PAPER • OPEN ACCESS

Numerical model of applying PCM boards for energy saving in lightweight buildings in Shanghai

To cite this article: Huakeer Wang *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **556** 012014

IOP Conf. Series: Materials Science and Engineering **556** (2019) 012014 doi:10.1088/1757-899X/556/1/012014

Numerical model of applying PCM boards for energy saving in lightweight buildings in Shanghai

Huakeer Wang[1], Wei Lu[1]*and Zhigen Wu[2]
[1] University of Shanghai for Science and Technology, 516 Jungong Road, Shanghai, 200093, PR China
[2] Tongji University, 1239 Siping Road, Shanghai, 200092, PR China
E-mail: wei.lu@usst.edu.cn

Abstract. The lightweight building industry develops fast, but it has competitively worse thermal comfort than traditional buildings because of less thermal mass. The use of phase change material (PCM) can help to solve the problem and boost the energy efficiency. In this paper, the effect of applying PCM-boards in air-conditioned lightweight buildings in Shanghai has been evaluated. A parametric study is performed considering different PCM-boards configurations, using an EnergyPlus single-zone model. The daily and annual situation have been simulated in this study, and the predictions show that the energy saving depends on the phase change temperature of PCM and seasonal temperature. The application of PCM can save up to 20.88% of energy for air conditioning system in buildings. The daily assessment reveals that the passive PCM technology inside the wall saves more energy under heating conditions than the cooling condition because of the overheating.

Keywords: PCM-boards, lightweight buildings, EnergyPlus, air conditioning energy saving

1. Introduction

Recent years, lightweight exterior wall panels are widely used in the construction industry [1]. However, they have low thermal mass, which increase the energy consumption of air conditioning. Meanwhile, these consumption generally takes up over one-third of energy consumption in buildings [2]. Use phase change material (PCM) to improve heat comfort is considered as a promising technology to solve the problem and reduce the power demand of air conditioning system [3]. The PCM can provide relatively high heat storage capability but with small mass and volume of material. Moreover, the temperature of the PCM remains almost constant during the phase change [4]. These features made it could be used to improve the thermal performance of building walls, reduce heating and cooling loads at the peak time, shift loads to low tariff hours and improve the indoor environment [5, 6]. In recent years, the PCM-enhanced building envelopes have been studied by increasingly researchers [7, 8]. The thermal performance of PCM wall is affected by many factors such as outdoor environment, the wall materials and the indoor environment [9, 10]. In this paper, a model with an innovative PCM enthalpy-temperature function has been built up to simulate a single PCM-boards enhanced room. The daily and annual energy saving have been predicted with the result of numerical simulation under weather situation in Shanghai.

2. Methodology

2.1. Numerical model

A standard 3-D building model was selected to simulate different conditions which is specified as ASHRAE-140 case-600. It is an air-conditioned single-zone model with the interior dimensions are 8m×6m×2.7m=129.6 m^3 as shown in Figure 1. All surfaces are external walls. This model assumed to have their windows on two sides to reflect current residential construction practices in Shanghai. On the south side, there are two windows while on the north side there is one window in the middle with the same size and shown in Figure 1. Moreover, the model is not obstructed by neighbouring buildings and the ground reflectance is equal to 0.2. The external walls properties and structure are shown in Table.1 and Figure.2. In the PCM-enhanced room, only walls and ceiling were installed with PCM-boards.

