

Preparation, Thermal Performance and Application of Shape-Stabilized PCM in Energy Efficient Buildings

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Abstract: Shape-stabilized phase change material (PCM) is a kind of novel PCM. It has the following salient features: large apparent specific heat for phase change temperature region, suitable thermal conductivity, keeping shape stabilized in the phase change process and no need for containers. The preparation for such kind material was investigated and the thermophysical properties of various samples developed by us were measured. Several applications of such material in energy efficient buildings (e.g., in electric under floor space heating system, in wallboard or floor to absorb solar energy to narrow the temperature swing of a day in winter) were studied. Some models of analyzing the thermal performance of the systems were developed, which were validated with our experiments. The following conclusions are obtained: (1) The applications of the novel PCM we put forward are of promising perspectives in different climate regions; (2) By using different paraffin, the melting temperature of shape-stabilized PCM can be adjusted; (3) The heat of fusion of the shape-stabilized PCM building component is in the range of 62-138 kJ/kg; (4) For PCM floor or wallboard to absorb solar energy to narrow the temperature swing in a day in winter, the suitable melting temperature of PCM should be a little higher than the average indoor air temperature of the room without PCM for the period of sunshine; (5) For the electric under-floor space heating system, the optimal melting temperature can be determined by simulation; (6) PCM layer used in the aforementioned application should not be thicker than 2 cm; (7) For given conditions, the numerical model developed by us can provide the prediction and optimal design for applications of shape-stabilized PCM in buildings.

Keywords: Energy Efficient Buildings, Shape-Stabilized PCM

1. INTRODUCTION

Thermal storage systems play an important role in many energy systems as in solar heating systems, in cooling or heating in dwellings and commercial buildings and in systems of waste heat application etc. They are able to balance out the discrepancies between energy demand and energy supply, which are time-wise out of phase^[1].

There are three kinds of thermal storage: sensible heat storage, latent heat storage and reversible chemical reaction heat storage. For many cases, latent heat storage demonstrates some preferable characteristics: (1) phase change process is nearly an isothermal process; (2) compared with sensible heat storage system, it has, in general, larger heat storage intensity; and (3) it is easier to control than a chemical reaction system. However, for traditional PCM, in order to store and to release the latent heat of the PCM, special latent storage device or containers to encapsulate the PCM is necessary. This increases not only the thermal resistance between PCM and the heat transfer fluid but also the first cost of the system. And the latter is exacerbated for salt hydrated because the container must be hermetically sealed. For example, though the bulk cost of $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ is only \$90 US per ton, storage modules based on this material cost more than \$3000 US per ton at the retail

level in Canada^[2]. In recent years, a kind of novel compound PCM, the so-called shape-stabilized PCM has been attracting the interests of the researchers^[3-6]. It consists of paraffin as dispersed PCM and high density polyethylene (HDPE) or other material as supporting material. Since the mass percentage of paraffin can be as much as 80% or so, the total stored energy is comparable with that of traditional PCMs.

Inaba et al.^[3] studied the thermal performance of shape-stabilized phase change material (PCM) composed of paraffin and HDPE. The material contained 74wt% paraffin, with the melting temperature of 54°C and heat of fusion 121.4kJ/kg. Ye and Ge^[4] investigated several kinds of HDPE with different melting index (MI) for use as supporting material and screened the optimal one. The melting temperatures of the paraffin they mentioned are 70-80°C, 18.1°C and -9°C, respectively. Xiao and Gong^[5, 6] selected styrene-butadiene-styrene copolymer (SBS) as supporting material to form shape-stabilized PCM. This material contained up to 80wt% paraffin. The melting temperature and the heat of fusion are 56-58°C and 165.21d/kg, respectively. In order to increase the thermal conductivity, some expandable graphite with high thermal conductivity was added to the material^[7]. Considering that the paraffin tends to diffuse to the surface and lose little by little, SBS may

be the best supporting material. However, it has the defect of rigidity, that is to say, the product containing SBS-paraffin high mass fraction SBS can not afford its own weight and will deform.

