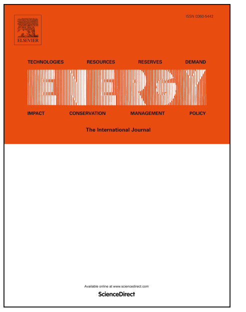
Journal Pre-proof



An exploration on the performance of using phase change humidity control material wallboards in office buildings

Na Zhu, Xingkun Li, Pingfang Hu, Fei Lei, Shen Wei, Wentao Wang

PII: S0360-5442(21)02682-7

DOI: https://doi.org/10.1016/j.energy.2021.122433

Reference: EGY 122433

To appear in: *Energy*

Received Date: 21 June 2021

Revised Date: 4 September 2021

Accepted Date: 23 October 2021

Please cite this article as: Zhu N, Li X, Hu P, Lei F, Wei S, Wang W, An exploration on the performance of using phase change humidity control material wallboards in office buildings, *Energy* (2021), doi: https://doi.org/10.1016/j.energy.2021.122433.

Credit Author Statement

Na Zhu: Conceptualization, Writing – original draft, Project administration, Supervision. **Xingkun Li**: Methodology, Software, Validation. **Pingfang Hu**: Investigation. **Fei Lei**: Investigation. **Shen Wei**: Writing – reviewing and editing. **Wentao Wang**: Writing – reviewing and editing.

An exploration on the performance of using phase change humidity control material wallboards in office buildings

*Na Zhu[1], Xingkun Li[1], Pingfang Hu[1], Fei Lei[1], Shen Wei[2], Wentao Wang[1]

[1]School of Environmental Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, Hubei, PR China

[2]The Bartlett School of Construction and Project Management, University College London, United Kingdom

**Corresponding author. Tel.: +86 027 87792164, E-mail: bezhuna@hust.edu.cn (N. Zhu)*

Abstract

In this study, a composite double-layer wallboard with shape-stabilized phase change humidity control materials (PCHCM) has been proposed for building usage. This novel PCHCM can absorb/release both heat and moisture to moderate indoor hygrothermal environment. Based on a numerical analysis in an office building in Wuhan (30.52°N, 114.32°E), China, the effects of PCHCM on both building energy consumption and indoor hygrothermal environment has been investigated. Firstly, a simulation model has been developed for the building integrated with PCHCM wallboards in EnergyPlus, combining both heat and moisture transfer finite solution algorithms. After a validation of the model, both heat and moisture transfer characteristics of the proposed composite wallboards were simulated, and its effects on indoor temperature, humidity and building energy consumption were analyzed. The simulation results showed that this novel PCHCM wallboard can effectively improve indoor hygrothermal environment, with reduced energy consumption by about 8.3% in summer and 24.9% in winter, comparing to the actually used materials in the case study building.

Keywords: Phase change humidity control material; hygrothermal; finite solution

algorithms; energy consumption

Nomenclature

C_p	specific heat capacity (J/(kg·°C))
D	thickness (m)
D^w	liquid transport coefficient (m^2/s)
h	evaporation enthalpy (J/kg)
H	latent heat of phase change material (kJ/(kg·K))
K^w	moisture dependent thermal conductivity (W/(m·°C))
P	pressure (Pa)
Q	load (kWh)
R	rate (%)
Δt	phase change temperature range (K or °C)
T	temperature (°C)
w	moisture content (kg/m^3)
x	distance between cell centers (m)

Greek symbols

λ	heat conductivity (W/(m·K))
φ	relative humidity (%)
ρ	density (kg/m^3)
δ	vapor diffusion coefficient in air (kg/(m·s·Pa))
μ	moisture dependent vapor diffusion resistance factor (-)
τ	time (s)

Subscripts

a	air
amb	ambient

b	balanced
c	cooling
ext	external
es	energy saving
h	heating
in	indoor
int	internal
l	liquid
lh	latent heat
m	melting
out	outdoor
sh	sensible heat
s	solid
sl	solid or liquid
v	vapor
w	water

1. Introduction

With rapid development of global economy and improved living standard of people, societal energy consumption has been increasing significantly, leading to very serious environmental issues [1, 2]. Considering the limited resources on the earth, this trend is definitely not sustainable for the future. Energy consumption by buildings accounts for 40% of global total energy consumption, with over 30% contributed by Heating, Ventilation and Air-Conditioning (HVAC) systems [3]. It has been widely demonstrated that reducing energy demand from HVAC systems can effectively decrease building energy consumption, hence limiting greenhouse gas emissions [4, 5].

To decrease building energy demand, many researchers have tried to develop high performance materials for building envelope. Due to ability of absorbing and releasing significant heat within specific temperature ranges, Phase Change Materials (PCMs) are widely used in buildings to modulate indoor air temperature [6, 7]. In reality, there are many types of PCMs, such as n-octadecane and paraffin [8], palmitic acid/expanded graphite [9] and butyl stearate [10], and existing studies have thoroughly demonstrated that using PCMs can both improve indoor thermal environment and reduce energy consumption of buildings [11-13].

Besides temperature, indoor humidity level can affect people's thermal comfort as well [14]. Existing data have suggested the best indoor relative humidity as between 50% and 60%, as the body of humans would have most comfortable feeling under this environment [15]. High level of moisture indoors will promote mold generation and reduce buildings' life, and low level of moisture will also reduce buildings' life [16]. Therefore, in many commercial applications, much energy is used by HVAC systems to maintain suitable indoor humidity level [17]. As a passive method, Humidity Control Materials (HCMs) can adjust indoor relative humidity through absorbing/releasing moisture for building applications [18, 19]. In reality, there are several types of HCMs, such as inorganic salts [20], inorganic minerals [21] and composite biomass [22], and many existing studies have thoroughly demonstrated that using HCMs can both improve indoor humidity environment and reduce energy consumption of buildings [23, 24].

In the literature, functional envelope materials were generally developed with a focus of one of their abilities, which was either adjusting temperature or adjusting humidity [25-27]. Phase Change Humidity Controlling Materials (PCHCMs), could control both temperature and humidity at the same time, and therefore may have a better energy saving potential. In the past years, some studies have been done to investigate the potential contribution of this type of materials on the performance of buildings. In order to evaluate the performance of PCHCMs in buildings, many researchers developed useful numerical models with coupled systems for analyzing both heat and moisture transfer processes. Qin et al. [28] performed a Laplace transformation for this coupled system and proposed a transfer function method to solve the temperature and moisture distributions. In another study, Qin et al. [29] developed a mathematical model using the finite difference method to decide both temperature and humidity distributions for multi-layered materials. Yang et al. [30] carried out a comparison among three existing thermal-humid models in EnergyPlus, namely, CTF (Conduction Transfer Function), CHMT (Combined Heat and Moisture Transfer) and EMPD (Effective Moisture Penetration Depth) models, in terms of their suitable application conditions. For hot and humid climates, the CHMT model had been justified as the most accurate for simulating indoor air temperature and relative humidity. Belarbi et al. [31] proposed a two-dimensional Luikov model, combining both finite difference technology and completely implicit time method. Using Matlab-simulink, Qin et al. [32] established a model that can predict both heat and moisture transfer processes, and used this model to predict indoor temperature, indoor humidity and energy consumption of buildings, under different climatic conditions. To solve the heat flow in coupled heat and moisture systems, Wang et al. [33] proposed a cyclic iterative method based on evaporation and condensation principles, in which water vapor pressure difference and temperature difference were adopted as main influential factors.

Shang et al. [34, 35] prepared a composite material of gypsum-based double-shell micro-nano phase change capsules, studied its compounding ratio, and analyzed the short-term (48h) effects of different composite materials on buildings' indoor environment. Their results showed that the room with PCHCMs had small fluctuation ranges for both temperature and relative humidity, and great energy saving potential was realized. Using building performance simulation, Zhang et al. [36] also analyzed the practical impact of composite PCHCMs in air-conditioned buildings in Nanjing and Lanzhou of China in summer, and the results also confirmed small fluctuations in terms of both temperature and relative humidity, with approximate energy saving potentials by PCHCMs of 28.8% and 11.6% for Lanzhou and Nanjing, respectively.

Wu et al. [37] have investigated the use of PCHCMs in cities with different climatic conditions (Beijing, Paris, Atlanta and Guangzhou) and the simulation results have strongly supported the positive contribution of PCHCMs to improved building performance.

