



Research Paper

Effect of sunshade thermal insulation curtain position and ventilation mode on performance of building with phase change material Trombe wall

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ARTICLE INFO

Keywords:

Trombe wall
Phase change material
Sunshade thermal insulation curtain
Energy-saving
Ventilation mode

ABSTRACT

Phase change material Trombe walls cause significant heat loss on winter nights and overheating indoors in the summer. This study proposes a phase change material Trombe wall building with a sunshade thermal insulation curtain, which acts as a shade in summer and insulation to reduce nighttime heat loss in winter. Firstly, the mathematical model of the proposed Trombe wall with the curtain is established by MATLAB, which is based on the implicit difference method and is solved by Newton-Raphson iteration. Then, the building envelope model was established using TRNSYS. The performance of the proposed building in Beijing, China, under different curtain positions and ventilation modes is studied based on the co-simulation of TRNSYS and MATLAB. The results show that for the curtain placed in the air passage and outdoor side, the heating load is reduced by 9.22% and 9.76%, and the cooling load is reduced by 7.54% and 12.98%, respectively, compared with the phase change material Trombe wall buildings without curtains. As latent heat grows, the heating load fluctuates less, and as the phase change temperature increases, it fluctuates more. The cooling load is hardly affected by the phase change temperature or latent heat. In the absence of air conditioning, the average indoor temperature in winter with the curtain placed in the air passage and outdoor side is 1.05°C and 0.81°C higher than that in the phase change material Trombe wall room without the curtain, and 4.5°C and 4.1°C higher than that in the room without the Trombe wall. It is more beneficial to reduce the cooling load and summertime room temperature with the curtain outside and only-night ventilation. This research can offer ideas for simulating the energy consumption of buildings with complex Trombe wall structures.

1. Introduction

The rapid growth of industry and urbanization has resulted in an annual increase in the area of buildings, and buildings now account for 30 % of global energy use [1]. Buildings can lower their fossil fuel consumption and carbon emissions by implementing renewable energy, such as geothermal energy solar energy, wind energy, biomass energy, water energy [2], etc. Furthermore, it can enhance human health and indoor air quality. Solar energy has garnered increasing attention due to its advantages, such as inexhaustible, safe, and easy to obtain [3]. The main forms of solar energy utilization are solar water heaters and hot water systems, solar photovoltaic power generation, solar building [4], solar dryers [5–7], solar ventilation [8], and solar collectors [9–11].

Solar wall, as a typical, simple way to use solar energy, was originally designed by French scientist Trombe [12], so it is also known as the Trombe wall (TW). The way it operates is that sunlight passes through the glass and is absorbed by black surface of the wall. Indoor air is heated by natural convection heat transfer with the black surface, thus providing heat to the room. In addition, vents can also be closed at night to keep the room from losing heat. But TW cannot supply heat at night or during rainy weather since solar energy is unstable and intermittent. To address the issue of the mismatch between supply and demand, thermal energy storage technology must be introduced. Phase change materials (PCM) can store a large amount of heat in a nearly constant temperature range [13]. Paraffin, as an organic PCM, has the advantages of high latent heat of melting, no phase separation, and small volume change

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Received 21 August 2024; Received in revised form 29 November 2024; Accepted 31 December 2024

Available online 31 December 2024

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Table 1
Summary of the energy simulation for the TW building.

Authors	Type of TW Building	The simulation method of energy consumption	Key results
Bevilacqua et al. [21]	TW building	DesignBuilder	TW can lower cooling energy usage by 36.1 % and heating energy consumption by 71.7 % in warm climates.
Hong et al. [22]	louver –TW building	Co-simulation of computational fluid dynamics (CFD) and EnergyPlus.	louver-TW in service, office, and residential buildings with outdoor ventilation can reduce cooling energy consumption by 5.7 %, 5.0 %, and 5.8 %, respectively, compared with traditional TW.
Simoes et al. [23]	TW building in the Mediterranean region	DesignBuilder and EnergyPlus	The TW system can reduce heating load by more than 20 % without affecting cooling load, and nighttime ventilation can result in a reduction of cooling load by more than 35 %.
Xiao et al. [24]	TW-PCM building	EnergyPlus	The heating load could be reduced by 71.53 %.
Askari et al. [25]	TW building with a double-layer PCM	DesignBuilder	There is a 39 % reduction in heating energy consumption with an air passage thickness of 20 cm; the issue of summertime indoor overheating can be resolved with the use of exterior shading facilities, and 50 cm is the ideal length for outdoor shading.
Zhu et al. [26]	TW buildings with a double-layer PCM	TRNSYS	The peak cooling and heating load were 9 % and 15 % lower than those of the traditional TW room, respectively.
Ma et al. [27]	Double-layer TW	THERB for HAM software	The range of energy efficiency is 31.18 % to 53.04 % in the summer and 30.27 % to 44.36 % in the winter.

caused by the phase process [14]. Khedher et al. used brick walls impregnated with PCM in passive buildings to reduce indoor temperature fluctuations [15,16]. TW with PCM (TW-PCM) can store latent heat during the day and supply heating at night, lowering temperature fluctuations and improving thermal comfort [17].

However, due to low thermal resistance of TW-PCM, indoor heat loss accelerates at night when the wall temperature falls below the room temperature, causing the reverse thermosiphon phenomenon. The better the heat storage performance of TW-PCM in winter, the more likely indoor overheating will occur in summer. To enhance the thermal performance of the TW-PCM, it is therefore required to implement thermal insulation measures on winter nights and shade facilities on summer days. By placing a thermal insulation layer on the outside of TW-PCM, Liu et al. [18] boosted the effectiveness of nocturnal heating.

According to the results, the average room temperature increased while fluctuations in temperatures decreased. Zhou et al. [19] studied a dynamic building envelope with TW-PCM through experiments, which made it face outdoors to absorb solar radiation when there was solar radiation and turn to the indoor side when there was no solar radiation, so that the heat from the solidification of the PCM was directly transferred to the indoor. The findings demonstrate that it can raise overall thermal efficiency by roughly 20 % and decrease PCM heat loss by 29 %. Stazi et al. [20] studied the thermal comfort of TW in Mediterranean-climate residential buildings through experiments and dynamic simulation with EnergyPlus. It was found that the use of double glazing can significantly improve the performance of TW, and shading and ventilation measures can reduce overheating to maintain a comfortable room temperature.

In addition, the energy-saving capabilities of TW buildings have been extensively studied by numerous academics. Some studies on energy consumption simulation of TW buildings are shown in Table 1. According to Table 1, so far, most of the studies adopted commercial software (such as EnergyPlus, TRNSYS, DesignBuilder, etc.) to simulate energy consumption of TW buildings. However, for TW-PCM buildings with complex structures, energy consumption cannot be calculated using commercial software alone. As a result, new simulation techniques for estimating energy usage are necessary.

1.1. Novelty

According to earlier studies, insulation measures on winter nights and shading and ventilation strategies in summer help reduce energy consumption in TW-PCM buildings. However, most studies used the horizontal baffle shading method in summer, and fewer studies used the vertical sunshade curtain to block the sunlight. In addition, the majority of earlier research ignored how ventilation time affected TW performance, and little research has been done on the summertime and wintertime performance of the same TW structure. In this study, a TW-PCM building with a sunshade thermal insulation curtain is proposed to address the issues of excessive heat loss on winter nights and summertime indoor overheating. The curtain can significantly reduce sunlight exposure in the summer, thereby preventing indoor overheating; in the winter, it can also be utilized as an insulating layer to lessen heat loss at night. The curtain can be set in the air passage or outdoor. TRNSYS and MATLAB software were used to build a building energy model that considered different ventilation modes and curtain positions. A study was done on load characteristics and the room temperature under different operating modes in both summer and winter.

2. Building description

2.1. Building structure

Fig. 1(a) depicts the building researched in this paper. Its dimensions are 5 m for length, 5 m for width, and 3 m for height. The composition of the external wall of the building is shown in Table 2, the structure composition of the roof is shown in Table 3, and the floor structure is shown in Table 4. Fig. 1(b) depicts the plane structure of the south wall with a 1.5 m x 1.8 m window. A TW-PCM with a sunshade thermal insulation curtain (TW-IC-PCM) is mounted on the right side of the window. Fig. 1(c) depicts the TW-IC-PCM architecture, in which the PCM layer (0.02 m), air passage (0.2 m), and double glass layer (0.006 m + 0.015 m + 0.006 m) are set outside the insulation layer of the south external wall. The sunshade thermal insulation curtain of 0.003 mm thickness is situated in the air passage (TW-IC(In)-PCM) or outdoor side near the outer glass (TW-IC(Out)-PCM), and there are 0.03 m separating the curtain from the glass. The proposed TW-IC-PCM is mainly used in residential buildings. This paper studies its application in Beijing, China. For PCM, paraffin wax is utilized, which has a latent heat of 210 kJ/kg and a phase change temperature of 27 °C ~ 29 °C. In practical

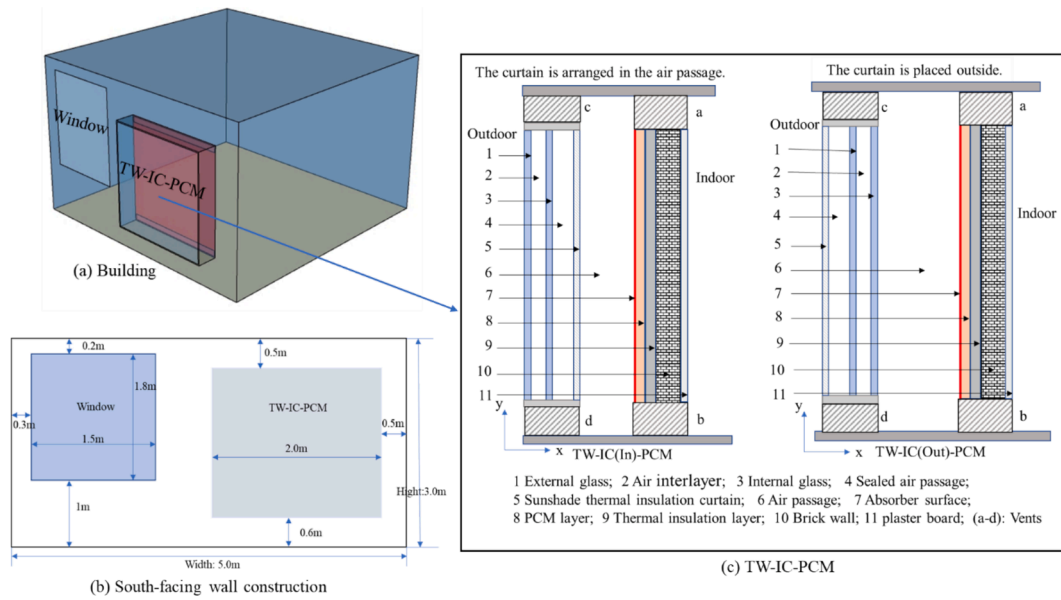


Fig. 1. Building structure.

Table 2
Composition of external wall.

Materials	Density (kg/m ³)	Thermal conductivity(W/m·K)	Specific heat capacity (J/kg·K)	Thickness (m)
Plaster board (indoor side)	800	0.16	1090	0.019
Brick	1800	0.814	879	0.24
Insulation layer (outdoor side)	200	0.04	1400	0.06

Table 3
Composition of the roof.

Materials	Density (kg/m ³)	Thermal conductivity (W/m·K)	Specific heat capacity (J/kg·K)	Thickness (m)
Plywood ceiling (indoor side)	600	0.17	2510	0.01
Concrete	2500	1.74	920	0.24
Insulation layer	200	0.04	1400	0.10
Waterproof layer	900	0.23	1620	0.01
Cement mortar (outdoor side)	1800	0.93	1050	0.02

Table 4
Composition of the floor.

Materials	Density (kg/m ³)	Thermal conductivity (W/m·K)	Specific heat capacity (J/kg·K)	Thickness (m)
Ceramic tiles (indoor side)	2300	1.3	840	0.01
Cement mortar screed	1800	0.93	1050	0.05
Concrete	2500	1.74	920	0.30
Insulating layer	200	0.04	1400	0.08
Waterproof layer	900	0.23	1620	0.03
Cement mortar screed (ground side)	1800	0.93	1050	0.05

applications, aluminum boxes can be used for macroscopic packaging of PCM to stop it from leaking. Table 5 provides the physical property parameters of the TW-IC-PCM component materials, which are the same in winter and summer.

2.2. Working mode in winter and summer

The winter working modes of TW-IC(In)-PCM and TW-IC(Out)-PCM are depicted in Fig. 2(a) and (b), respectively. In winter, the curtain is only used at night to create a sealed air layer that can improve the wall's thermal resistance. The daytime working mode is divided into two parts: when the sun is just coming out with low solar radiation, the vent is closed to preserve heat, and as solar radiation rises, the vent is opened to heating the room. The heating mode is activated at the start of the night and changes to the heat preservation mode when the wall temperature falls below the indoor temperature for the purpose of preventing large heat losses and indoor air backflow.

Fig. 3 shows that in summer, the curtains are opened during the day to shade the sun and closed at night to take advantage of the lower outdoor temperature to cool the wall. The TW-IC(In)-PCM and TW-IC(Out)-PCM working modes can be divided into two types according to the ventilation mode: all-day and only night outdoor ventilation.

3. Simulation method

The innovation of the simulation method in this paper is the co-simulation based on MATLAB and TRNSYS. Firstly, the TW-IC-PCM heat transfer mathematical model is established based on energy conservation by MATLAB, and then the building energy model is established by TRNSYS software. Finally, the TW-IC-PCM heat transfer model is coupled to TRNSYS.

3.1. Model of the phase change material Trombe wall with an inside curtain

The physical quantity represented by the symbols in this article is defined. The symbols T_{sky} , T_{am} , T_{eg} , T_{gap} , T_{ig} , T_{cair} , T_{curs} , T_{curb} , T_{air} , T_{pcm} , T_{pcms} , and T_{pcmb} represent the temperature of the sky, outdoor air, external glass, air interlayer, internal glass, sealed air passage, curtain outer surface, curtain inner surface, air passage, PCM, PCM outer surface, and PCM inner surface, K , respectively. The density of glass,

Table 5
Composition of TW-IC-PCM.

Materials	Density (kg/m ³)	Thermal conductivity(W/m·K)	Specific heat capacity (J/kg·K)	Thickness (m)	Phase change temperature (°C)	Latent heat (kJ/kg)
Glass	2500	0.76	780	0.006	--	--
PCM	Solid:880; Liquid:770	0.2	2000	0.02	27 ~ 29	210
Curtain	100	0.045	1340	0.003	--	--

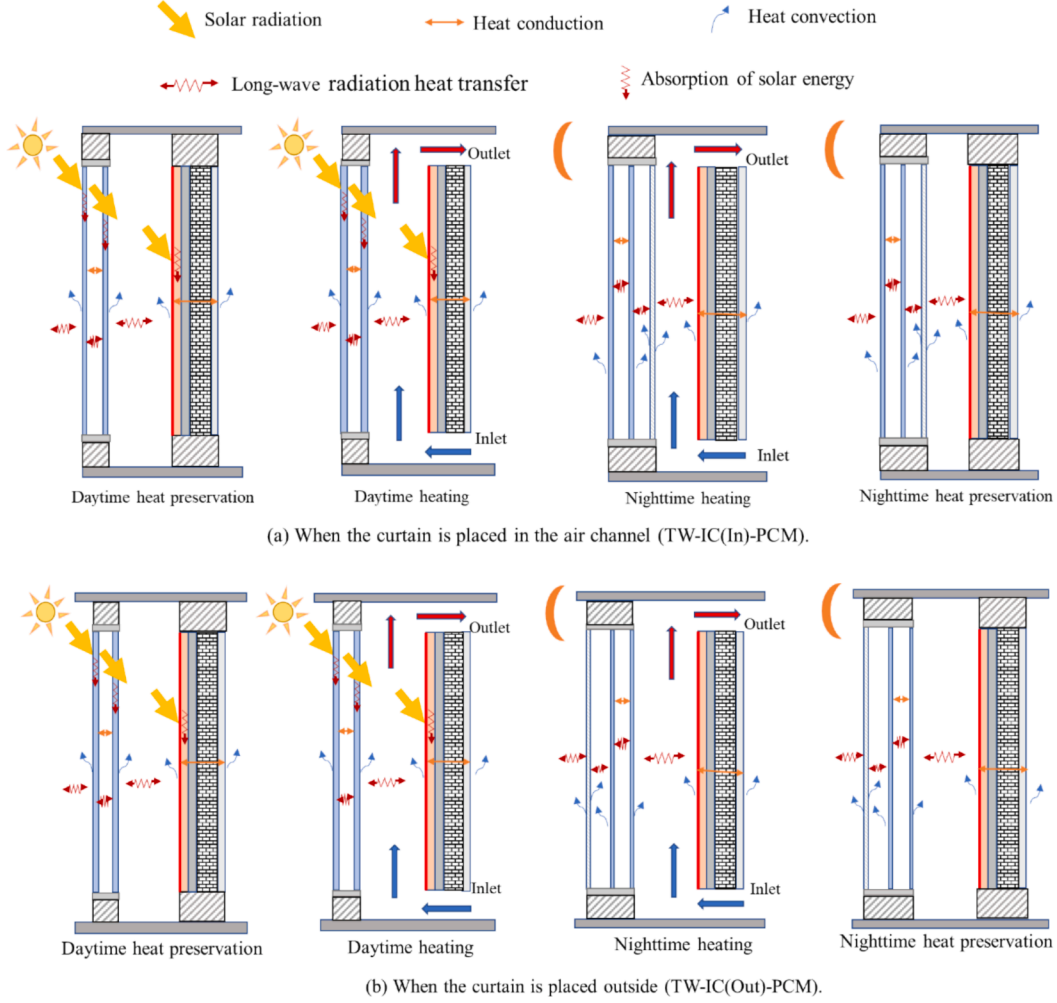


Fig. 2. TW-IC-PCM working mode in winter.

curtain, air, and PCM is denoted by the symbols ρ_g , ρ_{cur} , ρ_a , and ρ_{pcm} , respectively, kg/m³. The symbols c_g , c_{cur} , c_a , and c_{pcm} express the specific heat capacities of glass, curtain, air, and PCM, respectively, J/(kg·K). The symbols λ_g , λ_a , λ_{cur} , and λ_{pcm} , respectively, represent the thermal conductivity of glass, air, curtains, and PCM, W/(m·K). The symbols α_{eg} , α_{ig} , α_{cur} , and α_{pcm} indicate the absorption rate of solar rays on the surface of the external glass, internal glass, curtain, and PCM, respectively. The symbols τ_{eg} and τ_{ig} indicate the solar transmittance of the external and internal glass, respectively. For the external glass, internal glass, curtain, and PCM, the corresponding thermal emissivity is represented by the symbols ε_{eg} , ε_{ig} , ε_{cur} , and ε_{pcms} . G_r indicates the solar radiation intensity of south wall, W/m². t stands for time, s. σ is the Steven Boltzmann constant, 5.67×10^{-8} W/(m²·K⁴), and u_{am} is the wind speed, m/s. The TW-IC(In)-PCM heat transfer model consists of the following five sets of heat transfer differential equations.