Table1. Properties of construction materials

	Conductivity (W/m · k)	Density (kg/m^3)	Specific Heat (J/kg · K)	Thickness (m)
EPS	0.039	20	1380	0.05
Gypsum Board	0.31	1100	1160	0.012
OSB	1.21	650	2000	0.02
Lightweight Concrete	0.52	1300	920	0.05
Roof Membrane	0.16	1121.29	1460	0.0095
Wood	0.15	608	1630	0.0254
PCM	0.6	1500	2000	

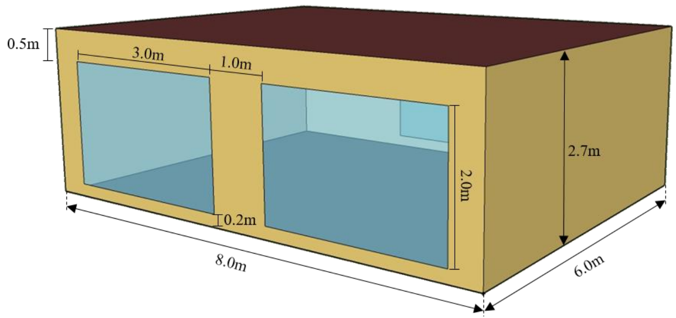
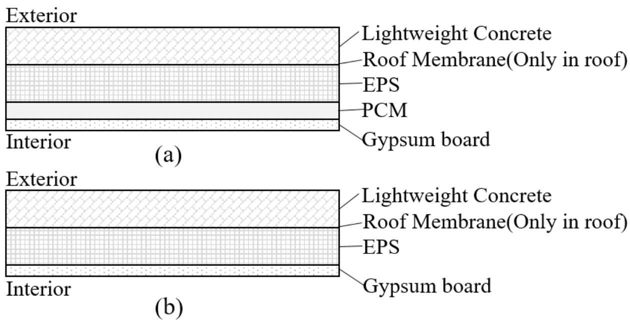


Figure 1. The building structure of the simulation model

Regarding internal heat gains, the building model was occupied by a maximum of 1 people per 1m^2 in sedentary activity with a constant metabolic rate of about 126W·person^{-1}. A maximum design lighting level of 10Wm^{-2} was considered for the equipment thermal gain. The air conditioner system in this study was *ideal loads air system* model in the EnergyPlus simulations. Regarding actual air temperature control, the thermostat was set with a cooling set point temperature of 26°C, and the heating set point temperature is 18°C. The air ventilation was set as one time per hour in this study.



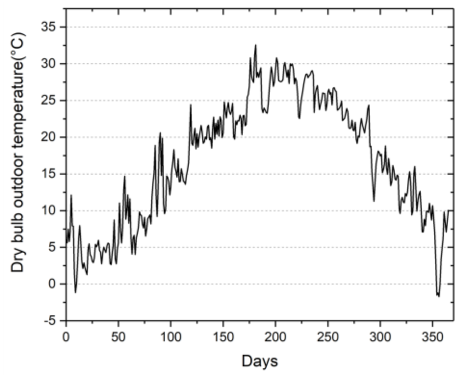


Figure 2. The envelope of the construction model (a) PCM-enhanced room (b)reference room

Figure 3. The temperature variation of Shanghai

2.2. Weather data

This parametric study is carried out in EnergyPlus 8.9.0. The CSWD Shanghai weather data file [11] is used to simulate the climate of Shanghai. The annual outdoor dry bulb temperature is shown in Figure 3. The climate zone of Shanghai is classified as hot-summer and cold-winter zone according to the *Code for design of civil buildings* [12]. The climate of Shanghai shows four distinct seasons. The warmest week, on average, is in the July with an average temperature of 27.49°C. The maximum temperature during the summer can reach 37°C. The most cooling mouth on average is January, with an average temperature of about 4.51°C, the minimum temperature can reach -4.3°C. More statistics information about the climate of Shanghai can be found in the weather data file [11].

2.3. Mathematical model

The annual cooling and heating energy demands are calculated in the lightweight reference model without PCM and compared with the PCM-enhanced lightweight model. The one-dimensional conduction finite-difference (ConFD) solution algorithm was adopted in this study which was validated against multiple test suites [13] in simulate the phase change process. In this study, according to Tabares et al [14], 1-minute time step was used in the simulation for assessing the annual and daily energy demand. Moreover, for the accuracy of hourly analysis, the space discretization was set to 0.4 for the CondFD model. This model read the inputs of the enthalpy-temperature information which was shown in the Figure 4.