Obviously, the shape-stabilized PCM can overcome the aforementioned shortcomings of traditional PCMs. Therefore, it may have many potential applications especially in the field of energy efficient buildings. However, as far as we know, few researches have been reported in the literature on this topic.

In the present paper, the preparation for such kind material is introduced and the thermophysical properties of various samples developed by us are presented. The principles of applying such material in energy efficient buildings are addressed. Several our recent experimental and simulation researches on applying this kind of shape-stabilized PCM in space-heating in winter (e.g., in electric under-floor space heating system, in floor to absorb solar energy to narrow the temperature swing of a day in winter) are reported. The results show that applying shape-stabilized PCM in buildings is a promising technique and should be studied further.

2. REPARATION OF SOME SHAPE-STABILIZED PHASE CHANGE MATERIALS

The paraffin with the melting point of 20°C or 60°C is chosen as the phase change material. As for supporting material, HDPE or a composite was used. In the latter each component played a different role: powder-like HDPE endowed PCM rigidity; SBS absorbed the paraffin strongly while it was in liquid state; inorganic filler improved the possibility of graphite or carbon fiber acted as a thermal conductive component. The paraffin and the supporting material were mixed evenly and co-extruded at about 140°C in a two-screw extruder. The shape of the product-plate, rod, pellet, etc. varied according to the different application manner. In order to prevent the possible leakage of paraffin, the surface treatment, such as grafting and cross inking was carried out on the product. In such a shape-stabilized material, paraffin particles (at the order of magnitude of tens of micrometer) were dispersed evenly in the polymer matrix (see Fig.1). No matter liquid or solid the paraffin is, the polymer network stands still to support the shape. Taking into account of the heat storage ability, the concentration of the paraffin should be as high as possible. The concentration of 80% of paraffin was proved to be the optimal value.

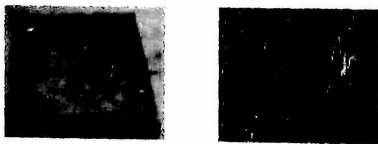


Figure 1: The shape-stabilized PCM plate developed by us.

3. THERMOPHYSICAL PROPERTIES OF THE SHAPE-STABILIZED PHASE CHANGE MATERIALS

Table 1 lists the thermophysical properties of the shape-stabilized PCMs developed by us with different supporting systems. The data were obtained by DSC device.

Table 1 The thermophysical properties of the shape-stabilized PCMs developed by us^[8]

Sample	Melting temperature (°C)	Heat of fusion (kJ/kg)
Paraffin	20.3	119.66
Paraffin /SBS /wollastonite =70/25/5	20.0	86.66
Paraffin /SBS /clay-1 =70/25/5	20.4	88.86
Paraffin/SBS/clay-2 =70/25/5	21.0	90.37
Paraffin/SBS/clay-3 =70/25/5	20.3	96.82
Paraffin/SBS/Mg(OH)2 =70/10/20	20.6	82.97
Paraffin/SBS/Mg(OH)2 =70/10/10	20.7	82.17
Paraffin/SBS =70/30	20.5	87.43
Paraffin/HDPE/diatomite =70/15/15	20.7	81.21
Paraffin/HDPE/diatomite =70/10/20	20.1	90.96
Paraffin/HDPE/diatomite =70/20/10	20.3	87.45
Paraffin/HDPE =75/25	20.6	87.43
Paraffin/SBS =70/30 (surface grafting)	20.7	62.76*
Paraffin/HDPE =75/25	60.0-62.0	130.8
Paraffin/HDPE =80/20	60.0-62.0	137.9

* Some paraffin may be lost during the grafting process.

4. PRINCIPLES OF APPLYING SHAPE-STABILIZED PCM IN ENERGY EFFICIENT BUILDINGS

A. For solar buildings

Solar radiation is a time-dependent energy source with an intermittent character and the peak solar radiation occurs near noon. Thermal energy storage can provide a reservoir of energy to adapt the changes of solar energy. Energy storage in the walls, ceiling and floor of buildings may be enhanced by impregnating some suitable PCM in them to adsorb solar energy at daytime when PCM change phase from solid to liquid state. Contrarily, when the room temperature falls down at evening, PCM releases the energy and freezes back to solid phase. Therefore, in winter the human comfort level can be increased by using PCM to lower the indoor air temperature swing and maintain it to the desired value in a longer time period. For this application, the melting temperature of the PCM should be around 20°C. If the melting temperature is too high, the quantity of heat stored by

PCM is low. If the melting temperature is too low, the indoor air temperature can not be maintained at a comfortable level without additional space heating. The questions needed to be studied are: (1) to determine the optimal melting temperature of PCM for different buildings in different climate regions, (2) to determine the effective methods of applying shape-stabilized PCM in energy efficient buildings.