3.1.1. The energy balance equation of double glass

The external glass energy balance equation is expressed by Eq. (1) [28]:

$$\rho_g c_g d_{eg} \frac{\partial T_{eg}}{\partial t} = d_{eg} \lambda_g \frac{\partial^2 T_{eg}}{\partial y^2} + h_{conv,am} (T_{am} - T_{eg}) + h_{rad,eg-sky} (T_{sky} - T_{eg}) + \frac{1}{R_{gap-eg}} (T_{gap} - T_{eg}) + h_{rad,eg-ig} (T_{ig} - T_{eg}) + \alpha_{eg} G_r \quad (1)$$

The sky temperature is expressed by Eq. (2) [29]:

$$T_{sky} = 0.0552 T_{am}^{1.5} \quad (2)$$

The heat resistance, (m²·K)/W, between the external glass and the air interlayer is defined as R_{gap-eg} . It is calculated by Eq. (3) [30]:

$$R_{gap-eg} = \frac{d_{gap}}{2\lambda_a} + \frac{d_{eg}}{2\lambda_g} \quad (3)$$

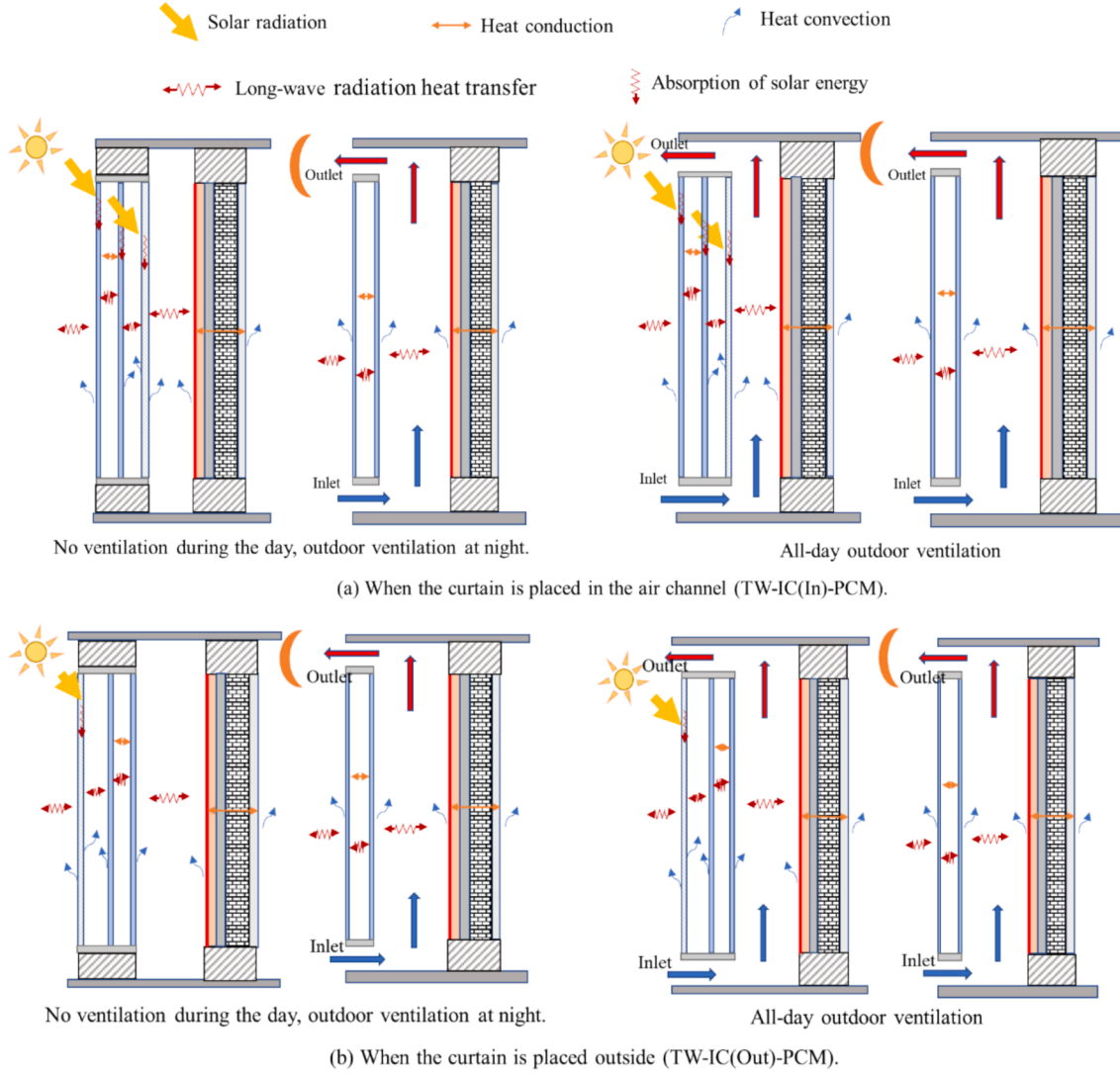


Fig. 3. TW-IC-PCM working mode in summer.

$h_{conv,am}$ refers to the convective heat transfer coefficient between the external glass and outside. It can be calculated using Eq. (4) [31]:

$$h_{conv,am} = 5.6 + 3.8u_{am} \quad (4)$$

$h_{rad,eg-sky}$ and $h_{rad,eg-ig}$ are the radiant heat transfer coefficients between the sky, internal glass, and external glass, $W/(m^2 \cdot K)$, respectively. They can be calculated by Eq. (5) and Eq. (6) respectively [32]:

$$h_{rad,eg-sky} = \epsilon_{eg} \sigma (T_{sky}^2 + T_{eg}^2) (T_{sky} + T_{eg}) \quad (5)$$

$$h_{rad,eg-ig} = \frac{\sigma (T_{eg}^2 + T_{ig}^2) (T_{eg} + T_{ig})}{\frac{1}{\epsilon_{eg}} + \frac{1}{\epsilon_{ig}} - 1} \quad (6)$$

The energy balance equation of the air interlayer is expressed by Eq. (7) [30]:

$$\rho_a c_a d_{gap} \frac{\partial T_{gap}}{\partial t} = \frac{1}{R_{eg-gap}} (T_{eg} - T_{gap}) + \frac{1}{R_{gap-ig}} (T_{ig} - T_{gap}) + d_{gap} \lambda_a \frac{\partial^2 T_{gap}}{\partial y^2} \quad (7)$$

where R_{gap-ig} is the heat resistance between the air interlayer and internal glass, $(m^2 \cdot K)/W$, which is expressed by Eq. (8) [30]:

$$R_{gap-ig} = \frac{d_{gap}}{2\lambda_a} + \frac{d_{ig}}{2\lambda_g} \quad (8)$$

The equation for internal glass energy balance is as follows: When the curtain is not in use [18]:

$$\rho_g c_g d_{ig} \frac{\partial T_{ig}}{\partial t} = d_{ig} \lambda_g \frac{\partial^2 T_{ig}}{\partial y^2} + h_{conv,ig-air} (T_{air} - T_{ig}) + \frac{1}{R_{gap-ig}} (T_{gap} - T_{ig}) + h_{rad,eg-ig} (T_{eg} - T_{ig}) + h_{rad,ig-pcms} (T_{pcms} - T_{ig}) + \alpha_{ig} \tau_{eg} G_r \quad (9)$$

When curtain is used [18]:

$$\rho_g c_g d_{ig} \frac{\partial T_{ig}}{\partial t} = d_{ig} \lambda_g \frac{\partial^2 T_{ig}}{\partial y^2} + h_{conv,ig-air} (T_{air} - T_{ig}) + \frac{1}{R_{gap-ig}} (T_{gap} - T_{ig}) + h_{rad,eg-ig} (T_{eg} - T_{ig}) + h_{rad,ig-curs} (T_{curs} - T_{ig}) + \alpha_{ig} \tau_{eg} G_r \quad (10)$$

where $h_{rad,ig-curs}$ and $h_{rad,ig-pcms}$ represent the radiant heat transfer coefficient between the curtain external surface, PCM external surface, and internal glass, $W/(m^2 \cdot K)$, respectively. They can be calculated by Eq. (11) and Eq. (12), respectively [28]:

$$h_{rad,ig-curs} = \frac{\sigma (T_{curs}^2 + T_{ig}^2) (T_{curs} + T_{ig})}{\frac{1}{\epsilon_{ig}} + \frac{1}{\epsilon_{cur}} - 1} \quad (11)$$

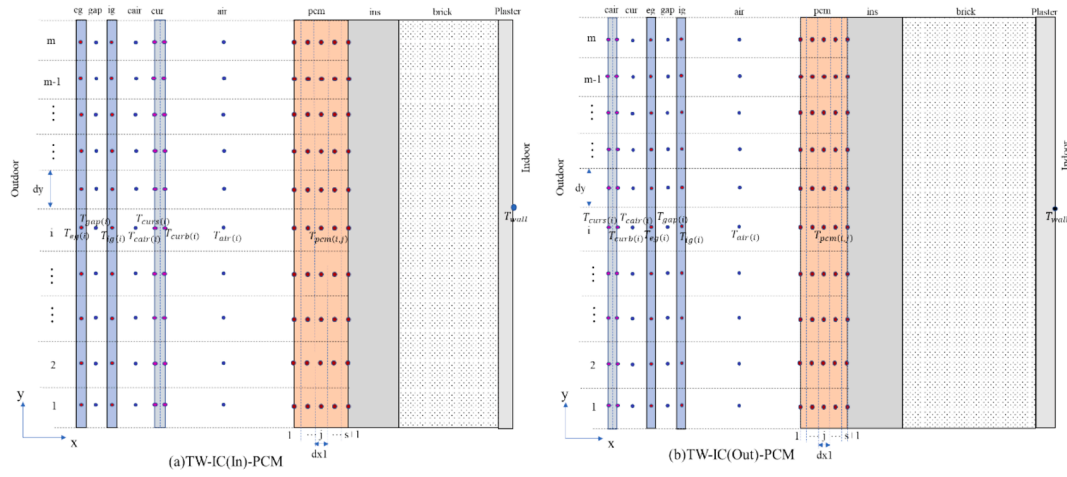


Fig. 4. Node division diagram of TW-IC-PCM.

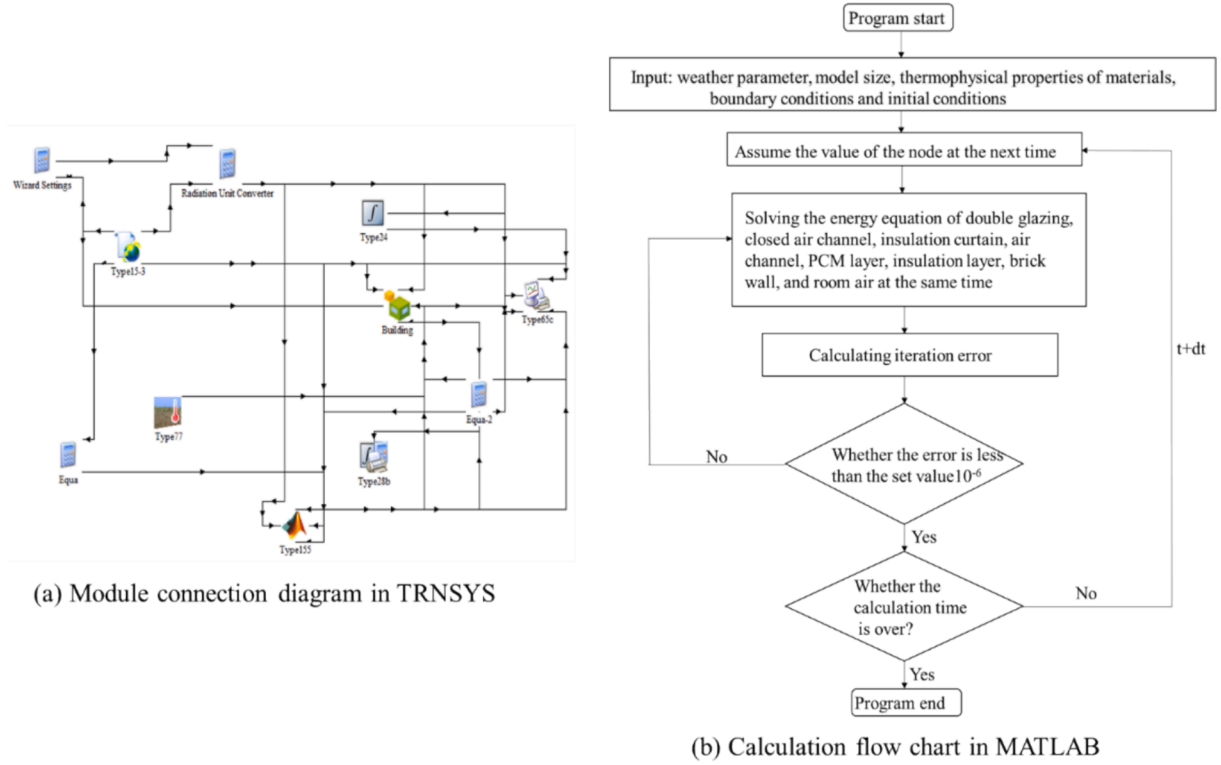


Fig. 5. The co-simulation diagram of MATLAB and TRNSYS.

$$h_{rad,ig-pcms} = \frac{\sigma(T_{pcms}^2 + T_{ig}^2)(T_{pcms} + T_{ig})}{\frac{1}{\epsilon_{ig}} + \frac{1}{\epsilon_{pcm}} - 1} \quad (12)$$

where $h_{conv,ig-air}$ stands for convective heat transfer coefficient, W/(m²·K), between the air passage and the internal glass. Its expression is as follows:

When the vent is opened [33]:

$$h_{conv,ig-air} = \frac{\lambda_a Nu_{air}}{H} \quad (13)$$

where H represents the height of the air passage, m. Nu_{air} can be expressed by Eq. (14) [34]:

$$Nu_{air} = \begin{cases} 0.68 + \frac{0.67Ra^{1/4}}{\left[1 + (0.492/Pr)^{9/16}\right]^{4/9}} & Ra \leq 10^9 \\ \left(0.825 + \frac{0.387Ra^{1/6}}{\left[1 + (0.492/Pr)^{9/16}\right]^{8/27}}\right)^2 & Ra > 10^9 \end{cases} \quad (14)$$

where Pr indicates the Prandtl number and Ra is the Rayleigh number, which can be computed using Eq. (15) and Eq. (16) [35]:

$$Pr = \frac{\mu C_a}{\lambda_a} \quad (15)$$

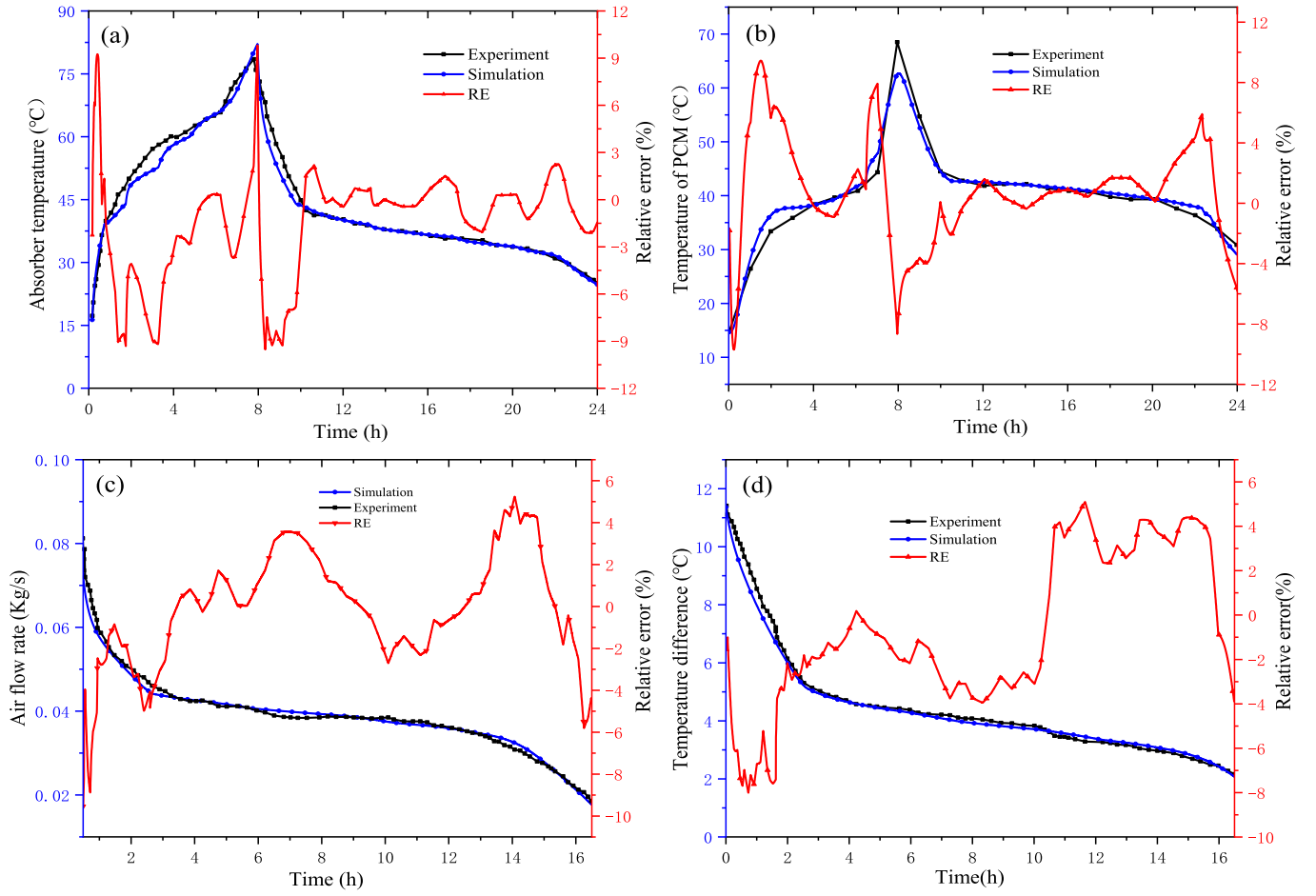


Fig. 6. Comparison of the modeling and Liu et al.'s experimental [40] results.