The DuPont™ PCM product was considered as the reference PCM. As proposed by Tabares and Soares [14, 15], based on the nonlinear enthalpy-temperature function of reference material, a new linear function can be plotted for a hypothetical PCM-boards to facilitate the parametric analysis. Seven PCM with the same latent heat but different melting peak temperature were considered in this study. The detailed enthalpy-temperature is showing in Figure 4, which is an ideal value referenced from Nelson et al [16] (pcm18 for the PCM with peak melting temperature of 18°C, and so on in a similar fashion).

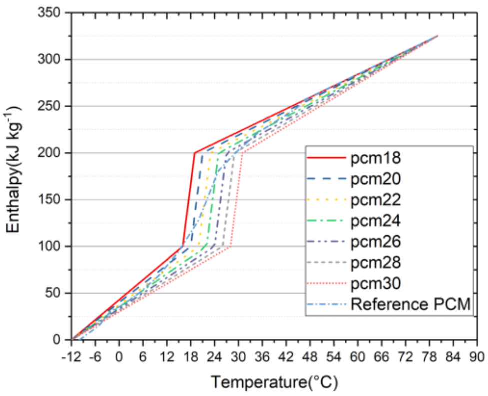


Figure 4. Enthalpy-temperature for the seven hypothetical materials of PCM-board *Reference data for DuPont™ Energain® PCM product obtained from differential scanning calorimeter (DSC) measurements with a heating rate of 0.05°C min^{-1}[17]

3. Results and discussion

3.1. Annual assessment for PCM-enhanced room and reference room without PCM

Compared with the reference room in which the air-condition cooling load is $E_{cool,ref}$ =137.45 kWh m^{-2} year^{-1}, and heating load is $E_{heat,ref}$ =59.96 kWh m^{-2} year^{-1}, the PCM enhanced room reduced the cooling load(Figure 5 (a)) and heating load(Figure 5 (b)), which can be found in Figure 5 ordered with different thickness and melting temperature. The Figure 5 (a) reveals that the best PCM for the cooling season is the pcm26 and pcm28. Maximum 10.67% annual cooling energy saving can be achieved by using pcm28 and thickness is 50mm. Figure 5 (b) shows the prediction in the heating season, the pcm20 is the best. Up to 56.75% energy saving can achieve in the thickness of 50mm. Moreover, simulations show that

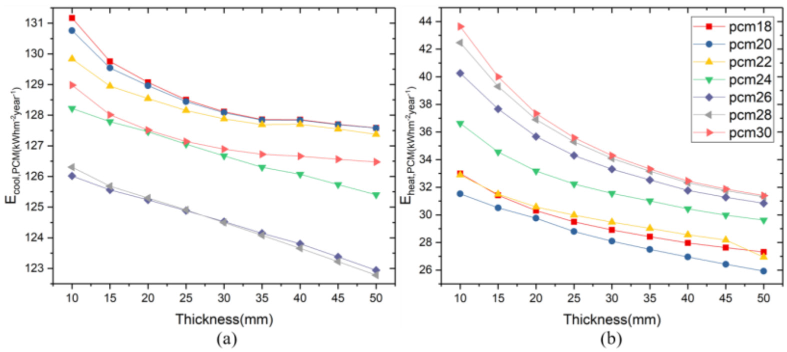


Figure 5. Annual (a) cooling and (b) heating energy demand for the PCM-enhanced room with different melting peak temperature and PCM-boards thickness

the energy load decreased with the increase of PCM thickness. It may be a good compromise to adopt 30mm instead of 50mm thick as the energy savings achieved with 30mm are close to those obtained with 50mm. This could be particularly important when taking into account the cost of the price of PCM-boards.

It is shown in Figure.6 that the annual air-condition energy consumption with different thickness of PCM. The pcm20 is the best for annual energy saving. The 20.88% energy saving is achieved in the thickness of 30mm. In addition, it is clear to see that the cooling energy saving has more influence on the annual energy saving, it will be discussed in the next section.

