be addressed to realise the full potential of this technology.

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Keywords: Chilled ceiling; Energy efficiency; Experiment; Phase change material (PCM); Radiant cooling; Thermal comfort

1. Introduction

2020 was recently ranked as the world's second-hottest year on record, closely behind 2016 [1]. The global climate continues to warm due to the extra heat-trapping greenhouse gas (GHG) emissions mainly caused by human activity and increased global energy consumption [2]. As the world keeps getting warmer, a range of changes on the human's routine life is come through. Focusing on the effects related to the indoor environments, the more extreme

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heat affects the occupants' comfort level and stimulates unprecedented demand for space cooling [3]. As the data indicate, buildings account for more than a third of final energy consumption worldwide, particularly due to the increasing demand for air-conditioners (ACs) [4]. 1.6 billion AC units are already installed worldwide and it could jump to around 5 billion units by 2050, becoming one of the main drivers of global energy demand [2,3]. To put this "cold crunch" on a sustainable path, more energy-efficient cooling technologies together with energy demand flexibility strategies need to be implemented in buildings.

In recent years, active radiant cooling systems (RCS) have received increasing recognition as a sustainable technology since they could save up to 30% of the energy use comparing to conventional cooling systems [5]. The other benefits of using such systems are related to the improved thermal comfort provision, quiet cooling, lower space requirement, and hygienic operation due to minimum air movement, resulting in no re-circulation of airborne pathogens, like COVID-19, in spaces [6].

A water-based RCS consists of pipes embedded in the main building structure or light-weight surface panels where chilled water is circulated to remove the indoor sensible heat mainly through radiant heat transfer [7]. As a downside, RCS is not applicable enough for load shifting control in peak demand management programs since it lacks high thermal mass for adequate thermal storage. The use of phase change material (PCM) as a thermal energy storage mechanism is proposed to overcome this deficit [8].

PCM absorbs and releases the thermal energy equal to its latent heat when the phase change occurs, thereby providing a considerable heat capacity over a narrow temperature range [9]. As a result of this high energy storage density, it is expected that the integration of PCM with active radiant cooling increases the thermal inertia of the building, shifts the peak load to off-peak period, enhances the thermal comfort by reducing the indoor temperature swings, and improves the cooling equipment efficiency mostly due to the night-time system operation at lower ambient temperature [10,11].

It is worth mentioning that amongst different building components and surfaces, ceiling panels are widely utilised in radiant cooling applications, called radiant chilled ceiling (RCC), due to their large and free-of-object surface area exposed to the indoor space, convenient architectural integration, and easy maintenance [12]. A number of research works have been carried out to comprehend PCM embedded radiant chilled ceiling (PCM-RCC) systems and compare their potentials over existing cooling technologies, see Koschenz and Lehmann [13]; Allerhand et al. [14]; Weindlader et al. [15]; Yasin et al. [16].

In this study, the operation and thermal-energy performance of a newly-developed PCM-RCC system were experimentally evaluated in a real-scale condition. The research aimed to figure out (1) the transient thermal behaviour of PCM panels and the heat transfer rates in both charge and discharge cycles, (2) the indoor comfort level provided by the system, and (3) the amount of energy consumed for PCM recharge overnight.

2. Methods

2.1. Experimental setup

2.1.1. Cabin characteristics

The experiments were performed on a stand-alone test cabin equipped with PCM-RCC, located in Melbourne, Australia (Fig. 1). This cabin has a conditioned volume of 96.73 m³ with a total floor area of 31.72 m². R4.8 and R4.3 sandwich panels were used as the cabin envelopes. The closed cavity façade with an area of 21.71 m² as well as with interstitial Venetian blind and total system (glass + frame) U-value of 2 W/(m²K) was also utilised. In addition, the floor and top-side of the ceiling were insulated using 60-mm-thick mineral wool.

2.1.2. PCM panel

A shape-stabilised organic PCM composite board with the phase change range of 15–20 °C and latent heat capacity of 900 kJ/m², laminated to a 1.5 mm thick aluminium tray, was used for experiments. 24 PCM panels in eight parallel rows are installed in the ceiling. As indicated in Fig. 1 (right), the chilled water flows within the blue capillary tubes incorporated in the panels to recharge PCM overnight. An 8-mm-thick insulation layer covers the PCM and capillary tubes. The panel surface is also painted using high-emissivity coatings to improve the ceiling emissivity rate.



Fig. 1. The test cabin at the University of Melbourne (left), and PCM ceiling panels with capillary tubes (right).