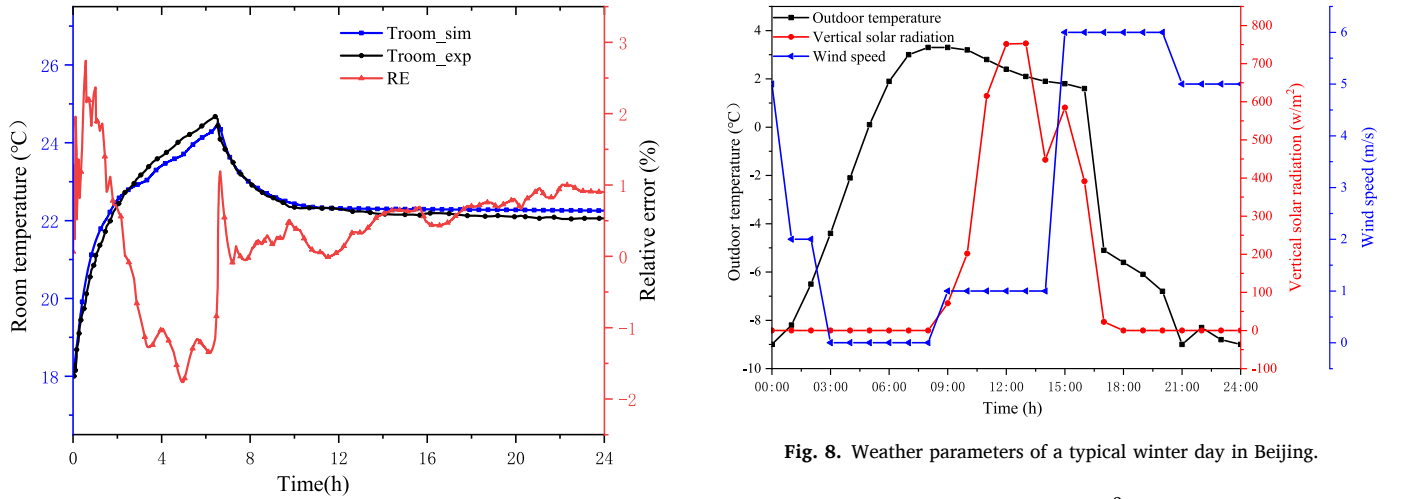


Fig. 7. Comparison of the room temperature simulation results with Zhou et al.'s experimental [41] findings.

$$Ra = \frac{g\beta(T_{air} - T_{ig})H^3}{\nu\kappa} \quad (16)$$

where β stands for air thermal expansion coefficient, $1/K$, and it can be computed using the equation: $\beta = 2/(T_{out} + T_{in})$. T_{out} and T_{in} are the temperatures of the air flow at the outlet and inlet, respectively, K ; ν represents the air kinematic viscosity, m^2/s , and its expression is $\nu = \mu/\rho$;

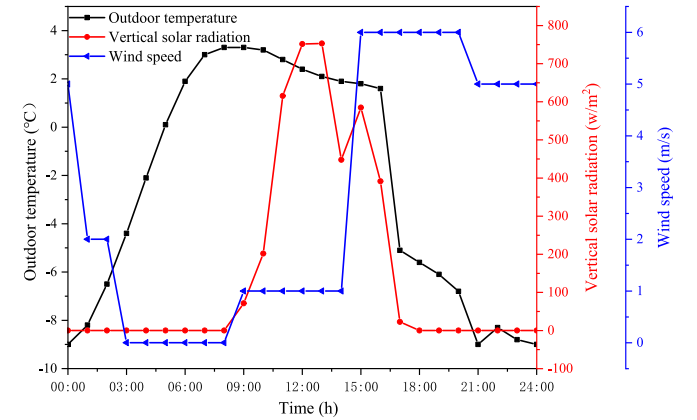


Fig. 8. Weather parameters of a typical winter day in Beijing.

μ represents air dynamic viscosity, $N\cdot s/m^2$; κ indicates the air thermal diffusion coefficient of air, m^2/s , $\kappa = \lambda_a / \rho c_a$.

When the vent is closed [36]:

$$h_{conv,ig-air} = \frac{\lambda_a Nu_{air}}{d_{air}} \quad (17)$$

$$Nu_{air} = \begin{cases} 1 & Gr_{air} \leq 2000 \\ 0.18Gr_{air}^{1/4}(d_{air}/H)^{1/9} & 2000 < Gr_{air} \leq 2 \times 10^5 \\ 0.065Gr_{air}^{1/3}(d_{air}/H)^{1/9} & 2 \times 10^5 < Gr_{air} \leq 2 \times 10^7 \end{cases} \quad (18)$$

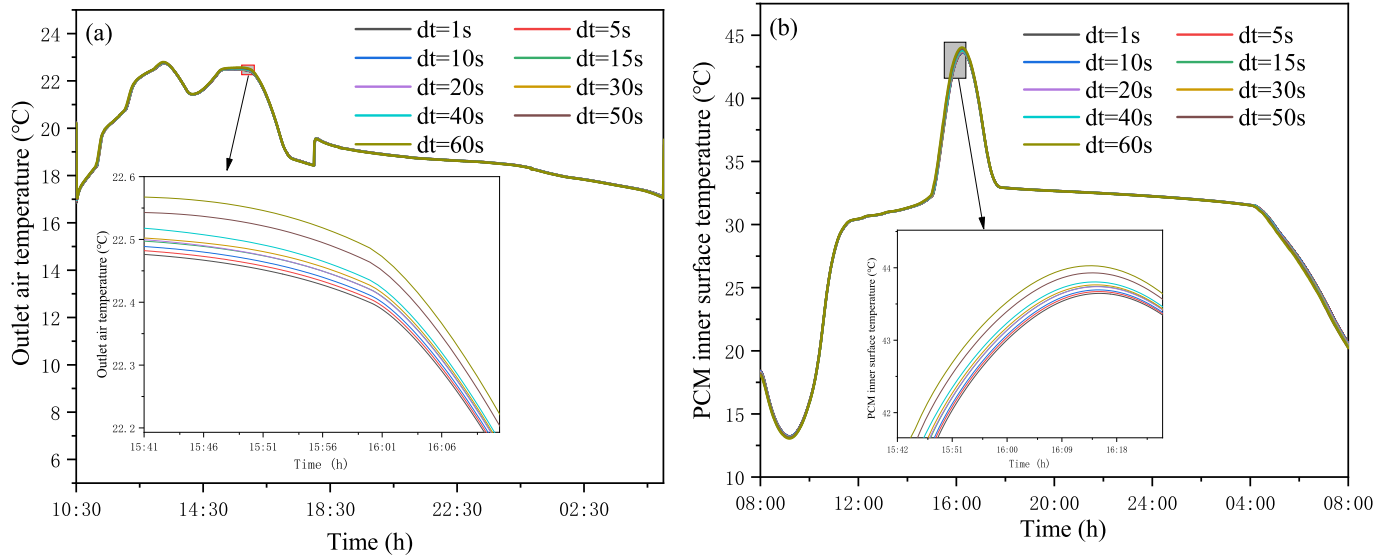


Fig. 9. Outlet air temperature and PCM inner surface temperature at different time steps.

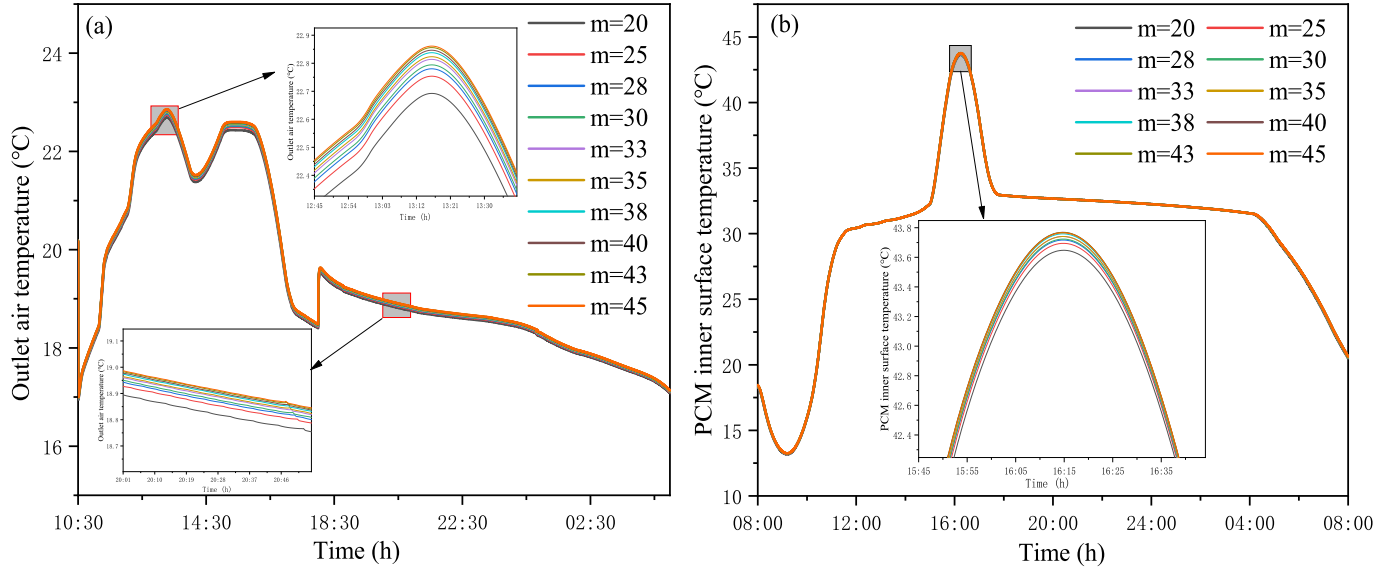


Fig. 10. Outlet air temperature and PCM inner surface temperature at different number of nodes in Y-axis.

where Gr_{air} is the Grashof number for the sealed air passage, which can be expressed by Eq. (19) [28]:

$$Gr_{air} = \frac{g\beta(T_{pcms} - T_{ig})d_{air}^3}{\nu^2} \quad (19)$$

When the curtain is in use, $h_{conv,ig-air}$ is the convective heat transfer coefficient between the internal glass and sealed air passage. It can be calculated referring to the equations (17–19).

3.1.2. The energy balance equation of sealed air passage

The sealed air passage does not exist when the curtain is not used; its energy balance equation is [37]:

$$T_{c air} = T_{air} \quad (20)$$

When the curtain is used [33]:

$$\rho_a c_a d_{c air} \frac{\partial T_{c air}}{\partial t} = h_{conv,ig-air}(T_{ig} - T_{c air}) + h_{conv,c air-curs}(T_{curs} - T_{c air}) \quad (21)$$

where $h_{conv,c air-curs}$ stands for the convective heat transfer coefficient, $W/(m^2 \cdot K)$, between the curtain external surface and the sealed air, and $h_{conv,c air-curs} = h_{conv,ig-air}$.

3.1.3. The energy balance equation of curtain

When the curtain is not in use [37]:

$$T_{curs} = T_{curb} = T_{air} \quad (22)$$

When the curtain is used:

The curtain external surface energy balance equation is [38]:

$$\begin{aligned} \rho_{cur} c_{cur} \frac{d_{cur}}{2} \frac{\partial T_{curs}}{\partial t} = & h_{rad,ig-curs}(T_{ig} - T_{curs}) + h_{conv,c air-curs}(T_{c air} - T_{curs}) \\ & + \frac{d_{cur}}{2} \lambda_{cur} \frac{\partial^2 T_{curs}}{\partial y^2} + \frac{\lambda_{cur}}{d_{cur}} (T_{curb} - T_{curs}) + \alpha_{cur} \tau_{ig} \tau_{eg} G_r \end{aligned} \quad (23)$$

The curtain internal surface energy balance equation is [38]:

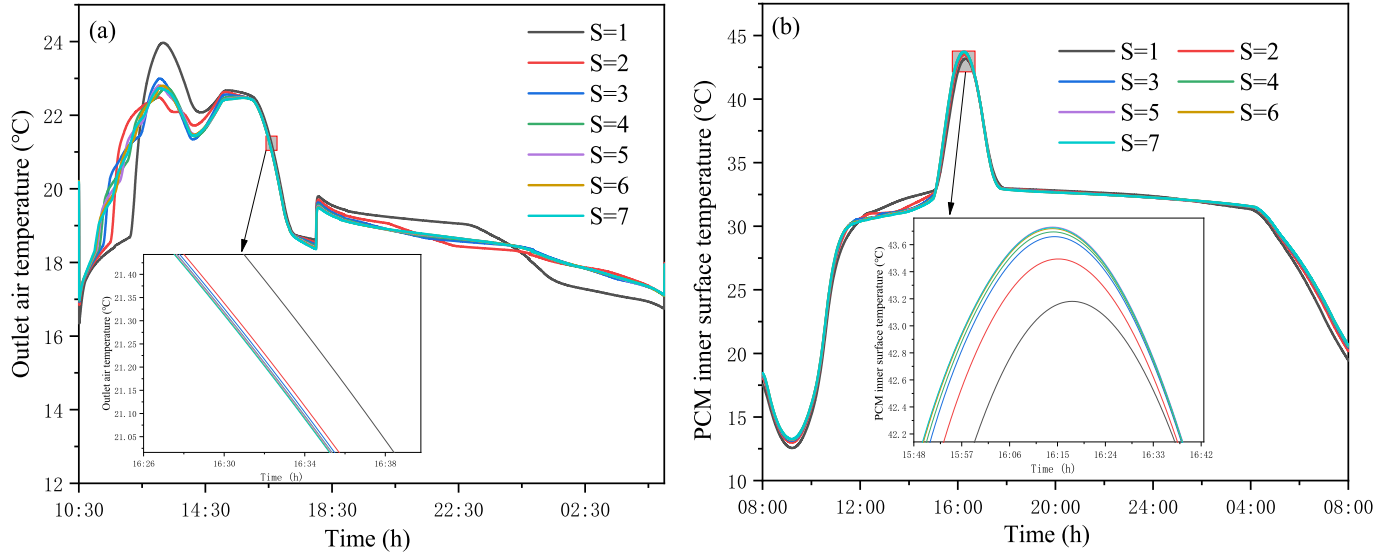


Fig. 11. Outlet temperature and PCM inner surface temperature with different number of nodes on X axis.

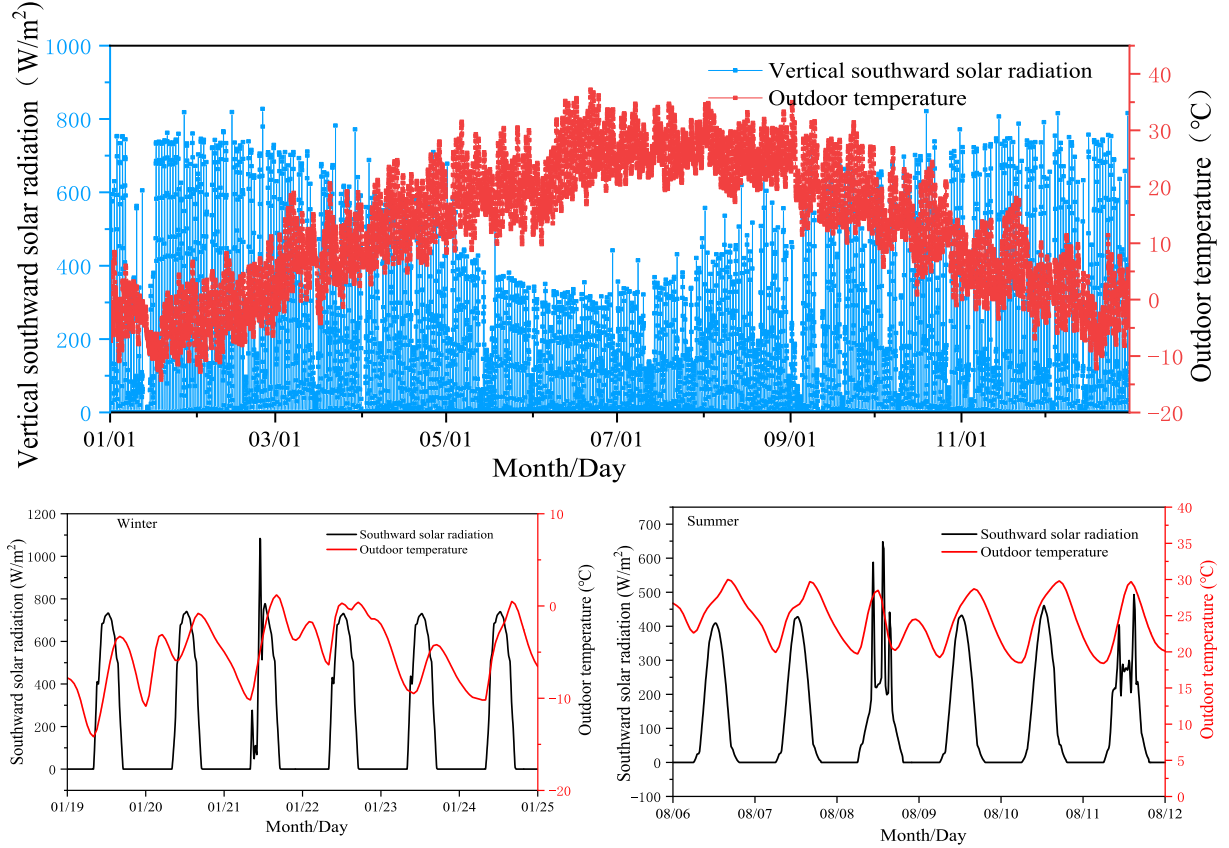


Fig. 12. Southward solar radiation and outdoor temperature distribution in Beijing.