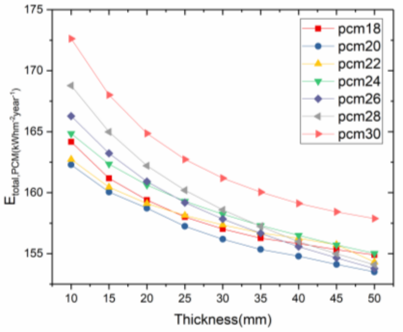


Figure 6. Annual air-condition energy demand for the PCM-enhanced room considering different melting peak temperature and PCM-boards thickness

3.2. Daily assessment basis for the effect of different melting temperature of PCM

To study the effect of different PCM on cooling and heating load of air conditioning system, three continuous days were picked up both in summer and winter. The pcm20 and pcm26 were employed as PCM. Figure 7 shows the case of summer from June 24th to 26th, and Figure 8 shows the prediction of winter from January 6th to 8th. The outdoor temperature have a big variation during these days. The area is used to indicate the cooling power consumption (Figure 7) in summer and heating power consumption (Figure 8) in winter time (read on left axis). The outdoor temperature, the temperature at the inside surface of PCM and the temperature of gypsum board at the same position in the reference room (read on right axis) are also plotted in lines.

In summer, due to the *ideal loads air system* model, the room temperature is maintained at the set point of 26°C. Figure 7(a) shows the case of the pcm20, because outdoor temperature and room temperature are always above 20°C so that PCM was in melting state. Therefore, PCM can be regarded as a layer of insulating material only. It can be seen that during the high outdoor temperature around noon, the energy consumption is reduced, but in the night, the cooling load of the PCM-enhanced room is higher than that of the reference room. However, the cooling load of PCM room during three days is similar to the reference room, but about 12.7% cooling load has been shifted from peak hour (8:00-21:00) to off-peak hour (22:00-6:00).

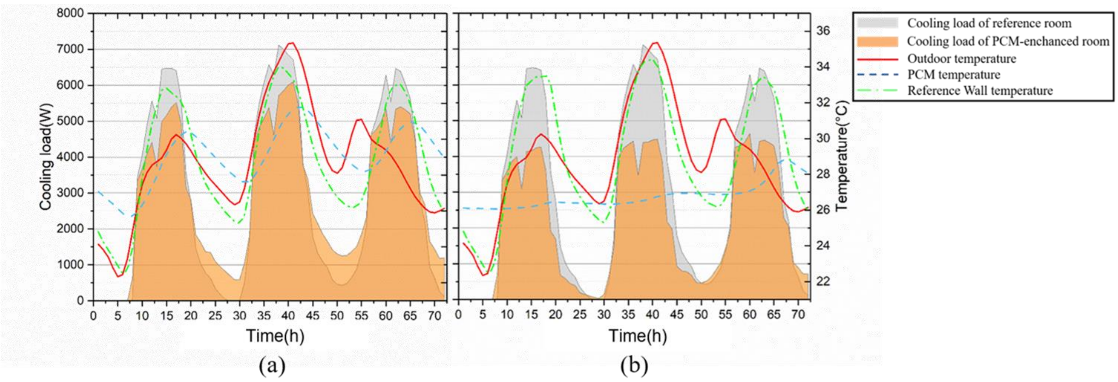


Figure 7. Hourly cooling load profiles and evolution of the estimated temperatures for the summer days (June 24th to 26th) for both the reference and the PCM-enhanced models (a) pcm20 (b) pcm26

In Figure 7(b), the temperature of the pcm26 is stabilized at melting temperature of 26°C in the first two days, when the PCM is absorbing heat. However, around the noon on the third day (65h), the temperature of the PCM exceeded 26°C, indicating that the PCM began to overheat. In the next night (70h), it can be seen that the temperature of PCM is higher than melting temperature and cooling load in PCM-enhanced room is higher than that of the reference room. This negative effect happened because PCM boards release heat at night.