According to the literature, it could be concluded that existing literature focused mainly on the application effect of PCHCMs at a specific phase change temperature in summer, which had limitations and uncertainties for climate areas with hot summer and cold winter. For example, an inappropriate phase change temperature may increase the wall thermal resistance. Therefore, this study proposed a novel double-layer PCHCM wallboard for building application, and analyzed its year-long performance in terms of both energy consumption and indoor hygrothermal environment in an office building located in Wuhan, China (hot summer and cold winter). In addition, this study optimized the phase change temperature of PCHCMs in order to maximize the effectiveness of the material.

2. Mathematical Model Development

2.1 Material and properties

The compound PCHCM used in this study included paraffin, diatomite, high density polyethylene and expanded graphite. Paraffin was used as phase change materials to absorb/release heat, and diatomite was used as humidity control materials. High density polyethylene was used as supporting materials to maintain PCHCMs in solid shape without leakage. Expanded graphite was used as additive to improve the thermal conductivity of PCHCMs. According to the material's melting temperature, there were two types of shaped PCHCMs, namely, high temperature phase change humidity control materials ($PCHCM_1$) and low temperature phase change humidity control materials ($PCHCM_2$), with their main physical properties listed in table 1 and table 2 [38, 39].

2.2 Governing equations

The combined heat and moisture transfer algorithm was based on a one-dimensional finite element method, considering the movement and storage of both heat and moisture in walls. It helped to calculate the distribution of heat and moisture on the surface of walls.

The governing equations included both a heat balance equation and a moisture balance equation. The heat balance equation described the storage, transportation and generation of heat, and the moisture balance equation described the storage of moisture, the transportation of liquid moisture, and the transportation of vapor. According to reference [40], the thermal balance equation was defined by Equation 1, and the moisture balance equation was defined by equation 2.

$$\frac{\partial H}{\partial T}\frac{\partial T}{\partial \tau}=\frac{\partial}{\partial x}\left(K^{w}\frac{\partial T}{\partial x}\right)+h_{w}\frac{\partial}{\partial x}\left(\frac{\delta}{\partial x}\frac{\partial T}{\partial x}\right) \tag{1}$$

$$\frac{\partial w}{\partial \varphi}\frac{\partial \varphi}{\partial \tau}=\frac{\partial}{\partial x}\left(D^{w}\frac{\partial w}{\partial \varphi}\frac{\partial \varphi}{\partial x}\right)+h_{w}\frac{\partial}{\partial x}\left(\frac{\delta}{\mu}\frac{\partial T}{\partial x}\right) \tag{2}$$

Where, H is latent heat of phase change material, T is temperature, K^{w} is moisture dependent thermal conductivity, h_w is evaporation enthalpy of water, φ is relative humidity, τ is time, δ is vapor diffusion coefficient in air.

The relationship between diffusion coefficient of water vapor in the air and temperature of vapor was defined by equation 3. The heat storage capacity $\left(\frac{\partial H}{\partial T}\right)$ was defined by equation 4, which reflects the relationship between the heat transfer process and the amount of moisture in the material [40].

$$\delta=\frac{2\times10^{-7}\times\left(T+273.15\right)^{0.81}}{P_{amb}} \tag{3}$$

$$\frac{\partial H}{\partial T}=\left(C_{p}\rho+C_{pw}w\right) \tag{4}$$

In existing studies [41, 42], this method had been demonstrated as having high accuracy when calculating heat and moisture transfers in materials. Combining this method and the effective heat capacity method, a mathematical model was established for calculating heat and moisture transfer processes of PCHCM wallboards.

2.3 Model development

The PCHCM model was obtained by amending original code based on HCM model on EnergPlus software, which wthout PCM model in this software. The complex heat capacity curve was simplified when calculating phase change processes using the effective heat capacity method, and the large latent heat of phase change materials was stored in a narrow phase change temperature region. There were many simplified calculation methods for heat capacity, and the curves of heat capacity with temperature were mainly isosceles triangles and mutant shapes. Existing studies [43] demonstrated that different simplified methods gave similar final heat transfer effect. The mutant heat capacity curve was used in this study, as shown in figure 1. The calculation process was defined in equation 5.

$$C_{pm} = C_{psl} + \frac{H}{\Delta t} \tag{5}$$

In the heat and moisture transfer model, C in equation 4 is the specific heat capacity of dry materials (J/(kg·°C)). Using the effective heat capacity method, the relationship between the specific heat capacity of dry materials and the temperature was established, as defined by equation 6.

$$C = \begin{cases} C_{psl}, t < t_m - 0.5\Delta t \; and \; t > t_m + 0.5\Delta t \\ C_{psl} + \frac{H}{\Delta t}, t_m - 0.5\Delta t \le t \le t_m + 0.5\Delta t \end{cases} \tag{6}$$

Combined with equation 1 (heat balance) and equation 2 (moisture balance), equation 6 became the final heat and moisture governing equation for calculating both moisture and temperature distributions for PCHCMs. The phase change temperature range is 1 °C in equation 6 [44].

2.4 Model validation

To validate the accuracy of the proposed heat and moisture transfer model, phase change and humidity control processes were key factors. In this study, there were two aspects needed to be verified. Firstly, the humidity control process had already been verified as reliable in reference [41, 42]. Then close humidity control function in the heat and moisture transfer model, considering phase change process only. Characteristics for both PCHCM building and PCM building were the same under this assumption. The simulation results on phase change process in this study were compared with experimental results in reference [45]. The thermal physical properties for both envelope and PCM were listed in table 3 and table 4, respectively.

In this study, the building with PCHCM wallboards was named as PCHCM building. The indoor air temperature was predicted for the case study during the period between 4th July and 6th July, following what had been done in reference [45]. Figure 2 showed the simulation result and figure 3 showed the experimental result. From the two figures, similar fluctuation trends could be found for indoor air temperature. In this study, the indoor air temperature in the PCHCM building was 39.6°C in maximal and 30.1°C in minimal. For the PCM building, it was 41.5°C in maximal and 31.0°C in minimal [45], with relative errors of 4.6% and 2.9%, respectively, for maximal and minimal indoor air temperatures, both below 5%. It demonstrated that the phase change process of the heat and moisture transfer model developed in this study was reliable.

3. Simulation definition

In this study, the simulation was performed for Wuhan, China, which has a cooling season from 1st June to 30th September, and a heating season from 15th December to 15th March (next year). The weather data in typical year used in this work was obtained from official website on EnegyPlus. Table 5 has listed some climatic parameters in Wuhan, reflecting hot summer and cold winter, with high humidity all over the year. The building investigated had a dimension of 5m in length, 4m in width and 3m in height. The north window had an area of 4m^2. The thermal properties of building materials in each layer were shown in table 6.

In this study, a novel double-layer PCHCM wall structure was proposed. PCHCM$_1$ wallboard had a higher melting temperature and PCHCM$_2$ wallboard had a lower melting temperature, both were placed on the inner surface of the main wall, respectively. Figure 4 has depicted a schematic of this double-layer PCHCM wallboard and the reference wallboard. According to ASHRAE [46], the internal and external moisture dissipation coefficients of the wall were taken as β_{int}=3.48×10^8 kg/(Pa.s.m^2), β_{ext} =10.42×10^8 kg/(Pa.s.m^2). The internal and external convective heat transfer coefficients of the wall were taken as h_{int}=8.3W/m^2, h_{ext}=17W/m^2.

In this study, four types of buildings have been simulated: 1) Phase change humidity control building integrated with PCHCM wallboards; 2) Phase change material (PCM) building integrated with PCM wallboards only; 3) Humidity control material (HCM) building integrated with HCM wallboards only, and 4) Reference building integrated with gypsum wallboards only. The thicknesses of PCM wallboards, HCM wallboards and gypsum wallboards were the same. For the gypsum wallboard, its physical parameters were the same as the PCHCM wallboard without phase change function.

4. Results and discussions

4.1 Melting temperature optimization

In the case study building, the indoor temperature set-point was selected as 26°C in summer and 18°C in winter. The indoor relative humidity was ranging between 40%-65% in summer and 30%-60% in winter. There were two people using the room. The ventilation rate was set as 0.5 time per hour. The working hours were between 8am and 6pm, with air-conditioners on during working hours and off during no-working hours.

The melting temperature of PCHCM wallboards is important to building energy consumption. In this study, the melting temperatures of both $PCHCM_1$ and $PCHCM_2$ on the total cooling load and heating load were studied, respectively, with simulation results shown in Fig. 5 and Fig. 6. In summer, when the melting temperature of $PCHCM_1$ wallboards was 25°C, the building had the lowest cooling load. In winter, when the melting temperature of $PCHCM_2$ wallboards was 17°C, the building had the lowest heating load. Therefore, the optimal melting temperatures of both $PCHCM_1$ and $PCHCM_2$ were defined as 25 °C and 17 °C, respectively.