B. For space heating with off peak electricity

In order to narrow the gap between the peak and valley loads of electricity demands, night and day tariff policy is being used in many cities of China. The electricity tariff at night is 1/2 -1/5 of that at daytime. Then the shift of electrical consumption from peak periods to valley periods will provide significant economic benefit.

As reported in recent studies, floor radiant heating can be an economically efficient alternative to other more common forms of heating [9]. It saves living and working space since it is integrated into the building envelopes [10]. Thermal mass integrated into a floor heating system can be used for off-peak storage of thermal energy. Thus, peak loads may be reduced and shifted to nighttime when electricity costs are lower [11]. The combination of radiant floor heating and thermal storage offers the possibility of significantly improving building energy efficiency without compromising thermal comfort.

5. OUR MODELING, SIMULATING AND EXPERIMENTAL RESEARCHES ON APPLICATIONS OF SHAPE-STABILIZED PCM IN ENERGY EFFICIENT BUILDINGS

A. Shape-stabilized PCM floor to absorb solar energy to narrow the temperature swing in a day in winter [12, 13]

The shape-stabilized PCM based floor developed by us is shown in Fig.2.

(1) Simulation model

In order to investigate: (1) the thermal performance of the shape-stabilized phase change material floor; (2) the influences of various factors on the thermal performance of the system; (3) the feasibility of applying such system in different Chinese climate regions, a simulation model for the shape-stabilized phase change material floor was developed by us [12].

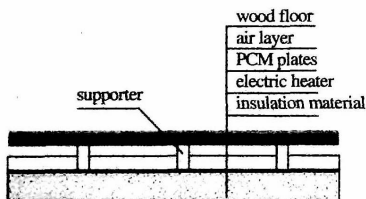


Figure2: Schematic shown of the shape- stabilized PCM floor

(2) Model validation experiments

For the purpose of verifying the model, an experimental cabin with the shape-stabilized PCM was built at Tsinghua University, Beijing. The dimensions of the cabin are 3m (depth)×2m (width) × 2m (height). There was a 1.6m × 1.5m double-glazed window facing south with 60% transmittance and overall heat transfer coefficient $1.4 \text{ W/m}^2\text{K}^{-1}$. The roof and the walls were made of 100-mm-thick polystyrene boards. The floor was composed of 20-mm-thick shape-stabilized PCM layer and a 50-mm-thick polystyrene layer. The experiments were performed in Nov., 2003. Air change per hour (ACH) was gained by the tracer-gas technique with methane [14]. The thermal physical properties of the walls and floor are listed in Table 2. The PCM's heat of fusion is 120 kJ/kg . Fig.3 verified the model and simulation procedure.

Table 2 Thermal physical properties of the walls and the floor

Materials	$\rho(\text{kg}/\text{m}^3)$	$c_p(\text{kJ}/\text{kg} \cdot \text{K})$	$k(\text{W}/\text{m} \cdot \text{K})$	$U(\text{W}/(\text{m}^2 \cdot \text{K}))$
PCM	850	1.0	0.2	---
Glass wall	2000	0.8	---	1.4
Gypsum wall	1500	0.8	0.3	---
Tile floor	2000	1.0	1.1	---

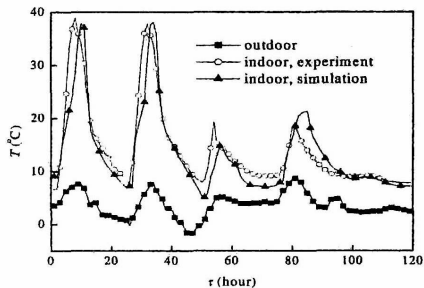


Figure 3: Comparison of the simulated and the measured results of the experimental cabin