Table 6

Daily working mode of TW-IC(In)-PCM and TW-IC(Out)-PCM in winter.

The time period	Operation mode
08:00 a.m. ~ 10:30 a.m.	daytime heat preservation
10:30 a.m. ~ 18:00p.m.	daytime heating
18:00p.m. ~ 07:30 a.m.	nighttime heating
07:30 a.m. ~ 08:00 a.m.	nighttime heat preservation

$$\rho_{cur} c_{cur} \frac{d_{cur}}{2} \frac{\partial T_{curb}}{\partial t} = h_{rad,curb-pcms} (T_{pcms} - T_{curb}) + h_{conv,curb-air} (T_{air} - T_{curb}) + \frac{d_{cur}}{2} \lambda_{cur} \frac{\partial^2 T_{curb}}{\partial y^2} + \frac{\lambda_{cur}}{d_{cur}} (T_{curs} - T_{curb}) \quad (24)$$

where $h_{rad,curb-pcms}$ represents the radiation heat transfer coefficient between the curtain internal surface and the PCM external surface, W/(m²·K), and the Eq.(25) can be used to compute it [28]:

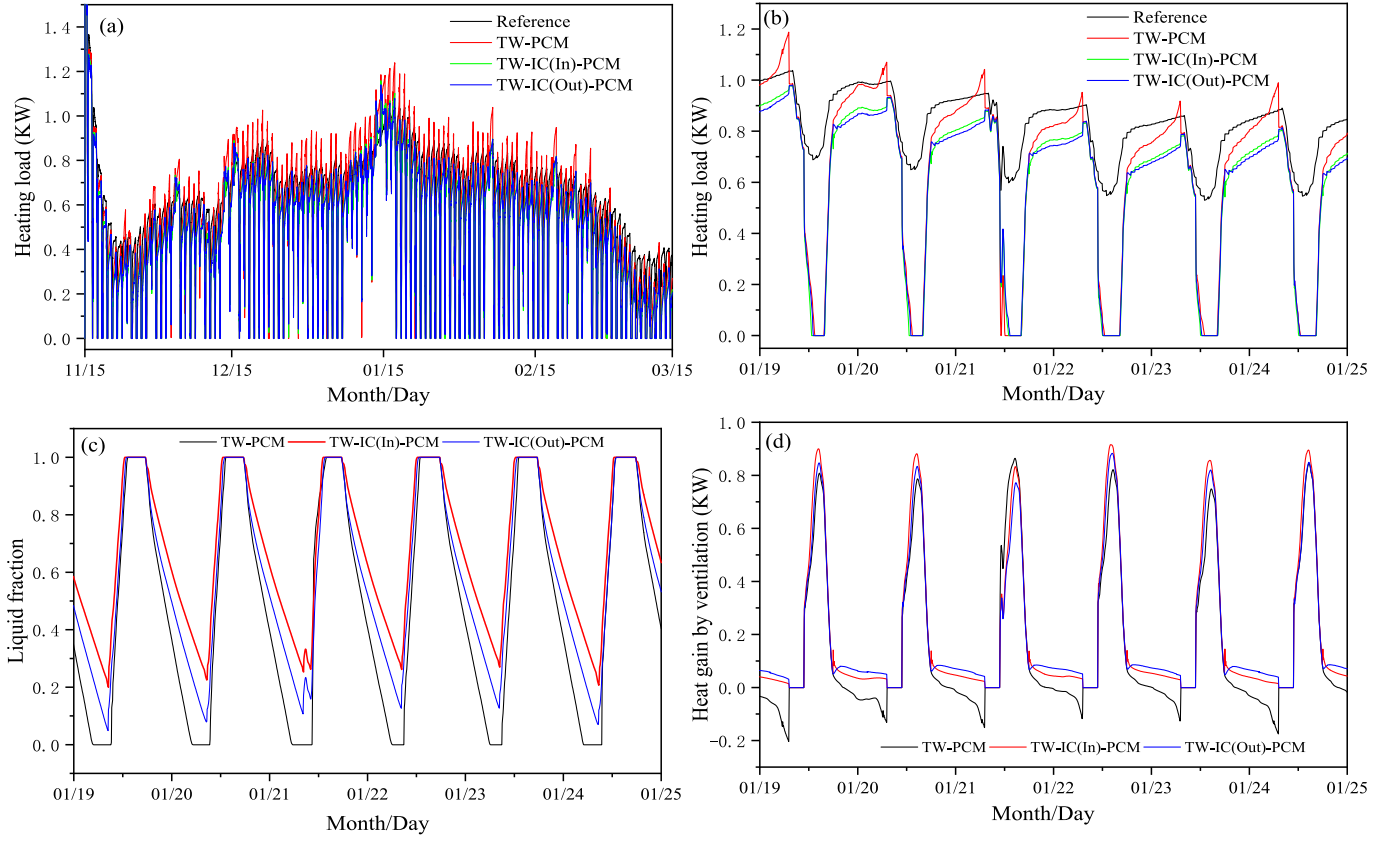


Fig. 13. The heating load, PCM liquid fraction, ventilation heat gain of TW-PCM, TW-IC(In)-PCM, TW-IC(Out)-PCM, and reference room.

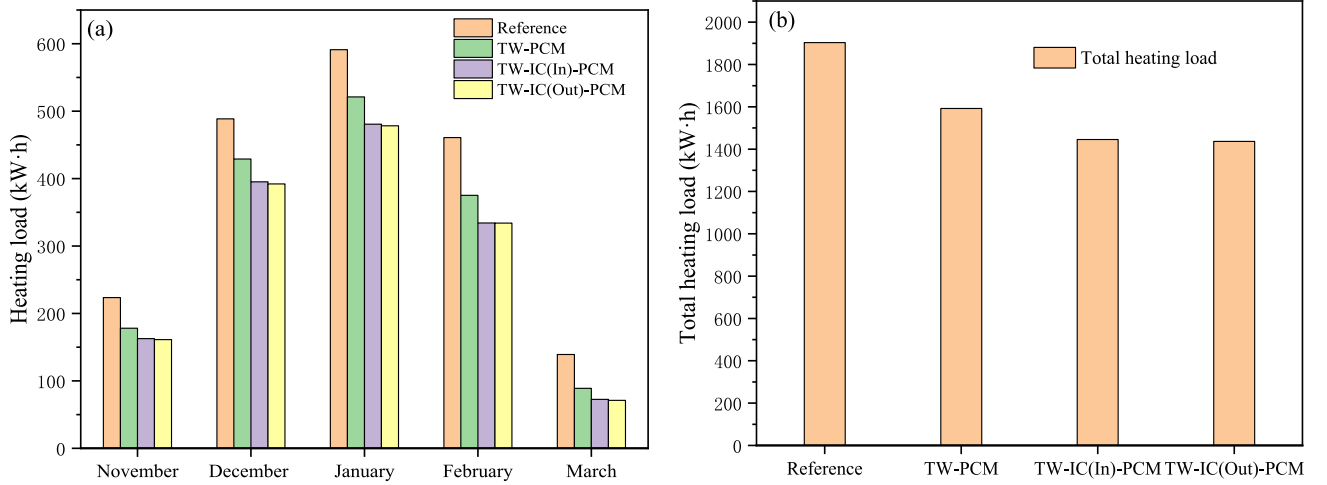


Fig. 14. Monthly and total heating loads of four different rooms.

Table 7

The heating load reduction rate when compared to the reference room.

Month	TW- PCM	TW-IC(In)-PCM	TW-IC(Out)-PCM
November	20.35 %	27.23 %	27.94 %
December	12.22 %	19.15 %	19.77 %
January	11.86 %	18.73 %	19.07 %
February	18.60 %	27.48 %	27.53 %
March	36.11 %	47.81 %	48.87 %
Total	16.35 %	24.07 %	24.52 %

$$h_{rad,curb-pcms} = \frac{\sigma(T_{pcms}^2 + T_{curb}^2)(T_{pcms} + T_{curb})}{\frac{1}{\epsilon_{cur}} + \frac{1}{\epsilon_{pcm}} - 1} \quad (25)$$

$h_{conv,curb-air}$ represents the convective heat transfer coefficient between curtain internal surface and air passage, $W/(m^2 \cdot K)$. The calculation formula can refer to the above calculation formula of $h_{conv,ig-air}$.

3.1.4. The energy balance equation of air passage

When the curtain is not in use:

When the vent is opened [33]:

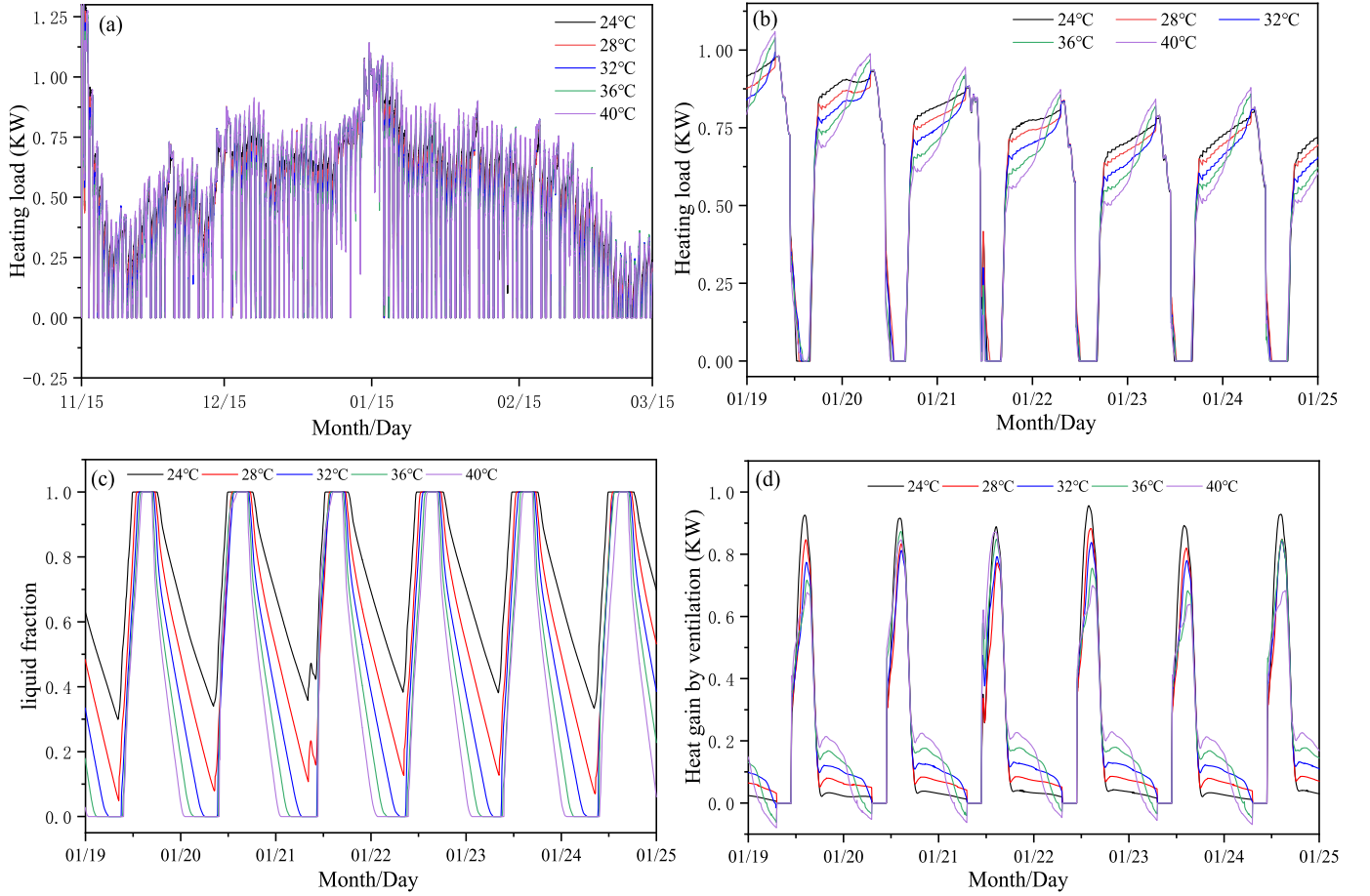


Fig. 15. The heating load, liquid fraction, and ventilation heat gain at different phase change temperatures of TW-IC(Out)-PCM.

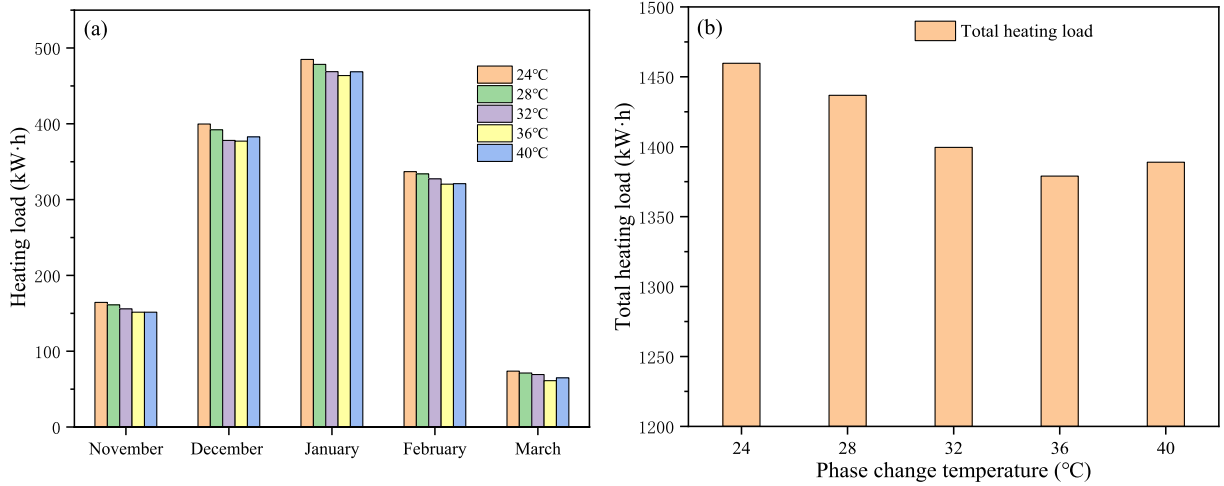


Fig. 16. Monthly and total heating loads of TW-IC(Out)-PCM at different phase change temperatures.

$$\rho_a c_a d_{air} \frac{\partial T_{air}}{\partial t} = h_{conv,ig-air} (T_{ig} - T_{air}) + h_{conv,air-pcms} (T_{pcms} - T_{air}) - \rho_a c_a d_{air} V_a \frac{\partial T_{air}}{\partial y} \quad (26)$$

When the vent is closed [33]:

$$\rho_a c_a d_{air} \frac{\partial T_{air}}{\partial t} = h_{conv,ig-air} (T_{ig} - T_{air}) + h_{conv,air-pcms} (T_{pcms} - T_{air}) \quad (27)$$

When the curtain is used, the air passage thickness changes from d_{air} to $d_{air,cur}$, and $d_{air,cur} = d_{air} - d_{cur} - d_{cair}$. Its energy balance equation is:

When the vent is opened [35]:

$$\rho_a c_a d_{air-cur} \frac{\partial T_{air}}{\partial t} = h_{conv,curb-air} (T_{curb} - T_{air}) + h_{conv,air-pcms} (T_{pcms} - T_{air}) - \rho_a c_a d_{air-cur} V_a \frac{\partial T_{air}}{\partial y} \quad (28)$$

Table 8

The reduction rate of the heating load of the TW-IC(Out)-PCM at different phase change temperatures compared to the reference room.

