

Impacts of PCM Location and Thickness on Dynamic Thermal Characteristics of External Walls for Residential Buildings



Tang Liu, Yan Liu, Liu Yang, Jiang Liu, Yuhao Qiao and Da Yan 

Abstract The effect of PCM wall is affected by many factors. To achieve full potential of phase change material used with structural insulated panel, the present paper investigates the impacts of PCM location and thickness on dynamic thermal characteristics of external wall of residential buildings, based on numerical simulation method. First, full implicit scheme of specific heat mathematical model of phase change wall is established by using finite difference method. Then, the boundary conditions in summer and winter are obtained based on a standard residential room under free running in Xi'an through typical meteorological year data. Finally, the thermal characteristics such as internal surface temperature, decrement factor and hourly heat flux are gained for each position and certain PCM thickness under the same boundary conditions. The results show that the optimal location is the PCM layer inside of SIP external wall and the optimum thickness is 0.04 m for SIP with heat transfer coefficient of $0.45 \text{ W m}^{-1} \text{ }^\circ\text{C}^{-2}$. The results could provide reference for engineering applications of phase change wall. The present work is a part of DeST3.0, which first introduces PCM module into DeST.

Keywords Phase change material · Numerical simulation · Dynamic thermal characteristics · Residential buildings · Structural insulated panel

1 Introduction

Recently, integrating phase change material with traditional building wall has been paid extensive attention. Phase change material with excellent thermal storage properties in a narrow temperature range can reduce indoor temperature fluctuation and

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increase thermal stability [1]. Meanwhile, structural insulated panel (SIP) is commonly used in engineering as a new lightweight construction system with poor thermal storage capacity, which consists of three material layers (two layers of OSB board as surface layers and insulation material extruded polystyrene-EPS board as the middle layer) [2]. Therefore, integrating PCM into SIP to be phase change wall is a potential way to solve this problem.

Many investigations on phase change materials' application in building envelopes have been carried out, including heat transfer calculation and effect evaluation, etc. Al-Saadi et al. [3] summarized the mathematical models of phase change wall heat transfer calculation including heat capacity method, heat source method and enthalpy method, and verified validity of eight numerical schemes through cold and hot box experiment. Tabares-Velasco et al. [4] validated accuracy of EnergyPlus 7.0 PCM module based on the verification methods in ASHRAE140 and pointed out key setting parameters of EnergyPlus 8.0 PCM module. The two studies show information for choosing PCM module for scholars. Zhou [5] obtained thermal characteristics of internal surface temperature and heat flow of shape-stabilized phase change material plate under different harmonic boundary conditions. Kong et al. [6] analyzed the heat storage, time lag and melting degree of phase change wall and compared impacts of PCM layout, optimum thickness and indoor convective heat transfer coefficient on heat storage. Yang et al. [7] obtained thermal characteristics of PCMs-based lightweight wallboards based on experiments under artificial controlled condition. Lv [8] defined three ways of using PCM into SIP in summer and determined the amount of phase change materials and phase change temperature under local climate conditions.

According to these studies, the dynamic thermal characteristics of phase change wall are affected by many factors such as climate conditions, indoor human thermal comfort demand, PCM location and PCM thickness. It is also an extremely important problem to achieve optimal effect with the least phase change material under actual outdoor and indoor conditions. However, there is lack of dynamic thermal characteristics analysis of SIP with PCM. The present work is to investigate the PCM location and PCM thickness based on full implicit scheme of heat capacity method when PCM is used in SIP construction, taking Xi'an as an example. The results will provide reference for PCM application in SIP construction.