4.2 Energy performance analysis

The thermal load includes both sensible load and latent load. The proportion of phase change function on sensible load and humidity control function on latent load was explored in this study. The thermal loads in the reference building, the HCM building, the PCM building and the PCHCM building were simulated, respectively. The melting temperatures for $PCHCM_1$ and $PCHCM_2$ in the PCHCM building were 25°C and 17°C, respectively. The initial moisture content of the PCHCM wallboard was 0.01kg/kg, and the ventilation rate was 0.5 times per hour as recommended parameters based on simulation.

The calculated cooling load and heating load for all four types of buildings are shown in figure 7 and figure 8, respectively. In summer, the total cooling loads in the HCM building, the PCM building and the PCHCM building were lower than that in the reference building, according to the comparison listed in table 7. Compared with the reference building, the energy saving rates in the HCM building, the PCM building and the PCHCM building were 0.002%, 7.4% and 8.3%, respectively, with the maximum reduction in total cooling load happening in the PCHCM building. The HCM building showed little superiority to the reference building, because the HCM absorbed vapor in the air, and then the vapor liquidated. The vapor released latent heat during this process, and this resulted in raised temperature. The sensible heat in the HCM building, therefore, was higher than that in the reference building, but the latent heat in the HCM building was lower than that in the reference building, resulting in nearly identical total cooling loads in both buildings.

In winter, the total heating loads in the HCM building, the PCM building and the PCHCM building were also lower than that in the reference building, according to comparison results listed in table 8. Compared with the reference building, the energy saving rates in the HCM building, the PCM building and the PCHCM building were 6.3%, 16.4% and 24.9%, respectively, with the maximum total heating load reduction found in the PCHCM building. The latent heats in all four types of buildings were all very low, so the contribution from the humidity control function was not obvious in winter.

4.3 Hygrothermal performance analysis

In summer, the melting temperature of the $PCHCM_1$ wallboard was 25°C, and setpoints for indoor temperature and relative humidity were 26°C and 40%-65%, respectively. The cooling season in Wuhan is between 1st June and 30th September. Taking 15th July to 19th July near typical summer weather day as example, indoor air temperature and relative humidity are shown in figure 9 and figure 10, respectively. From figure 9, it could be found that the indoor air temperatures in all four types of building were around 26°C in daytime. In night-time, the indoor air temperature in the PCHCM building was slightly higher than that in other building types, since the PCHCM wallboard absorbed solar radiation heat in daytime and released it at night. From figure 10, it could be found that the indoor relative humidity in the PCHCM building was maintained between the 55% and 60% in daytime, within the comfortable range. In nighttime, the indoor relative humidity in the PCHCM building was lower than that in other building types, showing that the PCHCM wallboard helped to improve indoor humidity comfort effectively in summer.

In winter, the melting temperature of $PCHCM_1$ wallboard was 17°C, with setpoints for indoor air temperature and relative humidity of 18°C and 30%-60%, respectively.

The heating season in Wuhan starts from 15th December and ends on 15th March next year. Taking 27th January to 31st January near typical winter weather day for example, indoor air temperature and relative humidity are shown in figure 11 and figure 12, respectively.

From figure 11, it could be found that the indoor air temperatures in all four types of buildings were around 18°C in daytime. In nighttime, the indoor air temperatures in the PCHCM building and the PCM building were higher than that in the HCM building and the reference building, demonstrating obvious control by phase change from the PCHCM and the PCM. The humidity control from the HCM, however, was not obvious. The reason could be that HCM could absorb heat in daytime and release it at night.

From figure 12, it could be found that the indoor relative humidity in the PCHCM building was between 37% and 50% in the daytime, within the comfortable range. The relative humidity in the reference building was between 40% and 60% in the daytime. In the nighttime, the indoor relative humidity in the PCHCM building was much lower than that in the PCM building and the HCM building, especially lower than the reference building. It reflects the positive contribution from PCHCM wallboards to improved indoor humidity comfort in winter.

5. Conclusions

In this study, the novel PCHCM can absorb/release both heat and moisture to moderate indoor hygrothermal environment. But the melting temperature of PCHCM was not optimized in literature, which decided. The effects of PCHCM wallboards on building energy consumption and indoor hygrothermal environment were studied for Wuhan city in China, which has hot summer and cold winter. For the evaluation, a mathematical model was developed for the PCHCM wallboard and validated against experimental results provided in existing studies [39, 40, 42]. According to simulation results based on TRNSYS, the PCHCM wallboard was justified to be able to both reduce energy consumption and improve indoor hygrothermal environment for the case study building significantly. Main conclusions from this study are listed as followings:

1) To minimize thermal loads, the optimal melting temperature of PCHCM wallboards is 25°C for summer and 17°C for winter, respectively, achieved by two layers with different PCMs in Wuhan area. There is different optimal melting temperature of PCHCM wallboard in different climate zones.

2) The energy saving rate in the PCHCM building is 8.3% in summer and 24.9% in winter, comparing to that in the reference building. The PCM control function is useful in summer, but the HCM control function is not useful in summer. However, both functions are useful in winter.

3) The effect of PCHCM wallboards on indoor hygrothermal environment is remarkable. In summer, the indoor air temperature in the PCHCM building was nearly the same as that in other building types with air-conditioners in the daytime. The indoor relative humidity in the PCHCM building, however, was reduced by about 5%, comparing to that in the reference building. In winter, the indoor air temperature was also nearly the same as that in other building types in the daytime. The indoor relative humidity, however, was reduced by about 5%, comparing to that in the reference building.

The experiment performance is still needed to be investigated in the further research. Additionally, many other factors are still needed to be studied, including different ratio of compound PCHCM, thickness, location, moisture content, ventilation rate and climate zones, etc. This study will provide valuable support on using phase change humidity control materials in heat and moisture transfer processes in buildings.

Acknowledgement

This work presented in this paper is financially supported by grants of National

Natural Science Foundation of China (No.51508212), Wuhan Youth Science and Technology Plan (No.2017050304010296) and The Central University Special Funding for Basic Scientific Research Business Expenses (No.2016YXZD071).

References

[1] A. Waqas, Z. Ud Din, Phase change material (PCM) storage for free cooling of buildings-a review, Renewable and Sustainable Energy Reviews 18 (2013) 607–625.

[2] X. Shi, S.A. Memon, W. Tang, H. Cui, F. Xing, Experimental assessment of position of macro encapsulated phase change material in concrete walls on indoor temperatures and humidity levels, Energy and Buildings 71 (2014) 80-87.

[3] Z. Chen, M. Qin, J. Yang, Synthesis and characteristics of hygroscopic phase change material: Composite microencapsulated phase change material (MPCM) and diatomite, Energy and Buildings 106 (2015) 175-182.

[4] Z. Chen, D. Su, M. Qin, G. Fang, Preparation and characteristics of composite phase change material (CPCM) with SiO_2 and diatomite as endothermal-hydroscopic material, Energy and Buildings 86 (2015) 1-6.

[5] R. Baetens, B.P. Jelle, A. Gustavsen, Phase change materials for building applications: a state-of-the-art review, Energy and Buildings 42 (2010) 1361–1368.

[6] Z. Rao, S. Wang, Z. Zhang, Energy saving latent heat storage and environmental friendly humidity-controlled materials for indoor climate, Renewable and Sustainable Energy Reviews 16 (2012) 3136-3145.

[7] A. Jamekhorshid, S.M. Sadrameli, M. Farid, A review of microencapsulation methods of phase change materials (PCMs) as a thermal energy storage (TES) medium, Renewable and Sustainable Energy Reviews 31 (2014) 531–542.

[8] H. Nazir, M. Batool, F.J. Bolivar Osorio, M. Isaza-Ruiz, X. Xu, K. Vignarooban, P. Phelan, Inamuddin, A.M. Kannan, Recent developments in phase change materials for energy storage applications: A review, International Journal of Heat and Mass Transfer 129 (2019) 491-523.

[9] A. Sari, A. Karaipekli, Preparation, thermal properties and thermal reliability of palmitic acid/expanded graphite composite as form-stable PCM for thermal energy storage, Solar Energy Materials and Solar Cells 93 (2009) 571–576.

[10] Lee T, Hawes DW, Banu D, Feldman D. Control aspects of latent heat storage and recovery in concrete. Solar Energy Materials and Solar Cells 62 (2000) 217–237.

[11] A. Sharma, V.V. Tyagi, C.R. Chen, D. Buddhi, Review on thermal energy storage with phase change materials and applications, Renewable and Sustainable Energy Reviews 13 (2009) 318–345.

[12] D. Lelievre, T. Colinart, P. Glouannec, Hygrothermal behavior of bio-based building materials including hysteresis effects: Experimental and numerical analyses, Energy and Buildings 84 (2014) 617-627.