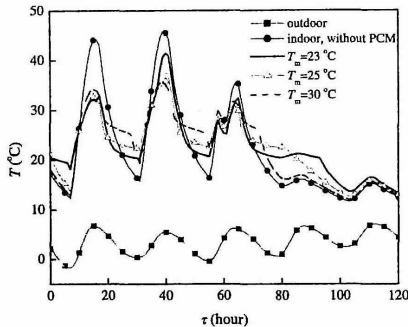
(3) Results and discussion

Melting temperature of PCM

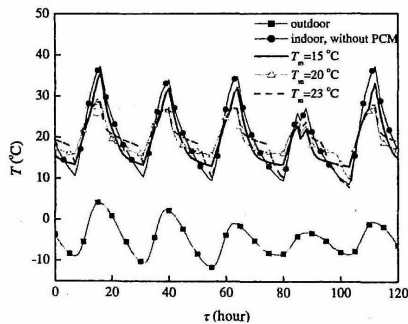
One key of applying shape-stabilized PCM floor in building is to select PCM with suitable melting temperature. For given climate condition and given buildings, just as mentioned above: If the melting temperature is too high, the quantity of solar radiation heat stored by shape-stabilized PCM is too little in the daytime; If the melting temperature is too low, it's difficult to maintain the indoor air temperature under a comfortable level at night time. Therefore, for a given climate region, there must be an optimal melting temperature of PCM. By using the PCM floor with suitable melting temperature, the indoor air temperature can be maintained at a relatively comfortable level. Obviously, for different climate

regions, the optimal melting temperatures are different. In the present paper, two cities, Beijing and Shanghai are considered. The building discussed here is without space heating system.

Through analysis for simulation results (see Fig.4), it is found that the optional melting temperatures of shape-stabilized PCM used in the buildings located in Beijing and Shanghai are 20°C and 25°C, respectively, which make the indoor air temperature fluctuate gentlest.



(a)



(b)

Figure 4: Indoor air temperature variation by using different melting temperature of PCM for (a) Beijing and (b) Shanghai

Heat of fusion

The heat of fusion of PCM is also an important factor influencing the ability of energy storage of the floor. Theoretically, the indoor air temperature swing decreases with increasing heat of fusion of PCM. Here, heat of fusion as 50kJ/kg, 90kJ/kg, 120kJ/kg and 150kJ/kg were used to calculate the variation of indoor air temperature with shape-stabilized PCM plates applied in Beijing in winter. δT is defined as indoor air temperature swing for a typical winter day. It is found from Fig.5 that δT changes little when the heat of fusion >90 kJ/kg and almost keeps the same

when heat of fusion ≥ 120 kJ/kg. Therefore, in practical usage, 120kJ/kg is high enough for PCM heat of fusion.

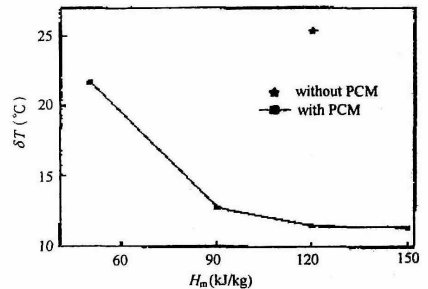


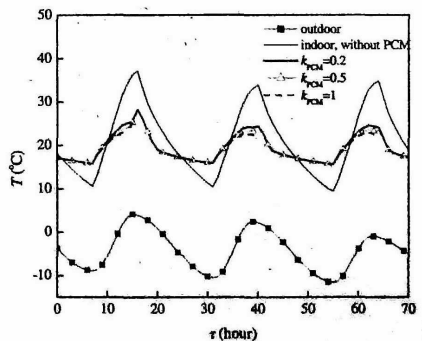
Figure 5: Indoor air temperature swing for different heat of fusion

Thermal conductivity

Improving the thermal conductivity can accelerate the solar energy absorbing speed of shape-stabilized PCM plates, and lower the indoor air temperature in the daytime. Here, thermal conductivity of $0.2 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, $0.5 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ and $1 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ were used to calculate the indoor air temperature in several days under the winter weather condition of Beijing. For the cases studied, the thermal conductivity has a little effect on lowering the peak of indoor air temperature as shown in Fig. 6 (a).

The air-gap between PCM and floor

For the shape-stabilized PCM plates used under floor covering, there tends to be an air-gap between them, which augments the thermal resistance and reduces the solar energy stored. It is seen from Fig.6 (b), the air-gap increases the indoor air temperature swing and should be eliminated as much as possible in practical application.



(a)

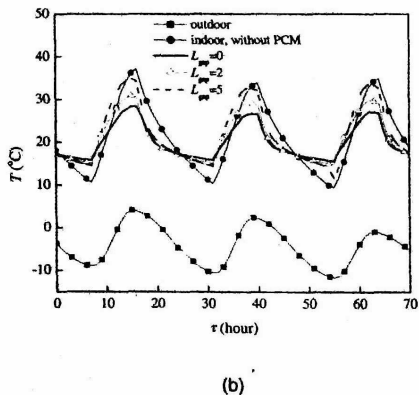


Figure 6: Indoor air temperature variation for (a) different thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$ and (b) different air-gaps, mm

Thickness of shape-stabilized PCM

The fluctuation of indoor air temperature δT decreases with increasing PCM plate thickness L_{PCM} (Fig.7). However, it is noted that δT hardly decrease with increasing L_{PCM} when $L_{PCM} \geq 20$ mm. It means that, in practical application, the thickness of shape-stabilized PCM layer should not be thicker than 20mm.

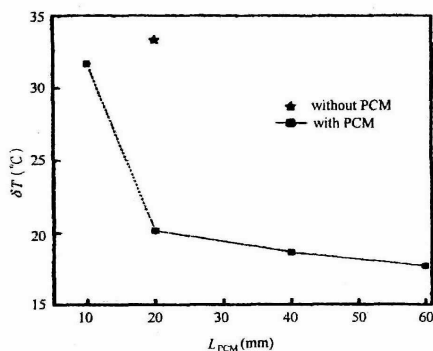


Figure 7: Indoor air temperature swing for different thickness of PCM layer

The floor covering materials

The floor covering material also influences the thermal performance of PCM floor because of its thermal conductivity. The tile or metal floor should be chosen instead of the wood floor as shown in Fig.8, because the wood floor has a larger thermal resistance.

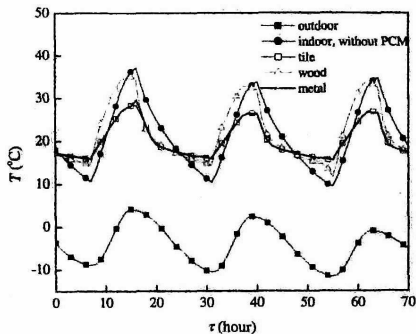


Figure 8: Indoor air temperature variation for different floor materials

B. Under-floor electric space-heating system with shape-stabilized PCM

The under-floor electric space-heating system with shape-stabilized PCM developed by us is shown in Fig.9.

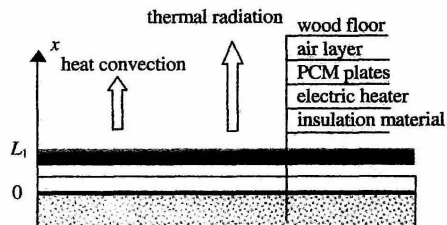


Figure 9: Schematic of under-floor electric heating system with shape-stabilized PCM plates

(1) Simulation model

In order to investigate: (1) the influences of various factors on the thermal performance of the system; (2) the feasibility and limitation of applying such system in different Chinese climate regions, a simulation model for under-floor electric space-heating system with shape-stabilized PCM was developed by us^[15].

(2) Model validation experiments

In order to investigate the thermal performance of the under-floor electric heating system with the shape-stabilized PCM plates, an experimental house with this system was set up in Tsinghua University, Beijing, China. The experimental house was equipped with the under-floor electric heating system including shape-stabilized PCM plates. The dimensions of the experimental house were 3m (depth) $\times$ 2m (width) $\times$ 2m (height). The under-floor heating system included 120-mm-thick polystyrene insulation, electric heaters, 15-mm-thick PCM, some wooden supporters,

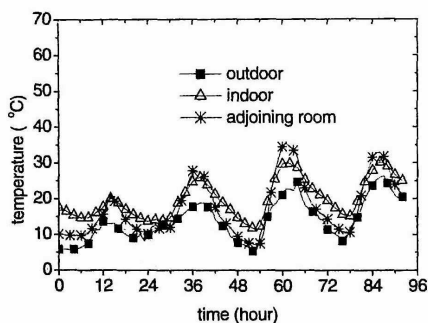
10-mm-thick air layer and 8-mm-thick wood floor. Fig.10 shows the photos of the house and the electric heating system. The thermal physical properties of the shape-stabilized PCM were measured and presented in Table 3.



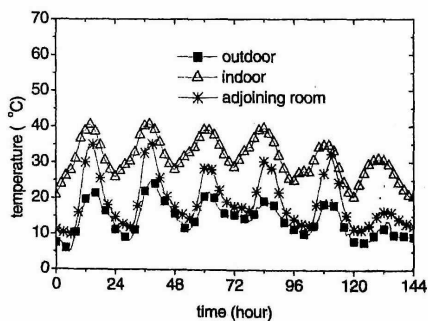
Figure 10: Photos of the house (a) the experimental house (b) the electric heating system

Table 3 Thermophysical properties of the shape-stabilized PCM

ρ (kg m ⁻³)	c_p (kJ kg ⁻¹ °C ⁻¹)	H_m (kJ/kg)	k (W m ⁻¹ °C ⁻¹)
850	2.0	150	0.15



(a)



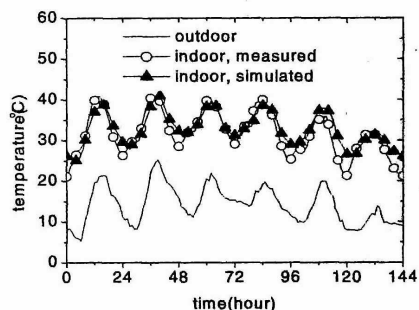
(b)

Figure 11: Measured air temperatures without and with night electric heating (adjoining means adjoining room without any space heating)

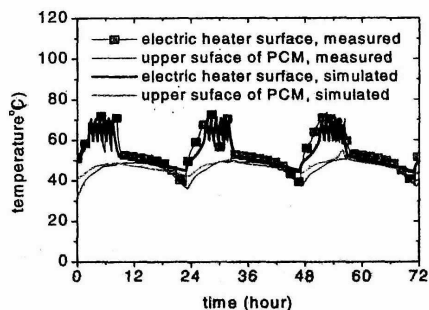
The experiments were carried out in April of 2003. The inner heat source was about 150W when all the apparatus were working. The apparatus worked for six days with night electric heating, and then for four days without electric heating. During the heating days, the heaters stopped working when their temperatures were higher than 70°C and operated again when they were below 55°C in the heating period (from 23:00 to 8:00 next day). Fig.11 shows the measured air temperatures with and without night electric heating.

The heating time in Beijing is from November 15th to March 15th. The average temperature during these days is about -1.3°C. However, the experiments were carried out in April, and the average temperature during the experimental days was 13.6 °C. Therefore, the measured indoor temperatures were high because of the high outdoor temperature in April, and the indoor temperature swing was large due to the small thermal capacitance of the prototype house.

Fig.12 shows the measured and simulated results of the indoor and PCM surface temperatures. It is seen that the agreement is satisfactory, which validates our model.



(a)



(b)

Figure 12: Comparison of the simulated and the measured results of the experimental house (a) Indoor temperature with night heating (b) PCM surface temperatures with night heating

(3) Results and discussion

The effects of applying such systems in other buildings or in other climates are different from the experiments. In order to study the influences of various factors on the thermal performance of such systems, an ordinary room is applied for simulation.

The dimensions of the simulated room are 5m (depth)×5m (width)×3m (height). It has a 370-mm-thick brick exterior wall facing south and three 180-mm-thick brick interior walls. The under-floor electric heating system consisted of 120-mm-thick polystyrene insulation, electric heaters, 15-mm-thick PCM, some wooden supporters, 10-mm-thick air layer and 8-mm-thick wood floor. A 1.5m×2.0m double-glazed window is fixed in the exterior wall. The ACH is assumed to be 1.0h^{-1} .

Fig.13 shows the simulated indoor temperature and the floor temperature of this room. The averaged indoor air temperature and the temperature difference between day and night are both acceptable. The average simulated heat load for this room is 29 (kWh)/day from January 1st to 10th and about 16.5 (kWh)/day electric heating energy is transferred from peak period to off-peak period.

In order to design suitable electric heating systems with the shape-stabilized PCM plates in different conditions, the influence of some factors of the electric heating system is investigated.

The influencing factors are melting temperature, heat of fusion, thermal conductivity k_p and thickness L_p for the PCM plates, thickness L_f for the wood floor, thickness for the air layer thickness L_a . The indoor air temperature of the simulated room was calculated when one of these factors varied while the others kept

constant.

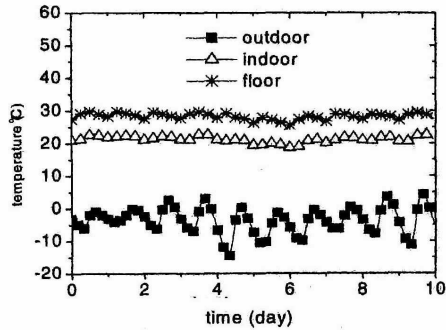


Figure 13: Indoor and floor temperatures of the simulated ordinary room during January 1st to 10th

The effects of various factors were investigated by simulation. As seen from Fig.14, t_m is an important factor of influencing the indoor air temperature; The air thickness L_a cannot be ignored because it is the main thermal resistance through the floor; H_m and L_p should be large to store enough thermal energy; the effects of other factors can be ignored. Therefore, after the quantity of PCM plates is determined corresponding to the heat load, the system can be designed by choosing proper t_m and L_a in different conditions.

The simulated results indicate that this heating system can perform well in ordinary buildings and that

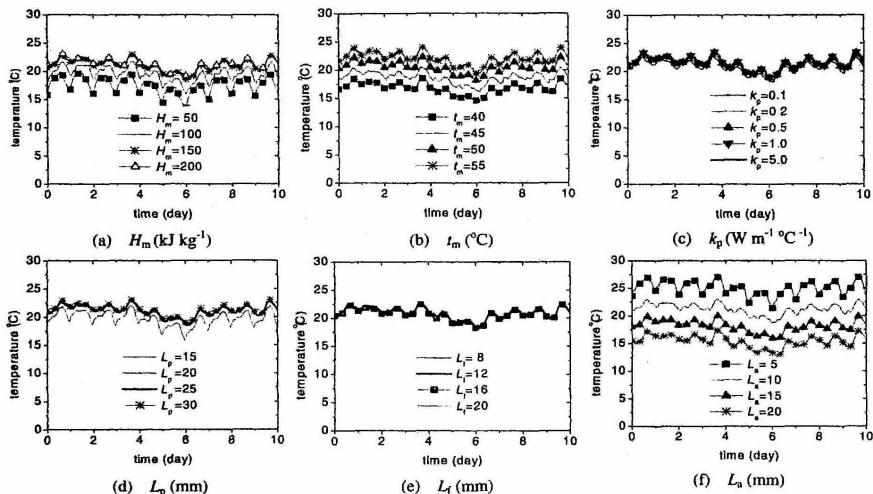


Figure 14: Effects of various factors to the indoor temperature during January 1st to 10th (Change them separately while the other factors kept constant)

it can be used in different conditions as long as the phase transition temperature and the thickness of air layer are properly chosen. The numerical model and the discussion are helpful to calculate and design available electric heating system with the shape-stabilized PCM plates.

6. CONCLUSIONS

The following conclusions are obtained: (1) The applications of the novel PCM we put forward are of promising perspectives in different climate regions; (2) By using different paraffin, the melting temperature of shape-stabilized PCM can be adjusted; (3) The heat of fusion of the shape-stabilized PCM building component is in the range of 62-138 kJ/kg; (4) For PCM floor or wallboard to absorb solar energy to narrow the temperature swing in a day in winter, the suitable melting temperature of PCM should be a little higher than the average indoor air temperature of the room without PCM for the period of sunshine; (5) For the electric under-floor space heating system, the optimal melting temperature can be determined by simulation; (6) PCM layer used in the aforementioned application should not be thicker than 2 cm; (7) For given conditions, the numerical model developed by us can provide the prediction and optimal design for applications of shape-stabilized PCM in buildings.

7. ACKNOWLEDGEMENTS

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REFERENCES

- [1] Zhang Yinping, M. Groll and D. Steiner, Experimental investigation and modelling of a new kind of latent heat storage system-Indirect contact Galisol system, *Heat Transfer-Asian Research*, 28(2), 1999, pp.115-128.
- [2] D. Feldman, M.M. Shapiro, D. Banu, Organic phase change materials for thermal energy storage, *Solar Energy Materials*, Vol. 13, 1986, pp. 1-10.
- [3] H Inaba, P Tu. Evaluation of thermophysical characteristics on shape-stabilized paraffin as a solid-liquid phase change material. *Heat and Mass Transfer*, 32(4), 1997, pp. 307-312.
- [4] YE Hong, GE Xinshi. Preparation of polyethylene-paraffin compound as a form-stable solid-liquid phase change material.

- Solar Energy Materials & Solar Cells*, 64(1), 2000, pp. 3744.
- [5] XIAO Min, FENG Bo, GONG Kecheng. Preparation and performance of shape-stabilized phase change thermal storage materials with high thermal conductivity. *Energy Conversion & Management*, 43(1), 2002, pp. 103-108.
- [6] XIAO Min, FENG Bo, GONG Kecheng. Thermal performance of a high conductive shape-stabilized thermal storage material, *Solar Energy Materials & Solar Cells*, 69(3), 2001, pp. 293-296.
- [7] Xavier Py, Pegis Olives, Sylvain Mauran. Paraffin/porous-graphite-matrix composite as a high and constant power thermal storage material. *Heat and Mass transfer*, 44(14), 2001, pp. 2727-2737.
- [8] Qin Penghua, Yang Rui, Zhang Yinping, et al., Thermal performance of shape-stabilized phase-change materials, *J. of Tsinghua Univ. (Sci. & Tech.)*, 43(6), 2003, pp.833-835.
- [9] Athienitis A.K., Chen T.Y. Experimental and theoretical investigation of floor heating with thermal storage. *ASHRAE Trans*, 99 (1), 1993, pp. 1049-1057.
- [10] Dale J.D., Ackerman M.Y. A comparison of radiant floor and forced air heating. *Proceeding of 15th Annual SESCO Conference*, 1989, pp. 15-18.
- [11] Braun J. Reducing energy costs and peak electrical demand through optimal control of building thermal storage. *ASHRAE Transactions*, 96 (2), 1990; pp. 876-888.
- [12] Xu Xu, Yinping Zhang, Kunping Lin, Hongfa Di, Rui Yang, Model and simulation on thermal performance of shape-stabilized phase change material floor, *International Solar Energy Conference*, Portland, OR, United States, 2004, pp.23-35.
- [13] Xu Xu, Hongfa Di, Kunping Lin, Yinping Zhang, Rui Yang, Experimental research on thermal performance of shape-stabilized phase change material floor, *International Solar Energy Conference*, Portland, OR, United States, 2004, pp.37-47.
- [14] Sherman M.H., Tracer-gas techniques for measuring ventilation in a single zone, *Building and Environment*, 25, 1990, pp. 365-374.
- [15] Kunping Lin, Yinping Zhang, Xu Xu, Hongfa Di, Rui Yang, Modelling and simulation of under-floor electric heating system with shape-stabilized PCM plates, *Building and Environment*. 39(12), 2004, pp. 1427-1434.