2 Methods

2.1 Simulation Details

In the present work, in order to conduct dynamic thermal characteristics analysis of PCM wall, heat capacity method model of phase change wall is employed to perform temperature evolution. Full implicit scheme is established by using finite difference method for numerical simulation. Successive over-relaxation iteration is

used to obtain nodes temperatures with MATLAB software. And the established PCM module will be introduced into DeST3.0 based on standard FMU-FMI pattern to exchange hourly data with other models. The governing equation and differential equation of phase change wall are as follows:

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

$$c_p \rho \Delta x \frac{T_i^{j+1} - T_i^j}{\Delta t} = \left(k_{E_i} \frac{(T_{i+1}^{j+1} - T_i^{j+1})}{\Delta x} + k_{W_i} \frac{(T_{i-1}^{j+1} - T_i^{j+1})}{\Delta x} \right) \quad (2)$$

where c_p is specific heat capacity, $\text{J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$; k is thermal conductivity, $\text{W m}^{-1} \text{ } ^\circ\text{C}^{-1}$; ρ is density, kg m^{-3} ; T is temperature, $^\circ\text{C}$; t is time, s ; x is the distance between current point and external surface, m ; $j + 1$ is new time step; j is present time step; i is present node; $i + 1$ is adjacent node to interior of construction; $i - 1$ is adjacent node to exterior of construction; Δt is time step, s ; Δx is space step, m .

The specific heat capacity of phase change material varies with temperature and the value at each time step is updated based on enthalpy–temperature curve according to the following equation:

$$c_p(T) = \frac{h_i^j - h_i^{j-1}}{T_i^j - T_i^{j-1}} \quad (3)$$

where h is enthalpy of phase change material node, J kg^{-1} .

The boundary condition for only heat convection is adopted, belonging to the third boundary condition. Indoor and outdoor convective heat transfer coefficients are $8.7 \text{ W m}^{-2} \text{ } ^\circ\text{C}^{-1}$ and $18.6 \text{ W m}^{-2} \text{ } ^\circ\text{C}^{-1}$ [5], respectively. According to the program in the previous study [9], the internal boundary condition is calculated by establishing a room model. The length, width and height of the room are 4.5 m, 3.6 m and 3 m, respectively. All the constructions are set based on the standards (GBT50176-2016 and JGJ 26-2010) [10, 11]. The boundary conditions of summer and winter are illustrated in Fig. 1a and b.

In the present work, three indexes (internal surface temperature, decrement factor and hourly heat flux) are employed to analyze dynamic thermal characteristics of PCM wall. They are calculated as follows:

$$T_s^j = \left(T_{\text{in, air}}^j + \frac{k_n^j T_n^j}{h_{\text{w, in}} \Delta x / 2} \right) / \left(1 + \frac{k_n^j}{h_{\text{w, in}} \Delta x / 2} \right) \quad (4)$$

$$f = \frac{A_{\text{is}}}{A_e} \quad (5)$$

$$q_c = h_{\text{w, in}} (T_s - T_{\text{in, air}}) \quad (6)$$

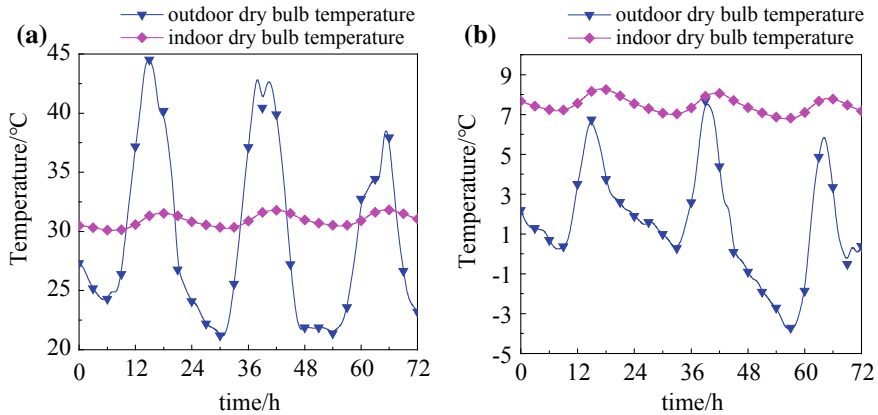


Fig. 1 Boundary conditions **a** in summer and **b** in winter

$$q_h = h_{w,in}(T_{in,air} - T_s) \quad (7)$$

where T_s is internal surface temperature, °C; $T_{in,air}$ is indoor dry bulb temperature, °C; f is decrement factor, dimensionless; A_{is} is internal surface temperature amplitude, °C; A_e is outdoor dry bulb temperature amplitude, °C; $h_{w,in}$ is indoor convective heat transfer coefficient, $W m^{-2} °C^{-1}$; q_c is hourly heat flux in summer, $W m^{-2}$; q_h is hourly heat flux in winter, $W m^{-2}$.