[13] H. Ling, C. Chen, S. Wei, Y. Guan, C. Ma, G. Xie, N. Li, Z. Chen, Effect of phase change materials on indoor thermal environment under different weather conditions and over a long time, Applied Energy 140 (2015) 329-327.

[14] D. Kong, H. Liu, Y. Wu, B. Li, S. Wei, M. Yuan, Effects of indoor humidity on building occupants’ thermal comfort and evidence in terms of climate adaptation, Building and Environment 155 (2019) 298-307.

[15] M. Hadjieva, R/ Stoykov, T. Filipova. Composite salt-hydrate concrete system for building energy storage. Renewable Energy 19 (2000) 111–115.

[16] J. Toftum, A.S. Jørgensen, P.O. Fanger, Upper limits of air humidity for preventing warm respiratory discomfort, Energy and Buildings 28 (1998) 15-23.

[17] M. Qin, G. Walton, R. Belarbi, F. Allard, Simulation of whole building coupled hygrothermal-airflow transfer in different climates, Energy Conversion and Management 52 (2011) 1470-1478.

[18] H. Zhang, H. Yoshino, K. Hasegawa, Assessing the moisture buffering performance of hygroscopic material by using experimental method, Building and Environment 48 (2012) 27-34.

[19] M. Shehadi, Review of humidity control technologies in buildings, Journal of Building Engineering 19 (2018) 539-551.

[20] Y. Kang, S. J. Chang, S. Kim, Hygrothermal behavior evaluation of walls improving heat and moisture performance on gypsum boards by adding porous materials, Energy and Buildings 165 (2018) 431-439.

[21] D.H. Vu, K. S. Wang, Bui Hoang Bac, Humidity control materials prepared from diatomite and volcanic ash, Construction and Building Materials 38 (2013) 1066-1072.

[22] M. R. Ahmad, B. Chen, Development of a new bio-composite for building insulation and structural purpose using corn stalk and magnesium phosphate cement, Energy and Buildings 173 (2018) 719-733.

[23] Y. Liu, M. Qin, Experimental analysis of the moisture buffering properties of different porous hygroscopic materials, Journal of Civil, Architectural and Environmental Engineering 37(5) (2015) 129-134.

[24] O. F. Osanyintola, C. J. Simonson, Moisture buffering capacity of hygroscopic building materials: Experimental facilities and energy impact, Energy and Buildings 38 (2006) 1270-1282.

[25] M. Zhang, M. Qin, Z. Chen, Moisture Buffer Effect and its Impact on Indoor Environment, Procedia Engineering 205 (2017) 1123-1129.

[26] Z. Wu, M. Qin, Z. Chen, Phase Change Humidity Control Material and its Application in Buildings, Procedia Engineering 205 (2017) 1011-1018.

[27] N. Mendes, F.C. Winkelmann, R. Lamberts, P.C. Philippi, Moisture effects on conduction loads, Energy Build. 35 (2003) 631–644.

[28] M. Qin, R. Belarbi, A. Aït-Mokhtar, A. Seigneurin, An analytical method to calculate the coupled heat and moisture transfer in building materials, International Communications in Heat and Mass Transfer 33 (2006) 39-48.

[29] M. Qin, R. Belarbi, A. Aït-Mokhtar, L. O. Nilsson, Coupled heat and moisture transfer in multi-layer building materials, Construction and Building Materials 23 (2009) 967-975.

[30] J. Yang, H. Fu, M. Qin, Evaluation of Different Thermal Models in EnergyPlus for Calculating Moisture Effects on Building Energy Consumption in Different Climate Conditions, Procedia Engineering 121 (2015) 1635-1641.

[31] R. Belarbi, M. Qin, A. Aït-Mokhtar, L.-O. Nilsson, Experimental and theoretical investigation of non-isothermal transfer in hygroscopic building materials, Building and Environment 43 (2008) 2154-2162.

[32] M. Qin, R. Belarbi, A. Aït-Mokhtar, F. Allard, Simulation of coupled heat and moisture transfer in air-conditioned buildings, Automation in Construction 18 (2009) 624-631.

[33] Y. Wang, C. Ma, Y. Liu, D. Wang, J. Liu, Effect of moisture migration and phase change on effective thermal conductivity of porous building materials, International Journal of Heat and Mass Transfer 125 (2018) 330-342.

[34] J. Shang, H. Zhang, D. Li, Preparation of composite material of gypsum-based double-shell micro-nano phase change capsules and performance research of temperature-humidity control, Acta Energiae Solaris Sinica,37(6) (2016) 1481-1487.

[35] J. Shang, H. Zhang, L. Xiong, Characteristic research on simulative wallboard of phase change and humidity storage under natural ventilation, Journal of Functional Materials, 46(18) (2015) 18083-18087.

[36] M. Zhang, M. Qin, Z. Chen, Study on impact of composite phase change moisture-controlled materials on indoor thermal and humid environment, Building Science, 32(12) (2016) 72-78.

[37] Z. Wu, M. Qin, M. Zhang, Phase change humidity control material and its impact on building energy consumption, Energy and Buildings, 174 (2018) 254-261.

[38] Z. Pavlik, J. Fort, M. Pavlikova, J. Pokorny, A. Trnik. Modified lime-cement plasters with enhanced thermal and hygric storage capacity for moderation of interior climate, Energy and Buildings 126 (2016) 113-127.

[39] J. H. Park, Y. Kang, J. Lee, S. Wi, J. D. Chang, S. Kim. Analysis of walls of functional gypsum board added with porous material and phase change material to improve hygrothermal performance, Energy and Buildings 183 (2019) 803-816.

[40] H. M. Kunzel. Simultaneous Heat and Moisture Transport in Building Component. One and two-dimensional calculation using simple parameters, suttgart: Fraunhofer IRB Verlag, 1995.

[41] J. Yang, H. Fu, M.o Qin. Evaluation of Different Thermal Models in EnergyPlus for Calculating Moisture Effects on Building Energy Consumption in Different Climate Conditions, Procedia Engineering 121 (2015) 1635-1641.

[42] S. Yu, Y. Cui, Y. Shao. Research on the Comprehensive Performance of Hygroscopic Materials in an Office Building Based on EnergyPlus, Energies 12 (2019) 191-208.

[43] E.L. Alisetti，S.K. Roy. Forced convection heat transfer to phase change material slurries in circular ducts, Thermophysical and Heat Transfer 14 (2000) 115-1641.

[44] N. Zhu, N. Hu, P. Hu, F. Lei, S. Li. Experiment study on thermal performance of building integrated with double layers shape-stabilized phase change material wallboard, Energy 165 (2019) 1164-1180.

[45] E. Meng, H. Yu, G. Zhan. Experimental and numerical study of the thermal performance of a new type of phase change material room, Energy Conversion and Management 74 (2013) 386-394.

[46] 2001 ASHRAE Handbook, Fundamentals(SI).American Society of Heating, Refrigerating and Air-conditioning, Engineers, Inc., 1791 Tullie Circle, N.E., Atalanta, GA30329.

Tables

Table 1 Thermophysical properties of PCHCM [38, 39]

Material	ρ (kg/m^3)	C_p (J/(kg·K))	H (kJ/(kg·K))	λ (W/(m·K))	Porosity (%)
$PCHCM_1$	700	800	100	0.15	50
$PCHCM_2$	700	800	100	0.15	50

Table 2 Balance moisture content of PCHCM

φ (%)	32.78	43.16	52.89	64.92	75.29	84.34	97.3
w_b (kg/m^3)	26.25	38.5	51	56.25	59	66	72

Table 3 Thermalphysical properties of envelope [43]

Material	D (m)	ρ (kg/m^3)	C_p (J/(kg·K))	λ (W/(m·K))
Color plate	0.0012	7850	480	48
EPS plate	0.075	20	1400	0.04
Color plate	0.0012	7850	480	48
PCM	0.01	-	-	-

Table 4 Thermalphysical properties of PCM [43]

Material	T_m (°C)	ρ (kg/m^3)	C_p (J/(kg·K))	H (kJ/(kg·K))	λ (W/(m·K))
SP29	28-30	1530（solid） 1520（liquid）	2000	190	0.6
RT18	17-19	880（solid） 770（liquid）	2000	225	0.2

Table 5 Climate parameters in Wuhan

Parameter	Average temperature (°C)	Maximum temperature (°C)	Lowest temperature (°C)	Average humidity %	Maximum humidity %	Minimum humidity %
Summer	27.25	38.70	17.2	76.71	100	34.49
Winter	5.54	16.85	-3.85	78.58	100	28.49
Annual	17.29	38.70	-3.85	75.73	100	14.51