2.1.3. Chilled water supply and distribution unit

An air-source heat pump (ASHP) was employed as a chilled water supply unit. A dedicated outdoor air system (DOAS) was also utilised to provide the required fresh air and supplementary cooling when needed. Fig. 2 schematically shows the hydronic system and PCM panels arrangement in the cabin. Each row, including three PCM panels in series, was separately linked to the water supply and return lines. Using the ceiling pump (pump 1), the chilled water circulates through the panels to absorb the heat from PCM, and then backs to the storage tank to be re-cooled and re-circulated. The operation of the ASHP, ceiling pump, and DOAS system (including fan and pump 2) was remotely controlled via an EasyIO FW28 programmable controller.

2.2. Field measurements and monitoring

The cabin was equipped with multiple sensors to measure various parameters required for PCM-RCC performance evaluation. These parameters were classified into five categories as listed in Table 1.

Except for flow meters, power meters, and ERS CO₂ sensors which use the LoRa technology for communication and data transfer, the other sensors were connected to a data logger unit with a sampling frequency of 5 s. All measured data were averaged every 5 min to reduce the random errors and sent to the cloud server. The data were then imported to the developed PowerBI app for visualisation and monitoring purposes.

2.3. Experimental schedule

In PCM-RCC, as mentioned earlier, PCM absorbs the indoor sensible heat during the daytime (discharge cycle) and starts melting. Overnight, the chilled water circulating through the panels rejects the PCM heat and force it to solidify (charge cycle). Fig. 3 indicates the planned cabin operating schedule for the current experiments. A setpoint of 9 °C was considered for the supply water temperature. The ceiling controller limited the panel minimum temperature to 14 °C to avoid chilling below the dewpoint, and thereby, preventing the condensation. DOAS was operated intermittently to achieve an average of 40 L/s for the airflow rate and to provide a supply air temperature around 15–17 °C. To simplify the variables, no heat gains corresponding to occupants, equipment, and lights were considered in this study. The data presented here belong to the first phase of the experiments conducted in a 3-month period from February to April 2021.

3. Results and discussion

3.1. PCM-RCC performance in charge–discharge cycle

Fig. 4 shows the measured data for PCM panel temperatures and heat flux in three consecutive hot days. Fig. 5 also indicates the measured water flow rate and the cooling energy delivered to the ceiling panels and DOAS unit. After a 6-hour night-time recharge cycle with an average of 475 L/h of water flow rate on the first day, the ceiling received 5.9 kWh of cooling energy in total and the panel surface temperature reached about 15 °C. The positive values of heat flux during the daytime confirms that the ceiling panels gradually absorbed the indoor heat while