2.2 Simulation Settings and Constructions' Parameters

Xi'an is in Western China and in the cold climate zone. The climate data for Xi'an is based on the standard CSWD weather files (<https://www.energyplus.net/weather>). The outdoor dry bulb temperature and solar radiation of typical days in summer (July 8 to July 10) and winter (December 21 to December 23) are illustrated in Fig. 1a and b. The time step is set to 60 s, and the space step is 0.002 m. The convergence standard is 0.0002 °C.

The main thermophysical properties of building materials for the constructions are listed in Table 1. Phase change material is chosen from BioPCM products (www.phasechange.com). The phase change temperature of BioPCM for summer and winter

Table 1 Thermophysical properties of building materials

	Conductivity ($W m^{-1} °C^{-1}$)	Density ($kg m^{-3}$)	Specific heat ($J kg^{-1} °C^{-1}$)
Gypsum	0.33	1050	1050
EPS	0.041	20	1380
PCM	1.325	1125	3350

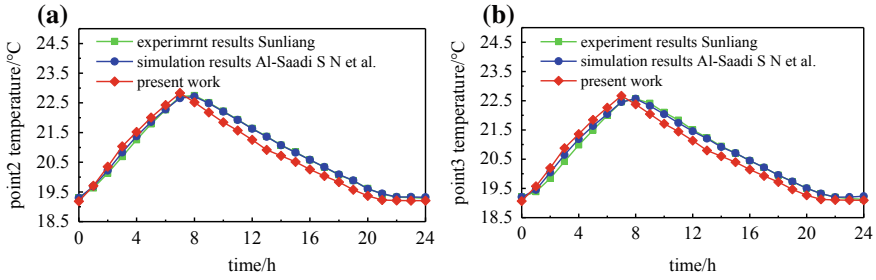


Fig. 2 a Point2 temperature comparison. b Point3 temperature comparison

is 29 and 6 °C, separately. The phase change range is 4 °C, and the latent heat is 210 kJ kg⁻¹. The heat transfer coefficient of the SIP construction is 0.45 W m⁻¹ °C⁻².

2.3 Validation

In the present work, in order to validate the established PCM module and the adopted algorithm, a cold and hot box experiment case study is adopted [3], which has been used to validate the PCM module in EnergyPlus. The boundary condition on both sides of the wall and the detailed description of the used case study can be found in the mentioned reference. The temperature of hot boundary condition varies with time and is divided into two stages (heating stage and cooling stage). The temperature of cold boundary condition is fixed on -20 °C. The temperatures in point2 and point3 are compared between the present work and experimental results, which are depicted in Fig. 2a and b. The root mean squared error (RMSE) is used to evaluate the absolute error. RMSEs in point2 and point3 are 0.11 °C and 0.08 °C, respectively. They indicate that the phase change material module and methods in the present work are reasonable and reliable to deal with dynamic thermal characteristics analysis of PCM wall.

3 Results and Discussion

In order to analyze impacts of PCM location, PCM is first placed on internal/external (position1/position2) surface of SIP system and in the middle of EPS as a sandwich (position3). Then, different construction walls with six thicknesses PCM (e = 0.01 m to 0.05 m, step size is 0.01 m) are simulated under the same boundary condition. Figure 3a and b shows the internal surface temperature evolution in summer and winter with PCM on position1, respectively. Obviously, it is noticed that differences in internal surface temperature among all working conditions in summer and winter.

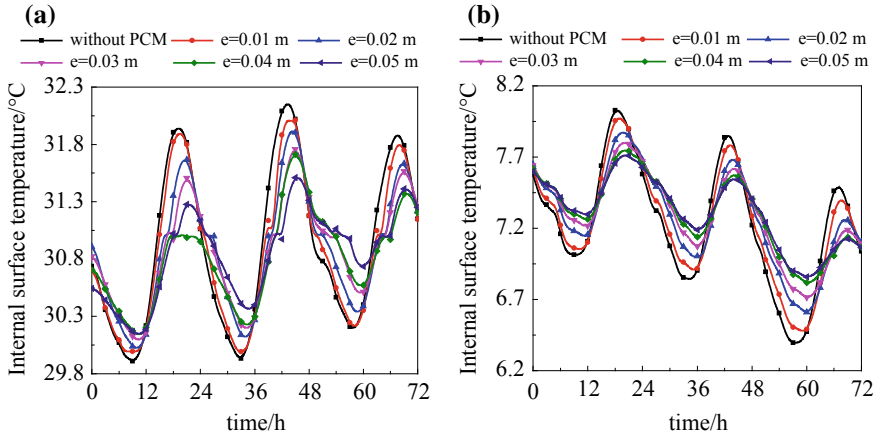


Fig. 3 Internal surface temperature evolution with PCM on position1, **a** in summer and **b** in winter

The optimum PCM thickness is 0.04 m for summer and winter. A nearly constant period of internal surface temperature could be noticed with 0.04 PCM during 18–24 h in Fig. 3a. While internal surface temperature with 0.04 m PCM is higher than that with 0.03 m and 0.05 m in this period. In other canyon periods, internal surface temperature with 0.04 m PCM is nearly equal to that with 0.03 m and lower than that with 0.05 m (close to comfort zone). The evolutions of internal surface temperature are nearly the same in winter with 0.04 and 0.05 m PCM.

The internal surface temperature evolution with PCM on position2 and position3 are represented in Figs. 4 and 5, separately. Only in the summer case of placing PCM on position3 weak differences between with PCM and without PCM could be seen.

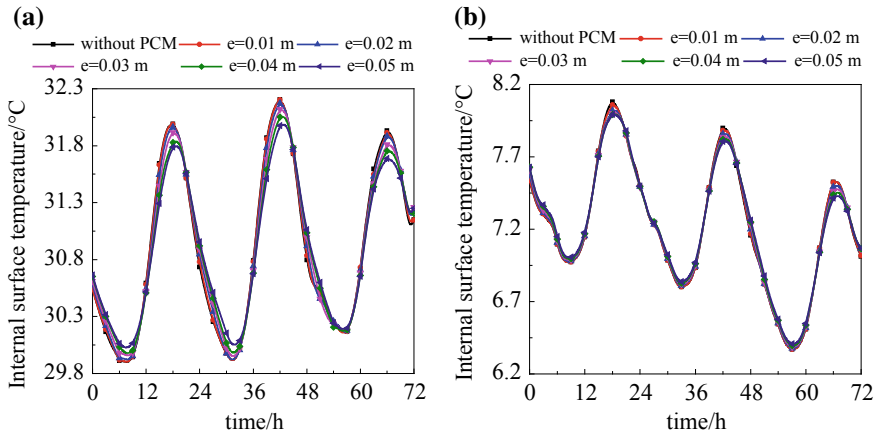


Fig. 4 Internal surface temperature evolution with PCM on position2, **a** in summer and **b** in winter

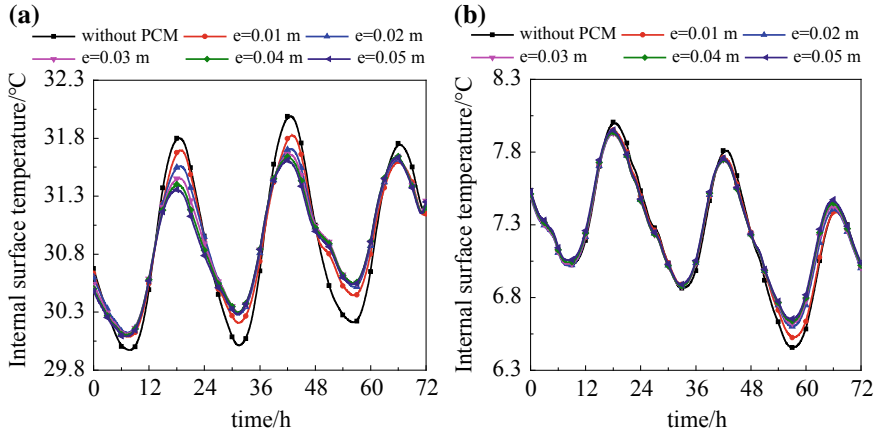


Fig. 5 Internal surface temperature evolution with PCM on position3 **a** in summer and **b** in winter

The optimum PCM thickness is 0.02 m. For all positions, setting PCM on the internal surface of SIP is the best position for heat storage and release. In other cases, due to high heat transfer coefficient of the SIP construction ($0.45 \text{ W m}^{-1} \text{ }^\circ\text{C}^{-2}$, conforming to standard requirement), heat is blocked into entering the room from outdoor or PCM stored through phase change.

Decrement factors under different working conditions are presented in Table 2. The outdoor dry bulb temperature amplitudes are 23.45 and 11.48 °C in summer and in winter, separately. The result shows that placing PCM on the internal surface of SIP construction has a better decrement than the other two positions. The max differences in decrement factors are 0.056 and 0.085 in summer and winter, separately. And 0.04 m PCM could help decrease internal surface temperature amplitudes to 1.31 °C in summer and 0.98 °C in winter. In addition, the decrement factors level indicates that the investigated SIP construction itself has a favorable thermal performance.

Hourly heat flux evolutions under three positions with 0.04 m PCM are presented in Fig. 6. In two seasons, hourly heat flux on the internal surface under position1 fluctuates more severely than the other two positions. This means phase change material works. The max hourly heat flux in summer could reach 7.38 W m^{-2} ,

Table 2 Decrement factors under different working conditions

PCM position	Summer			Winter		
	Without PCM	$e = 0.01 \text{ m}$	$e = 0.04 \text{ m}$	Without PCM	$e = 0.01 \text{ m}$	$e = 0.04 \text{ m}$
Position1	0.186	0.168	0.130	0.199	0.184	0.114
Position2	0.191	0.190	0.173	0.209	0.206	0.195
Position3	0.168	0.145	0.127	0.189	0.174	0.158

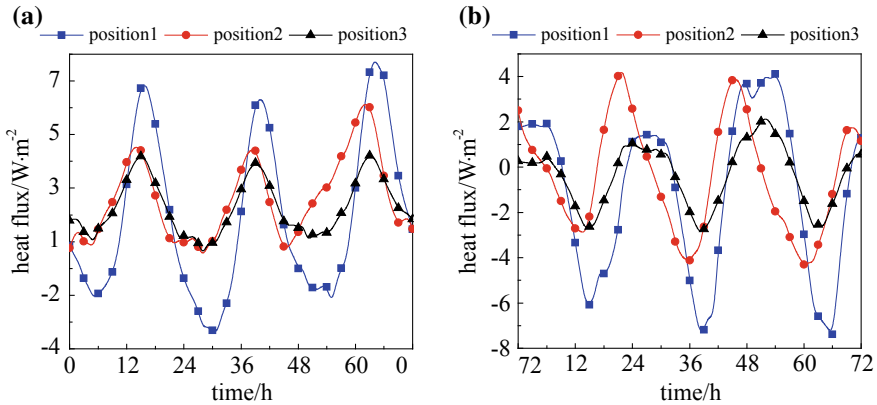


Fig. 6 Hourly heat flux evolution under three positions **a** in summer and **b** in winter

4.35 W m⁻² and 2.90 W m⁻² and in winter 7.34 W m⁻², 5.68 W m⁻² and 3.71 W m⁻² under three positions, respectively.

4 Conclusions

In the present paper, the dynamic thermal characteristics analysis of SIP construction with PCM as external wall of residential buildings is conducted. Taking Xi'an as an example, the impacts of PCM location and PCM thickness are investigated. The results show that the optimal location is to set PCM on the internal surface of SIP construction. The optimum thickness is 0.04 m for SIP construction with heat transfer coefficient of 0.45 W m⁻¹ °C⁻². The results could provide reference for engineering applications of phase change wall. In addition, it is also necessary to analyze the dynamic thermal characteristics analysis of SIP construction with lower heat transfer coefficient than 0.45 W m⁻¹ °C⁻² and with different surface materials. The present work has been integrated with DeST3.0, which first introduces PCM module.

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