Table 6 Thermal properties of building envelopes

Structure	Material	D (m)	ρ (kg/m^3)	C_p (J/(kg·K))	λ (W/(m·K))
Exterior wall	Plywood	0.02	530	1880	0.14
	Insulation	0.05	55	1880	0.04

	layer				
	Concrete	0.2	2100	920	1.28
	$PCHCM_1$	0.03	700	800	0.15
	$PCHCM_2$	0.03	700	800	0.15
Roof	Concrete	0.01	2100	920	1.28
	Insulation layer	0.1	55	1880	0.04
Ground	Insulation layer	0.1	80	840	0.04
Window	Double low-E	0.003+0.013+0.003			
	Window frame	0.045			2.27

Table 7 Cooling load component in four types of buildings

Type	Q_c (kWh)	Q_{sh} (kWh)	Q_{lh} (kWh)	R_{es} (%)
Reference building	827	493	334	-
HCM building	825	531	294	0.002%
PCM building	766	431	335	7.4%
PCHCM building	758	470	288	8.3%

Table 8 Heating load component in four types of buildings

Type	Q_h (kWh)	Q_{sh} (kWh)	Q_{lh}(kWh)	R_{es} (%)
Reference building	550	545	5	-
HCM building	515	511	4	6.3%
PCM building	460	456	4	16.4%
PCHCM building	413	409	4	24.9%