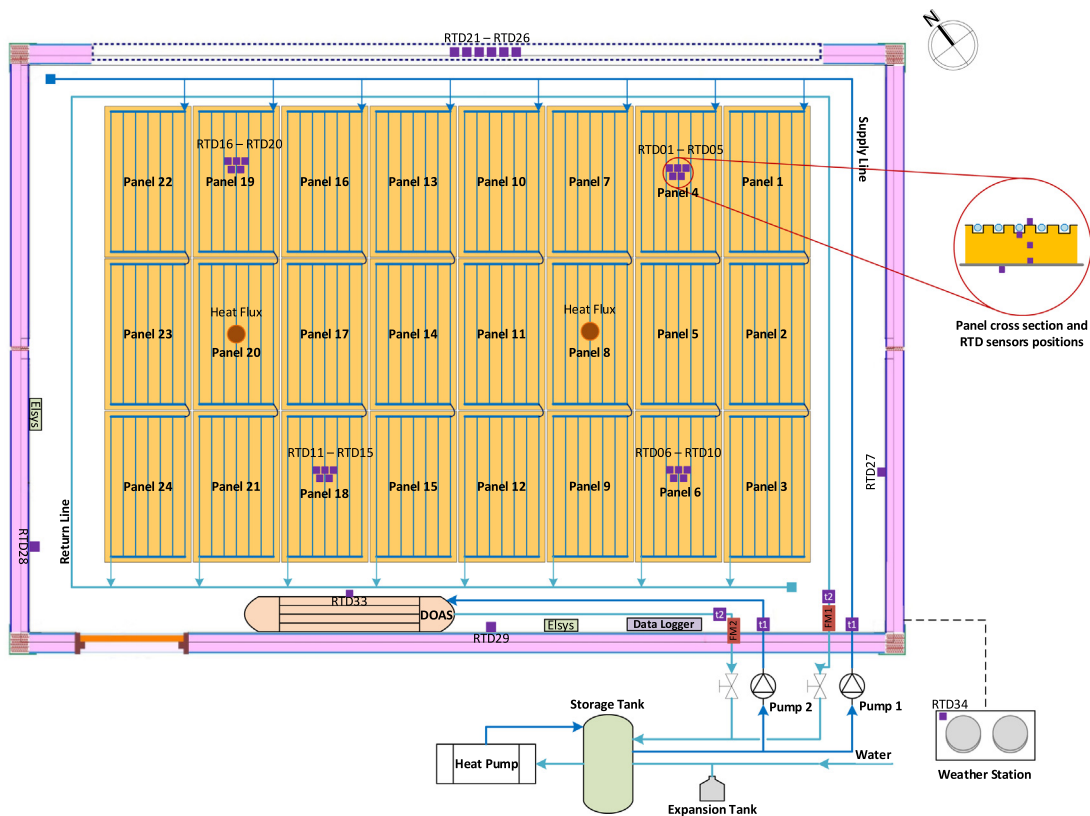


Fig. 2. PCM-RCC layout used in the test cabin (FM: flow meter, t1 and t2: supply and return flow temperatures).

Table 1. Different categories of parameters and sensors considered for the experiments.

Category	Measured parameter	Allocated sensors
PCM ceiling panels	- Temperature in different depths of PCM panels (see Fig. 2) - Heat transfer rate of PCM panels in charge–discharge cycles	20 RTD pt100 Class A for panels 4, 6, 18 and 19 (five for each) - Two heat flux sensors for panels 8 and 20
Indoor environment	- Air temperature in various heights (0.1, 1.1 and 1.7 m, based on ISO 7730) - Room operative temperature - Façade and wall surface temperatures - Relative humidity - CO₂ - Light - Occupancy	- Three RTD pt100 Class A for various heights - One black globe temperature sensor - Six RTD pt100 class A for façade and wall surfaces - Two ERS CO₂ sensors
Hydronic system	- Chilled water flow rate for ceiling and DOAS - Supply and return water temperatures for ceiling and DOAS	- Two flow meters - Four water temperature sensors (see Fig. 2)
Power usage	- Power - Voltage - Current	Four power meters for ceiling pump, DOAS (pump + fan), and the whole cabin (including ASHP)
Weather station	- Global and reflected solar radiation - Upward and downward longwave irradiance - Outdoor air temperature	- One 4-component net radiometer - One RTD pt100 Class A

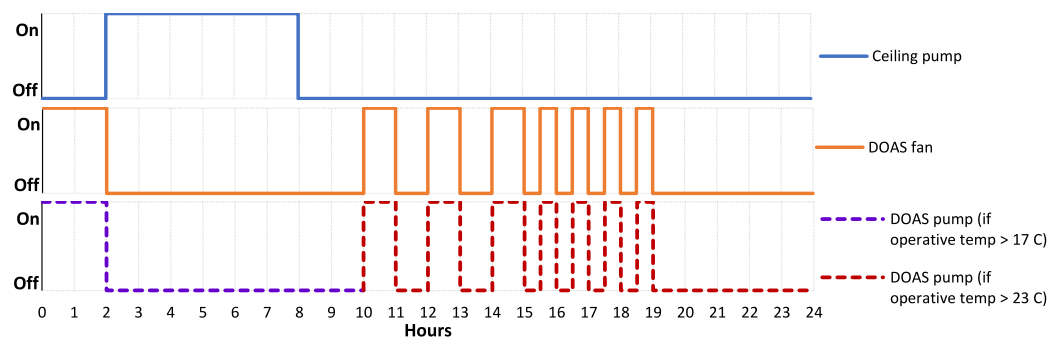


Fig. 3. Planned cabin operating schedule for the experiments.

