

Thermal and energy performance evaluation of a full-scale test cabin equipped with PCM embedded radiant chilled ceiling

Syedmostafa Mousavi^a, Behzad Rismanchi^{a,*}, Stefan Brey^b, Lu Aye^a

^a Renewable Energy and Energy Efficiency Group, Department of Infrastructure Engineering, Faculty of Engineering and Information Technology, The University of Melbourne, VIC, 3010, Australia

^b Invaus Pty Ltd., Melbourne, VIC, 3000, Australia

ARTICLE INFO

Keywords:

Phase change material (PCM)
Radiant cooling
Ceiling panel
Thermal comfort
Energy flexibility
Experiment

ABSTRACT

The escalating global demand for space cooling has led to the emergence of new cooling technologies, including the phase change material embedded radiant chilled ceiling (PCM-RCC) system. This technology improves energy efficiency and indoor environmental quality, while also offering demand-side flexibility. The present study experimentally evaluates the thermal efficiency and energy performance of a PCM-RCC system in a full-scale test cabin equipped with PCM panels. Here, the transient thermal behaviour of PCM ceiling panels besides the cooling energy delivered during charging-discharging cycles are examined. The indoor thermal comfort and peak electricity demand reduction enabled by the present PCM-RCC are also discussed. The results reveal that chilled water circulation for 4–5 h overnight was sufficient to fully recharge the PCM panels. Over 80% of the occupancy time was classified as “Class B” thermal comfort according to ISO 7730. The system’s daily electricity usage was mostly concentrated during off-peak hours, accounting for ~70% of the total usage. While the controlling schedule used in this study responded to the transient thermal behaviour of the indoor space and PCM ceiling panels, a more dynamic, predictive schedule is necessary to improve the system’s overall efficiency and further enhance indoor thermal comfort in response to the changing environmental conditions.

1. Introduction

Since 1990, energy consumption for space cooling has more than tripled, placing strain on electricity infrastructure and contributing to peak energy demand. In 2021, the demand for space cooling experienced the largest annual increase among all building end-uses, accounting for approximately 16% of global final energy consumption in the building sector (~2000 TWh) [1]. This is mainly driven by the growing global demand for air-conditioners (ACs), as a result of continuous climate change and population growth [2]. The number of in-use ACs worldwide has risen rapidly, from 1.6 billion units in 2020 to 2.2 billion in 2021 [1,3], and is projected to continue increasing under a business-as-usual scenario, with estimates of more than tripling by 2050 [4,5].

The data from the International Energy Agency (IEA) signifies how vital it is for the building and construction sector to firmly adopt not only effective policies but also more advanced, energy-efficient space cooling technologies [6]. In recent years, academia and industry have been exploring potential materials and technologies to enhance

buildings’ thermal performance [7–9] as well as the cooling efficiency of AC units [10,11]. One such technology involves the use of phase change material (PCM) embedded radiant chilled ceiling (RCC), called PCM-RCC. Many researchers have recommended PCMs as particularly attractive thermal storage materials for enhancing the thermal inertia of building structures [12]. This is due to their ability to absorb and release a significant amount of thermal energy within a narrow temperature range during the phase change process [13,14]. In the PCM-RCC system, the PCM acts as a thermal battery, charged overnight with chilled water flowing through the ceiling panels (freezing cycle), and then discharged in the daytime by absorbing the interior sensible heat (melting cycle). Thanks to the radiant cooling and thermal energy storage mechanisms, PCM-RCC offers end-users a variety of advantages in terms of efficiency and indoor environmental quality (IEQ) together with demand-side flexibility. Lower energy consumption, better space utilisation, improved thermal comfort, quiet operation, enhanced IEQ with limited re-circulation of pathogens, as well as peak load shifting are the benefits of the PCM-RCC technology, when compared to traditional AC systems [2].

Several experimental studies have investigated the cooling potential

* Corresponding author.

E-mail addresses: sm.mousavi@unimelb.edu.au (S. Mousavi), Brismanchi@unimelb.edu.au (B. Rismanchi).

<https://doi.org/10.1016/j.buildenv.2023.110348>

Received 2 March 2023; Received in revised form 19 April 2023; Accepted 21 April 2023

Available online 22 April 2023

0360-1323/Crown Copyright © 2023 Published by Elsevier Ltd.

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

This is an open access article under the CC BY-NC-ND license

Nomenclature		Abbreviations	
<i>Symbols</i>		AC	Air conditioner
A	PCM ceiling area [m^2]	CBE	Centre of the built environment
C_p	Specific heat capacity [$\text{J kg}^{-1} \text{K}^{-1}$]	DOAS	Dedicated outdoor air system
$\dot{m}$	Water flow rate [kg s^{-1}]	EN	European standard
$\dot{Q}''$	Heat flux [W m^{-2}]	HF	Heat flux
T	Temperature [$^{\circ}\text{C}$]	HVAC	Heating, ventilation, and air-conditioning
β	PCM liquid fraction [–]	IAQ	Indoor air quality
<i>Subscripts</i>		IEA	International energy agency
<i>abs</i>	Absorbed heat	IEQ	Indoor environmental quality
<i>c</i>	Convective	IoT	Internet of things
<i>ext</i>	Extracted heat	ISO	International organisation for standardisation
<i>ir</i>	Internal radiation	LF	Liquid fraction
<i>r</i>	Radiative	PCM	Phase change material
<i>rw</i>	Return water	PMV	Predicted mean vote
<i>sw</i>	Supply water	RCC	Radiant chilled ceiling
<i>s</i>	Solar radiation	REHVA	Representatives of European heating and ventilating associations
<i>w</i>	Water	RH	Relative humidity
		RTD	Resistance temperature detector
		ToU	Time of use

of PCM-RCC systems. Koschenz and Lehmann [15] tested a prototype PCM finned ceiling module in a laboratory setting and found that it could store up to 290 Wh.m^{-2} of thermal energy during a 7.5-h melting cycle with an average heat load of 39 W m^{-2} . Pavlov [16] examined the use of PCM-clayboard ceiling panels for space cooling and determined that an 8-h night-time water circulation with a flow rate and supply temperature of 150 kg h^{-1} and 18.5°C , respectively, could maintain an indoor operative temperature of $22\text{--}28.7^{\circ}\text{C}$ during occupancy hours. Weinläder et al. [17] investigated the thermal behaviour of two types of PCM ceiling panels (Type 1 with PCM above water tubes and Type 2 with PCM below water tubes) during the recharge process. They reported a solid fraction of 90–100% for Panel Type 1 and 80–90% for Panel Type 2 after the recharge cycle, with an energy intake of 253 Wh.m^{-2} required to fully recharge the melted PCM in the ceiling panels. Meanwhile, Jobli et al. [18] analysed the thermal characteristics of a PCM ceiling panel in a series of laboratory tests and found that the PCM recharge cycle could be accelerated by lowering the supply water temperature, though it was minimally affected by raising the water flow rate. Bogatu et al. [19] investigated the thermal performance of macro-encapsulated PCM ceiling panels in a climate chamber and observed a heat flux range of $5.3\text{--}27.7 \text{ W m}^{-2}$ between the interior space and the ceiling panels for a water flow rate of 140 kg h^{-1} and water supply temperature of 20°C . They recommended distributing PCM panels according to the heat gain distribution across the floor area to obtain a uniform heat flux. Gallardo and Berardi [20] evaluated the peak load shifting capabilities of a PCM-RCC system, showing that $180\text{--}230 \text{ Wh.m}^{-2}$ of internal heat gains could be passively absorbed by PCM ceiling panels during occupancy hours, with an average total heat transfer coefficient of $13.5 \text{ W m}^{-2}\text{K}^{-1}$. The indoor operative temperature during the experiments ranged between 22°C and 26°C . Finally, Skovajsa et al. [21] proposed a PCM ceiling panel with a specific cooling capacity of $\sim 87 \text{ W m}^{-2}$, which could achieve a peak temperature reduction of up to 3.2°C and energy savings of $10.8\text{--}27.5\%$ for space cooling.

Notwithstanding broad interest in PCM-RCC applications among the scientific and industry communities, the technology has not yet transitioned to its 'Limited Availability' stage. This is mainly due to those aspects of PCM-RCC's design and operation that have remained unanswered. There are scarcely any research studies examining the charging-discharging efficiency of PCM ceiling panels during consecutive hot days when the PCM undergoes repeated thermal cyclings. No detailed

comfort assessment has been found in the previous studies. To comprehend the potentials and challenges of the PCM-RCC technologies in load shifting and energy savings, it is also necessary to discuss the electricity usage of PCM-RCC's components in actual operations. To this aim, this work presents a field study on a full-scale test cabin equipped with a new PCM-RCC system, exploring the system's capabilities and potential challenges in real-world settings. The main objectives of this work, representing the novelty and key contributions, are:

- To evaluate the dynamic thermal behaviour of PCM ceiling panels during the charging and discharging cycles over three consecutive summer days. This includes quantifying the amount of cooling energy delivered by the panels, as well as analysing the liquid fraction of PCM based on its partial enthalpy and core temperatures.
- To assess the level of indoor thermal comfort provided by the PCM-RCC system, using both the predicted mean vote (PMV) index and the ANSI/ASHRAE adaptive comfort model, to identify potential operating issues of the technology leading to individual dissatisfaction.
- To investigate the potential peak electricity demand reduction offered by the present PCM-RCC, considering the electricity usage of the system's components during actual operation.

2. Material and methods

This section presents all necessary details about the experimental setup, PCM materials, and measuring equipment used for the current experiments, as well as the methodologies adopted to conduct the analyses.

2.1. Experimental setup

2.1.1. Test cabin

The current experiments were conducted on a full-scale test cabin equipped with a PCM-RCC system, at the Burnley campus of the University of Melbourne (37.83° South, 145.02° East). This test cabin, which had a conditioned volume of 96.7 m^3 , was exposed to real-world climatic conditions. The walls, floor and roof were constructed with R4.3 and R4.8 sandwich panels. Advanced floor-to-ceiling glazing with interstitial Venetian blinds and a vision area of 13.5 m^2 were also used to create a seamless connection to the natural surroundings, as is common in today's modern architectural design. Fig. 1 shows the test cabin and

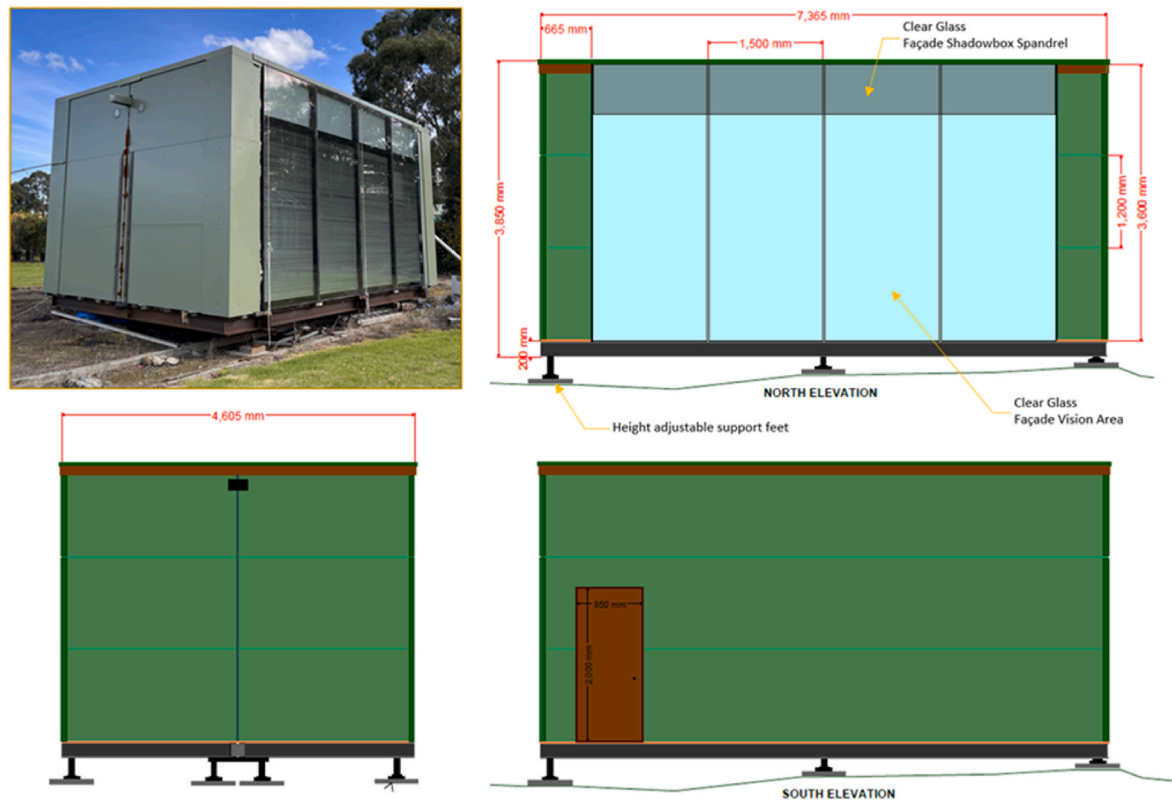


Fig. 1. The test cabin and its 2D drawing views (note: the drawings were prepared by the authors' industry partner, Invaus Pty Ltd.).

its 2D drawing views. Additional details on the cabin structure, including information on layer thickness, conductivity, capacity, and density, are presented in Table 1.

2.1.2. Shape-stabilised PCM composite boards

As shown in Fig. 2, organic-based shape-stabilised PCM boards, placed in a 1.5 mm-thick aluminium tray, were used in this study. These PCM boards, with the dimensions of 121.5 cm (L) $\times$ 65.2 cm (W) $\times$ 2.5 cm (D), had a phase change range of 15.6–19.6 °C, a density of 765 kg m⁻³, and a latent heat storage capacity of 900 kJ m⁻². The thermal storage properties of the PCM board were measured according to the ASTM C1784-14 standard, indicated in Fig. 3. Using a C-Therm conductivity analyser, its thermal conductivities in solid and liquid phases were also measured as 1.02 W m⁻¹ K⁻¹ and 0.68 W m⁻¹ K⁻¹ (with $\pm 5\%$ uncertainty), respectively.

24 PCM panels were installed in eight parallel rows, covering

approximately 60% of the cabin's ceiling area. In the current panel design, capillary tube mats were used for chilled water circulation during the PCM recharge cycle. These thin capillary tubes, made of recyclable polypropylene, are flexible and easy to assemble by plastic welding [2,18]. To enhance thermal contact between the capillary tubes and PCM, a 3-mm-thick plaster layer was applied on top of the PCM boards, based on the lessons learnt from the authors' previous study [3]. Additional insulation layers were also added to minimise unwanted heat gain from the roof. Moreover, panel surfaces were painted using high-emissivity paint to increase the ceiling emissivity rate.

A high-performance thermal infrared camera was employed to examine how PCM thermally responds to the chilled water circulation in the current panel design. The thermal data obtained shows that the temperature drop was dispersed throughout the entire panel, showing efficient heat extraction from the PCM during the recharge cycle. Fig. 4 presents the thermal infrared test setup and images captured at 5-min

Table 1

Details of the structures used in the current test cabin [22].

Layer	Description	Thickness[m]	Conductivity[kJ/hr m K]	Density[kg/m ³]	Capacity[kJ/kg K]
Wall					
1 (inside)	Steel	0.001	54	7800	1.8
2	Cellular foam	0.15	0.112	10	1.4
3 (outside)	Steel	0.001	54	7800	1.8
Floor					
1 (inside)	Yellow tongue particleboard	0.019	0.432	680	1.45
3	Steel	0.001	54	7800	1.8
4	Cellular foam	0.15	0.125	10	1.4
5 (outside)	Steel	0.001	54	7800	1.8
Roof					
1 (inside)	Steel	0.001	54	7800	1.8
2	Cellular foam	0.15	0.112	10	1.4
3	Steel	0.001	54	7800	1.8
4 (outside)	Roof sheet	0.001	54	7800	1.8

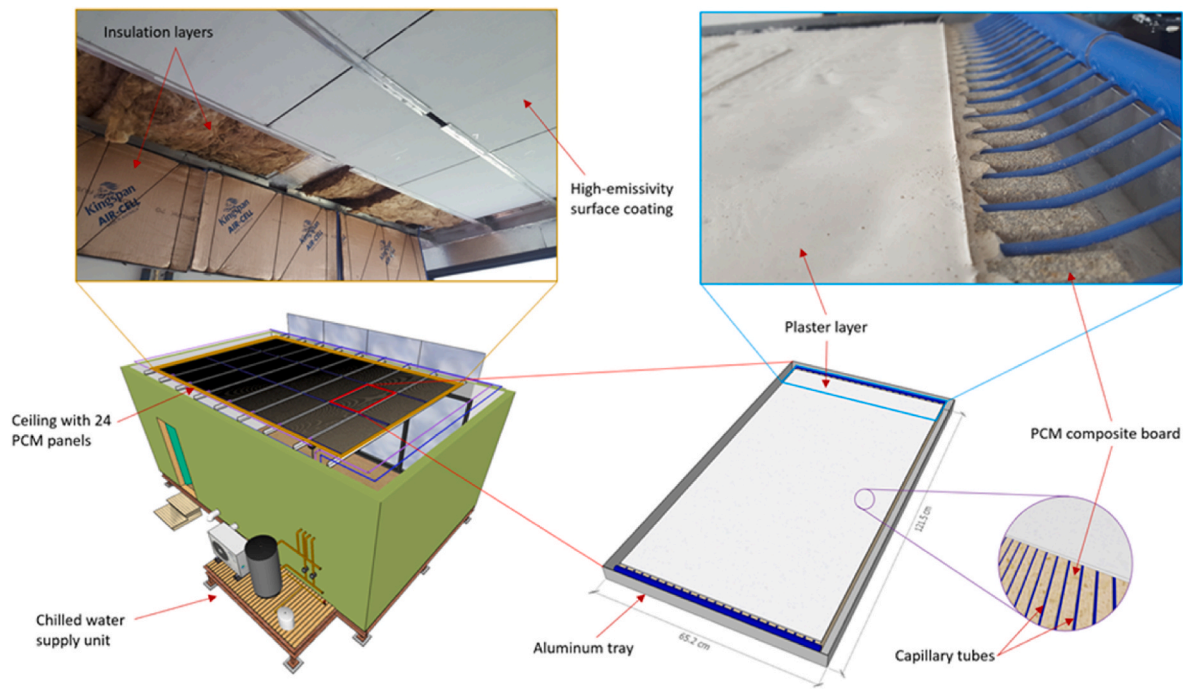


Fig. 2. PCM ceiling panels used for the presented PCM-RCC system.

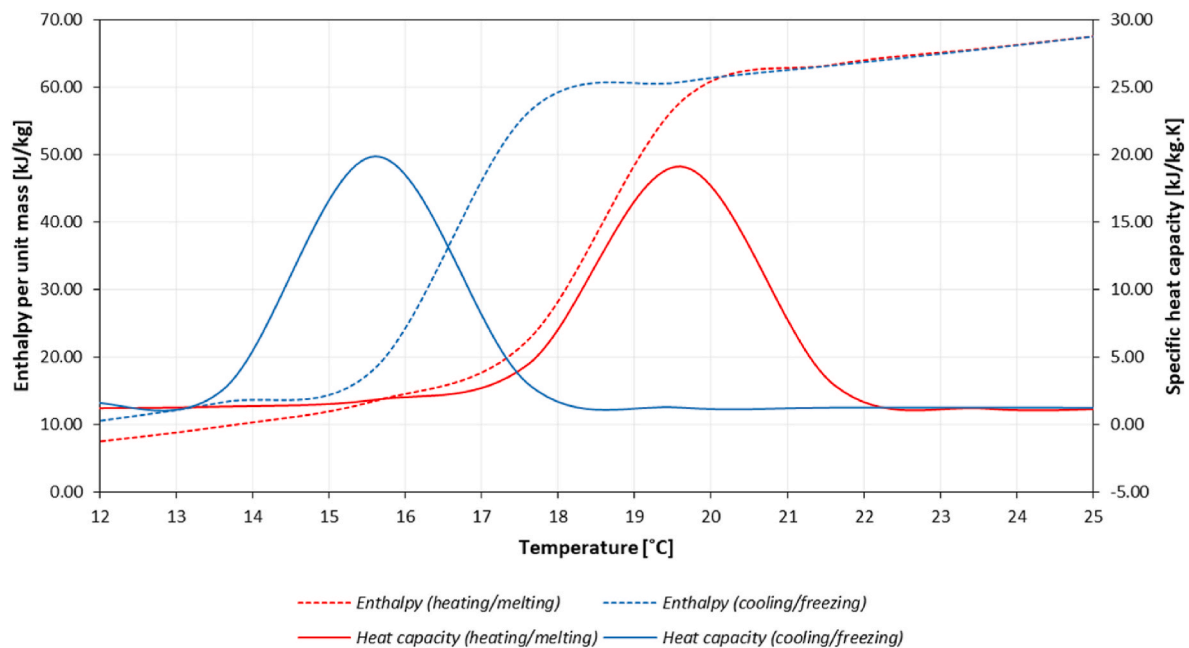


Fig. 3. Measured enthalpy per unit mass and specific heat capacity of the current PCM board.

intervals over a 90-min period.

2.1.3. Chilled water supply and distribution system

The hydronic system and the arrangements of PCM ceiling panels are schematically depicted in Fig. 5. Each row, comprising three PCM ceiling panels in series, was independently connected to the chilled water supply and return lines. Chilled water at a temperature of 10 °C, provided by an air-source heat pump, was circulated within the ceiling panels at an average flow rate of 470 L h⁻¹ to extract heat from PCM until the controlling setpoints of the recharge schedule were met. To minimise heat losses from the surroundings, supply and return lines and all fittings were insulated. The operation of equipment (i.e., circulating

pumps, heat pump, fan, and heater) was remotely controlled via an EasyIO-FW programmable logic controller.

2.1.4. Dedicated outdoor air system (DOAS)

A dedicated outdoor air system (DOAS) supplies cooled, dehumidified outdoor air to the indoor space, principally to provide fresh air and handle latent loads. DOAS units are often used with a parallel cooling system. Radiant ceiling panels have been recommended as the optimum choice to be coupled with DOAS units [23].

In this study, a DOAS system was installed in the cabin to deliver fresh air and supplementary cooling, when needed. This parallel cooling system design can further minimise potential indoor air quality (IAQ)

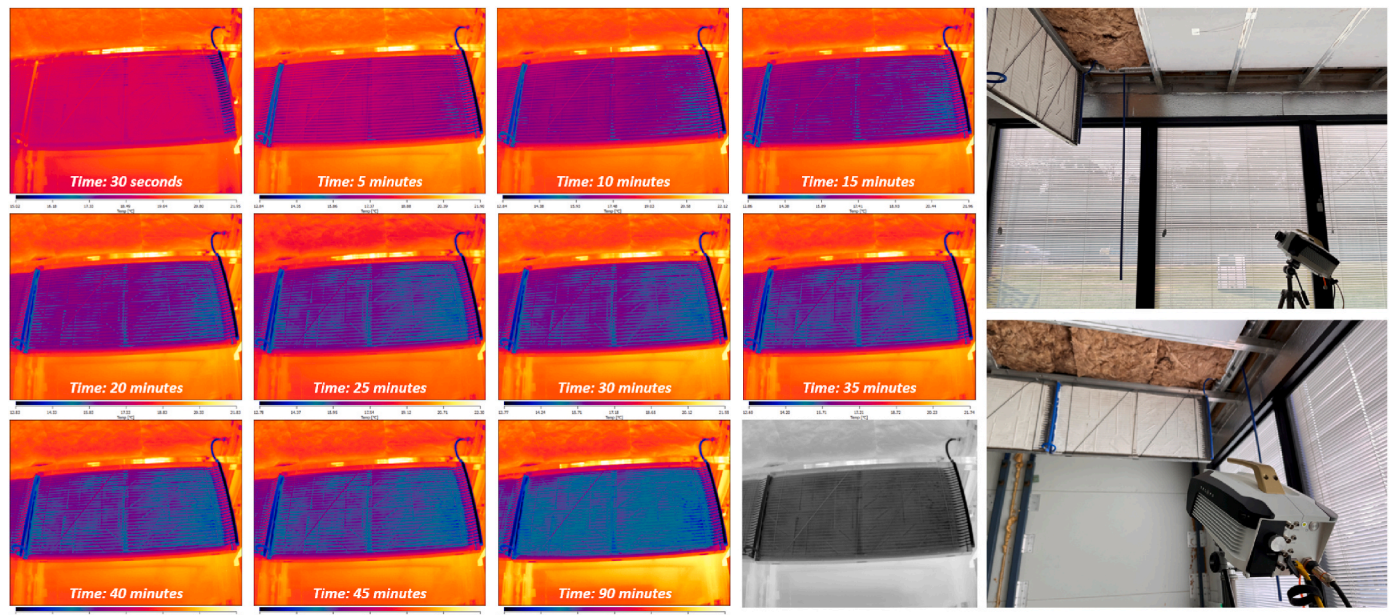


Fig. 4. Thermal behaviour assessment of the PCM panel during the recharge process.

issues [24].

2.1.5. Data acquisition and monitoring

Multiple sensors and internet of things (IoT) devices were used in the cabin to read and collect essential variables for evaluating the PCM-RCC performance. These variables were classified into five main categories, as presented in Table 2.

IoT devices used the LoRaWAN® technology to communicate with the system and transfer data to the cloud. Analog sensors were connected to a data logging system linked to the cloud via 4G technology. The collected data was then imported into a Power BI dashboard developed for visualisation and monitoring purposes.

The data presented in this study belong to the 2nd phase of the experiments conducted over a 3-month period from January to March 2022.

2.2. Analysis procedure

2.2.1. PCM liquid fraction estimation

It is critical to estimate the liquid fraction of PCMs when studying their behaviour during charging cycles. This estimation provides insights into the remaining thermal storage capacity, which requires recharging overnight. Here, the temperature method, which is a common technique used to determine the liquid fraction of PCMs during melting or freezing, has been employed to analyse the PCM regeneration behaviour [17]. This method uses the enthalpy-temperature curve of the PCM to estimate the liquid fraction, as shown in Fig. 3. Considering the phase change range of 15.6–19.6 °C, the PCM liquid fraction is calculated using Eq. (1):

$$\beta = \begin{cases} 0\% & \text{if } T_{PCM} < 15.6^\circ\text{C} \\ \frac{\int_{15.6}^{T_{PCM}} f_h(T) dT}{\int_{15.6}^{19.6} f_h(T) dT} \times 100\% & \text{if } 15.6^\circ\text{C} \leq T_{PCM} \leq 19.6^\circ\text{C} \\ 100\% & \text{if } T_{PCM} > 19.6^\circ\text{C} \end{cases} \quad (1)$$

where β [–] is the liquid fraction, f_h is the enthalpy function, and T is the temperature [°C]. It is worth noting that although the temperature method is a well-established technique, it is crucial to determine the

enthalpy-temperature curve accurately for the method's accuracy. As stated earlier, the thermal storage properties of the PCM in this study were measured according to the ASTM C1784-14 standard.

2.2.2. Heat transfer balance method

The heat flux between the indoor space and PCM ceiling panels ($\dot{Q}_{abs,ceiling}''$) can be calculated theoretically using the heat transfer balance method at the radiant ceiling surface (Fig. 6) [25]:

$$\dot{Q}_{abs,ceiling}'' = \dot{Q}_s'' + \dot{Q}_{ir}'' + \dot{Q}_c'' + \sum \dot{Q}_r'' \quad (2)$$

where the subscripts s , ir , c , and r denote, respectively, transmitted solar radiation absorbed by the radiant ceiling surface, radiative flux with internal heat sources (e.g., lights and equipment), convective heat flux with the interior environment, and radiative heat flux with other indoor surfaces. Moreover, the heat extracted from PCM ceiling panels by chilled water ($\dot{Q}_{ext,water}''$) during the recharge period is equal to [19]:

$$\dot{Q}_{ext,water}'' = \frac{\dot{m}_w C_{p,w} (T_{rw} - T_{sw})}{A_{panels}} \quad (3)$$

Here, $\dot{m}_w$ is the water flow rate [$\text{kg} \cdot \text{s}^{-1}$], $C_{p,w}$ is the specific heat capacity of water [$4182 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$], A_{panels} is the PCM ceiling area [m^2], and T_{rw} and T_{sw} are the return and supply water temperatures [°C], respectively.

2.2.3. Thermal comfort metrics

In this study, two methods of the predicted mean vote (PMV) and adaptive thermal comfort were used to evaluate the thermal comfort conditions provided by the present PCM-RCC system. The PMV method, a widely-used thermal comfort metric proposed by Fanger in the 1970s [26], predicts the average thermal sensation of a group of people [27]. Table 3 lists various categories for indoor thermal comfort specified by ISO 7730 [28] and EN 16798-1 [29] based on PMV levels. The PMV model was developed using Fanger's PMV equation, and the results were validated by comparing them with those obtained from the CBE thermal comfort tool [30]. Measured data for air temperature, black globe temperature, and indoor relative humidity were used for PMV calculations. The metabolic rate assumed for reading, typing, and filing activities was 1.2 met [31], and the minimum air velocity assumed was $0.05 \text{ m} \cdot \text{s}^{-1}$ because of the limited air movement in radiant cooling systems

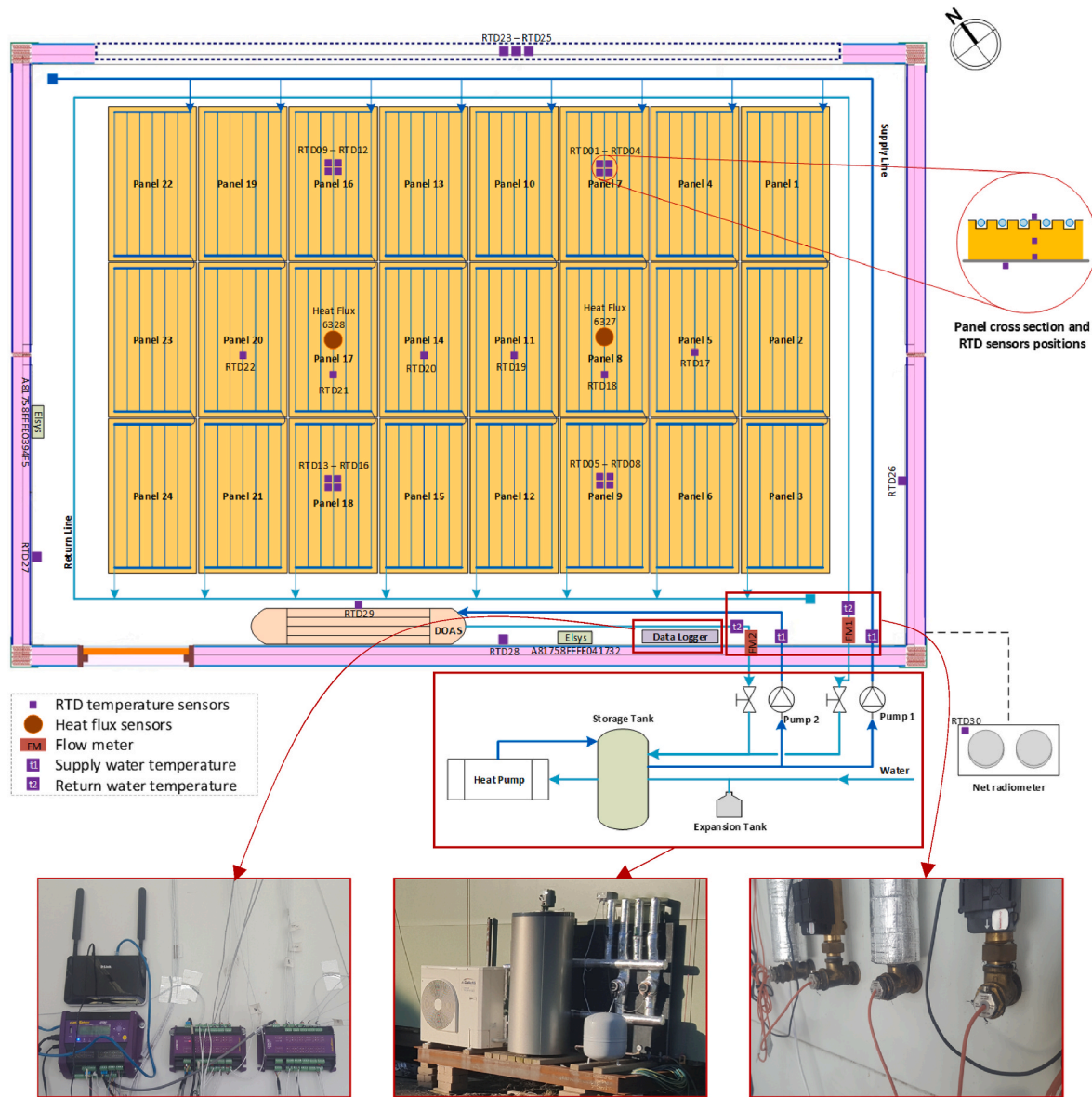


Fig. 5. PCM-RCC hydronic system and the arrangements of PCM ceiling panels in the test cabin.

[3]. The clothing factor for the summer season was assumed to be 0.65 clo, based on an analysis of the RP-884 database for HVAC buildings [32].

The adaptive thermal comfort model, which is based on the idea that individuals have different thermal adaptation levels and may comfort at different temperatures, is considered to be more adaptable and better aligned with human thermal physiology compared to the PMV index. Thus, the adaptive comfort model was also used here for thermal comfort assessments [31].

2.2.4. Uncertainty analysis in measurements

Experimental results can be affected by errors in measuring systems, procedures, data analysis, and the experimenter's skills. In measuring a quantity, two types of errors are expected, namely systematic (or data bias) and random errors [33]. A systematic error occurs when a measured value contains an offset because of a lack of proper calibration, failure to account for a relevant factor, errors in assumptions or calculations, and lag time (hysteresis) in instruments. A random error occurs when a measured quantity has different values in repeated experiments under the same circumstances [34]. This error is caused by

uncontrolled environmental factors (e.g., vibration, electronic noises, ripple in the power supply), instrument resolution, and instrument drift due to temperature changes [35]. To achieve an acceptable level of uncertainty, it is essential to minimise potential sources of errors and/or to keep track of those that cannot be eliminated.

All measurement instruments used in this study were calibrated prior to the experiments and installed in the cabin under their manufacturers' guidelines. Also, the data logging system with a sampling frequency of 5 s averaged the measured values over 5-min intervals to minimise random errors. Standard operating procedures (SOPs) as well as assumptions defined for the experiments were recorded in an experiment logbook to avoid potential human errors. Also, in the experimental uncertainty analysis, the uncertainties of the measuring instruments were considered, as specified by their manufacturers (see Table 4).

2.3. PCM-RCC control scheme

The PCM-RCC controlling schedule, presented in Table 5, was designed based on the current ceiling layout and PCM panel design, specifications of the equipment used in the system, findings of the

Table 2
Categories of measured variables in this study.

Measurement category	Measured variable	Allocated sensor
PCM ceiling panel	- PCM panel temperature - Panel heat flux	16 RTD sensors for Panels 7, 9, 16, and 18 (four for each^a) - Six RTD sensors for Panels 5, 8, 11, 14, 17, and 20 (one for each) - Two heat flux sensors for Panels 8 and 17
Indoor climate	- Cabin air temperature - Cabin operative temperature - Surface temperature - CO₂ level - Relative humidity (RH) - Light level - Occupancy (motion)	- Three RTD sensors in heights^b of 0.1 m, 1.1 m, and 1.7 m - One globe temperature sensor at a height of 1.1 m - Three RTD sensors for the façade (frame, cavity, and glass surface) - Three RTD sensors for wall surfaces [IoT] Two ERS devices^c (for CO₂, RH, light, and occupancy) [IoT] Two flow metres [IoT] Four temperature sensor^c
Hydronic unit	- Water flow rate - Supply water temperature - Return water temperature	
Power consumption	- Power usage - Voltage - Current	[IoT] Four power metres (for the heat pump, ceiling pump, DOAS, and the whole test cabin)
Weather station	- Ambient temperature - Global and reflected solar radiation - Upwelling and downwelling longwave radiation - Sky temperature - Outdoor RH - Rainfall - Wind speed & direction	- One 4-component radiometer (including pyranometers and pyrgeometers) - One temperature/RH sensor - One rainfall smart sensor - One wind speed sensor - One wind direction sensor

^a The location of each resistance temperature detector (RTD) sensor is shown in Fig. 5.

^b The mentioned heights were considered in accordance with ISO 7730 [3]: 0.1 m (for a person's ankle), 1.1 m (for a seated person's head), and 1.7 m (for a standing person's head).

^c The location of Elsys ERS devices, flow metres, and water temperature sensors are indicated in Fig. 5.

authors' previous analyses, and recommendations from IEQ-related standards and guidelines.

3. Results and discussion

3.1. Charging-discharging performance of PCM ceiling panels

Fig. 7 displays the measured data for ambient conditions, the cabin's indoor (globe) temperature, PCM ceiling temperatures, and ceiling heat flux during the system operation over three consecutive hot summer days. These hot days effectively showcase the maximum capacity of the current PCM-RCC system design. Fig. 8 demonstrates the hourly estimated partial enthalpy and liquid fraction of PCMs in the ceiling panels during the melting and freezing phases. On the first day, the active recharge cycle began with an initial ceiling temperature of 18.5 °C and a PCM liquid fraction of 71%. After 4 h of chilled water circulation with an average water flow rate of 470 L h⁻¹, the PCM panels were fully recharged. Positive values of heat flux in the daytime confirm that the PCM ceiling panels steadily absorbed the cabin interior heat as the PCM phase was changing (solid → mushy → liquid). The DOAS unit and the ceiling pump were operated intermittently to provide supplementary cooling and maintain the desired comfort condition. This supplementary cooling also added a residual cooling capacity to the PCM late afternoon, extending the active time of the panels. For the first day, the ceiling panels remained active until 07:30 p.m. A sharp increase in panel temperatures was then observed, confirming that PCMs had fully melted.

On the second day, as the data shows, the cabin and ceiling temperatures were around 22 °C, and the PCM liquid fraction was at 100% (fully liquid). Following the defined operating schedule, the DOAS was activated overnight before the ceiling pump operation to ventilate and cool the cabin using the cool nighttime ambient air. The estimated values of partial enthalpy and liquid fraction for the PCM panels in the early morning demonstrate that they were almost fully recharged. The PCM ceiling's cooling storage capacity nearly covered the entire occupancy period, thanks to the extra cooling provided periodically by the DOAS and ceiling operations. The same initial state of temperatures and

Table 3
Classification of thermal comfort conditions specified by ISO 7730 [28] and EN 16798 [29] standards.

Standard		PMV range
ISO 7730	EN 16798-1	
A	I	- 0.2 < PMV < 0.2
B	II	- 0.5 < PMV < 0.5
C	III	- 0.7 < PMV < 0.7
-	IV	- 1.0 < PMV < 1.0

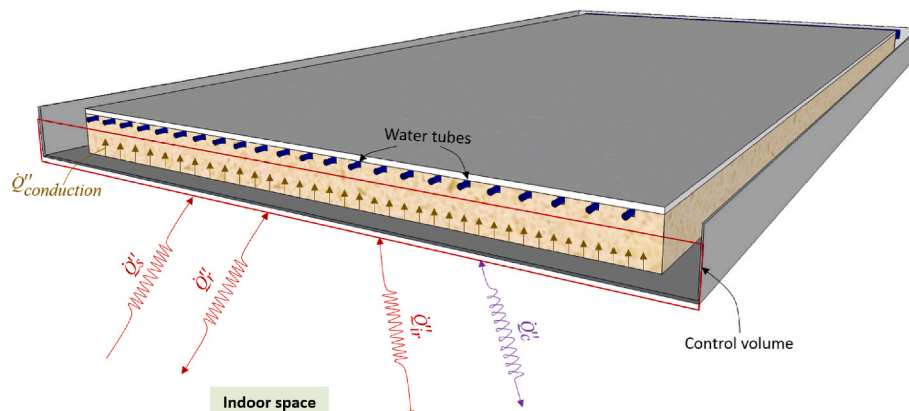


Fig. 6. Heat transfer balance method at the radiant ceiling surface.

Table 4

Specifications of measurement sensors/instruments used for the present study.

Sensor/ Instrument	Model (manufacturer)	Quantity	Measurement range	Uncertainty of sensor/ instrument
RTD sensor	Pt100 Class A (Omega)	30	−73 – 260 °C	±0.15 °C at 0 °C
Heat flow sensor	HFP01SC (Hukseflux)	2	−2000 – 2000 W/m ²	±1.84 × 10 ^{−6} V/(W/m ²)
Globe temperature sensor	GT-2™ (Dyacon)	1	−40 – 105 °C	±0.1 °C within 0–70 °C
ERS device	ERS CO ₂ (Elsys)	2	−40 – 120 °C	Temperature: ±0.2 °C RH: ±2% 4–2000 Lux 0–10,000 ppm 1.5–100 m ³ /h
Flow metre	Ultraflow 34 (kamstrup)	2	2–180 °C	±(0.4 + 4/ ΔT)%
Water temperature sensor pair	Multical 603 (kamstrup)	2	0.1–16 A	±1%
Power metre	R809A (netvox)	4	Spectral range solar: (285–3000) × 10 ^{−9} m	Pyranometer: ±0.20 × 10 ^{−6} V/(W/m ²)
Net radiometer	NR01 (Hukseflux)	1	Spectral range longwave: (4.5–40) × 10 ^{−6} m	Pyrgometer: ±0.78 × 10 ^{−6} V/(W/m ²)
Temperature/ RH sensor	S-THB-M002 (HOBO)	1	−40 – 75 °C 0–100% RH	Temperature: ±0.21 °C RH: ±2.5% ±1%
Rainfall sensor	S-RGB-M002 (HOBO)	1	0–12.5 cm (0–5 in)	±1.1 m/s (±2.4 mph) or ±4% of reading (whichever is greater)
Wind speed sensor	S-WSB-M003 (HOBO)	1	0–76 m/s (0–170 mph)	±5°
Wind direction sensor	S-WDA-M003 (HOBO)	1	0–355°	

PCM liquid fraction was also observed on the third day. However, because of the significant drop in ambient temperature in the afternoon, no supplementary cooling was required after 2:00 p.m., and the PCM ceiling's storage capacity, despite being exhausted around 4:00 p.m., was sufficient to maintain the indoor operative temperature within the standard comfort range.

The current panel design, which had been modified based on the authors' previous study [3], effectively addressed the issue of low thermal contact between the PCM composite board and capillary tubes, increasing the heat transfer rate between the PCM and chilled water. The night-time PCM ceiling recharge cycle was substantially shortened. For future panel design improvements, it was suggested that a type of water tubes be utilised to reduce water pressure drop and further enhance the heat transfer performance of PCM ceiling panels.

Focusing on the repeated night-time PCM recharge cyclings during three experiment days, it was observed that the efficiency of the recharge cycle gradually declined over subsequent hot days. It was uncertain to achieve fully-recharged PCM panels with the same active recharge schedule due to the accumulation of heat in the indoor space after consecutive hot days. The heat flux patterns also confirm that the first 1–2 h of the active recharge period in the second and third days dealt with removing indoor sensible heat, thus slowing the freezing rate of the PCM. Although the current system operating schedule aimed to respond to the transient thermal behaviour of indoor space and PCM ceiling panels, a more dynamic, optimal predictive schedule with precise weather forecasting is required to carefully manage uncertainties in the

Table 5

PCM-RCC controlling schedules for the present study.

Component	Controller logic
Ceiling pump	Un-occupied period^a (i) Run the pump for 4 h ^b overnight (03:00 a.m.–07:00 a.m.) if: - T _{max, outdoor} of the following day ≥ 25 °C (weather forecasting) - T _{PCM, core layer} > 18.5 °C (initial PCM state assessment) AND Stop the pump if T _{PCM, core layer} reaches 13.5 °C. OR (ii) Run the pump for 2 h ^c overnight (03:00 a.m.–05:00 a.m.) if: - T _{max, outdoor} of the following day < 25 °C (weather forecasting) - T _{PCM, core layer} > 18.5 °C (initial PCM state assessment) AND Stop the pump if T _{PCM, core layer} reaches 16 °C. Occupancy period Run the pump during DOAS fan operation if PCM panels are mostly liquid (T _{PCM, core layer} > 18.5 °C) AND T _{indoor} > 24 °C ^d .
DOAS unit	Un-occupied period (i) Run DOAS (fan only) from 10:00 p.m.–07:00 a.m. if: - T _{indoor} > 22 °C AND T _{outdoor} < T _{indoor} AND (ii) Run DOAS (fan + pump) from 12:00 a.m.–03:00 a.m. if T _{indoor} > 22 °C ^e . Occupancy period (i) Run DOAS fan based on 0.5-hr On/1-hr Off schedule ^f . AND (ii) Run DOAS pump during fan operation ^g if: - T _{outdoor} > 26 °C AND T _{indoor} > 24 °C ^d .
Heat pump	Un-occupied period Run the heat pump when the ceiling pump or DOAS pump is activated, to supply chilled water with a setpoint of 10 °C. Occupancy period Run the heat pump if the ceiling pump or DOAS is activated.
Heater	Run the heater in the early morning (06:30 a.m.–08:30 a.m.) ^h if T _{indoor} < 20 °C ^d .

^a The period of 9:00 a.m.–07:00 p.m. was referred to as an occupancy time. Outside of this period was considered as an un-occupied time.

^b According to the pre-assessment results of PCM-RCC operation under different scenarios, a maximum of 4–5 h was required to fully recharge PCM panels.

^c Two hours of recharge cycle provides approximately a half storage capacity of the installed PCM ceiling panels.

^d Indoor temperature limits were defined based on the ISO 7730 standard [28].

^e DOAS operation overnight effectively prevents cabin overheating and regulates indoor relative humidity.

^f With an average 90 L/s of airflow rate, the DOAS fan provides minimum fresh air for occupants during the occupancy period.

^g DOAS pump operation aimed to provide supplementary cooling during the occupancy period.

^h This schedule was set up to manage the possible issue of overcooling in the early mornings after the recharge cycle.

system performance.

3.2. Ceiling cooling energy

Over the three-day experimental period, the average total heat transfer coefficient from the PCM ceiling panels to the indoor space of the cabin was calculated to be $8.48 \pm 0.97 \text{ W m}^{-2} \cdot \text{K}^{-1}$ (Fig. 9-right). This value accounts for both radiative and convective heat transfer paths and is consistent with relevant standards, such as REHVA, EN1264-5, and EN15377-1 [36]. Furthermore, by employing the heat transfer balance method described in Section 2.2.2, the total daily energy absorbed by PCM ceiling panels from the indoor environment as well as the total heat extracted from the panels by chilled water during the active recharge period were calculated. Upon comparison of these two values, it was found that the cooling energy absorbed and extracted were almost identical (Fig. 9-left). The small difference observed on the first

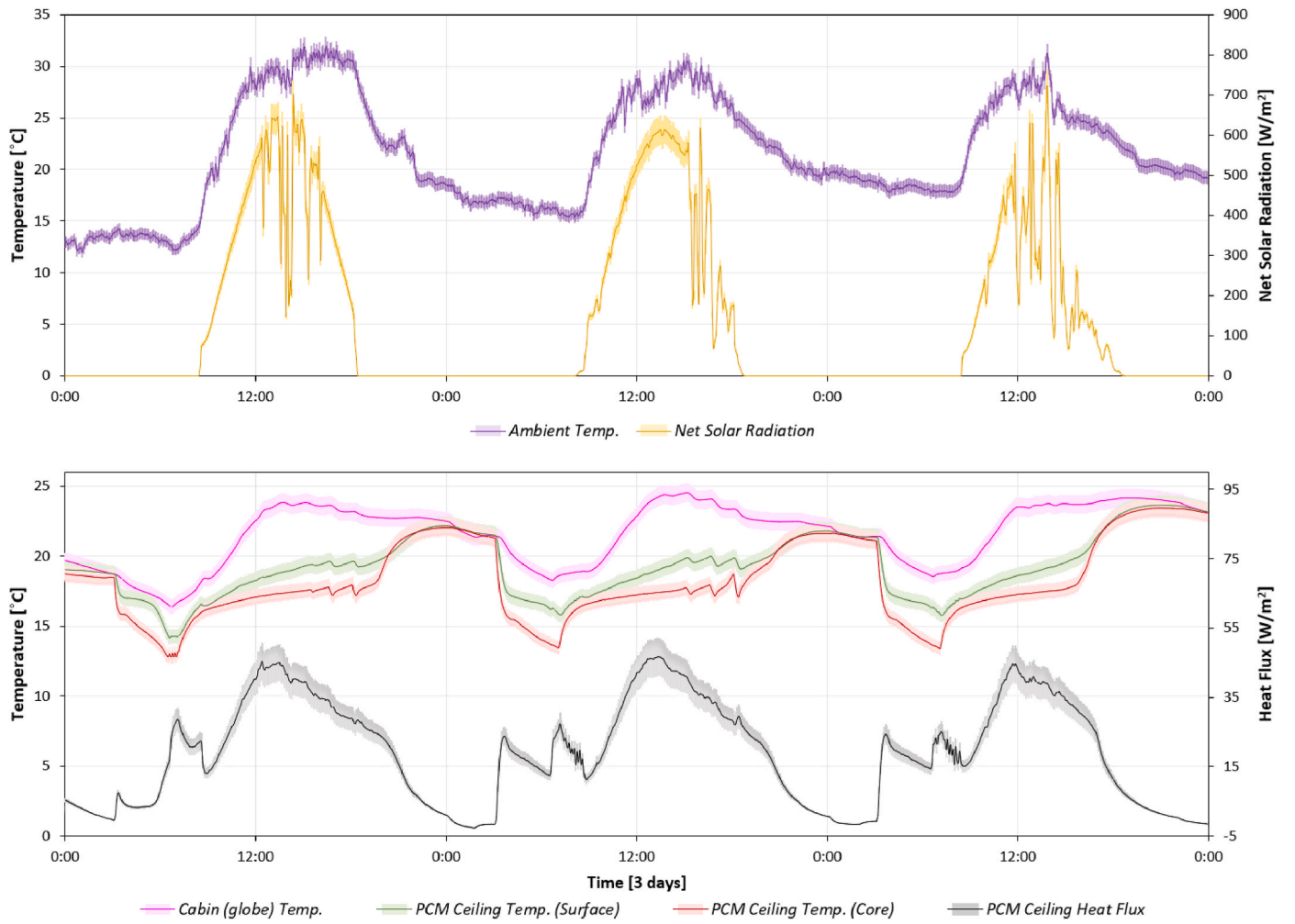


Fig. 7. (Top) Measured ambient temperature and net solar radiation, and (bottom) measured cabin (globe) and PCM ceiling temperatures plus PCM ceiling heat flux in 3 consecutive summer days (note: The experimental uncertainty, shown with the measured data, is estimated with a 95% confidence interval.).

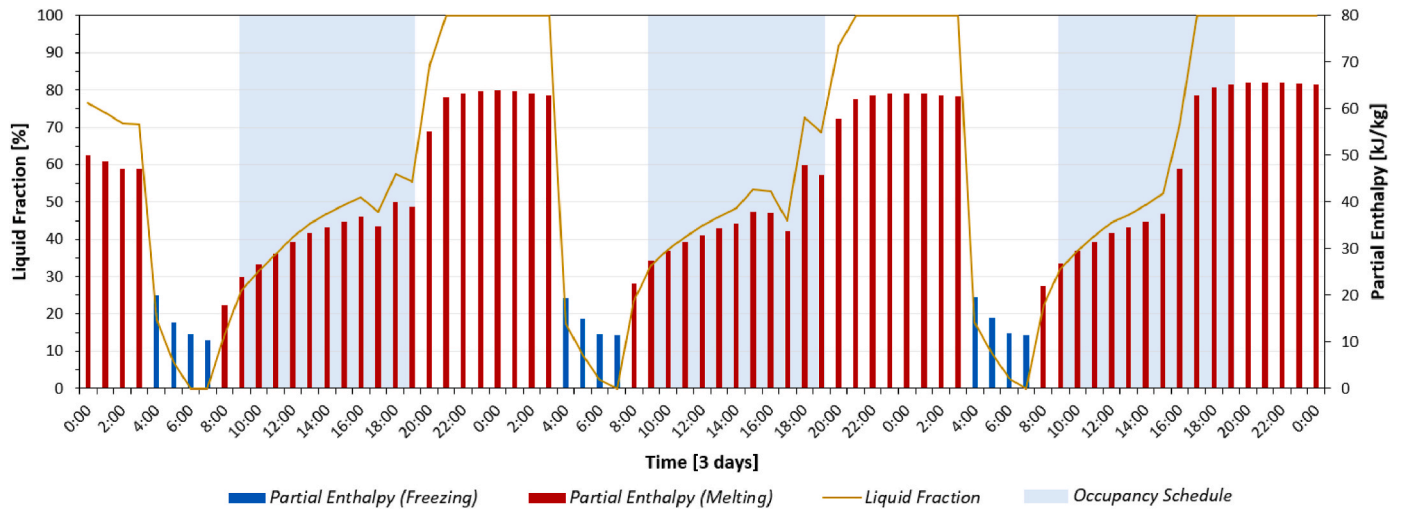


Fig. 8. Partial enthalpy and liquid fraction of PCM ceiling panels in 3 consecutive summer days.

day could be attributed to the residual cooling capacity in the PCM panels, which had a liquid fraction of 71% initially, resulting in less heat being extracted during the chilled water circulation time. On the second and third days, the differences in the extracted-absorbed values might

have been because of the accumulated indoor heat being removed directly by the hydronic system. As described in Section 3.1, during the first 1–2 h of the active recharge period overnight, the system focused on removing indoor sensible heat before extracting heat from the PCM

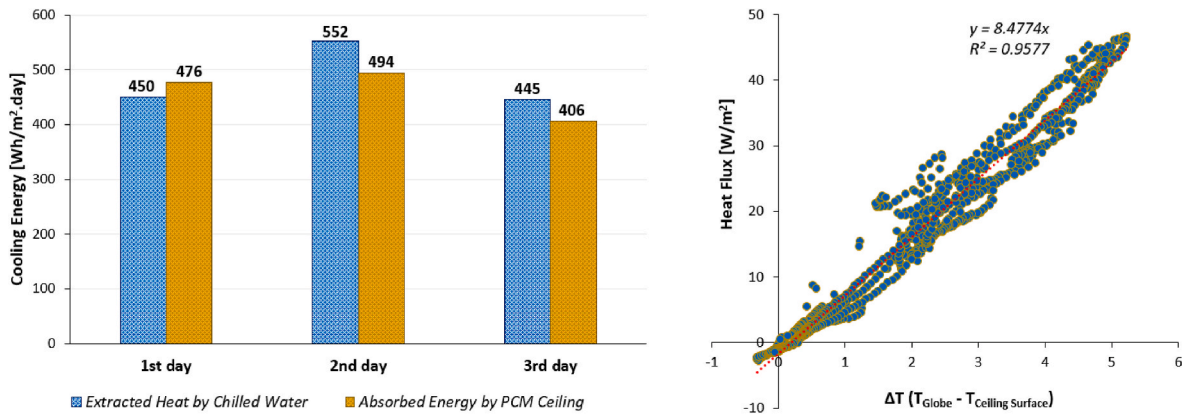


Fig. 9. (Left) Total energy absorbed by PCM ceiling panels from indoor environment and energy extracted from the ceiling during chilled water circulation periods, and (right) total heat transfer coefficient of PCM ceiling panels.

panels.

3.3. Thermal comfort assessment

Low-quality indoor thermal comfort leads to individual dissatisfaction and has a negative impact on their well-being, performance, and productivity [2]. It is essential to closely monitor thermal comfort and address any issues promptly. Heating, ventilation, and air-conditioning (HVAC) systems play a critical role in maintaining the desired indoor thermal conditions. Therefore, an inappropriate design and implementation of these systems raise the likelihood of thermal discomfort issues during regular building operations.

Assuming an occupancy time of 9:00 a.m.–07:00 p.m., both PMV and adaptive comfort assessments, presented in Section 2.2.3, reveal that the PCM-RCC system can provide an acceptable level of indoor thermal comfort, as indicated in Fig. 10. The “Out of Comfort Category” and/or “Category IV” were mostly because of the overcooling issue in the mornings caused by the active recharge. To overcome this issue, which had been already predicted by the authors, a small electric air heater was installed and operated in the early mornings according to the defined operating schedule (see Table 5); however, its heating capacity was not adequate as expected. In addition, as shown in Fig. 11, temperature measurements at heights of 0.1 m (for a person’s ankle), 1.1 m (for a seated person’s head), and 1.7 m (for a standing person’s head) confirm that the vertical temperature difference was always less than 2 °C, as per the ISO 7730 standard within Class A.

3.4. Total electricity usage

Considering the Timetime-of-use (ToU) tariff in Victoria, Australia, the daily time is typically divided into off-peak (22:00–7:00), shoulder (7:00–15:00 & 21:00–22:00), and peak (15:00–21:00) periods. Fig. 12 shows the electricity usage of PCM-RCC components during different Victoria’s ToU periods. The majority of electricity consumed belongs to the off-peak time, with 58.5% of daily usage on the first day, 59.1% on the second day, and 80.2% on the third day.

One limitation of this study is the absence of a similar second cabin equipped with radiant ceiling panels without PCM, which would have allowed us to compare the total energy usage of both RCC and PCM-RCC systems across different ToU periods. However, a preliminary analysis using a validated simulation model shows that removing PCM from the radiant ceiling panels can increase the system’s operating time by 45–50% during the day, with approximately 65% of this additional load occurring during shoulder hours and the rest during the peak time. This confirms the PCM-RCC system’s capability to shift a part of the peak cooling load to off-peak hours, enabling load-shifting benefits.

In addition to the load shifting benefit, more energy efficiency can be realised because of the heat pump operation overnight, as it can use less energy at lower ambient temperatures during the night-time. However, as discussed earlier, further improvements in the PCM-RCC’s potential in terms of load shifting and energy savings are expected if a more dynamically predictive operational strategy is developed and implemented.

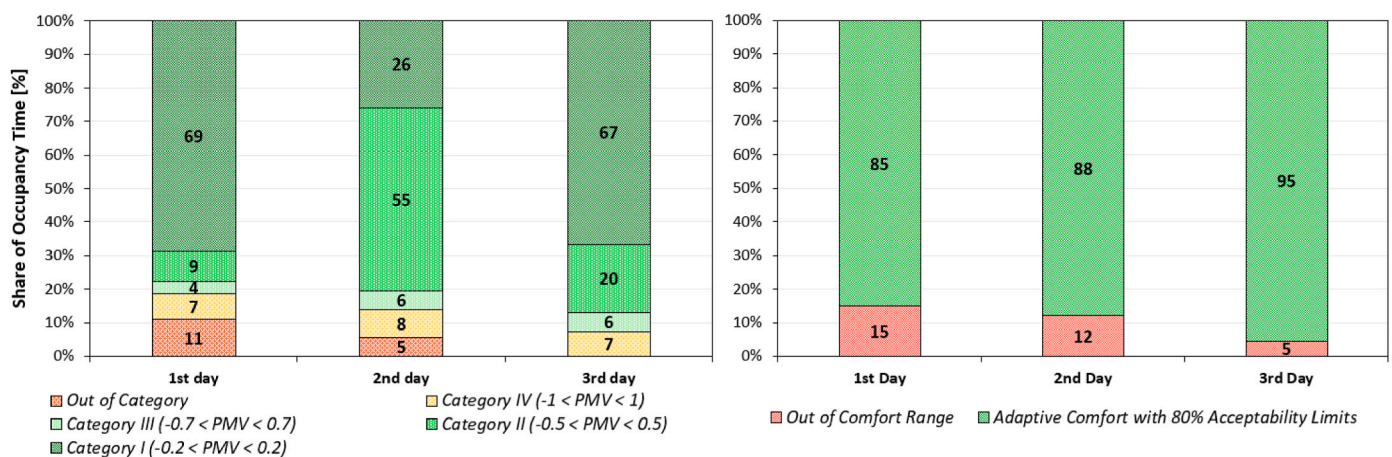


Fig. 10. Indoor thermal comfort level during the occupancy time: (left) PMV-based classification based on ISO 7730 [28] and EN 16798-1 [29], and (right) adaptive thermal comfort based on ANSI/ASHRAE Standard 55-2010 [31].

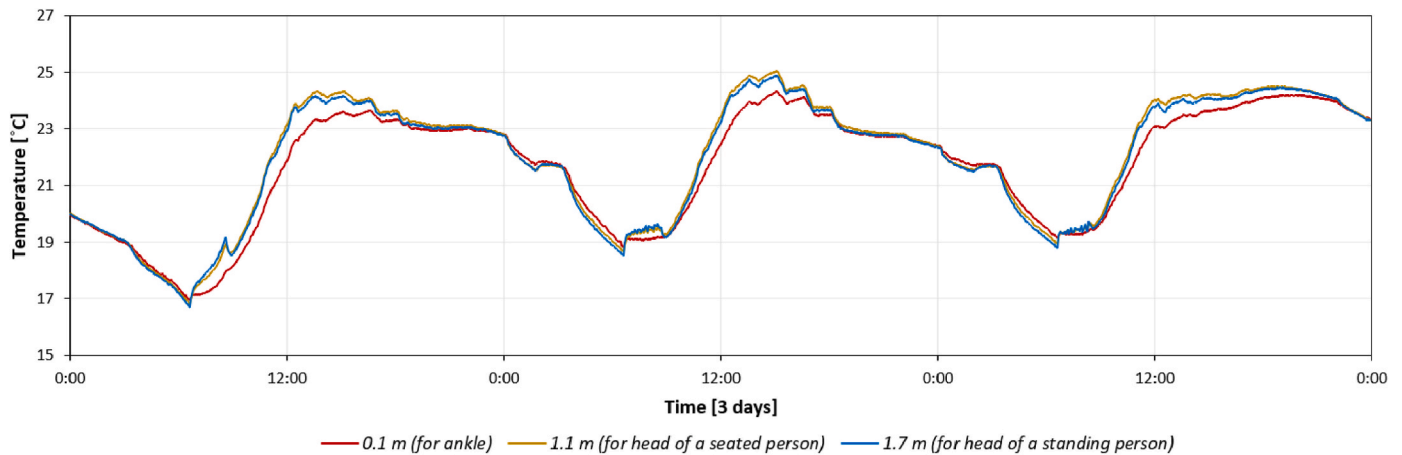


Fig. 11. Stratification assessment of indoor air temperature obtained at various heights.

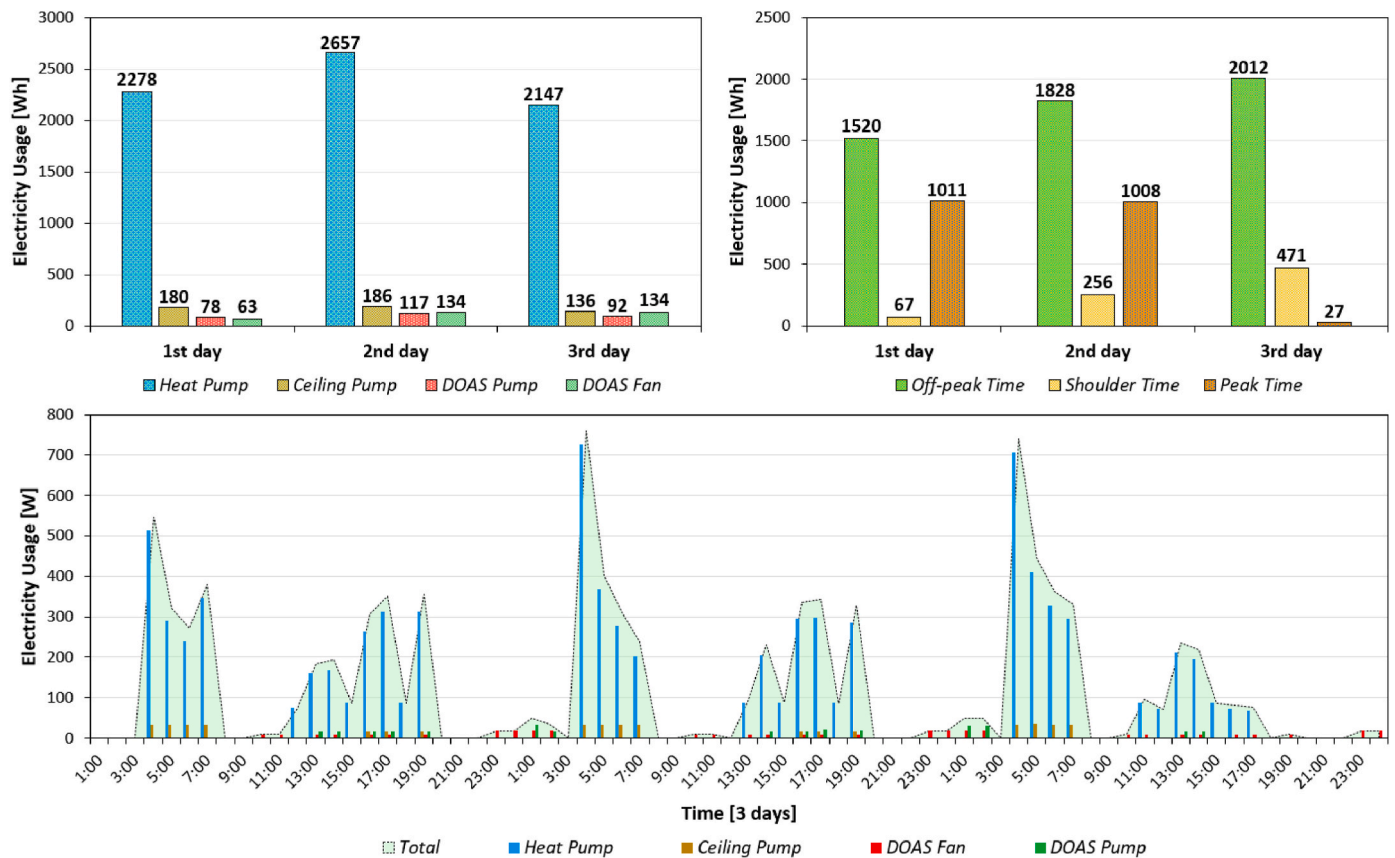


Fig. 12. Measured electricity usage of the proposed PCM-RCC: (top-left) the usage of system components per day, (top-right) the usage of the system in Victoria's TOU periods, and (bottom) hourly electricity usage of system components in 3 consecutive days.

3.5. Future outlook of PCM-RCC

PCM-RCC systems have been proposed as an innovative technology for space cooling in buildings, offering improved energy efficiency and flexibility compared to traditional cooling systems. However, the high initial cost of PCM products remains a challenge for the broader adoption of this technology. It is worth noting that the initial cost of new products under development is typically higher due to the research and development (R&D), manufacturing, and marketing costs involved. Nevertheless, as the technology becomes more popular and the production volume scales up, the cost of production can be reduced through economies of scale. Furthermore, technological advancements,

increased competition, and market forces can all contribute to reducing the cost of the product over time. In this context, it is expected that the cost of PCM products will gradually decrease as the number of manufacturers increases and the technology improves. The increased accessibility and affordability of PCM-RCC systems over the long term could lead to widespread adoption and significant energy savings in the building sector.

4. Conclusions

This study presented a new PCM-RCC technology developed for space cooling and discussed whether the technology's design and

operation are functioning as expected. Using a full-scale experimental setup, the study investigated the system's transient thermal behaviour and assessed its ability to provide the desired indoor thermal comfort and reduce peak electricity demand. Overall, the system could demonstrate satisfactory performance in daytime space cooling, effective load shifting from peak to off-peak time, and providing comfortable indoor thermal conditions. The findings and concluding remarks of this work are:

- Typically, 4–5 h of chilled water circulation overnight could fully recharge the PCM panels. Applying a thin plaster layer to the top surface of PCM panels sufficiently resolved the issue of low thermal contact between the PCM composite board and water capillary tubes. Further consideration of the type of water tubes used for PCM panels, is necessary to reduce water pressure drop and increase flow rates, thus shortening the recharge cycle overnight.
- The PCM ceiling surface had an average total heat transfer coefficient of $8.48 \pm 0.97 \text{ W m}^{-2} \cdot \text{K}^{-1}$, which complies with the relevant standards and guidelines.
- The thermal comfort analysis indicated that over 80% of the occupancy time (09:00 a.m.–07:00 p.m.) was within the “Class B” category of ISO 7730 (i.e., a range of ± 0.5 for PMV) or the 80% acceptability limits of adaptive comfort. The cabin overcooling in the early morning following the active recharge cycle was the main cause of thermal discomfort. Despite a heating provision, it was found that the capacity of the electric air heater was insufficient in addressing this issue.
- The present PCM-RCC system is effective in reducing peak electricity demand, with approximately 70% of daily electricity usage occurring during off-peak hours according to Victoria's ToU structure. The absence of a second cabin equipped with radiant ceiling panels without PCM limited the ability to compare the total energy usage of the systems with and without PCM. However, a validated simulation model revealed that removing PCM from the panels can increase the system's operating time by 45–50% during the day, confirming the PCM-RCC system's capability to shift peak cooling load to off-peak hours and provide load-shifting benefits.
- The high initial cost of PCM products is currently a barrier to the wider adoption of PCM-RCC systems, which is a common challenge faced by new products under development. However, the cost of production can be reduced through economies of scale and technological advancements, making PCM products more affordable over time. The expected decrease in the cost of PCM products as more manufacturers enter the market and the technology improves will increase the accessibility of PCM-RCC systems in the future.

CRedit authorship contribution statement

Syedmostafa Mousavi: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Behzad Rismanchi:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. **Stefan Brey:** Writing – review & editing, Resources, Funding acquisition. **Lu Aye:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization.

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.

Data availability

Data will be made available on request.

Acknowledgments

The authors would like to thank their industry partner, Invaus Pty Ltd, for preparing the test cabin. The authors are also grateful to Prof. Alessandro Toffoli for providing a high-performance thermal camera. This work was conducted within the Department of Infrastructure Engineering as a part of the PhD thesis of the first author, who has been supported by the University of Melbourne's Research Scholarship (MRS).

References

- [1] IEA, Space Cooling, International Energy Agency, Paris, France, 2022.
- [2] S. Mousavi, B. Rismanchi, S. Brey, L. Aye, PCM embedded radiant chilled ceiling: a state-of-the-art review, *Renew. Sustain. Energy Rev.* 151 (2021), 111601.
- [3] S. Mousavi, B. Rismanchi, S. Brey, L. Aye, Lessons learned from PCM embedded radiant chilled ceiling experiments in Melbourne, *Energy Rep.* 8 (2022) 54–61.
- [4] Y. Zhou, S. Zheng, G. Zhang, A review on cooling performance enhancement for phase change materials integrated systems—flexible design and smart control with machine learning applications, *Build. Environ.* 174 (2020), 106786.
- [5] IEA, The Future of Cooling, International Energy Agency, Paris, France, 2018.
- [6] IEA, Insights Brief: Space Cooling, International Energy Agency, Paris, France, 2017.
- [7] B. Ma, K. Wei, X. Huang, W. Shi, S. Chen, Y. Hu, et al., Preparation and investigation of NiTi alloy phase-change heat storage asphalt mixture, *J. Mater. Civ. Eng.* 32 (2020), 04020250.
- [8] W. Si, Y. Yin, Y. Hu, X. Kang, Y. Xu, A. Shi, et al., Analysis on factors affecting the cooling effect of optical shielding in pavement coatings, *Build. Environ.* 211 (2022), 108766.
- [9] W. Si, Y. Yin, D. Cao, Y. Hu, X. Kang, J. Liu, et al., Performance of a pavement optical coating prepared with tungsten bronze nanoparticle, *Constr. Build. Mater.* 340 (2022), 127700.
- [10] R. Mokhtari, R. Ghasempour, Feasibility study of integration of radiative cooling and hydronic radiant system for free cooling of single-family houses, *Appl. Therm. Eng.* 220 (2023), 119629.
- [11] M. Chen, D. Pang, X. Chen, H. Yan, Y. Yang, Passive daytime radiative cooling: fundamentals, material designs, and applications, *EcoMat* 4 (2022), e12153.
- [12] M. Anici, F. Bilgin, S. Nizetic, H. Karabay, PCM integrated to external building walls: an optimization study on maximum activation of latent heat, *Appl. Therm. Eng.* 165 (2020), 114560.
- [13] A.I.N. Korti, F.Z. Tlemsani, Experimental investigation of latent heat storage in a coil in PCM storage unit, *J. Energy Storage* 5 (2016) 177–186.
- [14] B. Ma, Y. Hu, W. Si, K. Wei, X. Chang, Study on the temperature control effects of an epoxy resin composite thermoregulation agent on asphalt mixtures, *Construct. Build. Mater.* 257 (2020), 119580.
- [15] M. Koschensch, B. Lehmann, Development of a thermally activated ceiling panel with PCM for application in lightweight and retrofitted buildings, *Energy Build.* 36 (2004) 567–578.
- [16] G.K. Pavlov, Building Thermal Energy Storage, Technical University of Denmark, 2014.
- [17] H. Weinläder, F. Klinker, M. Yasin, PCM cooling ceilings in the energy efficiency center-regeneration behaviour of two different system designs, *Energy Build.* 156 (2017) 70–77.
- [18] M.I. Jobli, R. Yao, Z. Luo, M. Shahrestani, N. Li, H. Liu, Numerical and experimental studies of a capillary-tube embedded PCM component for improving indoor thermal environment, *Appl. Therm. Eng.* 148 (2019) 466–477.
- [19] D.-I. Bogatu, O.B. Kazanci, B.W. Olesen, An experimental study of the active cooling performance of a novel radiant ceiling panel containing phase change material (PCM), *Energy Build.* 243 (2021), 110981.
- [20] A. Gallardo, U. Berardi, Experimental evaluation of the cooling performance of radiant ceiling panels with thermal energy storage, *Energy Build.* 262 (2022), 112021.
- [21] J. Skovajsa, P. Drabek, S. Sehnalek, M. Zalesak, Design and experimental evaluation of phase change material based cooling ceiling system, *Appl. Therm. Eng.* 205 (2022), 118011.
- [22] S. Mousavi, B. Rismanchi, S. Brey, L. Aye, Development and validation of a transient simulation model of a full-scale PCM embedded radiant chilled ceiling, *Build. Simulat.* (2023), <https://doi.org/10.1007/s12273-023-0985-5>.
- [23] C.L. Conroy, S.A. Mumma, Ceiling radiant cooling panels as a viable distributed parallel sensible cooling technology integrated with dedicated outdoor air systems, *Build. Eng.* 107 (2001) 578–585.
- [24] S.A. Mumma, Condensation issues with radiant cooling panels, *ASHRAE IAQ Applic.* (2001) 16–18.
- [25] J. Niu, J.V.D. Kooi, H.V.D. Ree, Cooling load dynamics of rooms with cooled ceilings, *Build. Serv. Eng. Res. Technol.* 18 (1997) 201–207.
- [26] P.O. Fanger, Thermal Comfort. Analysis and Applications in Environmental Engineering, Danish Technical Press, Copenhagen, Denmark, 1970.
- [27] T. Cheung, S. Schiavon, T. Parkinson, P. Li, G. Brager, Analysis of the accuracy on PMV-PPD model using the ASHRAE global thermal comfort database II, *Build. Environ.* 153 (2019) 205–217.
- [28] ISO, ISO 7730: Ergonomics of the Thermal Environment — Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the

- PMV and PPD Indices and Local Thermal Comfort Criteria, International Organization for Standardization, Geneva, Switzerland, 2005.
- [29] CEN, EN 16798-1: Energy Performance of Buildings — Ventilation for Buildings — Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics (Module M1-6), European Committee for Standardization, Brussels, Belgium, 2019.
- [30] F. Tartarini, S. Schiavon, T. Cheung, T. Hoyt, CBE thermal comfort tool: online tool for thermal comfort calculations and visualizations, *SoftwareX* 12 (2020), 100563.
- [31] ANSI/ASHRAE, Standard 55-2010: Thermal Environmental Conditions for Human Occupancy, American Society of Heating, Refrigerating and Airconditioning Engineers, Atlanta, 2010.
- [32] R. de Dear, G. Brager, D. Cooper, Developing an Adaptive Model of Thermal Comfort and Preference - Final Report on RP-884, MRL, Sydney, 1997.
- [33] EVO, International Performance Measurement and Verification Protocol: Statistics and Uncertainty for IPMVP, Efficiency Valuation Organization (EVO), 2014.
- [34] JCGM, Evaluation of Measurement Data-An Introduction to the 'Guide to the Expression of Uncertainty in Measurement' and Related Documents, Joint Committee for Guides in Metrology, 2009, pp. 1–20.
- [35] R.J. Moffat, Describing the uncertainties in experimental results, *Exp. Therm. Fluid Sci.* 1 (1988) 3–17.
- [36] J. Shinoda, O.B. Kazanci, S-i Tanabe, B.W. Olesen, A review of the surface heat transfer coefficients of radiant heating and cooling systems, *Build. Environ.* 159 (2019), 106156.