Figures

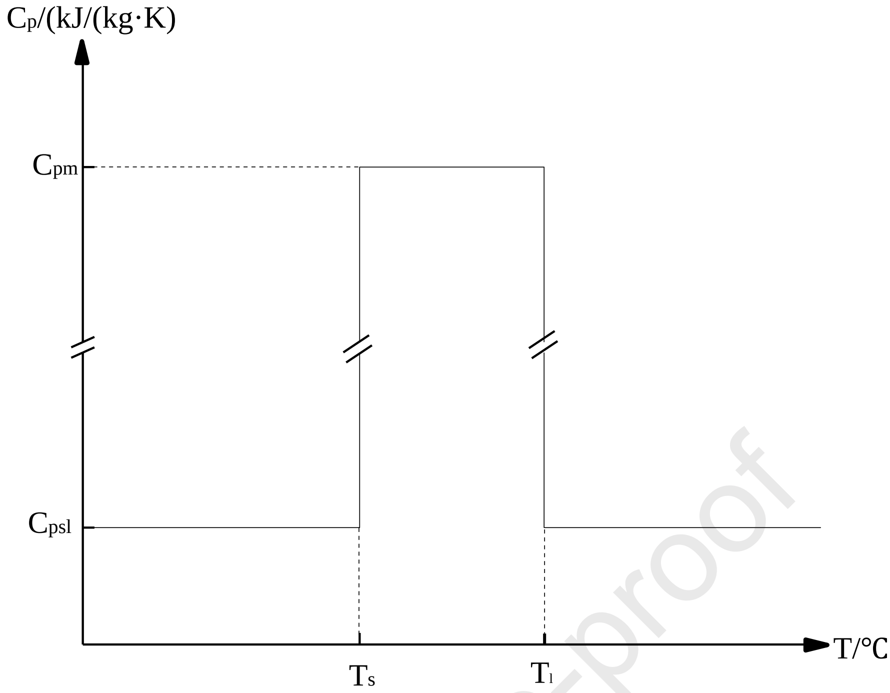


Fig. 1 Mutation heat capacity curve

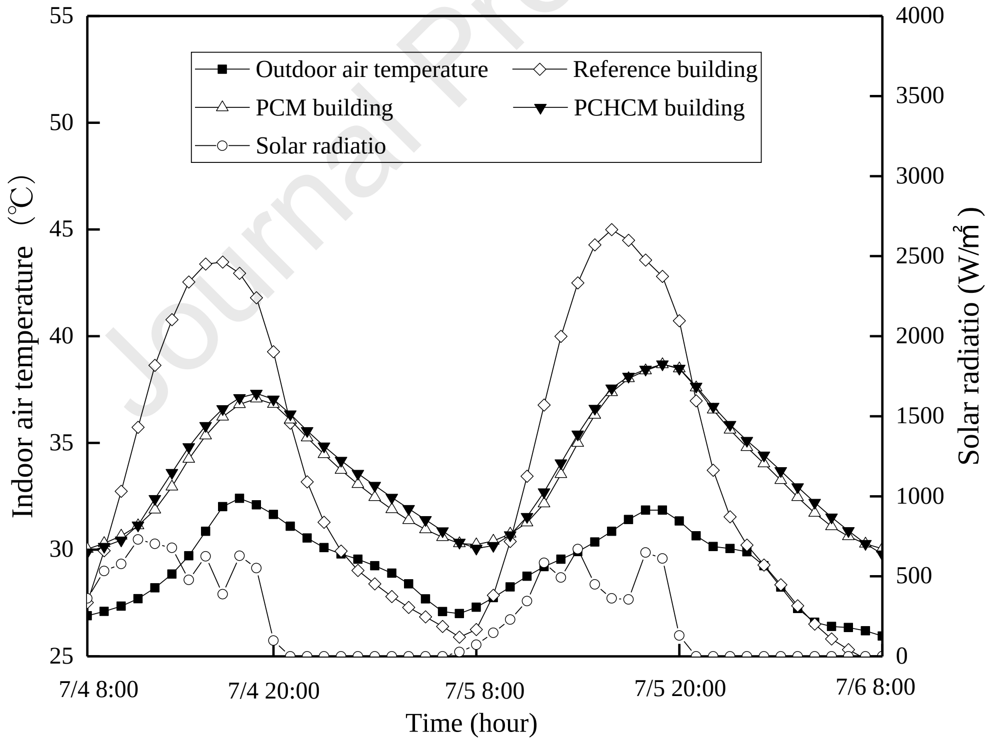


Fig. 2 The simulation results in this study

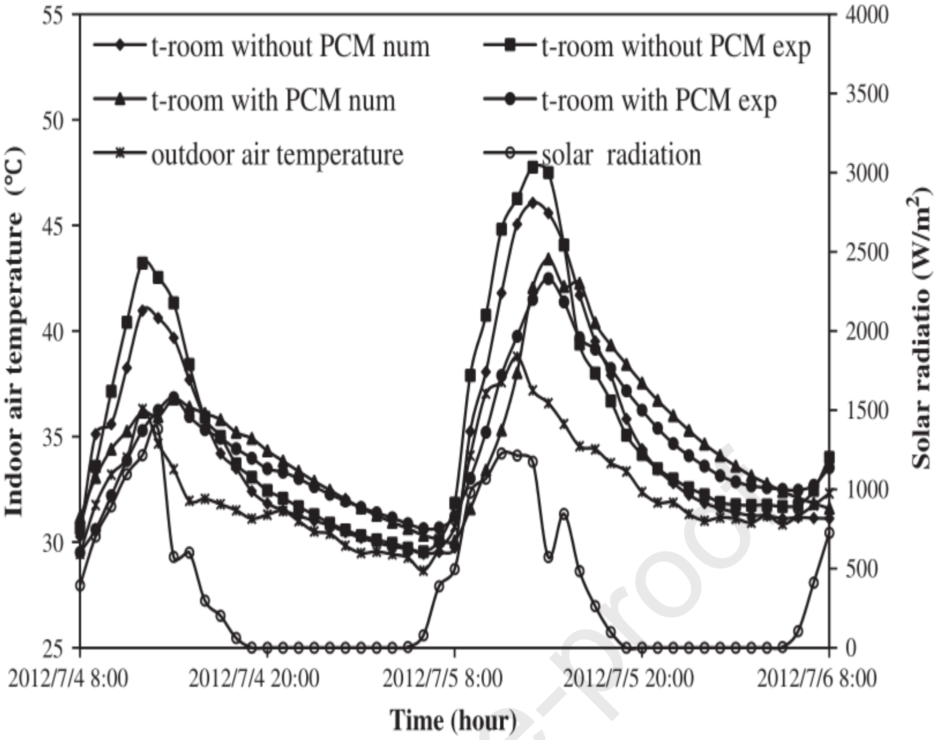
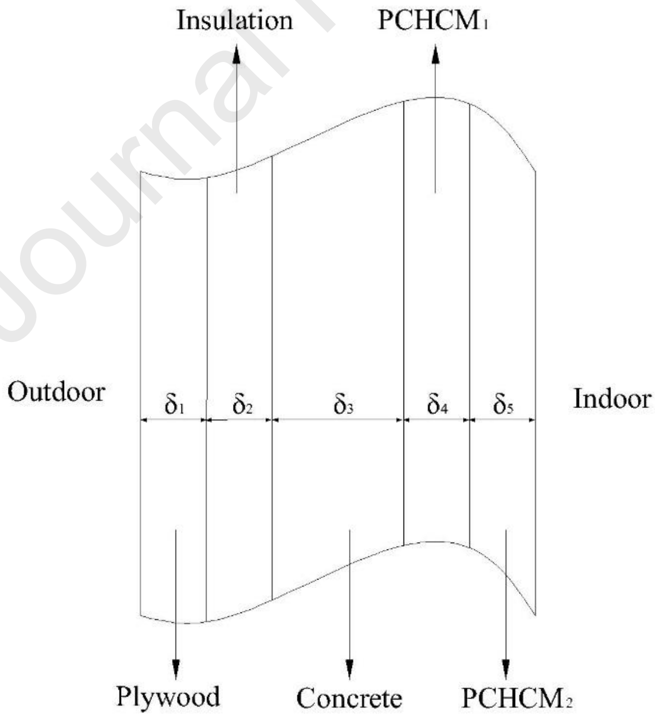
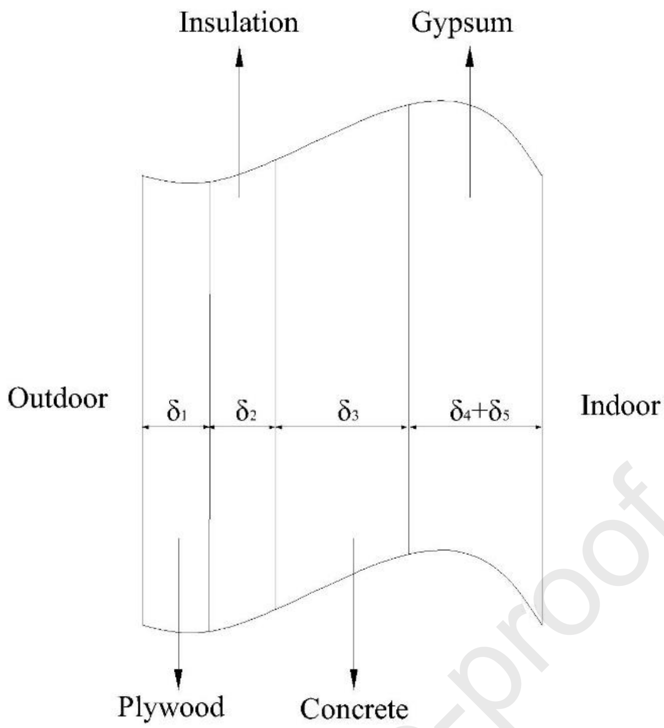


Fig. 3 The experiment results in reference [40]



(a)



(b)