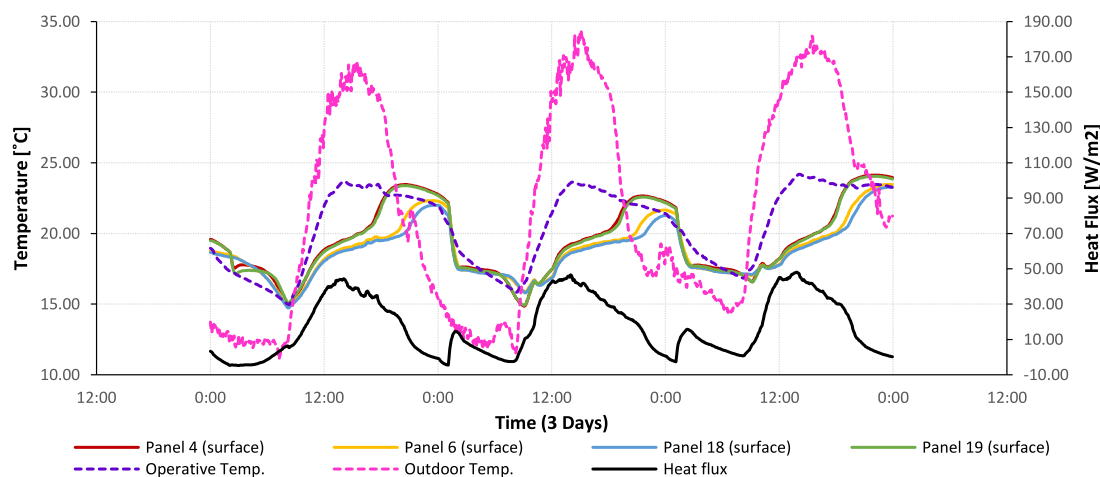


Fig. 4. Measured temperatures and heat flux in three consecutive hot days.

PCM phase was changing. Closely before 17:00, the melting phase of PCM in panels 4 and 19 which are adjacent to the façade (see Fig. 2) was almost ended as a sharp increase was recorded in panel temperatures. For panels 6 and 18 along the south wall, PCM remained active until around 20:00. The heat transfer rate was afterwards decreased with a steeper slope.

At the end of the first day, the ceiling and cabin operative temperatures were measured as nearly 23 °C and 22 °C, respectively. Due to this accumulated heat, it was predicted that with the same night-time schedule, the fully-recharged panels cannot be achieved the next morning. Hence, a longer recharge cycle (1:00–9:00) with the same water flow rate was set for the second and third days. The DOAS system was still in operation prior to starting the ceiling pump, as planned in Fig. 3, to minimise the cabin overheating and reduce the dewpoint and condensation risk. Besides, an operating strategy for peak design conditions, herein called “Day-Hold”, was also defined for very hot days. It provides supplementary cooling via the ceiling before the peak period and makes a residual cooling capacity for PCM panels late afternoon. According to the “Day-Hold” concept, the ceiling pump was activated from 10:00 to 12:00. As shown in Fig. 4, despite extending the recharge period overnight, it was not sufficiently managed to obtain the fully-recharged panels for the upcoming day. The first two hours of the recharge period just dealt with removing sensible heat before the phase change was commenced. However, the “Day-Hold” concept was confirmed as a beneficial strategy to preserve more ceiling cooling capacity for the peak demand period.

It was found that the efficiency of the recharge cycle in the current PCM panel design is not as adequate as expected. This is primarily due to the lack of heat transfer contact between the capillary tubes and the PCM composite material. A more dimensionally stable material for the water tubes would provide better integration within the PCM layer and thereby, an increased heat transfer rate between fluid and PCM panel. The obtained results also highlight that the dynamic implementation of optimal predictive operating schedules in response to the

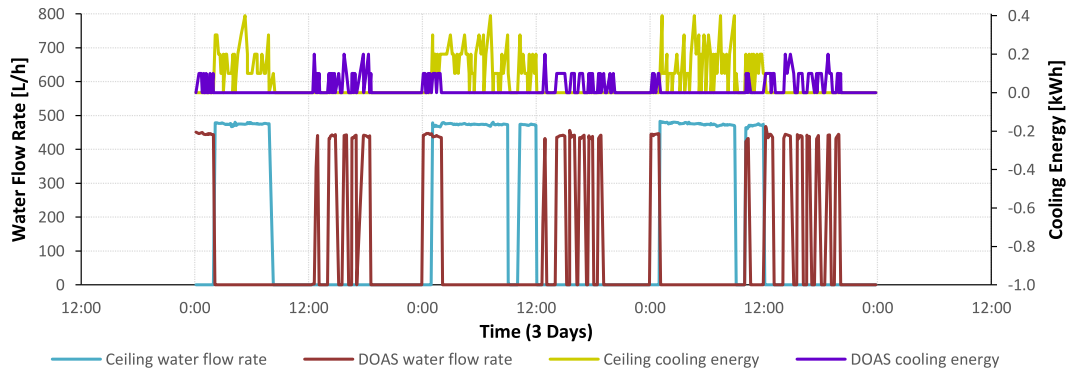


Fig. 5. Measured water flow rate and cooling energy provided by the ceiling and DOAS system.

transient thermal behaviour of PCM panels as well as accurate weather forecasting should be carefully addressed to realise the full capacity of PCM panels in the system.