In winter, the room temperature is maintained at 18°C. Figure 8(a) shows the prediction for room with pcm20. The temperature of PCM is maintained at about 20°C. Unlike in summer, energy savings mainly happened at night. Moreover, the temperature of the wall keeps steady around 20°C, which is good for room comfort and energy saving. Figure 8(b) shows the effect of the pcm26 during the winter. At this case, the outdoor temperature is lower than 26°C, PCM remains solidified. Although the PCM increases the heat capacity and thermal resistance of the wall, it can be seen from the figure that the outdoor temperature fluctuation still affects the indoor wall temperature in this case.

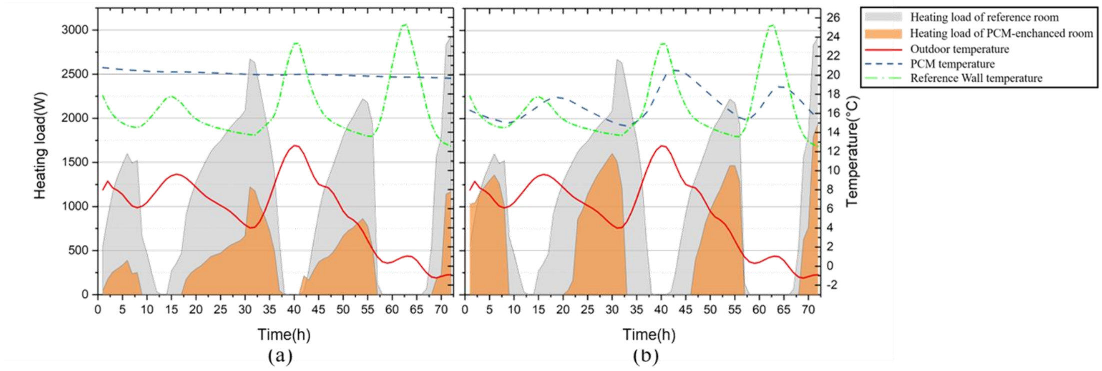


Figure 8. Hourly heating load profiles and evolution of the estimated temperatures for the winter days (January 6th to 8th) for both the reference and the PCM-enhanced models (a) pcm20 (b) pcm26

Combined with the summer and winter simulation, the following conclusions can be drawn: Firstly, when the outdoor temperature fluctuates around the melting temperature, the PCM has a weakening effect on the thermal fluctuation. Secondly, in summer, the most energy saving of the PCM happens around noon, and in the winter, it mainly happens at night. So the PCM can be chosen depending on the different service time of the room. Thirdly, Figure 9 shows the factors affecting the PCM melting and solidification in two seasons. The main difference is the solar radiation. In summer, the PCM is easily overheat under continuous high temperature because the sun keeps heating PCM, and it will have a negative impact on the power consumption for cooling when the PCM fails. Therefore, for summer, active PCM system may be a better choice. However, in winter PCM works stable because the sun can melt the PCM during daytime and the melted PCM is good for the night heat preservation.