Fig.4 Schematic of wall: (a) PCHCM wallboard; (b) reference wallboard

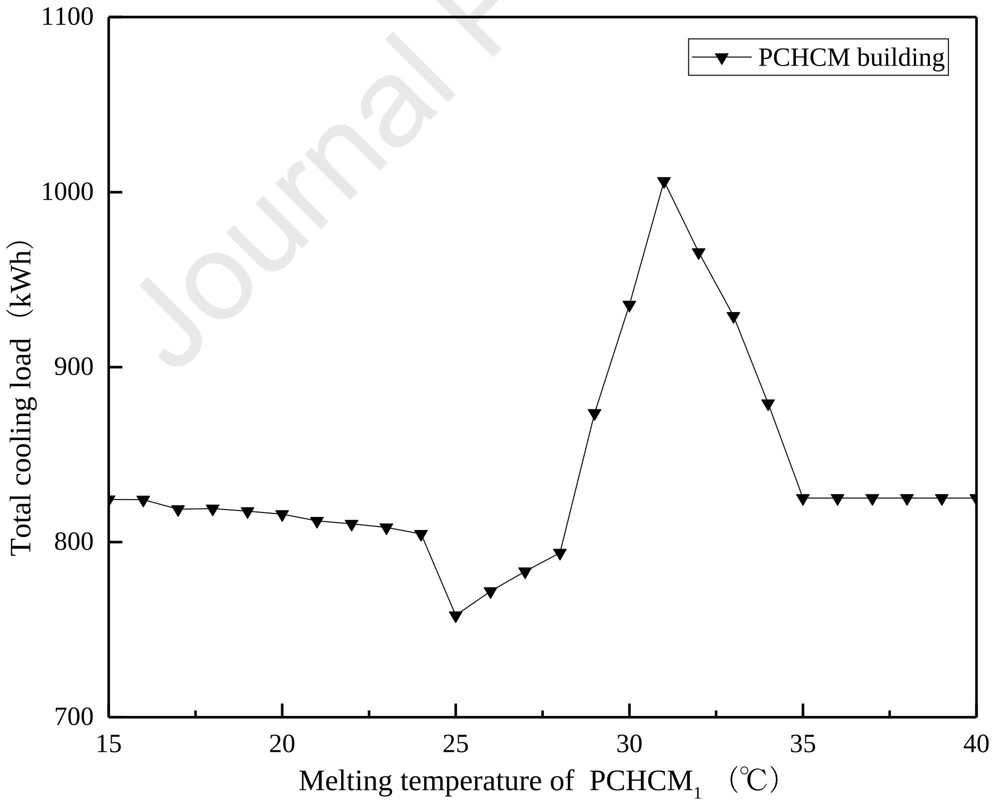


Fig. 5 Total cooling load varied with melting temperature of $PCHCM_1$

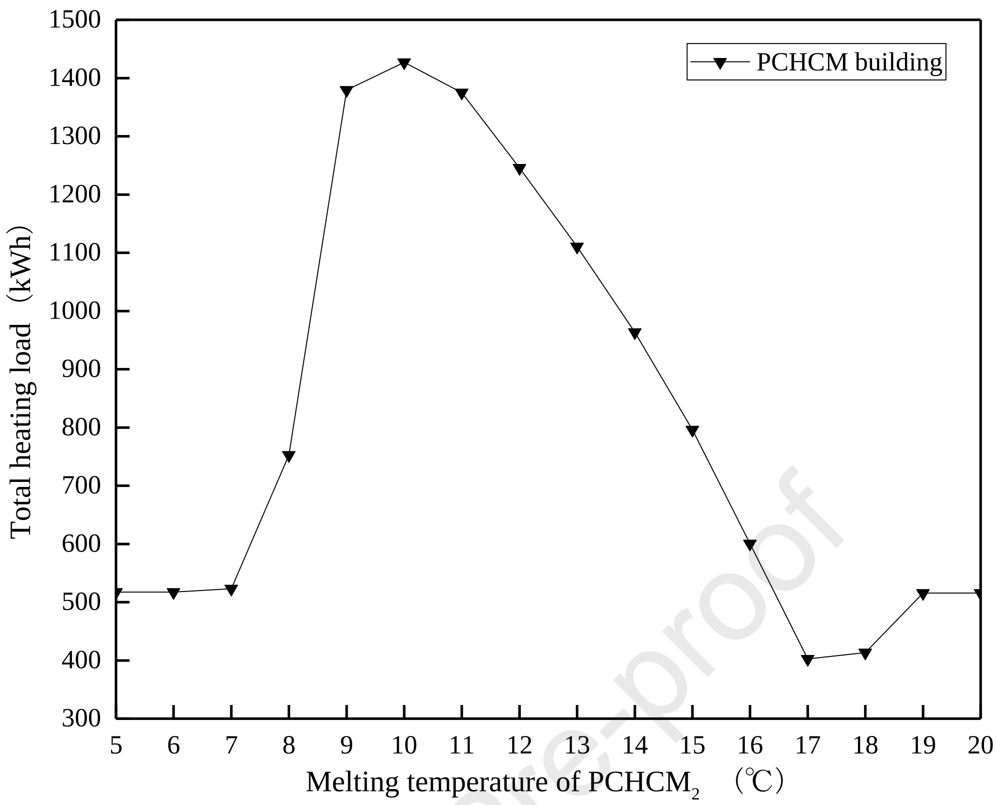


Fig. 6 Total heating load varied with melting temperature of $PCHCM_2$

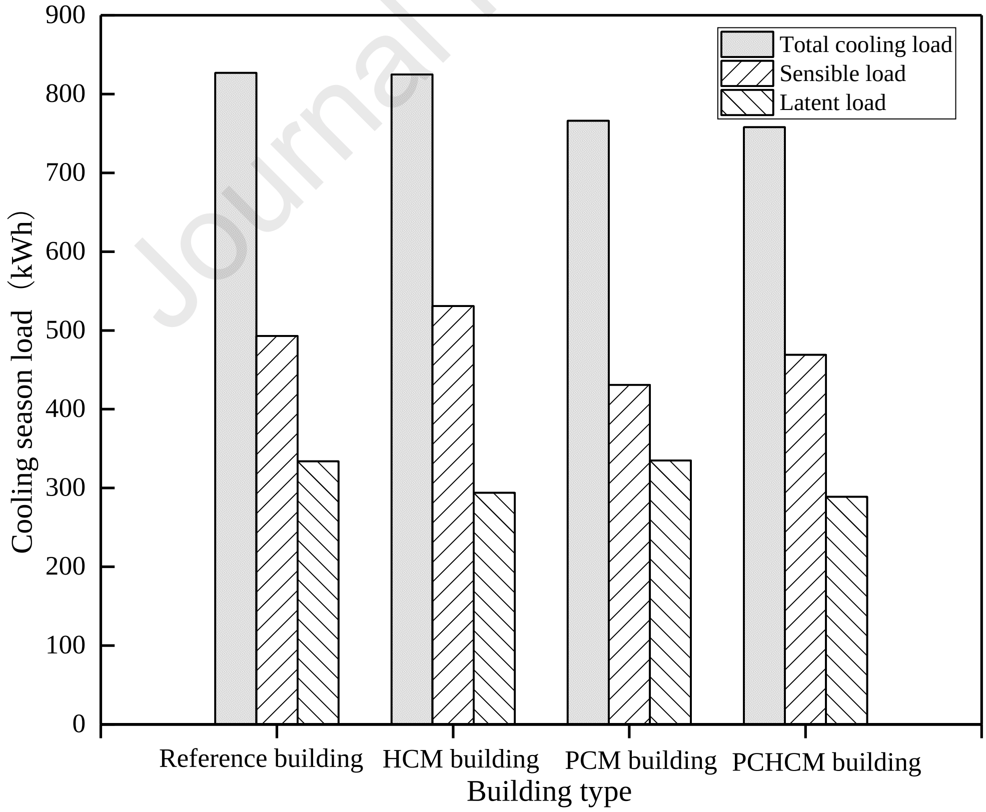


Fig.7 Cooling load components in four types of buildings

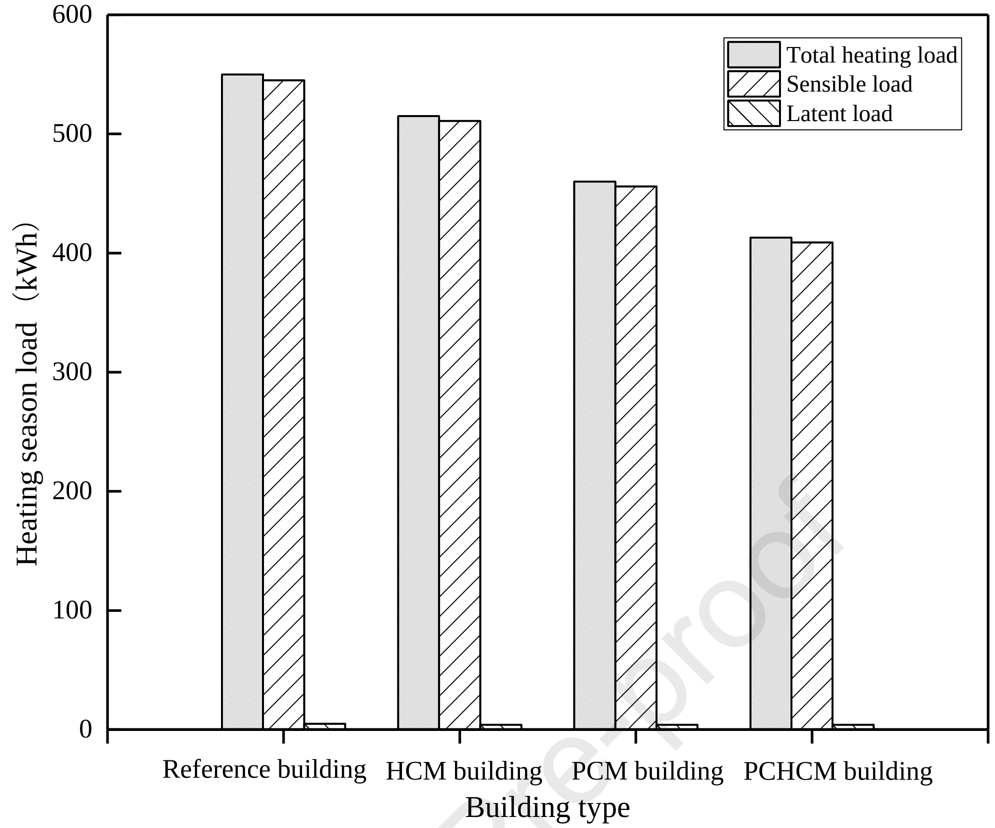


Fig.8 Heating load components in four types of buildings

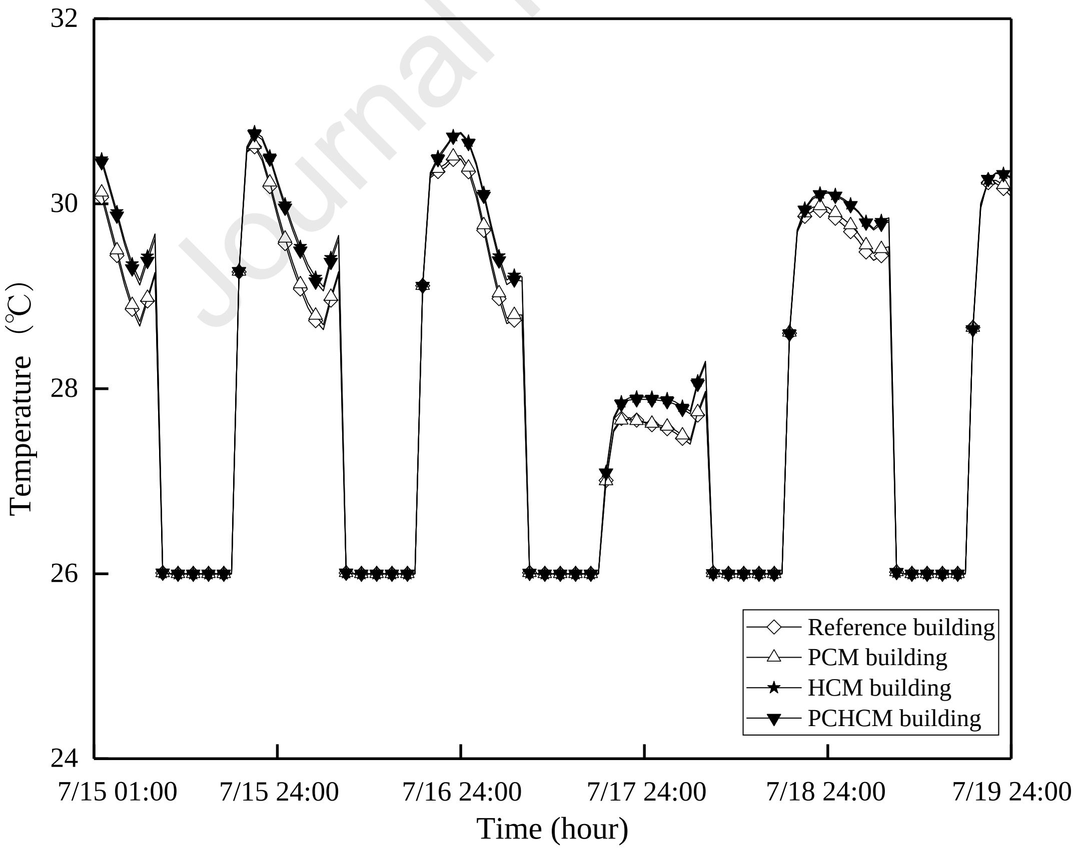


Fig.9 Indoor air temperature in four types of buildings during July 15th to 19th

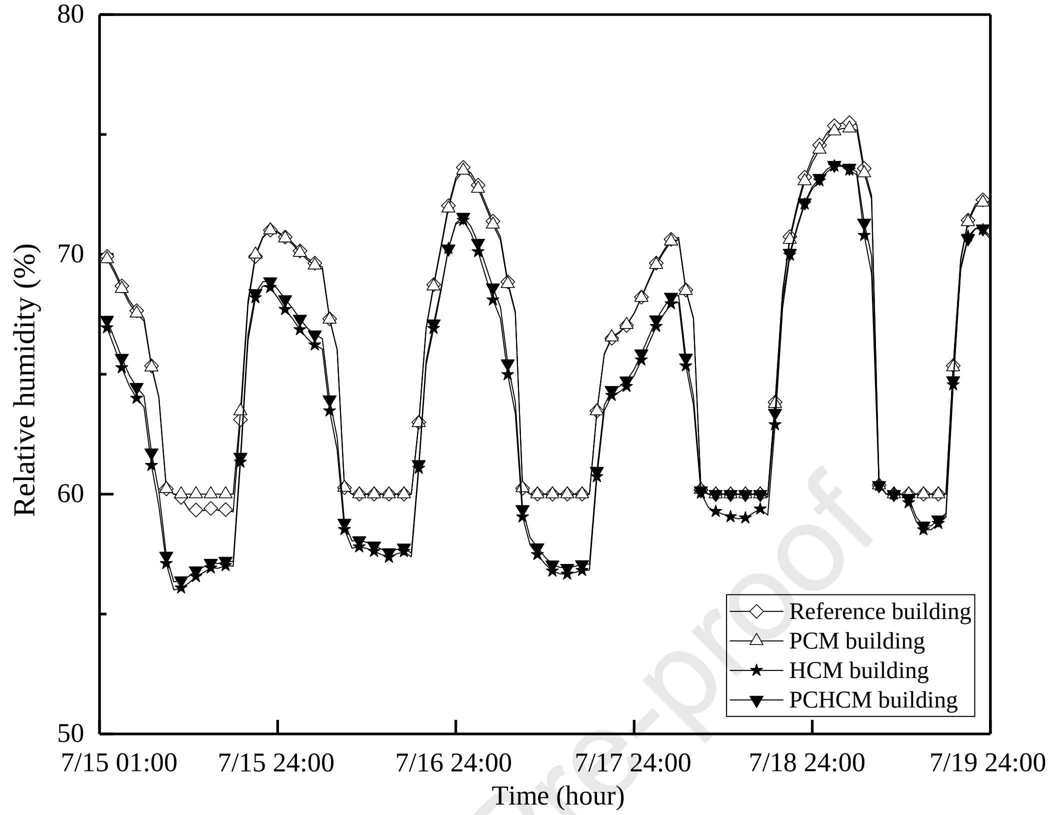