3.2. Indoor thermal comfort

ISO 7730:2005 specifies three classes for indoor thermal comfort: Class A (24.5 ± 1 °C), Class B (24.5 ± 1.5 °C), and Class C (24.5 ± 2.5 °C) [17]. According to this standard and also assuming the occupancy hours of 9:00–17:00, it was observed that the installed PCM-RCC system can maintain the indoor comfort level mostly within Class C due to overcooling in the mornings following the recharge process and also because of the test cabin limitations which did not have provision for heating. The comfort details for each day are presented in Table 2.

Table 2. Indoor comfort level during the occupancy time for each day based on standard ISO 7730.

↓ Class, Day →	Share of occupancy time [%]		
	1st day	2nd day	3rd day
Class A	10.5%	12.5%	49.0%
Class B	49.0%	47.9%	58.4%
Class C	62.5%	58.3%	69.8%
Out of class (16–22 °C)	37.5%	41.7%	30.2%

The measured relative humidity (RH) during the occupancy hours was $54 \pm 5\%$ for all three days, which is in the range of what ASHRAE 62-2001 recommends for a comfortable range ($25\% < RH < 60\%$) [18]. In addition, the vertical temperature between 0.1 m (for ankle), 1.1 m (for head of a seated person), and 1.7 m (for head of a standing person) was always found lower than 2 °C, as ISO 7730 defines within Class A.

3.3. Total energy usage

Fig. 6 (left) shows the power consumed by various PCM-RCC components. As expected, ASHP with about 70% of the total energy usage was identified as the main consumer of the system. The total energy consumption was raised by around 40% in the second and third days since a longer night-time recharge cycle plus the “Day-Hold” strategy was considered for these days.

Based on the electricity and energy tariffs in Victoria, Australia, the daily hours are typically divided into three time of use (TOU) periods: peak hours (15:00–21:00 weekdays), off-peak hours (22:00–7:00 every day), and shoulder (7:00–15:00 & 21:00–22:00 weekdays, 7:00–22:00 weekends). As shown in Fig. 6 (right), the most electricity was consumed during off-peak and shoulder periods, and 26%–27% of the daily energy usage belongs to the peak hours. PCM-RCC ability in peak load shifting can be further improved if a more refined, flexible control strategy is employed.

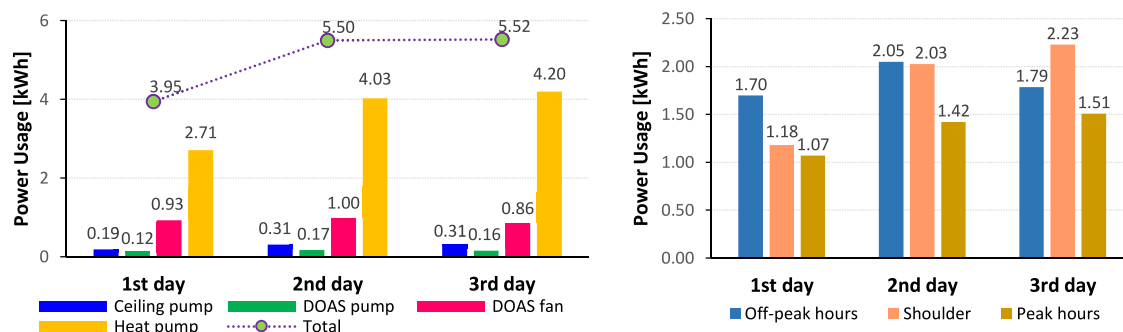


Fig. 6. Measured power usage (left), and system peak and off-peak demand (right).

4. Conclusions

This research presented the measured thermal and energy performance of the PCM-RCC system installed for space cooling. The system has a satisfactory performance in terms of thermal energy storage to meet the peak cooling demand during the daytime. Typically, 6–8 h of recharge cycle seems to be sufficient if no over-heating occurs before midnight. The issues identified in the current panel design are the low heat transfer rate of water capillary tubes and more significantly, the lack of full thermal contact between PCM and the tubes. For 58%–70% of the occupancy period, PCM-RCC provided the operative temperature within Class C of ISO 7730. The comfort in the morning was to some extent sacrificed due to lack of heating provision as well as cabin over-cooling caused by the recharge process. Regarding the electricity consumption, the system utilised about 70% outside of the peak period. Overall, an optimal operating and control strategy in response to the transient thermal behaviour of PCM, the indoor environment, and the weather condition should be implemented to realise the full potential of this technology. Further investigations will be presented in authors' future studies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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