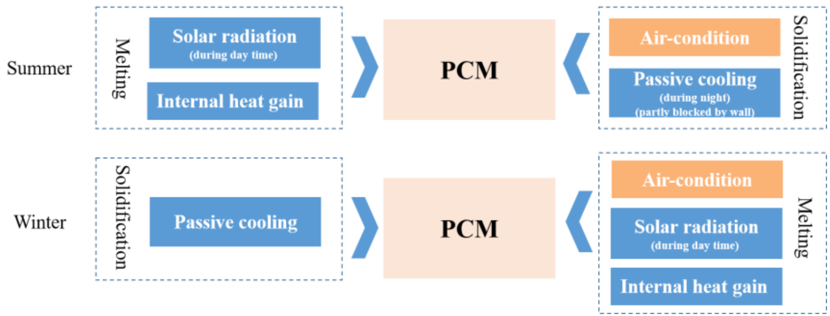


Figure 9. The different charging and discharging factors in summer and winter

4. Conclusion

This extensive EnergyPlus based parametric simulation study found that PCM-boards in lightweight construction in Shanghai helps to create annual savings of energy for cooling, heating up to 20%. The universal PCM-boards system with a thickness of 30mm and the melting temperature of the PCM at 20°C is recommended for the annual energy saving. It is also found that the passive PCM-boards does not appropriate for Shanghai in summer. It may have a negative impact when the PCM is fully melted. The active PCM system might be a better choice for summer energy saving. However, in winter the passive PCM have a good effect.

References

[1] J S Sage-lauck, D J Sailor 2014. Evaluation of phase materials for improving thermal comfort in a super-insulated residential building. Energy and Buildings 79 32-40

[2] International Energy Agency 2013. Technology roadmap: energy efficient building envelops, Oecd

[3] Anisur MR, Mahfuz MH, kibria MA, Saidur R, etc 2013. Curbing global warming with phase change materials for energy storage. Renew Sustain Energy Rev 18 23-30

[4] Mehing H, Cabeza LF 2008. Heat and cold storage with PCM: an up to date introduction into basics and applications. 1st ed. New York: Springer

[5] Genc Zk, Canbay CA, Acar SS, Sekerci M, Genc M 2015. Preparation and thermal properties of heterogeneous composite phase change materials based on camphene-palmitic acid. J Therm Anal Calorim 42 1759-72

[6] Castell A, Martorell I, Medrano M, et al 2010. Experiment study of using PCM in brick constructive solutions for passive cooling. Energy Build 42 531-40

[7] Saffari M, De Gracia A, Ushak S, et al 2017. Passive cooling of buildings with phase change materials using whole-building energy simulation tools: A review. Renewable & Sustainable Energy Reviews 80 1239-55

[8] Cabeza L F, Castell A, Barreneche C, et al 2011. Materials used as PCM in thermal energy storage in buildings. Renewable & Sustainable Energy Review 15(3) 1675-95

[9] Hasan M I, Basher H O, Shdhan A O 2018. Experimental investigation of phase change materials for insulation of residential buildings. Sustainable Cities and Society 36 42-58

[10] Kong X, Jie P, Yao C, et al 2017. Experimental study on thermal performance of phase change material passive and active combined using for building application in winter. Applied Energy 206 293-302

[11] Yi J. April 2005.China Standard Weather Data for Analyzing Building Thermal Conditions. Beijing. China Building Industry Publishing House

[12] Ministry of construction of the People's Republic of China. Code for design of civil buildings. GB50352-2005 7-8

[13] Tabares-Velasco P 2012. Energy impacts of nonlinear behavior of PCM when applied into building envelop. ASME 6TH International Conference on Energy Sustainability & 10th Fuel Cell Science, Engineering and Technology Conference. San Diego

[14] Tabares-Velasco P, Christensen C, Bianchi M 2012. Verification and validation of EnergyPlus phase change material model for opaque wall assemblies. Building and Environment 54 186-196

[15] Soares N, Gaspar AR, et al 2014. Multi-dimensional optimization of the incorporation of PCM-drywalls in lightweight steel-framed residential buildings in different climates. Energy and buildings 70 411-421

[16] Nelson S, Christoph F R, Ali H 2017. Simulation-based analysis of the use of PCM-wallboards to reduce cooling energy demand and peak-loads in low-rise residential heavyweight buildings in Kuwait. Build Simul 10 481-495

[17] Cao S, Gustavsen A, Barreneche C, et al 2010. The effect of wall-integrated phase change material panels on the indoor air and wall temperature-Hot box experiments. Renewable Energy Research Conference. Trondheim Norway.

Acknowledgement

This work is supported by National Natural Science Foundation of China (No.51406121 and No.51736007) and Eastern Scholar (No.QD2015017)