Month	24°C	28°C	32°C	36°C	40°C
November	26.47 %	27.94 %	30.32 %	32.23 %	32.24 %
December	18.21 %	19.77 %	22.61 %	22.82 %	21.66 %
January	17.95 %	19.07 %	20.69 %	21.55 %	20.72 %
February	26.92 %	27.53 %	28.95 %	30.47 %	30.34 %
March	47.06 %	48.87 %	50.26 %	56.10 %	53.39 %
Total	23.32 %	24.52 %	26.48 %	27.56 %	27.03 %

When the vent is closed [35]:

$$\rho_a c_a d_{air-cur} \frac{\partial T_{air}}{\partial t} = h_{conv,curb-air}(T_{curb} - T_{air}) + h_{conv,air-pcms}(T_{pcms} - T_{air}) \quad (29)$$

where V_a is the air flow velocity in air passage when the vent is opened, m/s. It can be calculated by Eq. (30) [38]:

$$V_a = \sqrt{\frac{0.5g\beta(T_{out} - T_{in})H}{C_{in}\left(\frac{A}{A_{in}}\right)^2 + C_{out}\left(\frac{A}{A_{out}}\right)^2 + C_f\left(\frac{H}{D}\right)}} \quad (30)$$

where A denotes the air passage cross-sectional area, m^2 ; A_{in} and A_{out}

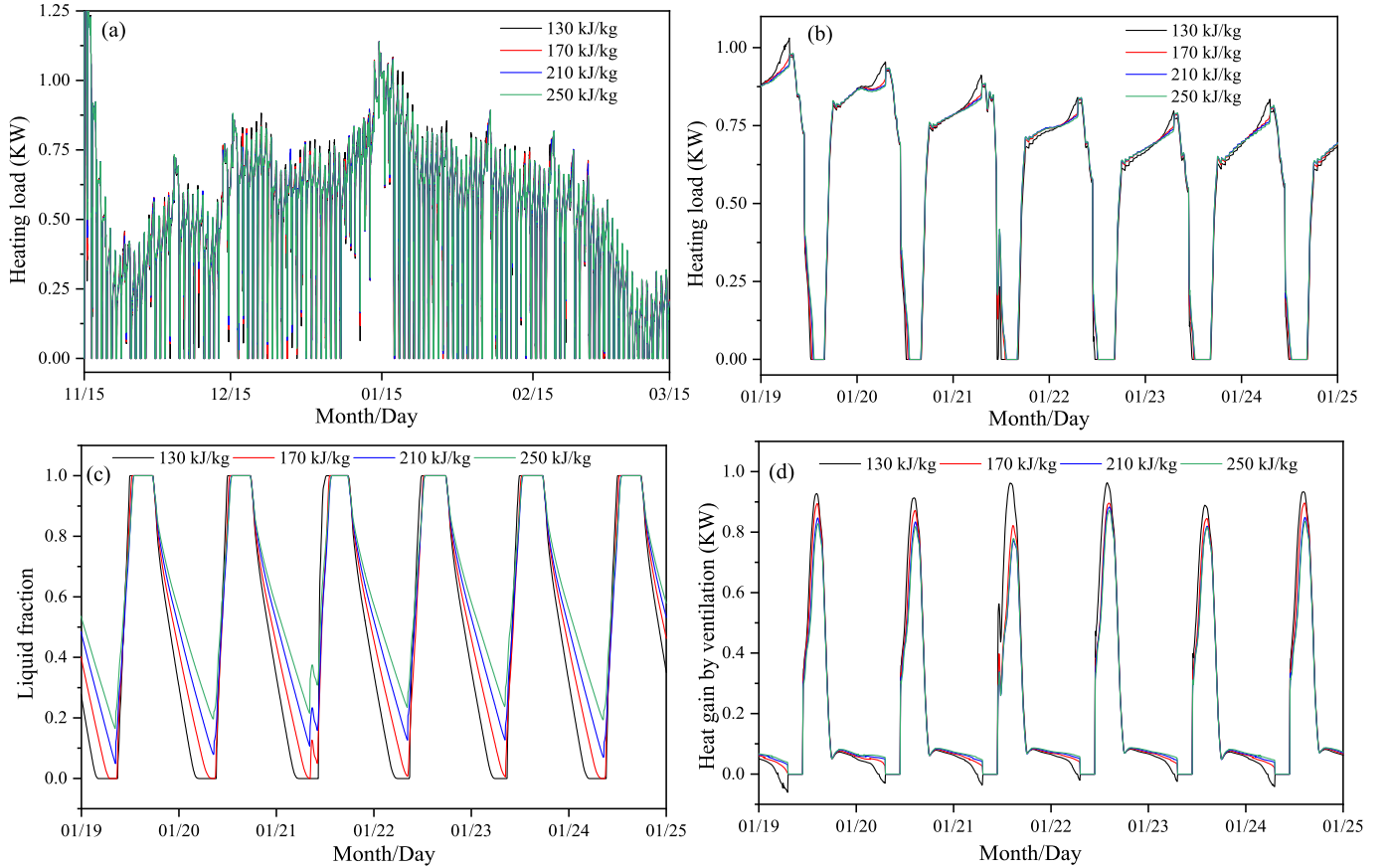


Fig. 17. Heating load, PCM liquid fraction, and ventilation heat gain of TW-IC(Out)-PCM at different PCM latent heat in winter.

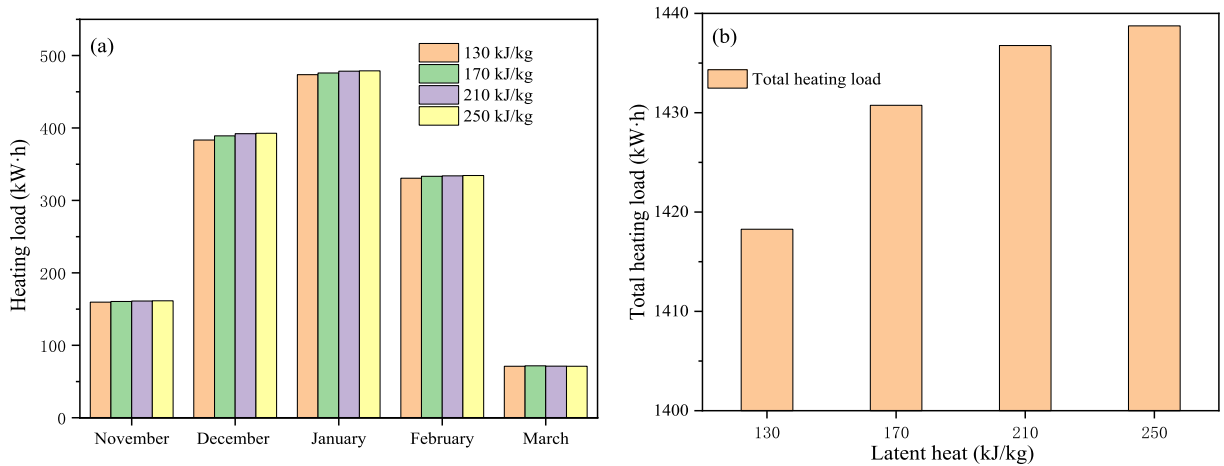


Fig. 18. Monthly and total heating load of TW-IC(Out)-PCM at different PCM latent heat in winter.

Table 9

The reduction rate of heating load of TW-IC(Out)-PCM at different PCM latent heat compared to the reference room.

Month	TW-IC(Out)-PCM (130 kJ/kg)	TW-IC(Out)-PCM (170 kJ/kg)	TW-IC(Out)-PCM (210 kJ/kg)	TW-IC(Out)-PCM (250 kJ/kg)
November	28.64 %	28.19 %	27.94 %	27.77 %
December	21.55 %	20.37 %	19.77 %	19.62 %
January	19.88 %	19.49 %	19.07 %	18.99 %
February	28.26 %	27.66 %	27.53 %	27.45 %
March	48.97 %	48.51 %	48.87 %	48.89 %
Total	25.49 %	24.84 %	24.52 %	24.42 %

Table 10

Different shade positions and ventilation methods in summer.

	TW-PCM	Daytime shade position (curtain position)	Nighttime shade position (curtain position)	External ventilation
Reference	--	--	--	--
Summer1	✓	--	--	The whole day
Summer2	✓	Air passage	--	The whole day
Summer3	✓	Outdoor	--	The whole day
Summer4	✓	Outdoor	--	Only night

represent air inlet and outlet areas, m^2 , respectively. H stands for air passage height, m . D represents the air passage hydraulic diameter, m , and $D = 4A/(d_a + w_a)$; d_a and w_a represent the air passage thickness and width, m , respectively. C_{in} and C_{out} represent air inlet and outlet local resistance coefficients, respectively; $C_{in} = 0.5$, $C_{out} = 0.3$. C_f is air passage resistance coefficient, $C_f = 0.4104Gr_{air}^{0.084}$.

3.1.5. The energy balance equation of phase change material

The PCM energy balance equation is expressed by Eq. (31) [35]:

$$\rho_{pcm} c_{pcm} \frac{\partial T_{pcm}}{\partial t} = \lambda_{pcm} \frac{\partial^2 T_{pcm}}{\partial x^2} + \lambda_{pcm} \frac{\partial^2 T_{pcm}}{\partial y^2} \quad (31)$$

The PCM external surface boundary condition is as follows: when the curtain is not in use [35]:

$$-\lambda_{pcm} \frac{\partial T_{pcm}}{\partial x} = h_{rad,ig-pcms} (T_{ig} - T_{pcm}) + h_{conv,air-pcms} (T_{air} - T_{pcm}) + \tau_{eg} \tau_{ig} \alpha_{pcm} G_r \quad (32)$$

when the curtain is used [35]:

$$-\lambda_{pcm} \frac{\partial T_{pcm}}{\partial x} = h_{rad,curb-pcms} (T_{curb} - T_{pcm}) + h_{conv,air-pcms} (T_{air} - T_{pcm}) \quad (33)$$

where $h_{conv,air-pcms}$ represents the convective heat transfer coefficient between PCM external surface and the air passage, $W/(m^2 \cdot K)$. Its calculation formula can refer to $h_{conv,ig-air}$.

The boundary condition for the PCM internal surface is expressed by Eq. (34) [30]:

$$-\lambda_{pcm} \frac{\partial T_{pcm}}{\partial x} = \frac{1}{R_{wall-pcmb}} (T_{wall} - T_{pcm}) \quad (34)$$

where T_{wall} is the plaster board internal surface temperature, K . $R_{wall-pcmb}$ is the thermal resistance between the plaster board internal surface and the PCM internal surface, $(m^2 \cdot K)/W$, and its expression can be calculated using Eq. (35) [30]:

$$R_{wall-pcmb} = \frac{d_{plaster}}{\lambda_{plaster}} + \frac{d_{brick}}{\lambda_{brick}} + \frac{d_{ins}}{\lambda_{ins}} \quad (35)$$

where $\lambda_{plaster}$, λ_{brick} , and λ_{ins} are the thermal conductivity of plaster

board, brick wall, and thermal insulation layer, $W/(m \cdot K)$, respectively; $d_{plaster}$, d_{brick} , and d_{ins} are the thickness of plaster board, brick wall, and insulation, m , respectively.

The specific heat capacity of PCM is based on the effective specific heat capacity model, which is calculated by Eq. (36) [39]:

$$c_{pcm} = \begin{cases} c_s, & T_{pcm} < T_s \\ (c_s + c_l)/2 + H_m/(T_l - T_s), & T_s \leq T_{pcm} \leq T_l \\ c_l, & T_{pcm} > T_l \end{cases} \quad (36)$$

T_s and T_l stand for the lowest and highest temperatures of the PCM during phase transition, K , respectively. c_s and c_l are the PCM specific heat capacity in solid and liquid phase, $J/kg \cdot K$, respectively.

The PCM liquid fraction can be calculated by Eq. (37) [35]:

$$l = \begin{cases} 0, & T_{pcm} < T_s \\ \frac{T_{pcm} - T_s}{T_l - T_s}, & T_l < T_{pcm} < T_s \\ 1, & T_{pcm} > T_l \end{cases} \quad (37)$$

3.2. Model of the phase change material Trombe wall with an outside curtain

When the curtain is located outdoor and is not in use, the curtain temperature is the same as the outdoor temperature, and the energy balance equation for the rest of the TW-IC(Out)-PCM is the same as TW-IC(In)-PCM. Between the curtain and the external glass, a sealed air passage occurs when the curtain is in use. The following describes the different parts of the energy balance equation when the curtain is used, compared to when the curtain is not in use. The different parts are the curtain internal and external surface, the sealed air passage, and the external glass.

The energy balance equation of the curtain external surface is expressed by Eq. (38) [38]:

$$\rho_{cur} c_{cur} \frac{d_{cur}}{2} \frac{\partial T_{curs}}{\partial t} = \frac{d_{cur}}{2} \lambda_{cur} \frac{\partial^2 T_{curs}}{\partial y^2} + \frac{\lambda_{cur}}{d_{cur}} (T_{curb} - T_{curs}) + h_{conv,am} (T_{am} - T_{curs}) + h_{rad,curs-sky} (T_{sky} - T_{curs}) + \alpha_{cur} G_r \quad (38)$$

The energy balance equation of the curtain internal surface is expressed by Eq. (39) [38]:

$$\rho_{cur} c_{cur} \frac{d_{cur}}{2} \frac{\partial T_{curb}}{\partial t} = h_{rad,curb-eg} (T_{eg} - T_{curb}) + h_{conv,curb-cair} (T_{cair} - T_{curb}) + \frac{d_{cur}}{2} \lambda_{cur} \frac{\partial^2 T_{curb}}{\partial y^2} + \frac{\lambda_{cur}}{d_{cur}} (T_{curs} - T_{curb}) \quad (39)$$

The energy balance equation of the sealed air passage is expressed by Eq. (40) [30]:

$$\rho_a c_a d_{cair} \frac{\partial T_{cair}}{\partial t} = h_{conv,curb-cair} (T_{curb} - T_{cair}) + h_{conv,cair-eg} (T_{eg} - T_{cair}) \quad (40)$$

The energy balance equation of the external glass is expressed by Eq. (41) [30]:

$$\rho_g c_g d_{eg} \frac{\partial T_{eg}}{\partial t} = d_{eg} \lambda_g \frac{\partial^2 T_{eg}}{\partial y^2} + h_{conv,cair-eg} (T_{cair} - T_{eg}) + h_{rad,eg-curb} (T_{curb} - T_{eg}) + \frac{1}{R_{gap-eg}} (T_{gap} - T_{eg}) + h_{rad,eg-ig} (T_{ig} - T_{eg}) \quad (41)$$

In the above formula, $h_{rad,curs-sky}$ represent the radiant heat transfer coefficient between the curtain external surface and the sky, $W/(m^2 \cdot K)$; $h_{rad,curb-eg}$ is the radiant heat transfer coefficient between the curtain internal surface and the external glass, $W/(m^2 \cdot K)$. The radiant heat transfer coefficient has been determined according to equations (5)–(6). $h_{conv,curb-cair}$ and $h_{conv,cair-eg}$ represent the convection heat transfer

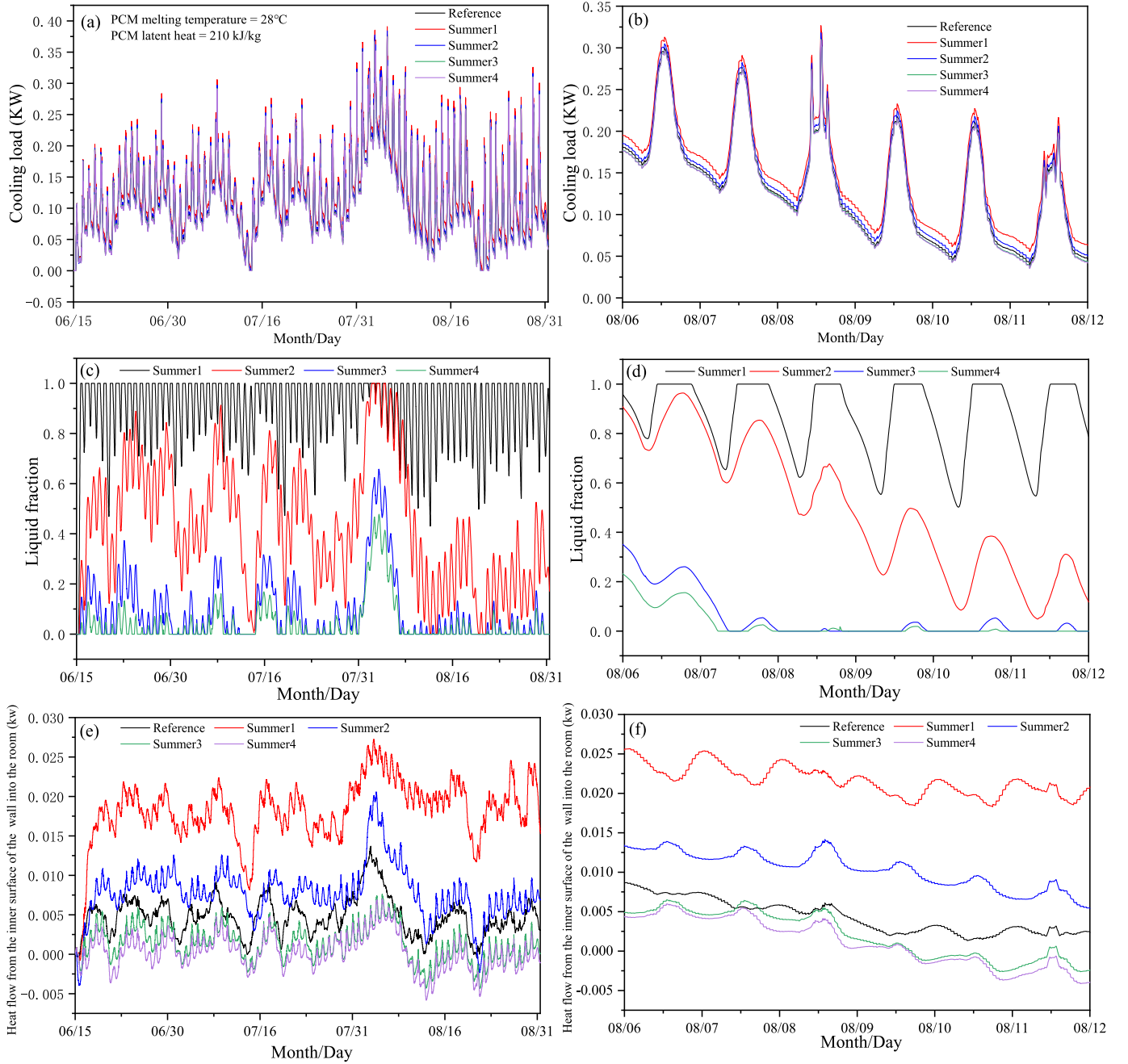


Fig. 19. Instantaneous cooling load, liquid fraction, and heat flow of the inner wall surface under different shading and ventilation modes in summer.

coefficient between the curtain internal surface, external glass, and the sealed air, $W/(m^2 \cdot K)$, respectively; $h_{conv,curb-cair} = h_{conv,cair-eg}$, and its calculation formula is the same as equations (17–19).

3.3. Building energy model

First, using the implicit difference approach, the heat transfer differential equations in sections 3.1 and 3.2 are discretized into algebraic equations, which are then solved via Newton-Raphson iteration. Fig. 4 shows the node division diagram of TW-IC-PCM. The calculation program was compiled by MATLAB. Then the building envelop is then established by TRNSYS. Additionally, in order to achieve the data interaction between TRNSYS and MATLAB, the Type155 module in TRNSYS calls the MATLAB program.

Fig. 5 shows the co-simulation schematic diagram of MATLAB and

TRNSYS. In the simulation process, the data interaction between MATLAB and TRNSYS is as follows: TRNSYS transmits the indoor temperature, outdoor meteorological parameters, and internal surface temperature of the wall where the TW-IC-PCM is installed to MATLAB. The air outlet temperature, air outlet flow rate, and PCM internal surface temperature are then sent to TRNSYS by MATLAB. Since the focus of this article is on the impact of TW-IC-PCM on building performance, loads generated by air infiltration, personnel, fresh air, and equipment are not set in the multi-zone building module Type 56.

3.4. Model verification

The accuracy of mathematical model was verified with the use of the available experimental data. First, verify the model with the vents open and closed. For a PCM solar chimney, Liu et al. performed an 8-hour heat

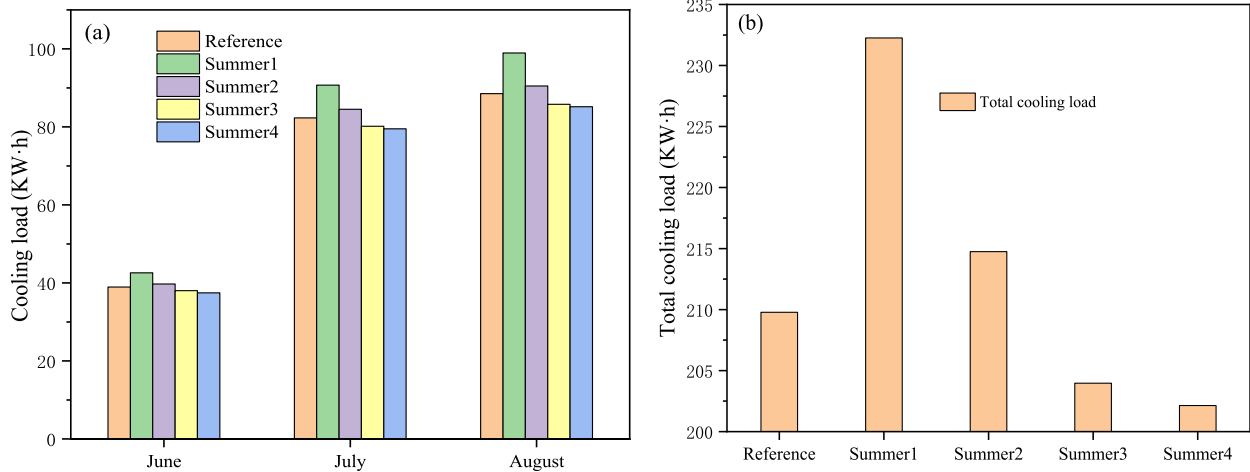


Fig. 20. Monthly and total cooling load under different shading and ventilation modes in summer.

Table 11

The comparison of this work with previous studies.

Building type	Energy saving	References
louver –TW building	5.8 % (cooling load)	[22]
TW building	20 % (heating load)	[23]
TW building with double-layer PCM	39 % (heating load)	[25]
Dynamic TW-PCM building	25.3 % (heating load)	[42]
TW-PCM building	22.47 % (heating load)	[43]
TW-PCM building with sunshade thermal insulation curtain	24.52 % (heating load)/3.64 % (cooling load)	This work

storage process by closing the vent and then opening the vent for a 16-hour heat release process [40]. Fig. 6 presents a comparison of the modeling and experimental results for the solar chimney. The figure shows that the temperature differential between the outlet and inlet, the mass flow rate at the outlet, the absorber temperature, and the PCM internal surface all correspond well with the experimental data.

Then verify the model when the curtain is opened and closed. A TW-PCM room [41] was built up by Zhou et al. The vents were kept open throughout the experiment. The light source was turned on during 9:00 a.m. ~ 15:30p.m. to keep the solar radiation intensity at 320 W/m². During 15:30p.m. ~ 9:00 a.m. the next day, the light source was turned off while the thermal insulation curtain was opened. In the TW-PCM building, Fig. 7 compares the simulated and experimental room temperature data. Results indicate a good agreement between numerical simulation and experimental results.

3.5. Grid and time step independence

The mesh size and time step have a significant impact on the mathematical model's calculation accuracy. Verifying the grid and time step independence is frequently required since it is not possible to choose the right mesh size and time step directly. This section uses the simulation results of TW-IC(In)-PCM under a Beijing typical winter day (as shown in Fig. 8) for verification. The working mode in winter is to close the vent for thermal insulation during 05:00 a.m. ~ 10:30 a.m. and open the vent for indoor heating during the rest of the time. The melting temperature was determined to be 31 °C ~ 33 °C, while the room temperature was fixed at 14 °C.

Fig. 9 shows the air outlet temperature and PCM inner surface temperature when the time steps are 1 s, 5 s, 10 s, 15 s, 20 s, 30 s, 40 s, and 50 s, respectively. In the process from 1 s to 10 s, the temperature changes little, and when the step size continues to increase, the temperature changes greatly. In this paper, the time step is selected as 10 s. Fig. 10 shows the temperature change with different numbers of nodes

along the height direction of the wall. When the number of nodes increases from 20 to 40, the temperature of the PCM internal surface and outlet rises with the number of nodes. As the number of nodes continues to increase from 40, the temperature hardly changes. Therefore, m is chosen as 40 for further calculation (that is, a node is set every 0.0475 m along the Y-axis). The impact of PCM node count (S) along thickness on the outlet and inner surface temperature is depicted in Fig. 11. When S increases from 1 to 5, the temperature changes greatly, but when S continues to increase, the temperature changes are not obvious. So S is selected as 5, that is, set a node at the PCM layer every 0.004 m along the X-axis.

4. Results and discussion

This study investigates the performance of the TW-IC-PCM building under Beijing's weather conditions. Fig. 12 shows the vertical southward solar radiation and outdoor temperature parameters of Beijing. The heating time in winter is set to be from November 15 to March 15, and the design room temperature is 18 °C. The cooling time in summer is from June 15 to August 31, and the design room temperature is 26 °C.

4.1. Heating load in winter

In winter, the period from 08:00 to 18:00 is daytime, and the rest of the time is night. Table 6 displays the daily working mode of TW-IC(In)-PCM and TW-IC(Out)-PCM in winter.

4.1.1. Comparison at different curtain positions

Fig. 13 shows the instantaneous heating load, PCM liquid fraction, and ventilation heat gain of TW-PCM, TW-IC(In)-PCM, TW-IC(Out)-PCM, and reference room. The reference room is the room that does not install TW. In Fig. 13(a), when compared to the reference room, TW-IC(In)-PCM and TW-IC(Out)-PCM can both lower the heating load during the day and night when solar radiation is enough; however, TW-PCM has a higher heating load because of significant heat loss at night. Fig. 13 (b) shows that during the period of six consecutive days with solar radiation, the heating load range of TW-IC(In)-PCM and TW-IC(Out)-PCM is 0KW–0.98KW, and their peak load decreases by 5.5 % compared with that of the reference room, but the TW-IC(Out)-PCM heating load at night is lower than TW-IC(In)-PCM. According to Fig. 13(c), during the day, the PCM in TW-PCM, TW-IC(In)-PCM, and TW-IC(Out)-PCM all melt completely. However, at night, the latent heat residual of TW-IC (In)-PCM is between 20 % and 26 %, while that of TW-IC(Out)-PCM is between 5 % and 12.6 %. In Fig. 14(d), the ventilation heat gain of TW-PCM at night is negative during 23:30–07:30, but after the curtain is set, the ventilation heat gain at night is positive. In contrast to TW-IC(In)-

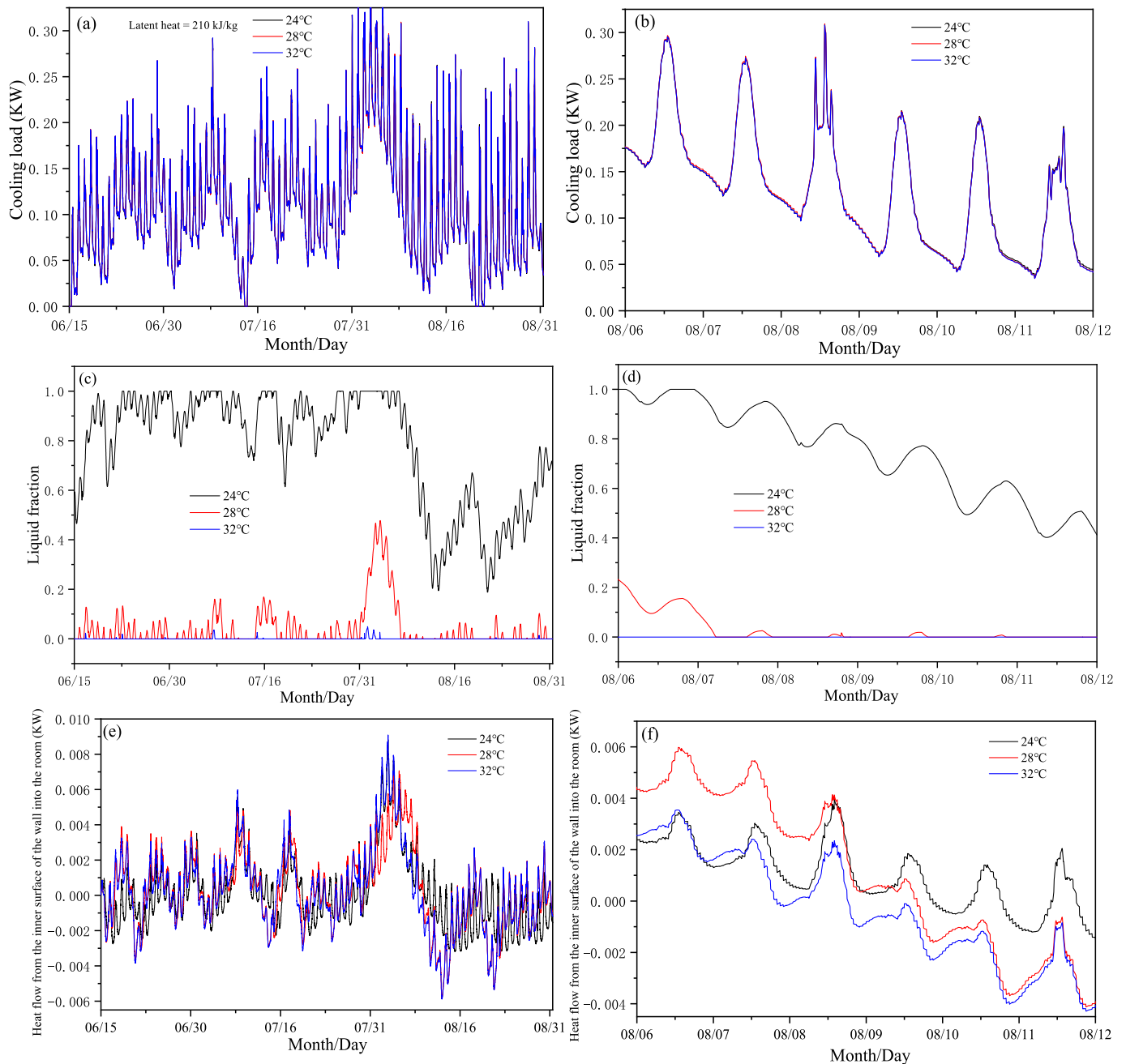


Fig. 21. Indoor cooling load, PCM liquid fraction, and heat flow on the inner surface of the TW-IC (Out)-PCM under different phase change temperatures in summer.

PCM, TW-IC(Out)-PCM has a higher ventilation heat gain between 20:00 and 07:30 but a lower ventilation heat gain between 10:30 and 20:00.

The monthly and overall heating loads of four distinct rooms during the winter are displayed in Fig. 14. It shows that the monthly heating load in descending order is January, December, February, March, and November. The total heating loads of Reference, TW-PCM, TW-IC(In)-PCM, and TW-IC(Out)-PCM are 1903.55 kW·h, 1592.23 kW·h, 1445.36 kW·h, and 1436.77 kW·h, respectively. Table 7 shows that the heating load of TW, TW-IC(In)-PCM, and TW-IC(Out)-PCM is reduced by 16.35 %, 24.07 %, and 24.52 %, respectively, compared to the reference room.

4.1.2. Effect of phase change temperature

The TW-IC (Out)-PCM instantaneous heating load, PCM liquid fraction, and ventilation heat gain are displayed in Fig. 15 at various phase change temperatures. As shown in Fig. 15(a), higher phase change temperatures lead to higher peak heating loads and higher daily

fluctuations in heating loads. Fig. 15(b) shows the heating load during six consecutive days from January 19 to January 25. The results show that the heating load is 0 during 13:00 ~ 16:00 in the daytime. A greater phase change temperature means faster growth and more fluctuation in heating load during the nighttime hours of 18:00 to 07:30. According to Fig. 15(c), PCM melts more slowly during the day and solidifies more quickly at night at higher phase change temperatures. As the phase change temperature rises, the ventilation heat gain decreases during the day, but it first rises before falling during the night, as illustrated in Fig. 15(d).

The monthly and total heating loads of TW-IC(Out)-PCM at various phase change temperatures are displayed in Fig. 16. The phase change temperature of 36 °C results in the lowest monthly and total heating loads, with a minimum total heating load of 1379.00 kW·h. Table 8 displays the heating load decrease rates at various phase change temperatures in comparison to the reference room. The data suggests that

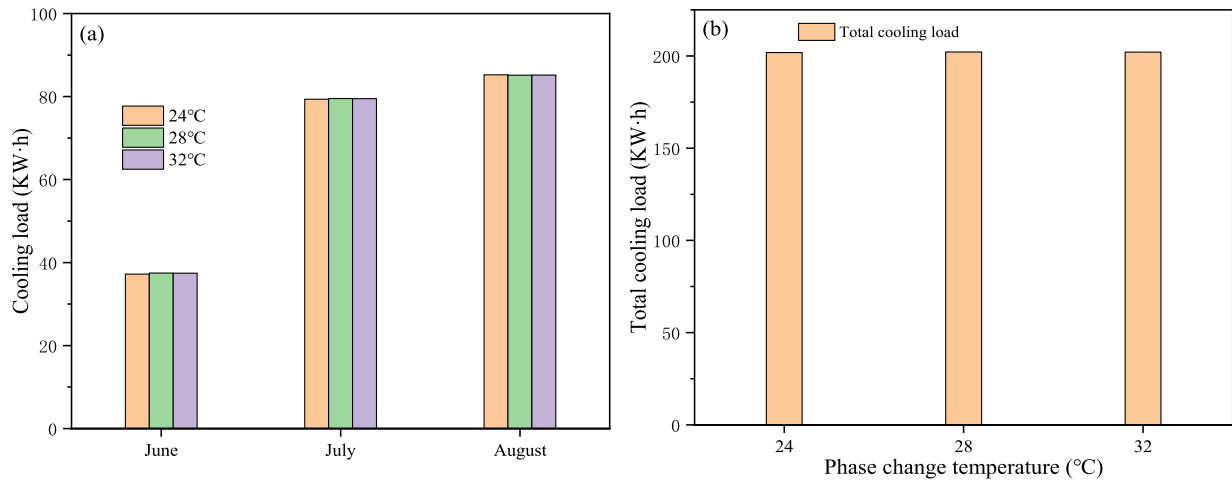


Fig. 22. Monthly and total cooling load at different phase change temperatures in summer.

the monthly reduction rates are the largest when the phase change temperature is 36 °C, which are 32.23 %, 22.82 %, 21.55 %, 30.47 %, and 56.10 % from November to March, respectively. The maximum reduction rate of the total heating load is 27.56 % when the phase change temperature is 36 °C.

4.1.3. Effect of latent heat

Fig. 17 shows the heating load, PCM liquid fraction, and indoor ventilation heat gain of TW-IC(Out)-PCM building at different latent heat. Fig. 17(a-b) shows that in the presence of solar radiation, the greater the latent heat, the greater the daytime heating load and the smaller the nighttime heating load. It found that the greater the latent heat, the smaller the fluctuation of heating load in one day. Fig. 17(c) shows the PCM liquid fraction under different latent heat. It can be seen that PCM can completely melt during the day, and the higher the latent heat, the slower the melting of PCM during the day and the slower the release rate of latent heat at night. In Fig. 17 (d), The heat gain by ventilation decreases with the increase of latent heat during the day and increases with the increase of latent heat at night. The greater the latent heat, the smaller the fluctuation of the heat obtained by ventilation within a day. This is because the greater the latent heat, the more solar energy PCM stores during the day, so that less heat enters the room through natural convection during the day and the more heat is released at night.

In winter, the monthly and total heating load at different latent heat is displayed in Fig. 18. Table 9 shows the reduction rate of heating load with different latent heat compared to the reference room. It can be seen that from November to February, the monthly heating load increases with the increase of latent heat, and the heating load in March increases first and then decreases with the increase of latent heat. When the latent heat increases from 130 kJ/kg to 250kJ/kg, the total heating load increases by 1.44 %. This is because the greater the latent heat, the more solar energy stored during the day and used at night, the greater the heat loss in the process of heat transfer, thus increasing the total heating load.

4.2. Cooling load in summer

4.2.1. Comparison at different curtain positions and ventilation modes

In summer, the curtain can be used as a shading facility to effectively improve the indoor thermal environment, and the period from 07:00 to 19:00 is defined as daytime, and the rest of the time is night. In this section, the melting temperature of PCM is $28 \pm 1^\circ\text{C}$ and the latent heat is 210 kJ/kg. Table 10 shows the different shading and ventilation modes in summer.

Fig. 19 shows the indoor cooling load, PCM liquid fraction, and heat flow on the inner surface of the wall under different shading and

ventilation modes. Fig. 19(a–b) demonstrates that the cooling load value in descending order is: Summer1 > Summer2 > Reference > Summer3 > Summer4, indicating that the all-day ventilation with a shading curtain in the air passage can reduce the cooling load of TW-PCM room, but the cooling load value is still greater than that in the reference room. However, when the shading curtain is set outdoors, the indoor cooling load is smaller than when it is placed in the air passage and the reference room. For the curtain set outdoor, ventilation only at night is more conducive to reducing the cooling load than all-day ventilation. Because of the high outdoor temperatures during the day, opening the vent does not help the wall dissipate heat. In Fig. 19(c–d), for the Summer1 condition, PCM can completely melt during the day, and the latent heat is not fully released at night. For Summer 2, PCM can melt completely in the hottest weather, and the rest of the time it is in a state of partial melting. For Summer 3, PCM cannot melt completely in the whole summer, and the liquid fraction can reach 0.66 in the hottest climate, while it is lower than 0.4 for most of the rest of the time. For Summer 4, the maximum liquid fraction can reach 0.47 under the hottest weather conditions, and the value of the liquid fraction is lower than 0.16 at the rest of the time. In addition, when there was solar radiation for 6 consecutive days from August 6 to August 12, the liquid fractions of Summer 1, Summer 2, Summer 3, and Summer 4 ranged from 0.5 to 1, 0.05–0.96, 0–0.35, and 0–0.23, respectively. In Summer 4, although the outdoor shading hinders the melting of PCM, the use of PCM in winter to store solar energy during the day while releasing latent heat for indoor heating at night is effective. In addition, the PCM liquid fraction is related to the phase change temperature, latent heat and outdoor meteorological parameter. Fig. 19 (e–f) shows that outdoor shading and only nighttime ventilation help reduce the amount of heat entering the room through the walls.

Fig. 20 shows the monthly and total cooling load under different shading and ventilation modes in summer. In Fig. 20(a), Summer 4 has the lowest cooling load. Compared with the reference room, the cooling load in Summer4 in June, July, and August was reduced by 4.0 %, 2.6 %, and 3.09 %, respectively. As shown in Fig. 20(b), when compared with the reference room, the cooling load in Summer 1 and Summer 2 increased by 10.72 % and 2.37 %, respectively, while the cooling load in Summer 3 and Summer 4 reduced by 2.77 % and 3.64 %, respectively. The energy-saving performance of the TW-IC-PCM building in this work is compared with that in other literature in Table 11. It is evident that the TW-IC-PCM building proposed performs relatively well in terms of energy conservation.

4.2.2. Effect of phase change temperature

According to the study in 4.2.1, it is more beneficial to reduce the cooling load by adopting an outdoor sunshade with only nighttime

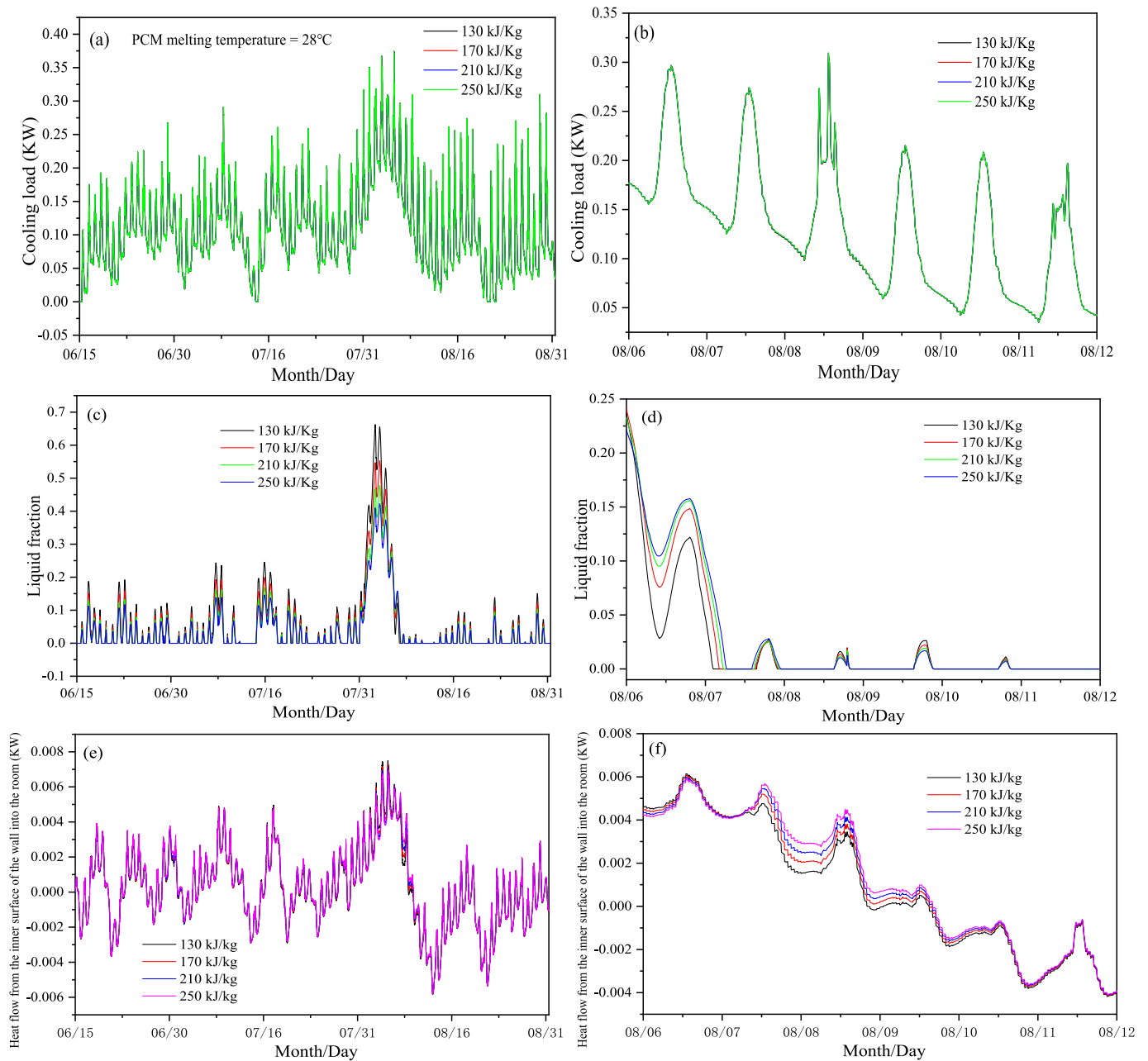


Fig. 23. Indoor cooling load, PCM liquid fraction, and heat flow from the inner surface of the wall into the room of TW-IC (out)-PCM under different latent heat in the summer.

ventilation mode. In this section, the effect of phase change temperatures on the cooling load of buildings with TW-IC(Out)-PCM is studied.

Fig. 21(a-b) shows the distribution of indoor cooling load at different phase change temperatures, from which it can be seen that phase change temperature has little influence on indoor cooling load. During the period from June 15 to August 31, the peak cooling load appears at 13:00 on August 15, and its value is 0.374 KW. Fig. 21(c) shows that during the whole summer, when the phase change temperature is 24 °C, the PCM liquid fraction is between 0.18 and 1, indicating that the PCM layer temperature is always greater than or equal to 23 °C. When the phase change temperature is 28 °C, the PCM liquid fraction is between 0 and 0.48, indicating the PCM layer temperature is always less than or equal to 29 °C. When the phase change temperature is 32 °C, in most of the time the liquid fraction is 0, indicating PCM does not melt and the PCM layer temperature is less than 31 °C, while only a few times its temperature is greater than 31 °C. Since there is no moment with the

liquid fraction value being 1 when the phase change temperature is 32 °C, the temperature of PCM is less than 33 °C. Fig. 21(d) shows that the PCM liquid fraction drops with a rise in phase change temperature from August 6 to August 12. When the phase change temperature is 32 °C, the liquid fraction is 0, and at this time, further increase of phase change temperature has no effect on the change of PCM layer temperature and cooling load. Fig. 21(e-f) shows that during the period from June 15 to August 31, as the phase change temperature increases, the difference between the maximum and minimum values of the heat flow on the inner surface wall is 11.938 W, 12.84 W, and 14.948 W, respectively. In addition, on summer nights, due to the low outdoor temperature and the radiation heat transfer between the external glass and the sky, the temperature of the entire wall is low, and the heat flow from the wall into the room is negative, indicating that the internal surface temperature of the wall is lower than 26 °C.

Fig. 22 shows the effects of different phase change temperatures on

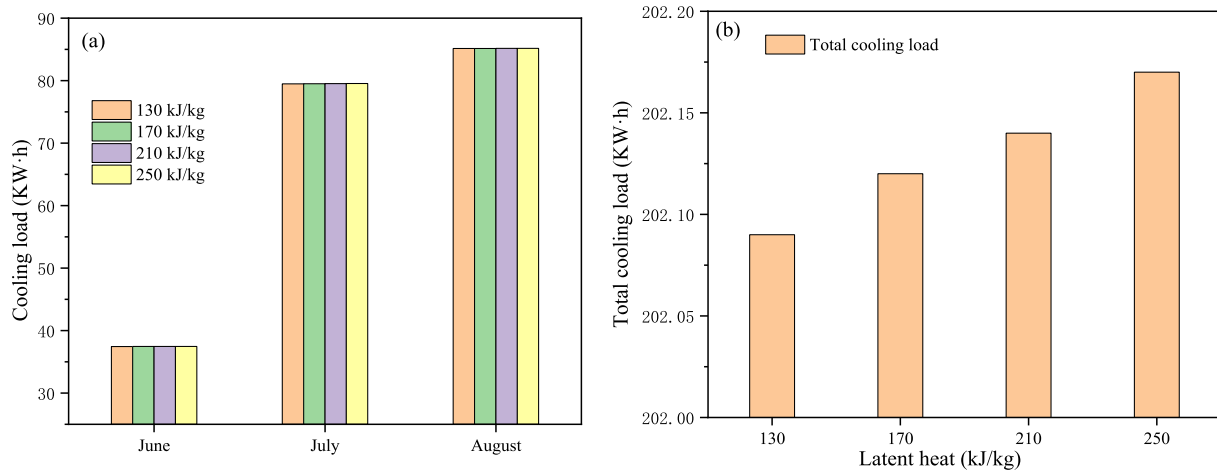


Fig. 24. Monthly and total cooling load of TW-IC(Out)-PCM under different PCM latent heat in summer.

the monthly and total cooling loads. When the phase change temperature is 24°C, 28°C, and 32°C, the total cooling load is 201.83 kW·h, 202.14 kW·h, and 202.1 kW·h, which is reduced by 3.79 %, 3.64 %, and 3.66 % compared with the reference room, respectively. The cooling load in June, July, and August accounted for 18.44 %, 39.32 %, and 42.24 % of the total cooling load, which decreased by 4.42 %, 3.58 %, and 3.7 % compared with the reference room, respectively, when the phase change temperature was 24 °C.

4.2.3. Effect of latent heat

This section studies the cooling load of TW-IC(Out)-PCM with different latent heat. Fig. 23 (a-b) shows that when the latent heat increases from 130 kJ/kg to 250 kJ/kg, the cooling load does not change significantly. Fig. 23(c-d) shows that when the phase change temperature is 28 °C, the larger the latent heat, the smaller the PCM liquid fraction in most of the summer. With the increase of latent heat, the maximum liquid fraction is 0.66, 0.55, 0.47, and 0.42, respectively. However, between August 6 and August 8, there was a phenomenon that the greater the latent heat, the greater the PCM liquid fraction. This may be due to the change of outdoor temperature from high temperature to low temperature in these two days; the greater the latent heat, the smaller the influence of outdoor temperature on the PCM temperature, and the smaller the fluctuation of liquid fraction. Fig. 23 (e-f) shows the heat entering the room through the inner surface of the wall with different latent heat. It is found that with the increase of latent heat, the change of heat entering the room is different under different outdoor weather conditions.

As shown in Fig. 24, monthly cooling load and total cooling load do not change significantly with the increase of latent heat. When the latent heat increases from 130 kJ/kg to 250 kJ/kg, the total cooling load only increases by 0.04 %. This is because the summer meteorological parameters of Beijing are used in this paper. As shown in Fig. 12, the outdoor temperature difference between day and night is large, and the average outdoor temperature in summer is 26.21 °C. This is similar to the summer indoor design temperature of 26 °C, resulting in less impact of latent heat on cooling load.

4.3. Indoor temperature without air conditioning

4.3.1. Indoor temperature in winter

Fig. 25(a-b) shows the indoor temperature at different curtain positions in winter without air conditioning. The TW-IC(Out)-PCM and the TW-IC(In)-PCM had average indoor temperatures that were, respectively, 1.05 °C and 0.81 °C higher than those of the TW-PCM room and 4.5 °C and 4.1 °C higher than those of the reference room. Fig. 25 (c-d) shows the indoor temperature of TW-IC (Out)-PCM at different phase

change temperatures. On most days, the nighttime indoor temperature fluctuates more with the increase in phase change temperature. With the increase in phase change temperature, the average indoor temperature was 8.70 °C, 8.86 °C, 8.88 °C, and 8.84 °C, respectively. Fig. 25 (e-f) shows the indoor temperature at different PCM latent heat. The higher the latent heat, the lower the indoor temperature during the day, and the higher the indoor temperature at night, the less fluctuation of indoor temperature within a day, resulting in better indoor thermal comfort. When the latent heat increased from 130 kJ/kg to 250 kJ/kg, the maximum indoor temperature decreased by 1.13°C and the minimum temperature increased by 0.16°C, but the effect of latent heat on the average indoor temperature was not significant.

4.3.2. Indoor temperature in summer

Fig. 26 (a-b) shows the indoor temperature under different shading and ventilation modes in the summer. The indoor temperature is ranked in descending order as follows: Summer1 > Summer2 > Reference > Summer3 > Summer4, showing that TW-IC(In)-PCM's room temperature is higher and TW-IC(Out)-PCM's room temperature is lower than that of the reference room. Furthermore, it is more effective to lower the room temperature by adopting outdoor ventilation only at night. The indoor temperature of TW-IC(Out)-PCM under various phase change temperatures with only night ventilation is displayed in Fig. 26(c-d). There was little change in room temperature as the phase change temperature rose from 24 °C to 32 °C. Fig. 26 (e-f) shows that room temperature does not change significantly with PCM latent heat. This is because the outdoor meteorological parameters selected in this paper are in Beijing, where the average outdoor temperature in summer is close to the indoor design temperature of 26°C. In hot summer areas, different phase change temperatures and latent heat may greatly affect the indoor temperature distribution.

5. Conclusion

This paper studies the influence of sunshade thermal insulation curtain position and ventilation mode on the energy performance of phase change material Trombe wall building in Beijing based on co-simulation of MATLAB and TRNSYS. The conclusions are as follows:

- (1) In winter, the total heating load of the phase change material Trombe wall building without curtains, with curtains inside, and with curtains outside decreased by 16.35 %, 24.07 %, and 24.52 %, respectively, compared with the reference room. The lowest total heating load occurs at a phase change temperature of 36 °C. When the latent heat increases from 130 kJ/kg to 250 kJ/kg, the total heating load increases by 1.44 %.

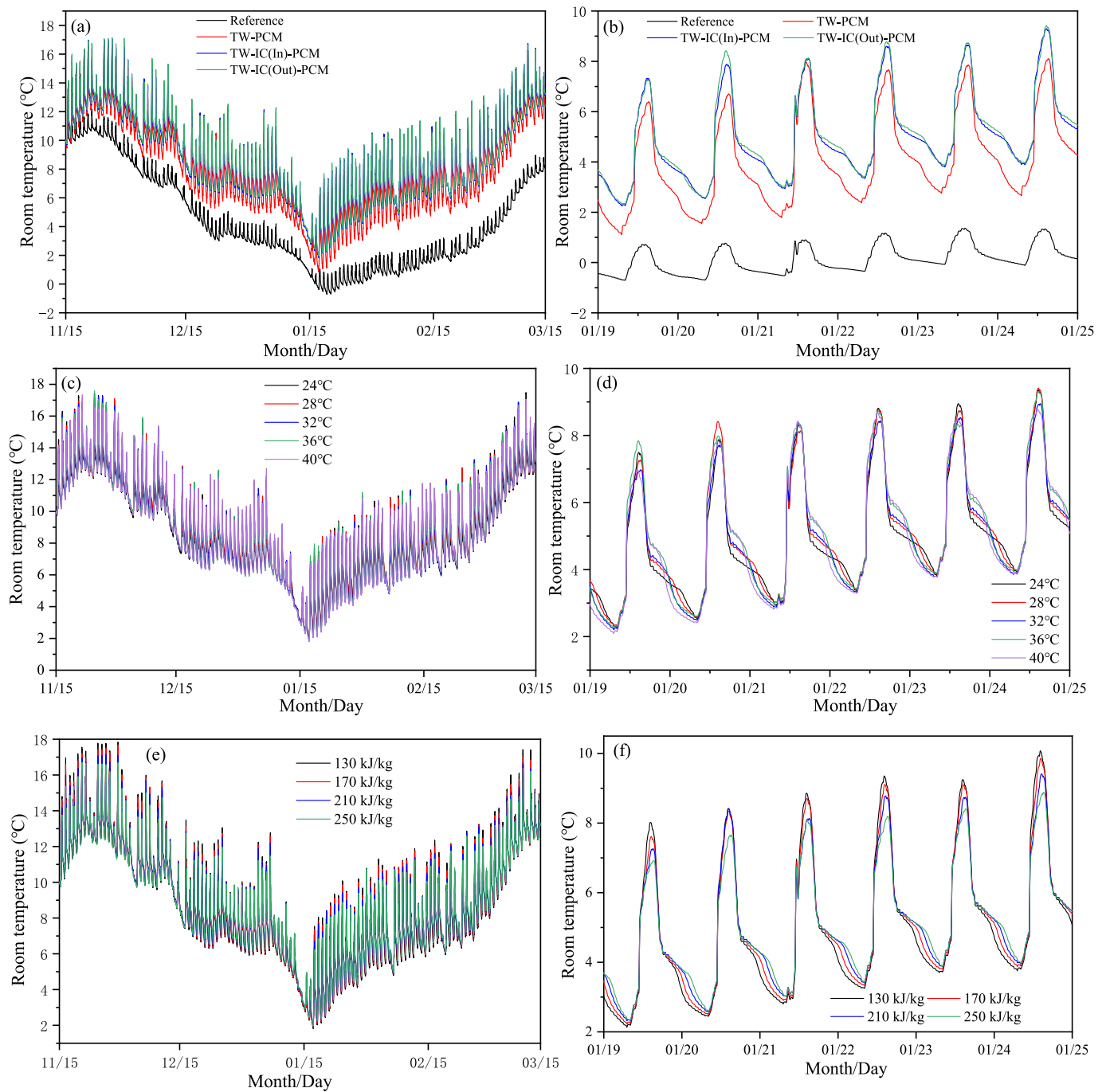


Fig. 25. Indoor temperature under different curtain position, phase change temperature and latent heat in winter.

- (2) In summer, the cooling load of phase change material Trombe wall with curtains inside is reduced by 7.54 % compared to that without curtains. The cooling load with a curtain outside in all-day ventilation and night ventilation mode is reduced by 12.18 % and 12.97 %, respectively, compared with that without a curtain. The phase change temperature and latent heat has very little effect on the cooling load.
- (3) In the absence of air conditioning, the indoor temperature of the phase change material Trombe wall building in winter with the curtain inside or outside was higher than that without the curtain and in the reference room. In summer, the indoor temperature is the lowest under the outdoor shade and night-only ventilation strategy. The higher the phase change temperature and latent heat, the more the indoor temperature fluctuates in the winter,

but the indoor temperature change is less noticeable in the summer.

In the future, the performance of phase change material Trombe wall buildings in different climate zones will be studied through experiments and simulations. In addition, because this paper blocks solar radiation through shading in summer, solar radiation is not effectively used in summer, and photovoltaic thermal systems can be added in the future to make use of solar radiation to generate electricity and produce hot water.

Declaration of competing interest

The authors declare that they have no known competing financial

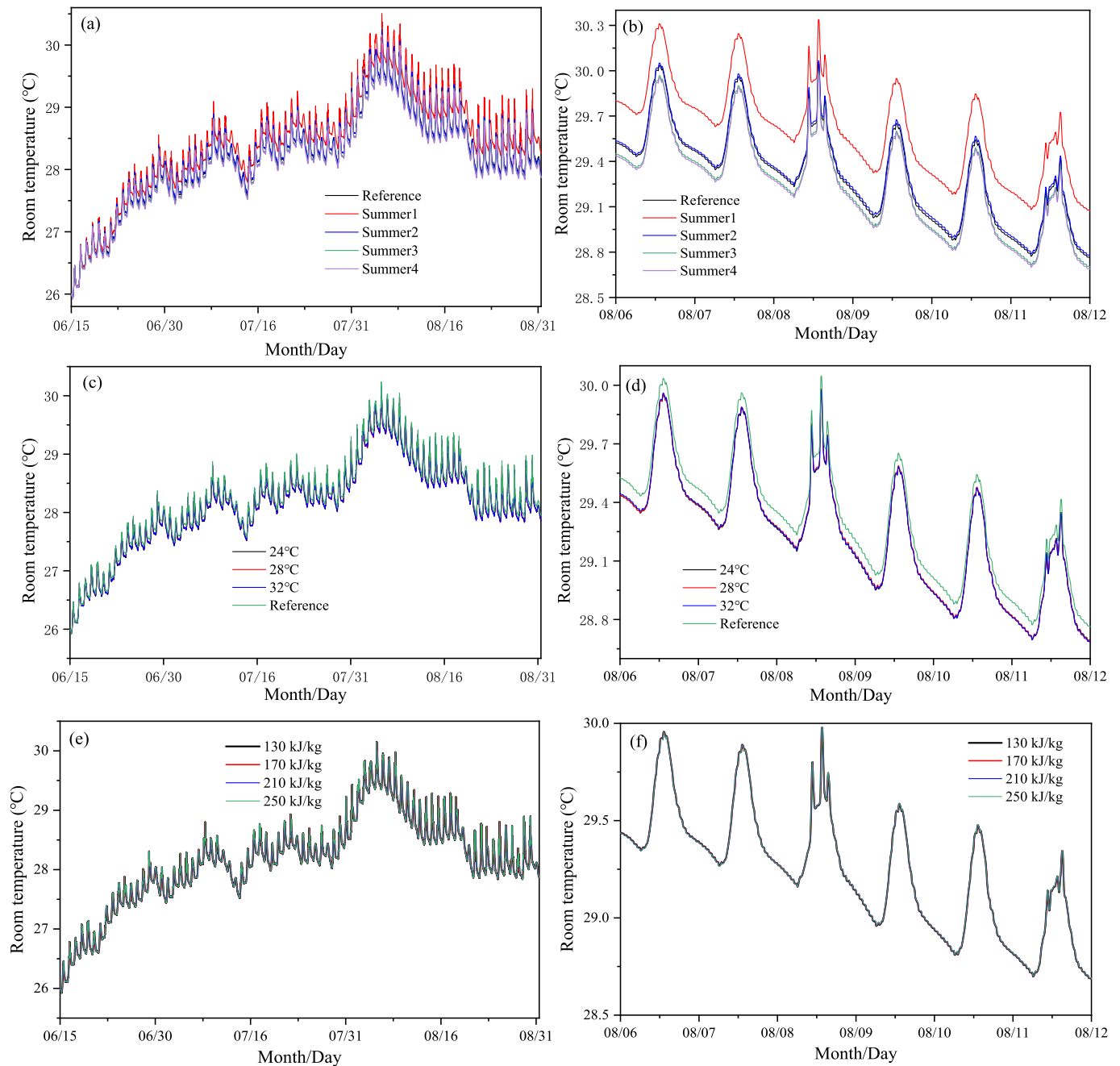


Fig. 26. Indoor temperature under different shading and ventilation methods, phase change temperature and latent heat in summer.

interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (No. 52108077), the Natural Science Foundation of Sichuan Province (No. 2023NSFSC0896), and the Hebei Natural Science Foundation, China (No. E2024105026).

Data availability

Data will be made available on request.

References

- [1] Z.-S. Li, G.-Q. Zhang, D.-M. Li, J. Zhou, L.-J. Li, L.-X. Li, Application and development of solar energy in building industry and its prospects in China, *Energy Policy* 35 (2007) 4121–4127, <https://doi.org/10.1016/j.enpol.2007.02.006>.
- [2] D. Milenić, P. Vasiljević, A. Vranješ, Criteria for use of groundwater as renewable energy source in geothermal heat pump systems for building heating/cooling purposes, *Energ. Buildings* 42 (2010) 649–657, <https://doi.org/10.1016/j.enbuild.2009.11.002>.
- [3] A.O.M. Maka, T. Ghalut, E. Elsaye, The pathway towards decarbonisation and net-zero emissions by 2050: The role of solar energy technology, *Green Technol. Sustainability* 2 (2024) 100107, <https://doi.org/10.1016/j.grets.2024.100107>.
- [4] H.-Y. Chan, S.B. Riffat, J. Zhu, Review of passive solar heating and cooling technologies, *Renew. Sustain. Energy Rev.* 14 (2010) 781–789, <https://doi.org/10.1016/j.rser.2009.10.030>.
- [5] M.S.B. Jahromi, Evaluation of performance, energy, and exergy analysis of a solar parabolic dish collector connected to a dryer with nanofluid and PCM, *J. Storage Mater.* (2024).

- [6] H.S. Akhijahani, Experimental study on the solar drying of Rhubarb (*Rheum ribes* L.) with parabolic trough collector assisted with air recycling system, nanofluid and energy storage system, *J. Storage Mater.* (2023).
- [7] M.S.B. Jahromi, Recent progress on solar cabinet dryers for agricultural products equipped with energy storage using phase change materials, *J. Storage Mater.* (2022).
- [8] M.S.B. Jahromi, Performance analysis of a new solar air ventilator with phase change material: Numerical simulation, techno-economic and environmental analysis, *J. Storage Mater.* (2023).
- [9] M. Iranmanesh, CFD modeling and evaluation the performance of a solar cabinet dryer equipped with evacuated tube solar collector and thermal storage system, *Renew. Energy* (2020).
- [10] M.S.B. Jahromi, Energy and exergy analysis of an unglazed transpired collector connected to a dryer with a porous plate and phase change material, *J. Storage Mater.* (2023).
- [11] M.S.B. Jahromi, Thermo-economic analysis of solar drying of Jerusalem artichoke (*Helianthus tuberosus* L.) integrated with evacuated tube solar collector and phase change material, *J. Storage Mater.* (2022).
- [12] Y. Xiao, Q. Yang, F. Fei, K. Li, Y. Jiang, Y. Zhang, et al., Review of Trombe wall technology: Trends in optimization, *Renew. Sustain. Energy Rev.* 200 (2024) 114503, <https://doi.org/10.1016/j.rser.2024.114503>.
- [13] D. Yan, M. Li, Efficient solar thermal energy utilization and storage based on phase change materials stabilized by MOF@CuO composites, *J. Storage Mater.* 73 (2023) 108885, <https://doi.org/10.1016/j.est.2023.108885>.
- [14] Jahromi MSB, Kalantar V, Sefid M, Iranmanesh M, Akhijahani HS. Experimental Study of Phase Change Process of the Paraffin as a PCM with Copper Foam and Iron Wool 2023;10.
- [15] N. Ben Khedher, H. Togun, A.M. Abed, H.M.T. Al-Najjar, A. Dulaimi, H. I. Mohammed, et al., Discharge performance assessment of a vertical double-pipe latent heat storage unit equipped with circular Y-shaped fins, *Journal of Building Engineering* 75 (2023) 106870, <https://doi.org/10.1016/j.jobe.2023.106870>.
- [16] N. Ben Khedher, S. Ben Nasrallah, Three-dimensional simulation of the thermal performance of porous building brick impregnated with phase change material, *Int. J. Heat Technol.* 32 (2014) 163–169.
- [17] D. Wang, L. Hu, H. Du, Y. Liu, J. Huang, Y. Xu, et al., Classification, experimental assessment, modeling methods and evaluation metrics of Trombe walls, *Renew. Sustain. Energy Rev.* 124 (2020) 109772, <https://doi.org/10.1016/j.rser.2020.109772>.
- [18] Y. Liu, L. Hou, Y. Yang, Y. Feng, L. Yang, Q. Gao, Effects of external insulation component on thermal performance of a Trombe wall with phase change materials, *Sol. Energy* 204 (2020) 115–133, <https://doi.org/10.1016/j.solener.2020.04.010>.
- [19] S. Zhou, A.G. Razaqpur, Efficient heating of buildings by passive solar energy utilizing an innovative dynamic building envelope incorporating phase change material, *Renew. Energy* 197 (2022) 305–319, <https://doi.org/10.1016/j.renene.2022.07.073>.
- [20] F. Stazi, A. Mastrucci, C. Di Perna, The behaviour of solar walls in residential buildings with different insulation levels: An experimental and numerical study, *Eng. Buildings* 47 (2012) 217–229, <https://doi.org/10.1016/j.enbuild.2011.11.039>.
- [21] P. Bevilacqua, F. Benevento, R. Bruno, N. Arcuri, Are Trombe walls suitable passive systems for the reduction of the yearly building energy requirements? *Energy* 185 (2019) 554–566, <https://doi.org/10.1016/j.energy.2019.07.003>.
- [22] X. Hong, M.K.H. Leung, W. He, Effective use of venetian blind in Trombe wall for solar space conditioning control, *Appl. Energy* 250 (2019) 452–460, <https://doi.org/10.1016/j.apenergy.2019.04.128>.
- [23] N. Simões, M. Manaia, I. Simões, Energy performance of solar and Trombe walls in Mediterranean climates, *Energy* 234 (2021) 121197, <https://doi.org/10.1016/j.energy.2021.121197>.
- [24] Y. Xiao, T. Zhang, Z. Liu, F. Fei, H. Fukuda, Optimizing energy efficiency in HSCW buildings in China through temperature-controlled PCM Trombe wall system, *Energy* 278 (2023) 128015, <https://doi.org/10.1016/j.energy.2023.128015>.
- [25] M. Askari, M.H. Jahangir, Evaluation of thermal performance and energy efficiency of a Trombe wall improved with dual phase change materials, *Energy* 284 (2023) 128587, <https://doi.org/10.1016/j.energy.2023.128587>.
- [26] N. Zhu, S. Li, P. Hu, F. Lei, R. Deng, Numerical investigations on performance of phase change material Trombe wall in building, *Energy* 187 (2019) 116057, <https://doi.org/10.1016/j.energy.2019.116057>.
- [27] Q. Ma, X. Dong, X. Wei, Y. Xiao, H. Ma, Experimental and simulation study of the effect of temperature and air supply on energy performance of a temperature-controlled ventilated double-layer Trombe wall, *Sol. Energy* 282 (2024) 112955, <https://doi.org/10.1016/j.solener.2024.112955>.
- [28] J.-W. He, J.-H. Deng, X.-Y. Huang, Z.-Y. Shu, Y. Cai, Y. Lv, et al., Comparative study on the performance of a solar photocatalytic Trombe wall with different types of collectors: Copper/Thermoelectric/PV plate, *Appl. Therm. Eng.* 239 (2024) 122131, <https://doi.org/10.1016/j.applthermaleng.2023.122131>.
- [29] H. Wu, N. Li, G. Zhang, G. Zhang, J. Ji, B. Yu, Performance analysis on a wood-color thermal catalytic Trombe wall in wood buildings, *Eng. Buildings* 308 (2024) 114034, <https://doi.org/10.1016/j.enbuild.2024.114034>.
- [30] S. Duan, C. Jing, Z. Zhao, Energy and exergy analysis of different Trombe walls, *Buildings* 126 (2016) 517–523, <https://doi.org/10.1016/j.enbuild.2016.04.052>.
- [31] L. Xiao, L.-L. Qin, S.-Y. Wu, Proposal and application of comprehensive thermal comfort evaluation model in heating seasons for buildings with solar Trombe wall, *Appl. Therm. Eng.* 213 (2022) 118774, <https://doi.org/10.1016/j.applthermaleng.2022.118774>.
- [32] C. Guo, J. Ji, W. Sun, J. Ma, W. He, Y. Wang, Numerical simulation and experimental validation of tri-functional photovoltaic/thermal solar collector, *Energy* 87 (2015) 470–480, <https://doi.org/10.1016/j.energy.2015.05.017>.
- [33] H. Liu, P. Li, B. Yu, M. Zhang, Q. Tan, Y. Wang, The performance analysis of a high-efficiency dual-channel Trombe wall in winter, *Energy* 253 (2022) 124087, <https://doi.org/10.1016/j.energy.2022.124087>.
- [34] L. Che, N. Li, M. Fan, G. Zhang, G. Zhang, B. Yu, A novel catalytic/sterilization PV-Trombe wall system: Analysis on PV electrical and air purification performance in winter, *Build. Environ.* 255 (2024) 111423, <https://doi.org/10.1016/j.buildenv.2024.111423>.
- [35] Y. Sun, N. Zhang, Z. Zhang, M. Sultan, Y. Yuan, Thermal performance of a solar heat collection and storage wall with night insulation in winter: A numerical study, *Eng. Buildings* 303 (2024) 113835, <https://doi.org/10.1016/j.enbuild.2023.113835>.
- [36] D. Wang, Y. Liu, Y. Wang, Q. Zhang, J. Liu, Theoretical and experimental research on the additional thermal resistance of a built-in curtain on a glazed window, *Eng. Buildings* 88 (2015) 68–77, <https://doi.org/10.1016/j.enbuild.2014.11.047>.
- [37] L. Hou, Y. Liu, T. Liu, L. Yang, Y. Feng, Q. Gao, Dynamic heat preservation at night for a Trombe wall with a built-in panel curtain in Western China, *Sol. Energy* 213 (2021) 284–299, <https://doi.org/10.1016/j.solener.2020.10.090>.
- [38] Y. Luo, L. Zhang, Z. Liu, Y. Wang, F. Meng, J. Wu, Thermal performance evaluation of an active building integrated photovoltaic thermoelectric wall system, *Appl. Energy* 177 (2016) 25–39, <https://doi.org/10.1016/j.apenergy.2016.05.087>.
- [39] E. Meng, H. Yu, G. Zhan, Y. He, Experimental and numerical study of the thermal performance of a new type of phase change material room, *Eng. Convers. Manage.* 74 (2013) 386–394, <https://doi.org/10.1016/j.enconman.2013.06.004>.
- [40] S. Liu, Y. Li, An experimental study on the thermal performance of a solar chimney without and with PCM, *Renew. Energy* 81 (2015) 338–346, <https://doi.org/10.1016/j.renene.2015.03.054>.
- [41] G. Zhou, M. Pang, Experimental investigations on thermal performance of phase change material – Trombe wall system enhanced by delta winglet vortex generators, *Energy* 93 (2015) 758–769, <https://doi.org/10.1016/j.energy.2015.09.096>.
- [42] S. Zhou, A.G. Razaqpur, CFD modeling and experimental validation of the thermal performance of a novel dynamic PCM Trombe wall: Comparison with the companion static wall with and without PCM, *Appl. Energy* 353 (2024) 121985, <https://doi.org/10.1016/j.apenergy.2023.121985>.
- [43] Zhou Y. Structure and regional optimization of a phase change material Trombe wall system 2024.