Fig.10 Indoor relative humidity in four types of buildings during July 15th to 19th

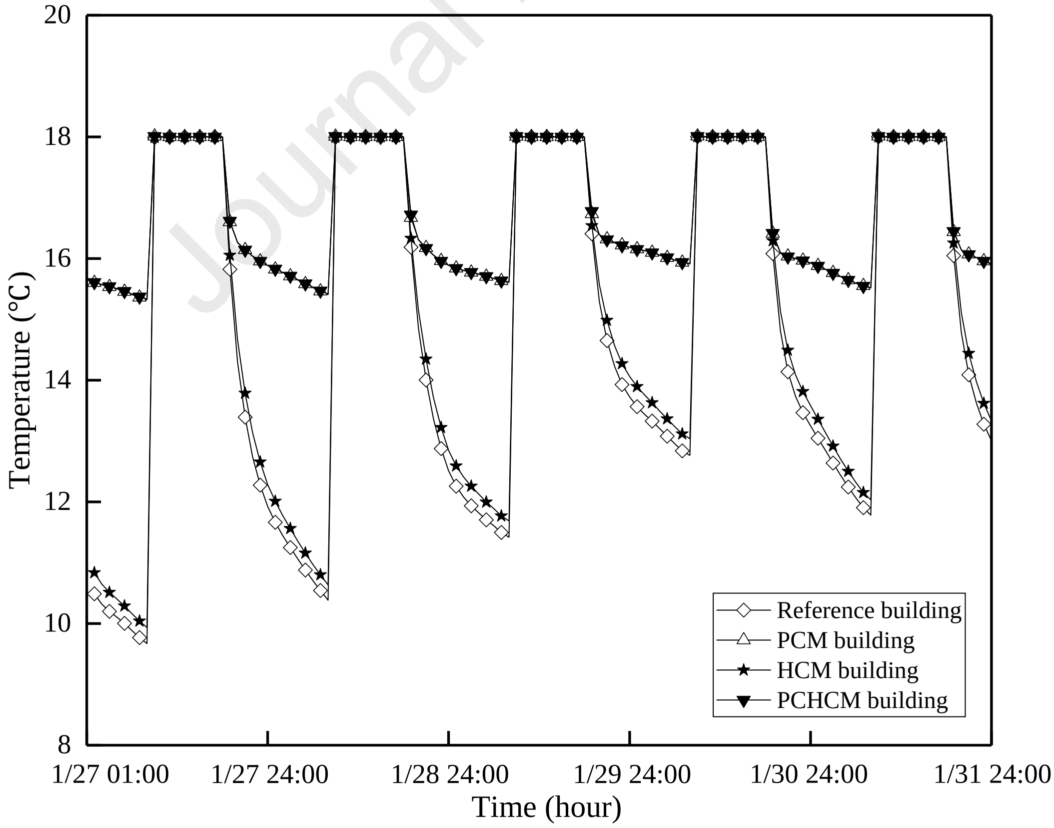


Fig.11 Indoor air temperature in four types of buildings during Jan. 27th to 31th

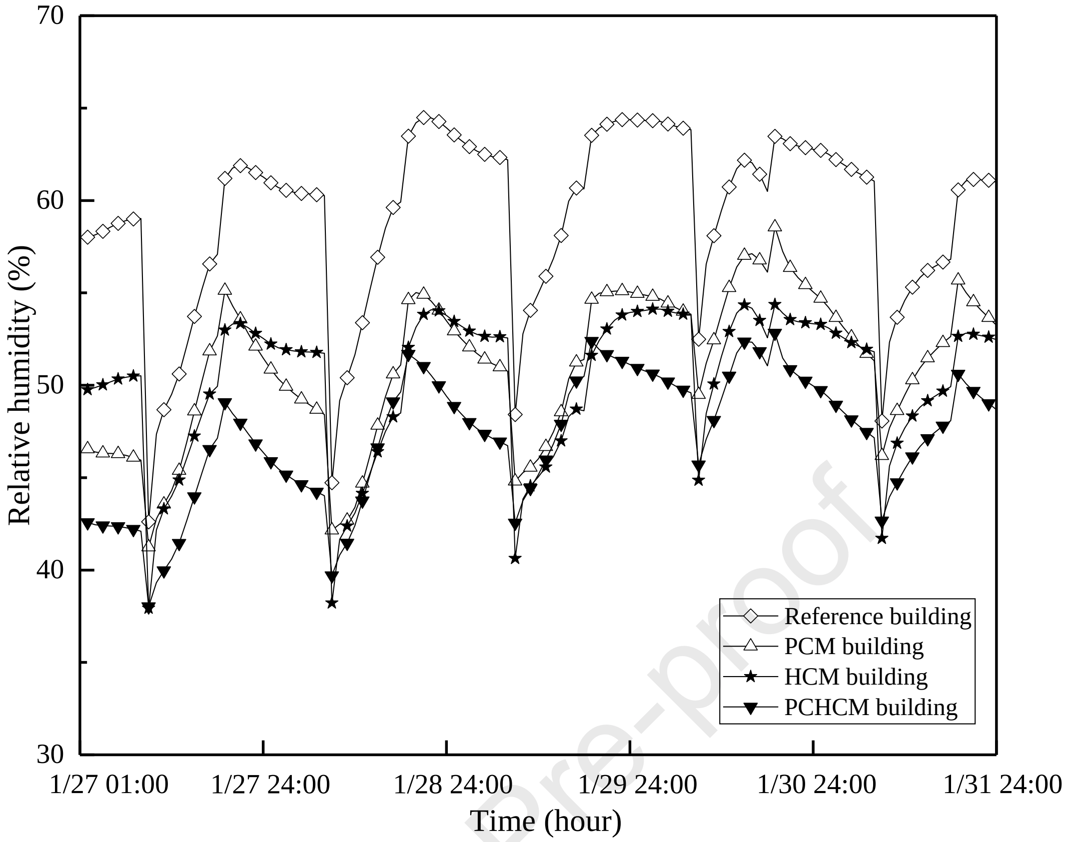


Fig.12 Indoor relative humidity in four types of buildings during Jan. 27th to 31th

Highlights

- A phase change humidity control material (PCHCM) wallboard was proposed
- The double-layer PCHCM wallboard active in summer and winter
- Melting temperatures of PCHCM wallboard were optimized
- Energy and Hygrothermal performance of PCHCM wallboard are analyzed

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: