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Development and validation of a transient simulation model of a full-scale PCM embedded radiant chilled ceiling

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Abstract

The recent significant rise in space cooling energy demand due to the massive use of air-conditioning systems has adversely changed buildings' energy use patterns globally. The updated energy technology perspectives highlight the need for innovative cooling systems to address this growing cooling demand. Phase change material embedded radiant chilled ceiling (PCM-RCC) has lately acquired popularity as they offer more efficient space cooling together with further demand-side flexibility. Recent advancements in PCM-RCC applications have increased the necessity for reliable simulation models to assist professionals in identifying improved designs and operating settings. In this study, a transient simulation model of PCM-RCC has been developed and validated using measured data in a full-scale test cabin equipped with newly developed PCM ceiling panels. This model, developed in the TRNSYS simulation studio, includes Type 399 that uses the Crank-Nicolson algorithm coupled with the enthalpy function to solve transient heat transfer in PCM ceiling panels. The developed model is validated in both free-running and active operation modes, and its quality is then evaluated using several validation metrics. The results obtained in multiple operating scenarios confirm that the model simulates the transient behaviour of the PCM-RCC system with an accuracy within $\pm 10\%$. Aided by this validated model, which offers the user detailed flexibilities in the system design and its associated operating schemas, PCM-RCC's potentials regarding peak load shifting, energy savings, and enhanced thermal comfort can be investigated more reliably.

Keywords

phase change material (PCM);
radiant cooling;
ceiling panel;
modelling and simulation;
validation

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1 Introduction

Active radiant chilled ceilings (RCC) combined with phase change materials (PCMs), hereinafter called PCM-RCC, is an innovative cooling technology that has acquired much popularity in recent years in response to the significant increase in space cooling energy demand in buildings (IEA 2022; Mousavi et al. 2022). This technology, with the advantages of lower energy consumption, higher level of indoor environmental quality (IEQ), and peak load shifting, delivers more efficient space cooling (10%–40%) together with greater demand-side flexibility as compared to traditional air-conditioning systems (ACs) (Bogatu et al. 2021; Singh et al. 2021). Classifications, working principles, as well as

potential of PCM-RCC systems in terms of energy savings, load shifting, and thermal comfort can be found in Mousavi et al. (2021).

Considering the technology pathway, PCM-RCC is expected to transition from “*In Development*” to the “*Limited Availability*” phase (DOE 2021). Various types of PCM products are also commercially available, with new ones on the way to the market (Kalnæs and Jelle 2015). However, from what is found in the literature and the relevant community discussions, there are still debates regarding the approaches to design, implementation, and control of PCM-RCC systems, making professionals and decision-makers hesitant to use the technology. These concerns need to be credibly addressed to speed up the

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Nomenclature

Symbols

C_p	specific heat capacity [$\text{kJ kg}^{-1} \text{K}^{-1}$]
d	diameter [m]
dx	pipe spacing [m]
H	specific enthalpy [J kg^{-1}]
k	thermal conductivity [$\text{kJ hr}^{-1} \text{m}^{-1} \text{K}^{-1}$]
L	latent heat of fusion [J kg^{-1}]
$\dot{m}$	mass flow rate of water [kg hr^{-1}]
$\dot{Q}$	energy gain [kJ hr^{-1}]
R_p	thermal resistance of pipe [K W^{-1}]
R_w	thermal resistance of water [K W^{-1}]
R_x	thermal resistance of pipe spacing [K W^{-1}]
R_z	thermal resistance of panel depth [K W^{-1}]
Re	Reynolds number [—]
t	time [s]
T	temperature [K]
β	PCM liquid fraction [—]
δ	thickness [m]

Subscripts

Conv	convection
hf	heat flux
in	inner
l	active layer
out	outer
p	pipe
pw	pipe wall
rad	radiation

S	surface
w	water

Abbreviations

AC	air-conditioning system
ACH	air change rate
AEST	Australian Eastern Standard Time
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
ASTM	American Society for Testing and Materials
CC	correlation coefficient
CI	confidence interval
FDM	finite difference method
HF	heat flux
IEQ	indoor environmental quality
IES	Illuminating Engineering Society
M&S	modelling and simulation
NMBE	normalised mean bias error
PCM	phase change material
RCC	radiant chilled ceiling
RH	relative humidity
CVRMSE	coefficient of variation of the root mean squared error
RTD	resistance temperature detector
TABS	thermally activated building system
TRNSYS	TRaNsient SYstems Simulation program
2D	two-dimensional
3D	three-dimensional

acceptance of PCM-RCC systems in the building and construction sector.

Modelling and simulation (M&S) is always an essential element in quantifying different aspects of the technology performance under diverse scenarios and climatic conditions (Birta and Arbez 2013). It enables professionals to make informed design decisions and acquire confidence that the technology's design and operation are functioning as expected (González and Bandera 2022; Wang et al. 2022). In conjunction with experimental analyses, M&S also provides supplementary data to aid troubleshooting and most importantly, to reduce the cost of experiments and/or product redesign (Wetter 2009). Thus, a validated PCM-RCC simulation model is not only desired but crucial for the uptake of the technology.

Despite broad interest in PCM-RCC systems in academia and industry, developing a simulation model that has been validated using full-scale experiments in realistic climatic

conditions remains a challenge. Several research groups performed simulation-based investigations on PCM-RCC performance. However, the models employed in their studies were not validated. For example, Tzivanidis et al. (2012) applied the three-dimensional (3D) finite difference method (FDM) to solve relevant heat transfer equations in order to predict the thermal behaviour of a PCM-RCC system. They selected the effective thermal capacity method to simulate the PCM phase change process. Bourdakos et al. (2016) developed a software-based model to assess the performance of a PCM-RCC system coupled with solar collectors. A two-person office space with PCM ceiling panels was simulated in their study. Using a mathematical model, Zhang et al. (2017) described the two-dimensional (2D) heat transfer process of a PCM ceiling panel with capillary water tubes. In this model, steady indoor air and surface temperatures were assumed. Rucevskis et al. (2019) macroscopically modelled the phase change phenomenon

in PCM panels using the effective thermal capacity method in the ANSYS Fluent software. The authors also presumed that PCM behaviour remains consistent in both melting and freezing paths. Allerhand et al. (2019) simulated the thermal environment of an office room equipped with PCM ceiling panels using TRNSYS 17. They concluded that full-scale experiments are highly required for validating the developed model and widening its applicability in building energy performance assessments.

Koschenz and Lehmann (2004) and Jobli et al. (2019) presented validated PCM-RCC models in their works; however, measured data from laboratory-scale test setups were used for the model validations. A few researchers monitored the real-scale data to evaluate their simulation models. Pavlov (2014) and Bourdakos et al. (2015) obtained experimental data from a test chamber that was not exposed to the real-world outdoor environment. Indeed, the actual patterns of ambient temperatures, solar radiations, cloud cover, relative humidity (RH), wind speed/direction, etc., that can affect the system performance, in reality, was not taken into account. Yang et al. (2016) simulated finned tubes filled with PCM which were hung beneath the ceiling. No radiant ceiling panel system was used in their study. A validated model was also presented by Yasin et al. (2019). Their proposed method for equivalent cross-section modelling of ceiling panels, although was creative, required laboratory facilities and extra measurements. In case of modifying PCM panel design, where PCM type, PCM layer thickness, pipe spacing, and so on probably change, those initial laboratory tests must be repeated, limiting the use of their developed model. Using Type 1270 in TRNSYS, Skovajsa et al. (2022) recently developed a PCM-RCC model validated with measurements in a compensated chamber. Type 1270 simulates PCM behaviour using a basic constant-temperature phase change method that ignores PCM hysteresis and variable thermal conductivity. Additionally, this type is unable to model water tubes embedded in PCM layers (Mousavi et al. 2021).

The relevant literature study and community discussions have revealed the lack of a simulation model of PCM-RCC systems that has undergone a detailed validation procedure based on full-scale experiments in different operational modes under realistic climatic conditions. As stated earlier, such a validated model is essential for conducting credible research on numerous facets of the development and implementation of this technology. To this end, the current paper aims to create a transient simulation model of PCM-RCC in TRNSYS 18 and validate it using a full-scale experimental setup. The main objectives of this research, reflecting the novelty and major contributions, are summarised as follows:

- To develop and validate a real-scale test cabin model

equipped with a newly developed PCM-RCC technology using four most influential variables of the system in both free-running and active operation modes under real-world ambient conditions.

- To evaluate the model's capability in simulating the non-linear behaviour of PCM panels in charge and discharge cycles over ten consecutive summer days with varying operational schedules. It is crucial to ensure how the model satisfactorily simulates the system behaviour for long-term operation under diverse operating scenarios and climatic conditions.
- To develop a PCM-RCC model with a high degree of details and flexibilities that can be used for further investigations on the technology design and its control strategy implementations.

In the following sections, the experimental setup and its components are described. Next, the modelling of this test setup and the PCM-RCC system in TRNSYS is explained in detail, and the validation workflow for quality assessment of the developed model is presented. In Section 3, simulation and validation results of the whole system in both free-running and active modes of PCM-RCC operations are presented and discussed. Section 4 also describes the application of the developed PCM-RCC model for future investigations of the technology. Finally, Section 5 summarises the key findings of this study.

2 Method

2.1 Experimental setup description

2.1.1 Real-scale test cabin

A real-scale stand-alone cabin equipped with the PCM-RCC system is established at the University of Melbourne (37.83° S, 145.02° E). As shown in Figure 1, the cabin with a conditioned volume of 96.7 m³ and a total floor area of 31.7 m² is directly exposed to real-world conditions, resembling a particular unit of a modern building. An advanced closed-cavity façade with a total U -value of around 2 W·m⁻²·K⁻¹ and a vision area of 13.5 m² is employed. R4.8 and R4.3 sandwich panels with natural air-filled cells are used for the cabin envelopes to deliver exceptional thermal and fire performance. Galvanised corrugated roof sheets and 45-mm-thick Rockwool insulation are also used for the roof and floor, respectively. Additionally, the gaps in the cabin structure are also filled by expanding foam and insulation material, and all joints are carefully sealed.

2.1.2 Taphcore® PCM ceiling panels

For the current PCM-RCC system, Taphcore® shape-stabilised organic PCM composite boards, laminated to

a 1.5-mm-thick aluminium tray, are used (see Figure 2). Characteristics of the Taphcore[®] PCM ceiling panel are listed in Table 1. Figure 3 also shows its enthalpy per unit mass ($\text{kJ}\cdot\text{kg}^{-1}$) and specific heat capacity ($\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$), measured based on ASTM C1784-14 standard.

By installing 24 panels in eight parallel rows, approximately 60% of the overall ceiling area of the cabin is covered by PCM-RCC panels. As seen in Figure 2, the chilled water circulates within capillary tubes embedded into the panels for PCM recharge purposes. An insulation layer covers

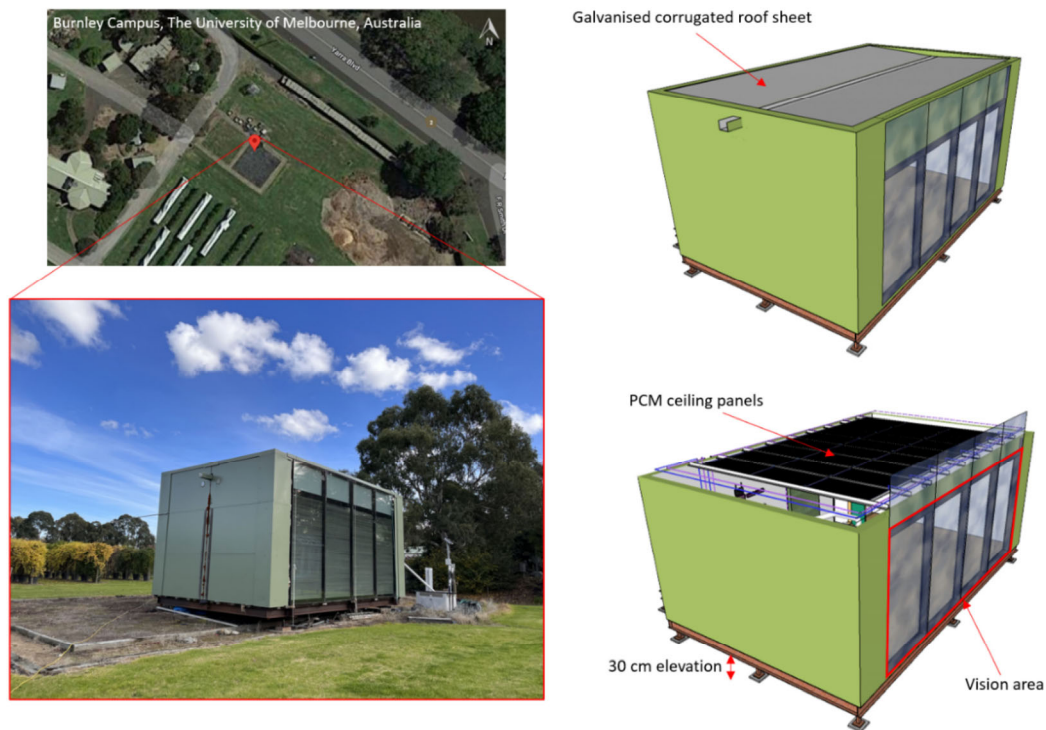


Fig. 1 The test cabin employed for the PCM-RCC experiments

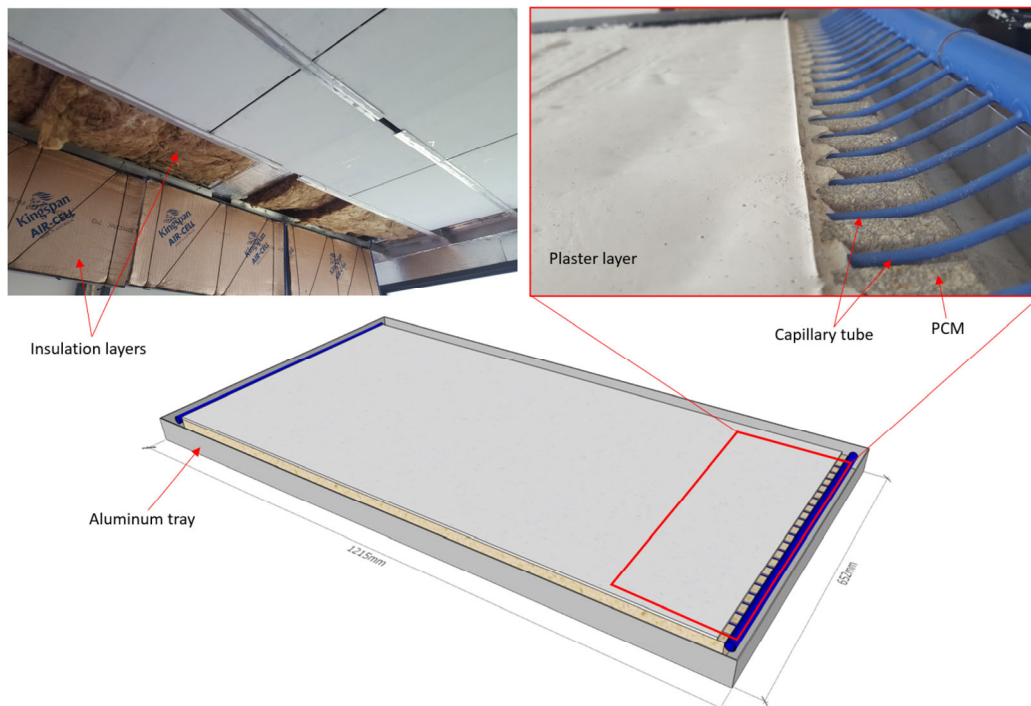


Fig. 2 The PCM ceiling panel: construction details and panel layout in the ceiling

Table 1 Characteristics of the Taphcore[®] PCM ceiling panels

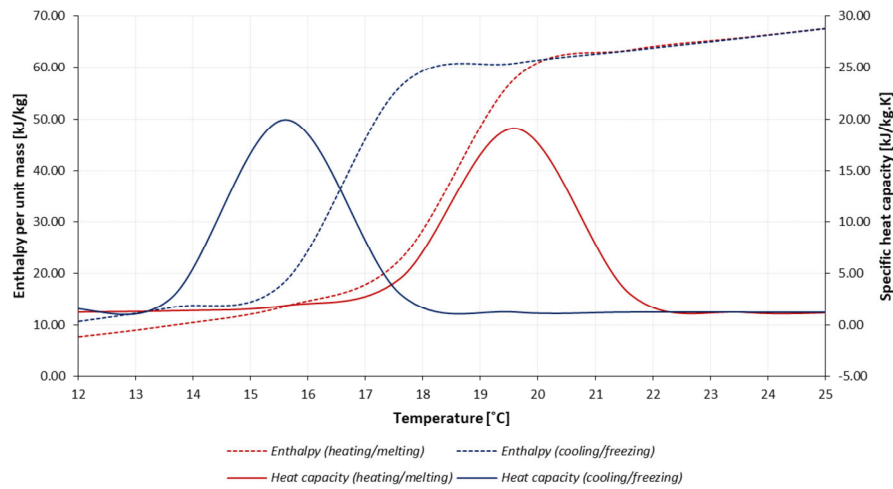
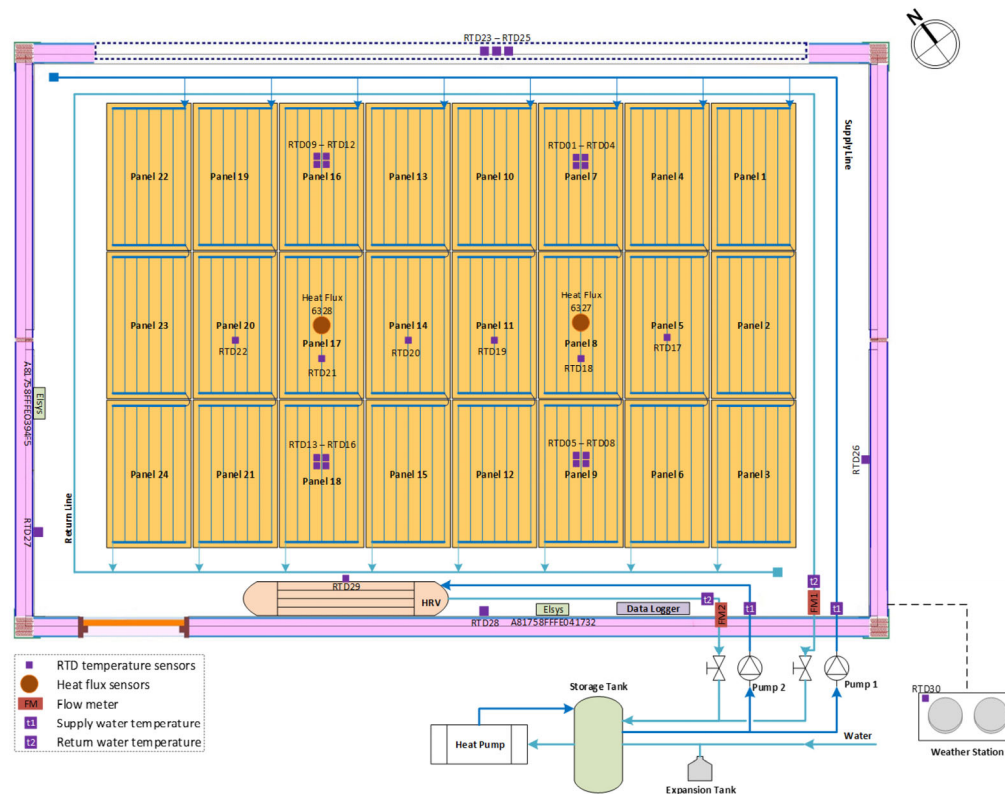
Parameter	Value [unit]
Dimension	121.5 L × 65.2 W × 2.5 D [cm]
Density	765 [kg·m ⁻³]
Phase change range	15.6–19.6 [°C]
Latent heat capacity	900 [kJ·m ⁻²]
Thermal conductivity*	(Solid phase) 1.02 [W·m ⁻¹ ·K ⁻¹] (Liquid phase) 0.68 [W·m ⁻¹ ·K ⁻¹]

* Thermal conductivity was measured using a C-Therm analyser with ±5% uncertainty.

the top surface of the panel, reducing heat transfer energy losses to the roof.

2.1.3 Chilled water distribution unit

A schematic of the hydronic system and PCM panel layouts in the cabin is indicated in Figure 4. Chilled water is pumped to the ceiling and circulates through the panels to remove PCM heat, and then returns to the storage tank to be re-chilled. All pipes and fittings used for the supply and return lines are fully insulated to prevent heat transfers from the surroundings.

**Fig. 3** Measured thermal storage and specific heat capacity of the Taphcore[®] PCM board**Fig. 4** Hydronic system and the layout of PCM ceiling panels used in the test cabin

2.1.4 Real time data acquisition

The test cabin is equipped with multiple sensors and data logging devices to measure and collect necessary variables for the PCM-RCC model validation. These variables are classified into four main categories as presented in Table 2. It is also worth mentioning that all temperature sensors are calibrated to $\pm 0.1^\circ\text{C}$ prior to the experiments. The other devices are either self calibrated or factory calibrated.

2.2 Experiment schedules

To fully validate the thermal zone and PCM-RCC models developed in TRNSYS, two modes of system operation have been considered for experiments. Table 3 shows experiment schedules and the relevant operating conditions. In the free-running (or passive) mode, all PCM-RCC components are inactive, allowing PCM panels to absorb interior sensible heat during the day (PCM discharging) and reject it overnight (PCM charging) using no auxiliary systems. The free-running mode is beneficial for the validation of the developed cabin zone model and all of its geometry and non-geometry information before including PCM-RCC active operation in the simulation. Furthermore, two different operating schedules have been defined for the active mode to validate the thermal zone and PCM-RCC models during charge-discharge cycles under varied conditions. In Schedule 1, the PCM recharge cycle runs from 02:00 a.m. to 07:00 a.m. To recharge (solidify) PCMs during this time, chilled water with a setpoint of 10°C and a flow rate of around $470\text{ L}\cdot\text{hr}^{-1}$ circulates through the ceiling panels. The system controller additionally restricts the minimum temperature of panel surfaces at 13°C to prevent chilling below the dewpoint. PCM panels are then discharged (melted) during the day by absorbing indoor sensible heat. Schedule 2 also follows the same operating settings; however, the recharging cycle occurs between the hours of 07:00 a.m. and 12:00 p.m.

2.3 Development of TRNSYS models

Different simulation tools have been employed in recent years to simulate PCM-enhanced structures (Mousavi et al. 2021). Here, TRNSYS is used due to its capability in modelling transient thermal behaviour of building energy systems as well as detailed radiative exchanges and occupant comfort (Belmonte et al. 2015; Klein et al. 2017).

TRNSYS, which is a type-based simulation program, models the thermal behaviour of building envelopes based on conduction transfer and response function approaches developed by Stephenson and Mitalas (1971). These algorithms, however, are not applicable to model building structures

Table 2 Categories of measured variables for PCM-RCC model validation

Measurement category	Measured variable
PCM ceiling panel	PCM temperature Panel heat transfer rate
Cabin indoor environment	Cabin operative temperature Surface temperature Relative humidity (RH)
Hydronic unit	Water flow rate Supply chilled water temperature Return water temperature
Weather station	Ambient temperature Global and reflected solar radiation Upwelling and downwelling longwave radiation Sky temperature Outdoor RH Wind speed/direction

Table 3 Validation-related experiment schedules and their operating conditions

Mode	Operating condition
Free running mode	PCM-RCC is out of operation for whole day
Active mode	Schedule 1: PCM-RCC operates from 02:00 a.m. to 07:00 a.m. Schedule 2: PCM-RCC operates from 07:00 a.m. to 12:00 noon

containing PCMs or other materials with non-constant, time-invariant thermophysical characteristics (Claros-Marfil et al. 2014). To overcome this issue, various types have been developed in TRNSYS to simulate PCM layers in building envelopes (Mousavi et al. 2021). Since PCM-RCC systems are actively operated with chilled water circulated within tubes during the recharge cycle, a type with the ability to model PCM layers with embedded tubes is required. This requirement is satisfied by Type 399, developed by Dentel and Stephan (2013).

Type 399 uses the Crank-Nicolson finite difference algorithm coupled with the enthalpy function to model and solve transient heat transfer in a building structure with PCM (Figure 5). In this approach, the number of nodes considered for each structure layer can be adjusted based on its thickness to achieve the stability criteria and efficient simulation times (Claros-Marfil et al. 2014). In Type 399, the enthalpy method, which is able to predict the details of PCM's nonlinear behaviour during the phase change process, is formulated as follows (Swaminathan and Voller 1992, 1993):

$$\frac{\partial}{\partial t} \rho H = \frac{\partial}{\partial x_i} \left(k \frac{\partial T}{\partial x_i} \right) \quad (1)$$

where H denotes the specific enthalpy [$\text{J}\cdot\text{kg}^{-1}$], t is time [s], k is the thermal conductivity of PCM [$\text{kJ}\cdot\text{hr}^{-1}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$], and

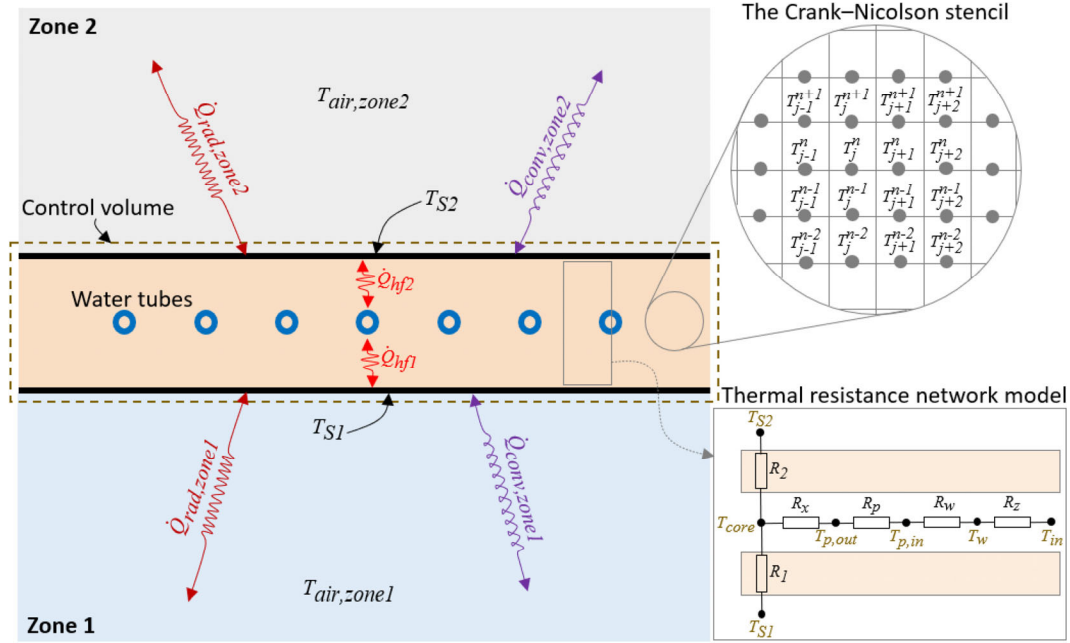


Fig. 5 Schematic of energy balance in PCM ceiling panels with water tubes, plus the Crank-Nicolson method and star resistance network model used in TRNSYS Type 399 (note: the definition and unit of each parameter are presented in the Nomenclature section)

T is the temperature [K]. H , as seen in Eq. (2), is the sum of sensible heat (h) and latent heat (ΔH) of PCM (Voller and Prakash 1987; Voller et al. 1989):

$$H(T) = h(T) + \Delta H(T) = \int_T^{T_{low}} C_{p,solid} dT + \beta L + \int_{T_{up}}^T C_{p,liquid} dT \quad (2)$$

In which, C_p is the specific heat capacity of PCM [$\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$], L is the latent heat of fusion [$\text{J}\cdot\text{kg}^{-1}$], and T_{low} and T_{up} are lower and upper phase change temperatures, respectively. Also, β is the liquid fraction [—] (Voller et al. 1987; Voller and Swaminathan 1991):

$$\beta = \begin{cases} 0 & \text{if } T < T_{low} \quad (\text{Solid phase}) \\ \frac{T - T_{low}}{T_{up} - T_{low}} & \text{if } T_{low} < T < T_{up} \quad (\text{Mushy phase}) \\ 1 & \text{if } T > T_{up} \quad (\text{Liquid phase}) \end{cases} \quad (3)$$

Therefore, PCM enthalpy is calculated as follows:

$$\text{Solid phase: } H(T) = C_{p,solid} T \quad (4)$$

$$\text{Mushy phase: } H(T) = C_{p,solid} T_{low} + \frac{T - T_{low}}{T_{up} - T_{low}} L \quad (5)$$

$$\text{Liquid phase: } H(T) = C_{p,solid} T_{low} + L + C_{p,liquid} (T - T_{up}) \quad (6)$$

As found in the mentioned equations and indicated in Figure 6, Type 399 takes into account the PCM phase (i.e., fully solid, mushy, or fully liquid) as well as the energy flow

(cooling down or heating up) in each time step of phase change modelling to decrease inaccuracies in simulation results. Indeed, this type employs two external files, including C_p values of PCM in both heating and cooling paths, to consider the phase transition hysteresis, which is a typical characteristic of different PCMs (Claros-Marfil et al. 2014).

Type 399, on the other hand, is capable of simulating PCM-RCC systems in both passive and active operating modes. In the active mode, the embedded piping system is modelled using a thermal resistance network proposed by Koschenz and Lehmann (2000). As shown in Figure 5, the water supply temperature in the piping system is linked to the core temperature of the active layer and zones temperatures using single resistances in a star network model. In addition, Type 399 calculates the Reynolds number (Re) and automatically distinguishes between the capillary tube system ($Re \leq 2300$) and thermally activated building system or TABS ($Re > 2300$). It then applies specified sets of equations and assumptions for each piping configuration (Claros-Marfil et al. 2014). Here, Re is calculated as 2290, confirming that capillary tubes are considered for the simulation, as what have been used in Taphcore[®] PCM ceiling panels. Table 4 also presents the resistance network equations used for current PCM panels with embedded capillary tubes.

In this work, the TRNSYS3D plug-in for SketchUp is used to create a thermal model for the test cabin. Since the installed PCM panels do not cover the whole ceiling of the cabin, as shown in Figure 7–top, it is separated into two surfaces in order to predict more realistic cooling performance

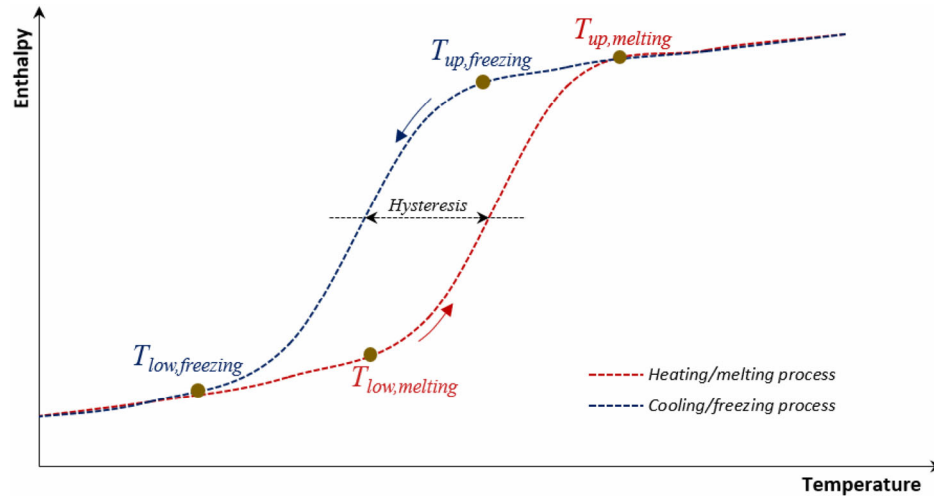


Fig. 6 Specific enthalpy as a function of PCM temperature in heating/melting and cooling/freezing processes

Table 4 Thermal resistance equations in PCM panels with embedded capillary tubes (Claros-Marfil et al. 2014) (Note: The definition and unit of each parameter are presented in the Nomenclature section)

Thermal resistance	Equation	Eq. No.
Panel depth thermal resistance	$R_z = \frac{1}{2\dot{m}C_{p,w}}$	(7)
Water thermal resistance	$R_w = \frac{dx}{\pi k_w} \left(49.03 + \frac{16.68\dot{m}C_{p,w}dx}{\pi k_w} \right)^{\frac{1}{3}}$	(8)
Pipe thermal resistance	$R_p = \frac{dx \log\left(\frac{d_p}{d_p - 2\delta_{pw}}\right)}{2\pi k_p}$	(9)
Pipe spacing thermal resistance	$R_x = \frac{\frac{dx}{3} \left(\frac{dx}{\pi d_p} \right)}{2\pi k_i}$	(10)

of PCM ceiling panels. Additionally, as mentioned in Section 2.1.2, there are eight parallel rows of PCM panels installed in the cabin; thus, the PCM ceiling surface is split into eight corresponding sections, providing more control over PCM-RCC potential assessments under various operating scenarios later on. Once the geometry features of all surfaces have been established, the model is then imported into the TRNSYS simulation studio. The building's North-to-East rotation is determined to be +37° using the geo-location tools. In the TRNSYS assembly (see Figure 7–bottom), a multi-zone building (Type 56) is linked to Type 399 and other necessary modules (i.e., data readers, radiation processors, equations, control signals, and graphical-numerical outputs). The meteorological data measured during the period of experiments are used for the model development and validation. Figure 8 shows boundary conditions, inputs, their values as well as connections between Types 56 and 399 used

in the current simulations. In addition, all parameters except dimensions of the cabin model are modified in the TRNBuild. Table 5 lists the thickness and properties for each layer of the cabin model. The uncontrolled air leakage, a.k.a. infiltration, is also specified in accordance with ANSI/ASHRAE/IES Standard 90.1-2016 (Goel et al. 2017). Moreover, the air change rate (ACH) of the cavity zone under the cabin is derived using the method proposed by Langmans et al. (2015).

2.4 Model validation workflow

A flow chart of the validation workflow is presented in Figure 9. By comparing the simulation results with the experimental data in both free-running and active modes of PCM-RCC operation, the accuracy of the developed TRNSYS model is evaluated. The most important variables used for validation are the cabin operative (globe) temperature, PCM ceiling surface temperature, PCM panel heat flux, and the heat extracted from the ceiling through water circulation. Here, as ASHRAE Guideline 14:2002 (ASHRAE 2002) recommended, the coefficient of variation of the root mean square error (CVRMSE), normalised mean bias error (NMBE), and correlation coefficient (CC) are used to assess the quality of the simulation model (EVO 2019; Shah 2019):

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (m_i - s_i)^2}{n}} \quad (11)$$

$$CV(RMSE) = \frac{RMSE}{m_{mean}} \times 100 (\%) \quad (12)$$

$$MBE = \frac{\sum_{i=1}^n (m_i - s_i)}{n} \quad (13)$$

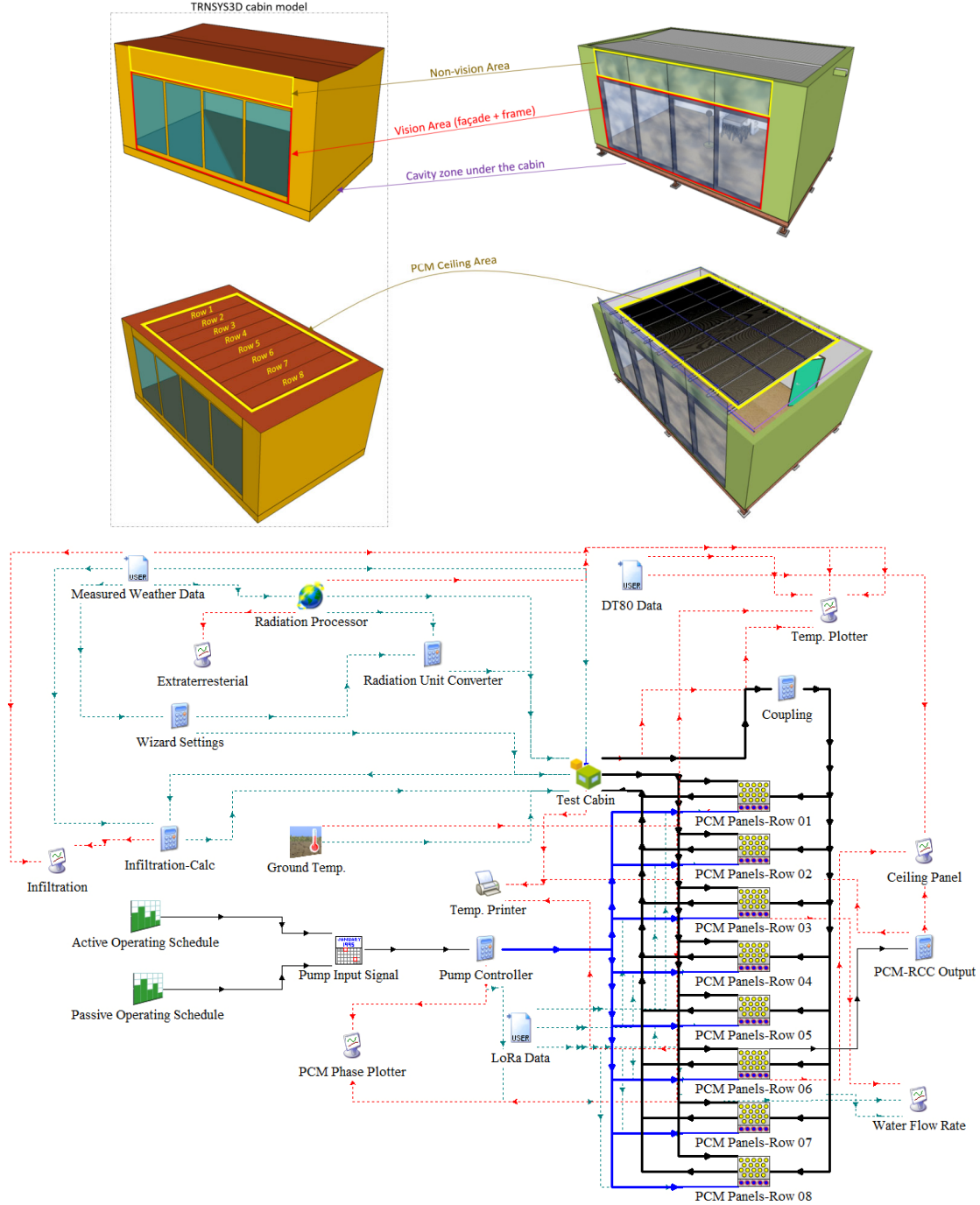


Fig. 7 (top) 3D test cabin thermal model in TRNSYS3D, (bottom) TRNSYS assembly layout developed for the validation

$$NMBE = \frac{MBE}{m_{\text{mean}}} \times 100 (\%) \quad (14)$$

$$CC = \frac{\sum_{i=1}^n [(s_i - s_{\text{mean}})(m_i - m_{\text{mean}})]}{\sqrt{\sum_{i=1}^n (s_i - s_{\text{mean}})^2 \cdot \sum_{i=1}^n (m_i - m_{\text{mean}})^2}} \quad (15)$$

where s_i and m_i are the simulated and measured values at i^{th} time step, respectively, n is the total number of time steps, and the subscript “mean” shows the mean values of data.

Lower RMSE values refer to better agreements between simulated and measured data. Positive values in MBE mean overestimation, whereas negative values show an underestimation of the model. CC also presents the strength of correlation between measured and simulated data, showing a perfect positive correlation if $CC = 1$ and a perfect negative correlation when $CC = -1$. Table 6 shows the thresholds for the aforementioned metrics based on ASHRAE Guideline 14:2002.

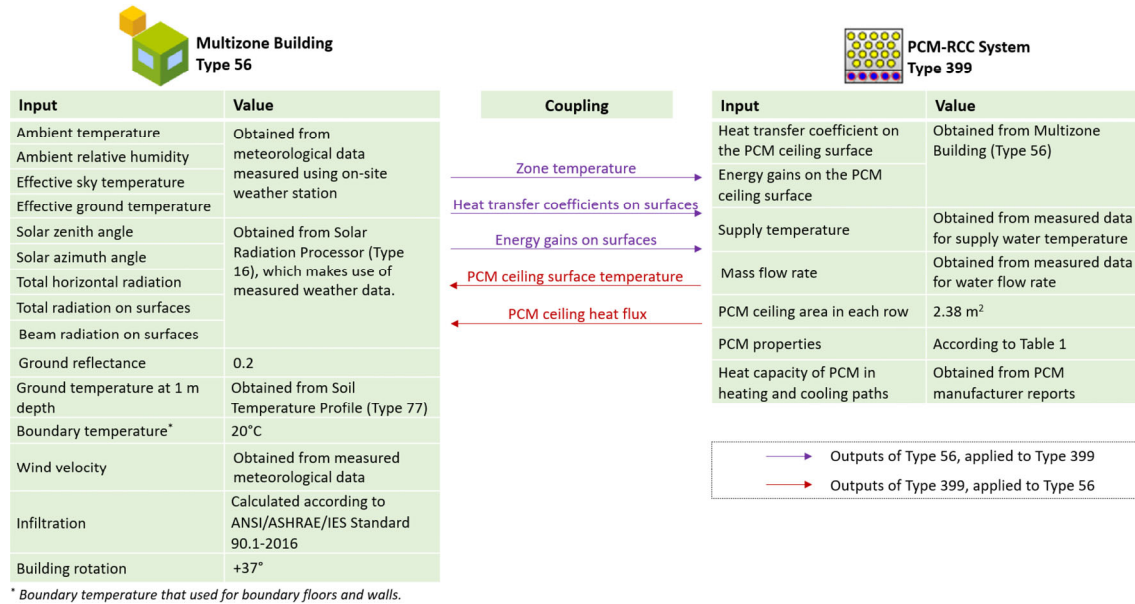


Fig. 8 Boundary conditions, inputs, outputs, and couplings of Types 56 and 399 used in the current simulations

Table 5 Thickness and properties for each layer of the test cabin model

	Layer No.	Description	Thickness [mm]	Conductivity [kJ/(hr·m·K)]	R-value [hr·m ² ·K/kJ]	Density [kg/m ³]	Capacity [kJ/(kg·K)]
External wall-1	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
External wall-2	1 (inside)	Foilboard	0.04	0.038	—	15	1.25
	2	Aluminium sheet	0.001	720	—	2700	0.86
	3	Low-density polyethylene	0.004	1.2	—	920	2.1
	4	Aluminium sheet	0.001	720	—	2700	0.86
	5	Airspace	—	—	0.044	—	—
	6 (outside)	Façade glass	0.0057	3.6	—	2500	0.75
Floor	1 (inside)	Yellow tongue particleboard	0.019	0.432	—	680	1.45
	2	Rockwool blanket	—	—	0.39	—	—
	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
External 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	Airspace	—	—	0.044	—	—
	5 (outside)	Roof sheet	0.001	54	—	7800	1.8

3 Results and discussions

3.1 Validation for the free-running mode

The validation workflow, as stated earlier, comprises two

stages. The first stage aims to validate the test cabin in the free-running mode, in which PCM panels are passively used with no water circulation. Indeed, it tries to validate the cabin zone model itself and all of its geometry (e.g., cabin structure) and non-geometry (e.g., infiltration) information before introducing PCM-RCC operation in the simulation.

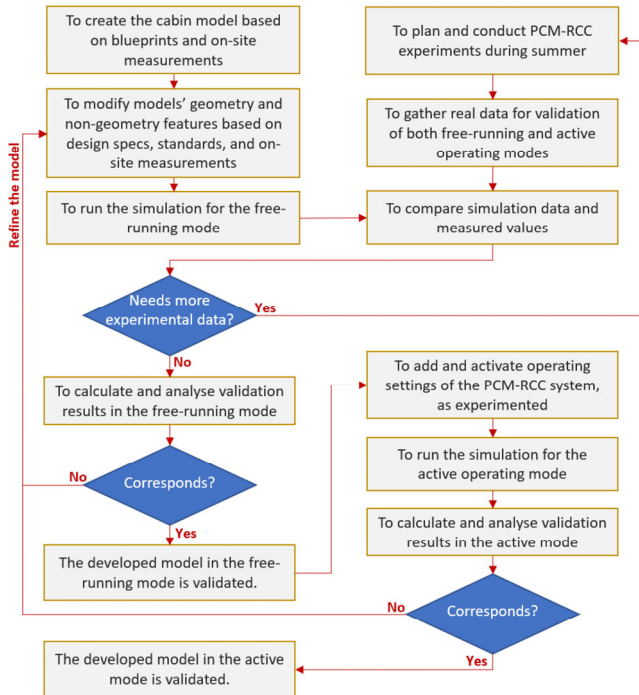


Fig. 9 A workflow for the validation of the developed TRNSYS simulation model

Table 6 Recommended ranges of validation metrics based on ASHRAE guideline 14:2002 (ASHRAE 2002)

Validation time step	Metric	ASHRAE threshold
Monthly	CV(RMSE)	15%
	NMBE	±5%
Hourly	CV(RMSE)	30%
	NMBE	±10%

This step-by-step model validation technique enables earlier detection of potential error (or mismatch) sources, comprehension of the impact degree of both controllable and uncontrollable variables, and the establishment of more realistic assumptions and calculations before the system becomes more complex. Figure 10 depicts the meteorological data, including ambient temperature, net solar radiation, relative humidity (RH), and wind velocity, for the representative days measured using the on-site weather station. All data is presented in accordance with Australian Eastern Standard Time (AEST), i.e., (UTC+10). The data for net solar radiations are also examined using the extra-terrestrial radiation on horizontal to ensure the “*shift in solar time*” is correctly calculated in the simulation.

Figure 11 shows the measured and simulated values of cabin operative temperature, PCM ceiling surface temperature, and PCM panel heat flux in the free-running mode. The experimental uncertainty is estimated with a 95% confidence interval (CI) and is shown with the measured data. As indicated, there is a good agreement between measured and simulated values for all selected variables. The deviations between measured and simulated values are within the ±5% range. CV(RMSE), NMBE, and CC values are also summarised in Table 7.

3.2 Validation for the active mode

Once the test cabin in the free-running operation has been satisfactorily validated, the PCM-RCC components are activated in the model. To validate the model in the active mode, the measured data for 10 consecutive days have been utilised to ensure the developed model is reliable enough

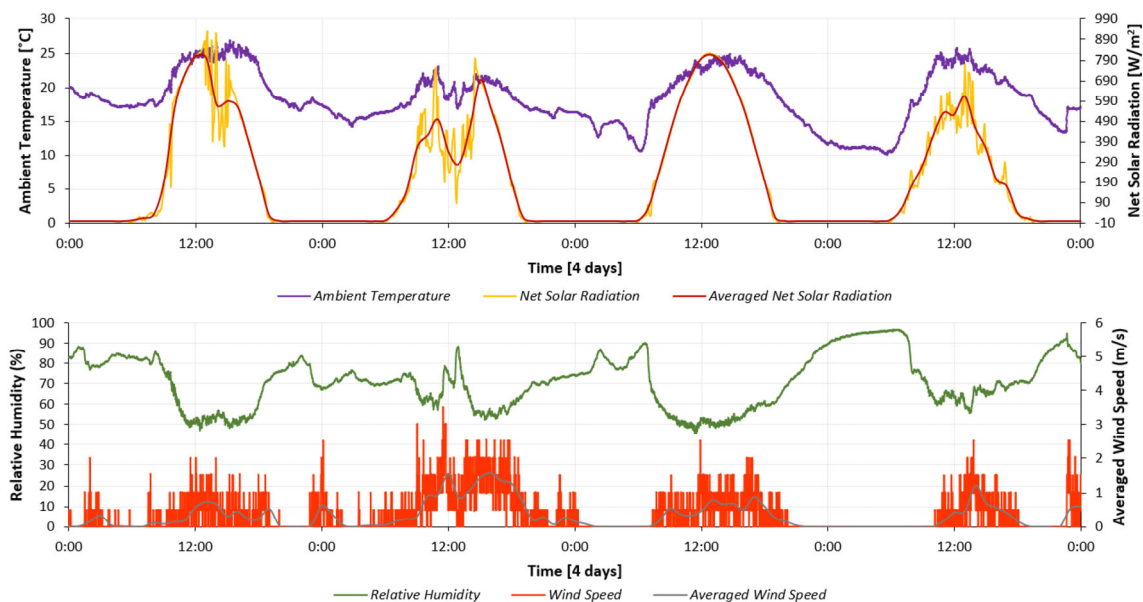


Fig. 10 The measured meteorological data used for validation of the free-running mode

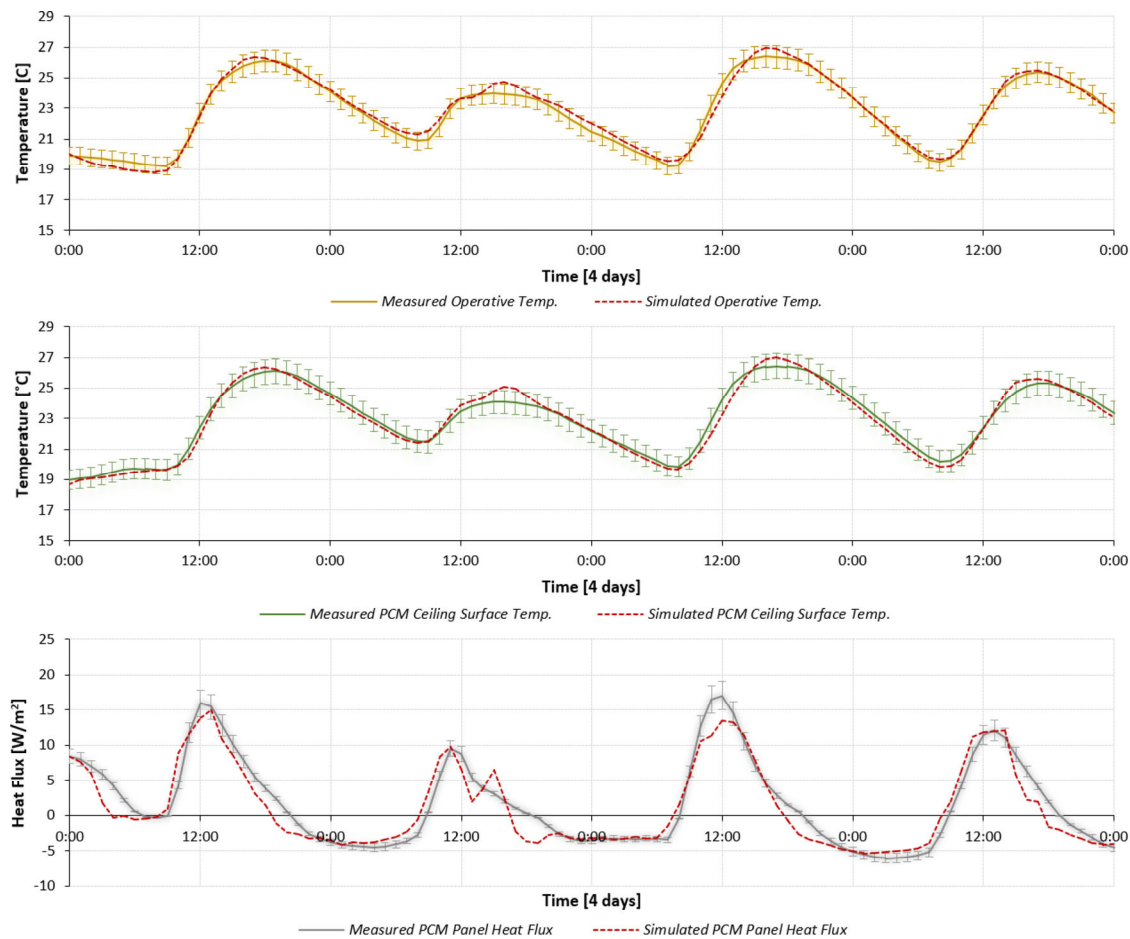


Fig. 11 Measured and simulated operative temperature, PCM ceiling surface temperature, and panel heat flux in the free-running mode of system operation

Table 7 Indicators used for the quality assessment of developed simulation models

	Variable	RMSE [$\pm$ unit]	CV(RMSE) [%]	MBE [unit]	NMBE [%]	CC [—]
Free-running mode	Operative (globe) temperature	± 0.31 °C	1.38	+0.08 °C	0.36	0.99
	PCM ceiling surface temperature	± 0.35 °C	1.53	−0.06 °C	−0.26	0.99
	PCM panel heat flux	± 1.94 W·m ^{−2}	29.34	−0.51 W·m ^{−2}	−3.83	0.95
Active mode	Operative (globe) temperature	± 0.57 °C	2.70	−0.37 °C	−1.77	0.99
	PCM ceiling surface temperature	± 0.93 °C	5.10	+0.30 °C	1.61	0.95
	PCM panel heat flux	± 6.03 W·m ^{−2}	28.82	+0.73 W·m ^{−2}	3.50	0.92
	Heat extracted from the PCM ceiling	± 0.19 kW	29.01	+0.03 kW	4.49	0.98

under diverse conditions. PCM-RCC operates based on Schedule 1 for the first six days, as specified in Section 2.2. The system is then operated for the next four days following Schedule 2. Figure 12 shows the measured meteorological data used for the active mode validation.

Figure 13 presents the simulated and measured data (with 95% CI for experimental uncertainty) for four critical parameters, i.e., operative temperature, PCM ceiling surface temperature, panel heat flux, and the heat extracted from the ceiling through water circulation. According to the

results, a satisfactory agreement is obtained between the simulated values and the measured data. The developed model validly simulates PCM phase change transition during charging and discharging cycles, which is of high importance in performance assessments of PCM-based systems. The deviations between simulated and measured values are mostly within the $\pm 10\%$ range. CV(RMSE), NMBE, and CC values for this mode of the simulation are listed in Table 7; All are well within ASHRAE thresholds. The RMSE values are also much lower than what the VDI 6020 standard

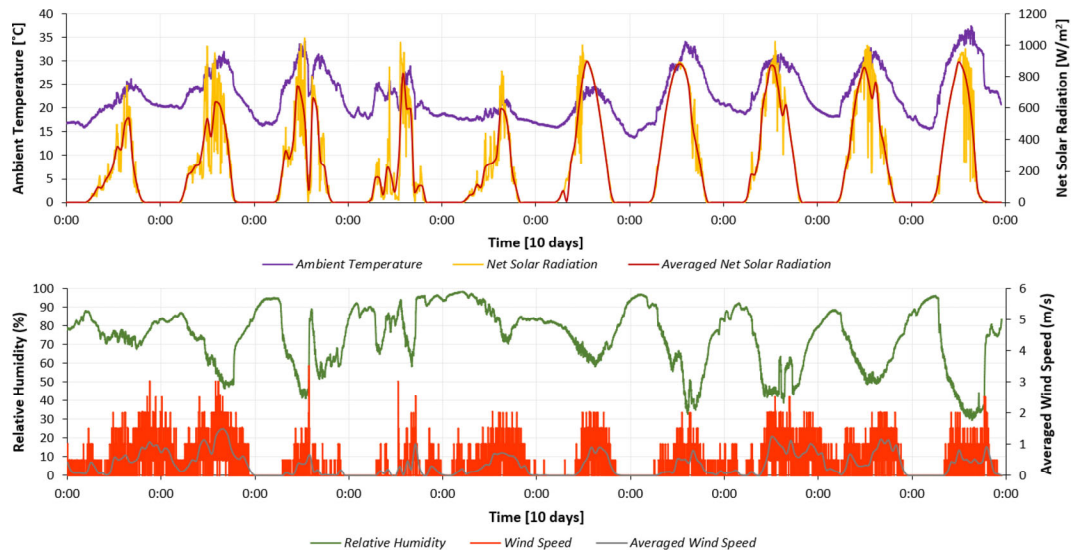


Fig. 12 The measured meteorological data used for validation of the active mode

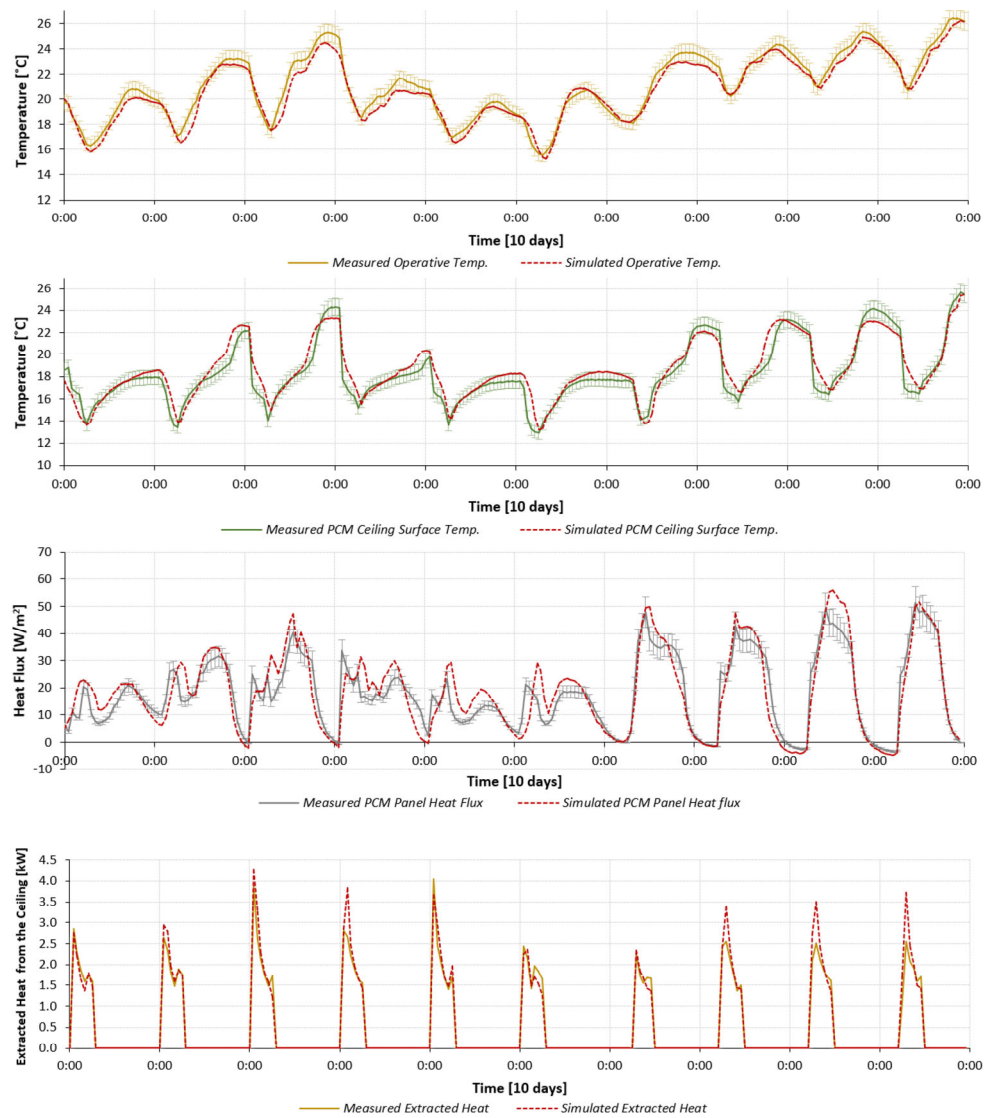


Fig. 13 Measured and simulated operative temperature, PCM ceiling surface temperature, panel heat flux, and PCM ceiling's $Q_{\text{extracted}}$ in the active mode of system operation

specifies for operative temperature (± 1.5 °C) (VDI-6020 2002).

Overall, the simulation results demonstrate high accuracy for the operative temperatures in both free-running and active operation modes. However, the simulated surface temperatures and heat fluxes of PCM ceiling panels show slightly higher deviations, especially during the phase change process. It might be due to the phase transition hysteresis model employed in Type 399. As mentioned in Section 2.3, this model uses two external files of C_p values in fixed temperatures for heating (melting) and cooling (freezing) paths. These temperatures are set as switching points at which PCM may change the path depending on its temperature differences. However, there are no set temperature points in reality and PCM can switch between heating and cooling paths when temperature varies.

As seen in Figure 11, PCM ceiling surface temperatures in the free-running mode were mostly over 20 °C, revealing that PCM constantly remains in the liquid phase, and no phase change transition occurs during this mode of PCM-RCC operation. Therefore, the simulation results observed in the free-running mode were not considerably impacted by the abovementioned issue of phase change transition modelling in Type 399, showing better RMSE, MBE, and CC values compared to the active mode. Additionally, the developed PCM-RCC model does not consider water pressure drops in the capillary tubes that may occur in reality during the active operation mode. Here, constant hourly water flow rates based on measured data have been used for the simulations. This might also be the other reason for slightly higher deviations between measured and simulated values in the active mode.

4 Applications of the validated model

Since the thermal and energy performance of PCM-RCC highly depends on selecting the appropriate sets of design and operational settings, the validated simulation model will be beneficial in order to properly design the system and evaluate its configuration and main variables affecting the overall performance of the technology. Besides, PCM manufacturers also benefit from the modelling results to develop the qualities of their products and make them as suitable as feasible for use in such systems.

The present validated model offers the user detailed flexibilities to set up and modify numerous characteristics of the PCM-RCC system regarding the design of PCM panels (including panel construction, PCM type, PCM layer thickness, pipe-to-pipe distance, pipe material and its diameter), the configuration and the number of PCM panels used in the ceiling, and the operational setpoints (like supply water temperature, water flow rate, and active PCM

recharge duration). The standards for ACH and infiltration calculations as well as the climate conditions can be also adjusted based on user requirements.

As a demonstration, a parametric analysis has been performed here to describe the impact of four effective variables on the PCM-RCC performance, i.e., PCM thermal conductivity, supply water temperature, PCM layer thickness, and water flow rate. Schedule 1, mentioned in Table 3, is also considered for simulations. As shown in Figure 14, using PCM with greater thermal conductivities accelerates the rate of heat transfer from PCM panels to the room, resulting in lower indoor operative temperatures. For $k > 1.5 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, the changes in room temperature, ceiling temperature, and heat flux are negligible. The results obtained from various supply water temperatures demonstrate that while lower water temperatures improve PCM solidification efficiency during the recharge cycle, they also lead to lower interior temperatures since a part of the coolness provided by the chilled water is used to cool the space. Thus, the designer must be aware of this dual effect of supply water temperature when scheduling the operating setpoints. Additionally, lower water temperatures lead to lower ceiling surface temperatures, which raises the possibility of surface condensation—a problem that frequently arises in radiant cooling systems. Given various PCM layer thicknesses, it is found that when the layer thickness increases, with the same chilled water circulation time, the fluctuations of indoor air temperatures and ceiling temperatures are reduced due to the enhanced thermal storage capacity provided by PCM panels. However, panels with thicker PCM layers, although offer adequate cooling capacity for the whole occupancy time on hot days, require a longer water circulation period to be fully recharged. This extends the system operation time and may compromise the load-shifting and energy-saving potentials of PCM-RCC systems. Finally, changing the water flow rate from 400 to 550 L·hr⁻¹ is of negligible effect on the system performance. At higher flow rates, more fresh chilled water flows quickly through the PCM ceiling panels, shortening the time of heat transfer between chilled water and PCM.

5 Conclusions

In this work, a transient PCM-RCC simulation model of an existing full-scale test cabin is developed employing the TRNSYS studio. The model, which includes all necessary components of the system and its associated operating signals, is then validated using field measurements for both free-running and active operation modes. Comparison between the experimental data and simulation values are presented for four influential variables of the system as well as the cabin indoor environment for transient conditions.

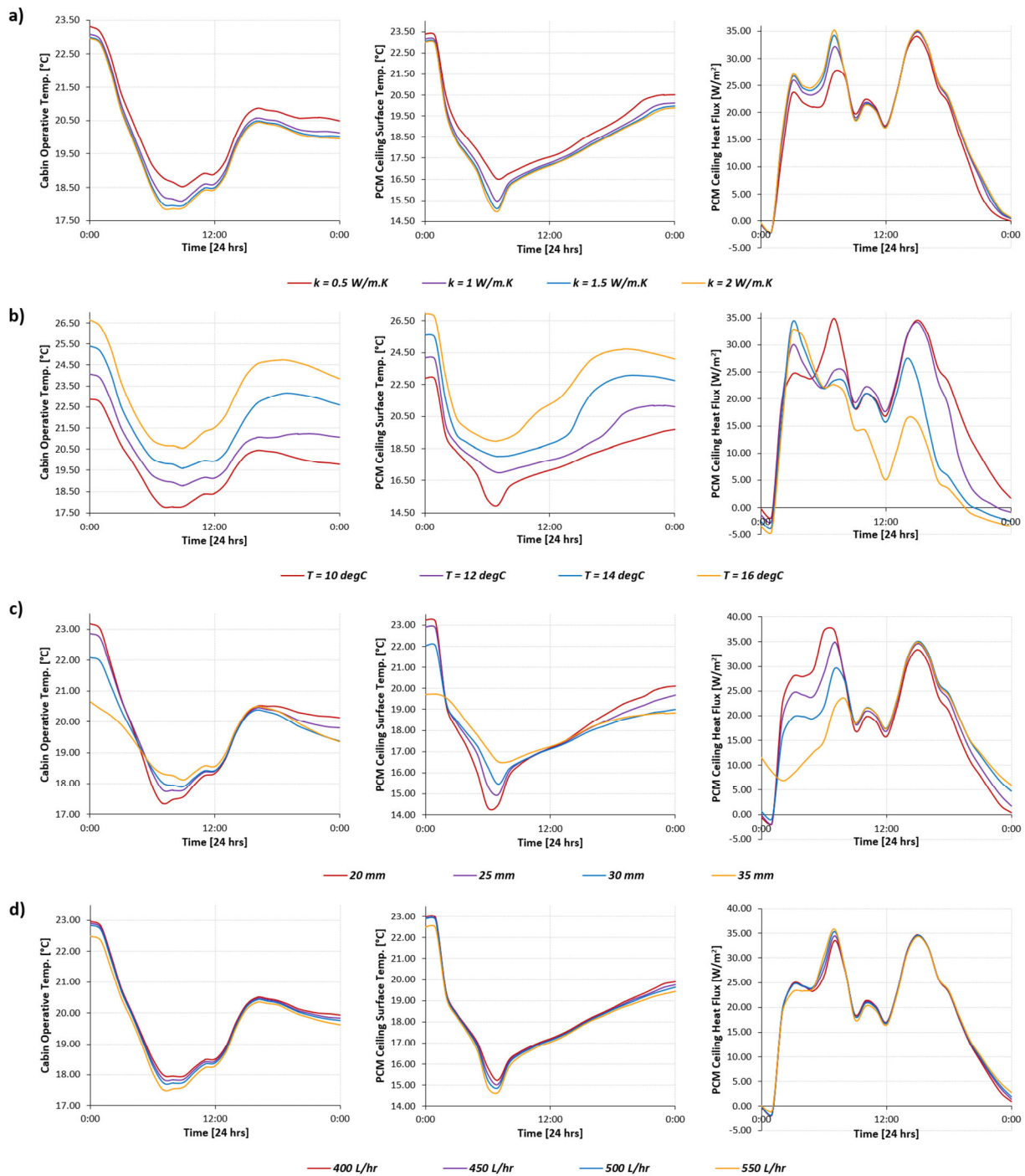


Fig. 14 Impact examination of various PCM-RCC parameters (a: PCM thermal conductivity, b: supply water temperature, c: PCM layer thickness, d: chilled water flow rate) on indoor operative temperature, PCM ceiling surface temperature, and PCM ceiling heat flux

CV(RMSE), NMBE, and CC indicators are also used to assess the quality of the simulation model.

According to the validation results, it has been confirmed that the developed model is able to simulate the transient behaviour of the PCM-RCC system with high accuracy. The deviations between simulated and measured data points are within the $\pm 10\%$ range. CC values also demonstrate a strong positive correlation between measurements and simulations.

Minor deviations observed are most likely due to the hysteresis model applied in TRNSYS Type 399. To conclude, the current PCM-RCC model provides a high flexibility for the user to change the embedded layers of PCM ceiling panels, change the configuration of piping systems, and add or remove different panel rows based on the space cooling load requirements. PCM-RCC potential for peak load shifting, energy savings, and improved indoor thermal comfort

can be also analysed more realistically with the use of this validated model.

Data availability statement

Raw data were generated at the University of Melbourne. Derived data supporting the findings of this study are available from the corresponding author Behzad Rismanchi on request.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

Author contribution statement

Syedmostafa Mousavi: conceptualisation, methodology, software, validation, formal analysis, investigation, data curation, visualisation, writing—original draft. Behzad Rismanchi: conceptualisation, resources, writing—review & editing, supervision, project administration, funding acquisition. Stefan Brey: resources, writing—review & editing. Lu Aye: Writing—review & editing, supervision.

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