Energy & Buildings 179 (2018) 301–310

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

An experimental study on applying PCMs to disaster-relief prefabricated temporary houses for improving internal thermal environment in summer

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ARTICLE INFO

Article history:
Received 8 May 2018
Revised 12 August 2018
Accepted 19 September 2018
Available online 26 September 2018

Keywords:
Disaster-relief
Prefabricated temporary houses
Phase change materials
Thermal environment
Summer
Experiments

ABSTRACT

During disaster relief reconstructions, prefabricated temporary houses (PTHs) have been extensively used for resettling disaster victims. However, due to the nature of disaster relief, PTHs are normally light-weighted, without an electrical thermal environmental control systems installed. Hence, the thermal environments inside these PTHs can become intolerably hot in summer. Therefore, simple and low cost measures should be applied to disaster-relief PTHs for improving their indoor thermal environments. In this paper, an experimental study on applying PCMs to disaster-relief PTHs is reported. Two different designs of applying PCMs were examined. In Design 1, PCMs were fixed to the internal surfaces of a model PTH and the related experimental results demonstrated that both indoor air temperature and internal surface temperature of the model PTH can be reduced at daytime. However, in Design 2, a movable PCM based energy storage system (PESS) was used and the related experimental results suggested the use of the mobile PESS with a total charge of 148.8 kg PCM helped reduce the average indoor air temperature by 3.2–3.6 °C. The experimental results from both Designs suggested that, due to the nature of disaster relief and since outdoor air at a lower temperature may be the only cooling energy source for charging the PCM, a movable PESS system was preferred, so that it can be moved to outdoor at nighttime for being charged with more cooling energy using lower temperature outdoor air not adversely increasing the air temperature inside PTHs.

1. Introduction

Prefabricated temporary houses are massively used in disaster relief reconstructions due to the advantages of convenient transport, easy installation and short construction period [1]. For example, after the 2008 Wenchuan earthquake in China, more than 21 million victims were resettled in PTHs during the post-disaster transitional period of up to 36 months, as shown in Fig. 1. In most cases, such fast-installed prefabricated temporary houses were the only choice for disaster victims during a post-disaster transitional period, which may last for several months to several years. On the other hand, due to fast urbanization in China, 1.5 billion square meters of new buildings are being added to existing building stocks every year [2]. Consequently, there is a large need to use PTHs as temporary site offices, and hence up to 15 million square meters of PTHs are used in construction industry annually. However, given their temporary nature, no indoor thermal environmental control systems are usually installed and therefore, the indoor thermal environment inside PTHs is cold in winter and hot if not intolerable in summer [3]. The long-term severity in indoor thermal environment may result in physical and mental illness of PTHs' occupants, especially those disaster victims [4]. Therefore, improving the indoor thermal comfort for occupants in PTHs using simple and low cost measures, such as passive designs [5], is urgently needed.

On the other hand, for the purpose of improving indoor thermal environment in conventional buildings, different technologies and building materials have been used, such as aerogel, gas filled panels, closed cell foams, vacuum insulation panels and phase change

Abbreviations: PCMs, phase change materials; PTHs, prefabricated temporary houses; MHs, model houses; PESS, phase change material energy storage system.

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https://doi.org/10.1016/j.enbuild.2018.09.028

Nomenclature

T_i	the air temperature inside the PTH °C
T_o	the outdoor air temperature °C
TR_3'	the internal surface temperature of the west wall for the reference MH °C
TP_3'	the internal surface temperature of the west wall for the PCM based MH °C
TR_5'	the internal surface temperature of the roof for the reference MH °C
TP_5'	the internal surface temperature of the roof for the PCM based MH °C
TR_6	the air temperature inside the reference MH °C
TP_6	the air temperature inside the PCM based MH °C
TD_{ia}	the temperature difference between the air temperatures inside the PTHs and the occupant's tolerant temperature °C
TD_{ia_r}	the temperature difference in the reference MH °C
TD_{ia_p}	the temperature difference in the PCM based MH °C
TD_{ia_f} '	the temperature difference in the full-scale PTH with PESS °C
TD_{ia_f}	the temperature difference in the full-scale PTH without PESS °C

Fig. 1. Prefabricated temporary houses intensively used in disaster relief in the 2008 Wenchuan earthquake in China.

materials (PCMs) [6,7]. Amongst these, PCMs have the characteristics of high latent heat capacity and small temperature change during a phase change process, thus making possible the application of PCMs to controlling indoor thermal environment in buildings [8–15]. The main methods of incorporating PCMs into buildings include (i) material modification, (ii) constructional composite and (iii) independent PCMs energy storage systems in buildings. Cabeza et al. [16] developed a kind of innovative concrete, which enabled the use PCMs as part of building structure, for good structural strength as well as indoor comfort improvement. The study result showed that the buildings using the innovation concrete can provide their occupants with a better indoor thermal environment than those using conventional concrete. Lee et al. experimentally investigated the thermal performance of PCMs incorporated panel [17]. Castell et al. [18] experimentally compared the indoor thermal environment in different passive houses in the Mediterranean regions. The comparisons were based on using different bricks, insulation materials and phase change materials. In addition, the actual energy consumption and reduced CO_2 emissions were also studied.

Current PCM applications to conventional buildings were mainly for improving energy use efficiency or reducing building energy consumption. These included: (i) Storage of solar energy with a PCM based energy storage system, and using the stored energy in cold winter to reduce the energy consumption for space heating; (ii) Helping reduce indoor air temperature fluctuation and improve indoor comfort level; (iii) Reducing or delaying the peak value of energy consumption. Lin et al. [19] provided solutions to thermal performance improvements for residential buildings through applying PCMs and using solar photovoltaic thermal collectors. A series on-site tests were carried out to investigate the arrangement of different PCMs and the selection of insulation materials, etc. Lee et al. [20] studied mitigating the energy demand in coastal California during transitional climates by using phase change frame walls.

Although PCMs have been widely applied to conventional buildings for reducing energy consumption and demand, and for improving indoor thermal comfort level, they were rarely applied to light-weight disaster-relief PTHs. This may be due to the temporary nature of PTHs since they were not expected for long term use. However, as the actual use of PTHs may no longer be temporary, which was particularly true in the case of mega-scale disaster relief such as the 2008 Wenchuan earthquake, it became highly necessary to explore the use of PCMs in PTHs for improving their indoor thermal environment, for the well-beings of disaster victims. To this end, an experimental study on applying PCMs to disaster relief PTHs for improving their internal thermal environments in summer has been carried out and the study results are presented in this paper. Two different designs of applying PCMs to PTHs were studied, one model house based and the other full-scale PTH based. In this paper, firstly, the experimental setups for the two designs are presented. This is followed by reporting the experimental results for the two designs. Thirdly, discussions on the energy sources for charging of PCMs, the comparison between the experimental results of the two designs, and the economics of applying PCMs to PTHs are presented. Finally, a conclusion is given.

2. Experimental setups for the two designs

In the experimental study reported in this paper, the two different designs, named as Design 1 and Design 2 respectively, were examined. In Design 1, two different model houses (MHs) were used and in Design 2, a full-scale experimental PTH used. Design 2 was implemented following the experimental outcomes of Design 1 and therefore the studies with the two designs were not carried out at the same time. The experimental setups for the two designs are detailed in this section.

2.1. Design 1

Two model PTHs, a reference model house (MH) and a PCM based MH were purposely built. Both were the scaled down models of a full-scale PTH, and of identical dimensions of 1.0 m × 0.8 m × 1.3 m. Both houses used light-weight prefabricated insulation panels for their envelopes. However, for the PCM based MH, a PCM layer of 20 mm-thick was added to the internal surfaces of the envelopes, as shown in Fig. 2.

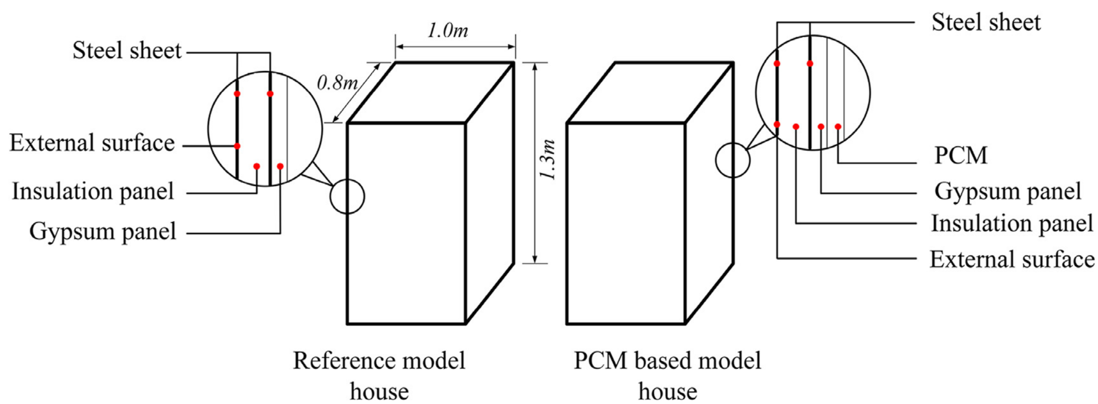

Fig. 2. Details of the two experimental MHs for Design 1.

Table 1
Materials of building envelope used in the two MHs.

Building envelope	Reference MH	PCM based MH
Floor	Steel panel	Steel panel
	EPS insulation panel	EPS insulation panel
Roof and walls	Steel panel	Steel panel
	EPS insulation panel	EPS insulation panel
	Gypsum panel	Gypsum panel
		Phase change material

Table 2
Physical and thermal properties of the materials used in the two MHs.

Materials	Thickness (mm)	Thermal conductivity (W/m·K)	Density (kg/m^3)	Specific heat (J/kg·K)
Steel	0.5	45.28	8000	460
EPS	75	0.035	20	1100
Gypsum	8	0.18	580	870
PCM	20	0.25–0.5	1300	1780

The details of envelope materials, and the physical and thermal properties of these materials are given in Table 1 and Table 2, respectively. In addition, there were no windows or doors in the two MHs.

The two MHs were placed on the flat roof of a four-story building in the campus of Sichuan University, Chengdu, China. To ensure an accurate comparison between the thermal environments inside the two MHs, they were placed side by side, with a distance of only 1.2 m in between.

To measure and compare the thermal performances inside the two MHs, T-type thermocouples were used, with an accuracy of ±0.5 °C. All T-type thermocouples were calibrated before they were used in the experiments, and were connected to a data logger where all the measured temperatures were recorded at an interval of 5 min.

The arrangement of locating thermocouples for the two MHs is shown in Fig. 3, and their details are given in Table 3. All the thermocouples for measuring surface temperatures were located at the center of each of the surfaces, and those for measuring air temperatures inside the two MHs at the center of the two MHs.

2.2. Design 2

The experimental results from the study with Design 1, to be reported in Section 3, suggested that the use of PCM in a PTH on a permanent basis was only good for improving indoor thermal comfort at daytime, but counter-productive at nighttime. It was therefore considered necessary to apply PCM to PTHs on a moveable basis. However, the two MHs were too small to install a mobile PESS and therefore Design 2 was implemented with a full scaled PTH.

Table 3
Temperature measuring locations for the two MHs.

Locations	Reference MH	PCM based MH
External surface of east wall	TR_1	TP_1
External surface of south wall	TR_2	TP_2
External surface of west wall	TR_3	TP_3
External surface of north wall	TR_4	TP_4
Internal surface of east wall	TR_1'	TP_1'
Internal surface of south wall	TR_2'	TP_2'
Internal surface of west wall	TR_3'	TP_3'
Internal surface of north wall	TR_4'	TP_4'
External surface of roof	TR_5	TP_5
Internal surface of roof	TR_5'	TP_5'
Indoor air	TR_6	TP_6
Internal surface of floor	TR_7'	TP_7'
External surface of floor	TR_7	TP_7

Table 4
Materials of building envelope used in the full-scale experimental PTH.

Building envelope	Materials
Roof and external wall	Steel
	EPS
Floor	Wood

Table 5
Physical and thermal properties of the materials used in the full-scale experimental PTH.

Materials	Thickness (mm)	Thermal conductivity (W/m•K)	Density (kg/m^3)	Specific heat (J/kg•K)
Steel	0.5	45.28	8000	460
EPS	75	0.035	20	1100
Wood	13	0.15	521	1630

In Design 2, a full-scale experimental PTH, having a dimension of 5.6 m × 3.8 m × 2.7 m, with two 1.7 m × 0.9 m windows and one 2.0 m × 0.8 m door was used, as shown in Fig. 4. The full-scale PTH was made of light-weight prefabricated insulation panels and wood. The details of envelope materials, and the physical and thermal properties of these materials are given in Table 4 and Table 5, respectively. This full-scale experimental PTH represented those typical conventional PTHs in the current Chinese market, in terms of both dimensions and envelope materials.

The full-scale experimental PTH was also placed on the flat roof of the four-story building in the campus of Sichuan University, where the two MHs were previously placed. The flat roof was surrounded by a 1.5m-high parapet, and there was a 7.5m-high elevator shaft 2 m away from the south wall of the full-scale PTH.

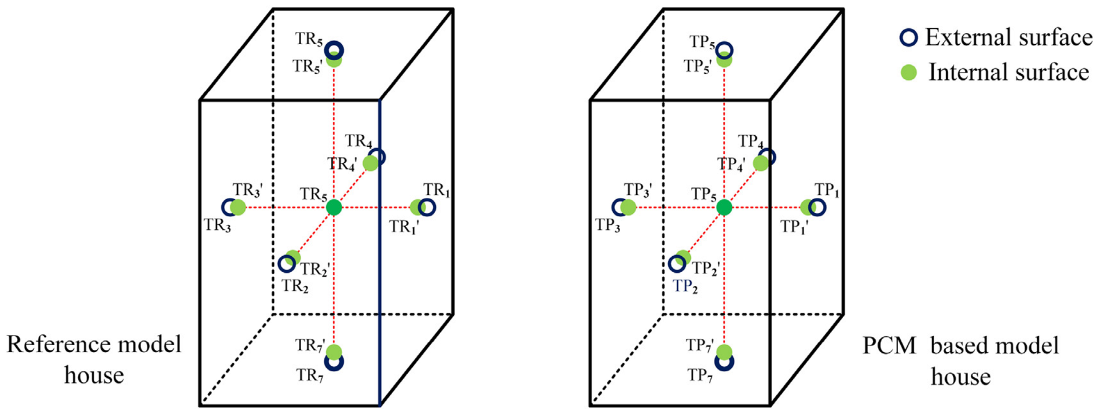

Fig. 3. The locations of T-type thermocouples in the two MHs.

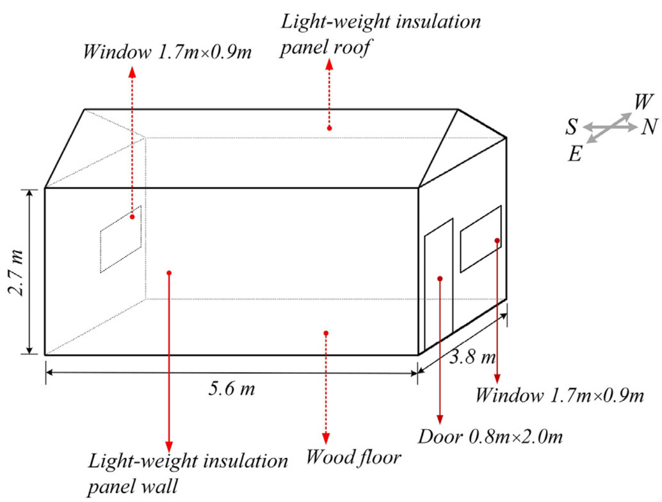

Fig. 4. 3D-Illustration of the full-scale experimental PTH.

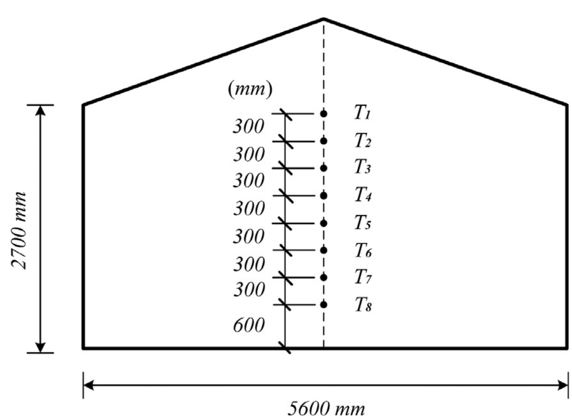

Fig. 5. The locations of T-type thermocouples inside the full-scale experimental PTH.

Inside the full-scale PTH, eight number of thermocouples were placed and their locations are shown in Fig. 5. These eight thermocouples were located at the center of the full-scale PTH, with a distance of 300 mm between any two of them. The indoor air temperature (T_i) inside the full-scale experimental PTH was obtained by averaging the readings from the eight thermocouples. In addition, a thermocouple was also used to measure the outdoor air temperature (T_o).

Table 6
Physical and thermal properties of PCMs in the PESS.

Physical and thermal properties	Values
Basse material	Inorganic salts
Phase change temperature	18–26 °C
Operating temperature	0–60 °C
Latent heat	216 kJ/kg
Specific heat capacity	1785 J/(kg•K)
Thermal conductivity (solid)	0.5 W/(m•K)
Thermal conductivity (liquid)	0.25 W/(m•K)
Density at (16–28°C)	1300 kg/m^3
Total enthalpy at 16–28°C (heating)	50 kWh/m^3
Total enthalpy at 16–28°C (cooling)	58 kWh/m^3
Encapsulation material	Aluminum composite membrane
Flammable	Nonflammable
Toxicity	Non-toxic

Table 7
Details of the movable PESS.

Parameters	Values
Parameters of phase change material tube	
Weight of one PCM tube	120 g
Length of one PCM tube	175 mm
Width of one PCM tube	35 mm
Thickness of PCM tube	20 mm
Total PCM tubes in PESS	1240
Dimensions of PCMs energy storage system (PESS)	
Length of PESS	5500 mm
Height of PESS	2700 mm
Thickness of PESS	20 mm

A movable PCM energy storage system (PESS) was specially made to be placed inside the full-scale experimental PTH. It consisted of (i) a supporting steel shelf, (ii) a plastic net-shape container for holding PCM-tubes and (iii) PCMs inside tubes. The physical and thermal properties of PCMs and the details of PESS are given in Table 6 and Table 7, respectively. Totally there were 1240 tubes which were horizontally tiled onto the plastic net-shape container. Inside each tube, 120 g PCM was filled. The container was suspended on the steel shelf, with variable distances from the west wall, as shown in Fig. 6. Such a configuration for the PESS would enable the largest possible heat transfer surface area between the PCMs and indoor air. Furthermore, since the solar heat gain by the west wall would be the highest in the afternoon, the PESS was therefore placed close to the west wall, as shown in Fig. 7. In addition, since the PESS was movable, experiments can be carried out with and without the PESS placed inside the full-scale PTH for comparison purposes.

Fig. 6. The movable PESS placed inside the full-scale experimental PTH.

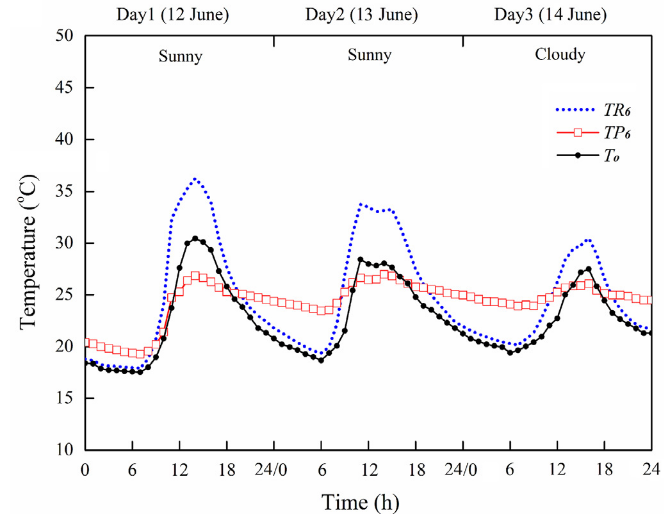

Fig. 8. Measured outdoor air temperature, air temperatures inside the reference MH and the PCM based MH.

3. Experimental results

3.1. Experimental results of Design 1

Experiments using the two MHs in Design 1 were carried out in the summer for three days starting from 12 June and ending 14 June, 2014. During the three-day periods, the measured outdoor air temperature (T_o) varied from 17 °C to 30.5 °C, and the air temperature inside the two MHs were continuously measured. Also during the experiments, the PCM based MH was not provided with any measure to charge its PCM, so that the only source for charging the PCM was the outdoor air at a lower temperature at nighttime.

In Fig. 8, the measured outdoor air temperature, the measured air temperatures inside the reference MH and the PCM based MH during the three days are profiled. As seen from Fig. 8, during the three days, the air temperature inside the reference MH (TR_6) varied from 17.5 °C to 37.5 °C. Clearly, there was a synchronization in the variation patterns of the outdoor air temperature and the air temperature inside the reference MH. However, due to the solar heat gain and no ventilation, the air temperature inside the reference MH could be much higher than outdoor air temperature. For example, when the highest outdoor air temperature was 30.5 °C on a sunny day of 12 June, the indoor air temperature was at 37.5 °C due to solar heat gain, much higher than outdoor air temperature. Hence, indoor air temperature in the reference MH was intolerably high [21] throughout most of the daytime on that day. However, on the cloudy day of 14 June, as solar radiation was weaker and outdoor air temperature lower, the highest indoor air temperature was also lower than that on Day 1, 12 June, but still higher than comfort air temperature at 30.5 °C. Furthermore, for the reference MH, its inside air temperature at nighttime on the three days was only just slightly higher than the outdoor air temperature.

However, as also seen in Fig. 8, the air temperature inside the PCM based MH (TR_6) exhibited a variation profile which was significantly different from that inside the reference MH. Firstly, the air temperature inside the PCM based MH (TP_6) was always lower than TR_6 at daytime, and even lower than T_o in the afternoon, during the three days. This was considered due to the effect of the discharged cooling energy from the PCM which was charged with cooling energy during the nighttime. Secondly, TP_6 was actually higher than both TR_6 and T_o during nighttime during the three days. This suggested that while the PCM absorbed heat at daytime to achieve a lower indoor air temperature, the absorbed heat was discharged at nighttime, leading to a higher TP_6.

For evaluating the thermal conditions inside the MHs, an index of TD_{ia} was used, which was defined as the temperature difference between occupant's tolerant temperature of 28 °C [21] and the air temperature inside an MH. Hence TD_{ia_r} was for the temperature

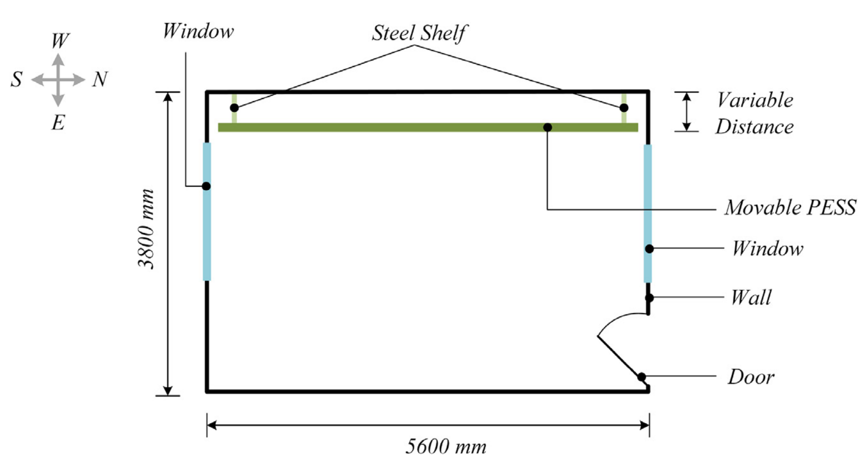

Fig. 7. Top view of the PESS placed inside the full-scale experimental PTH.

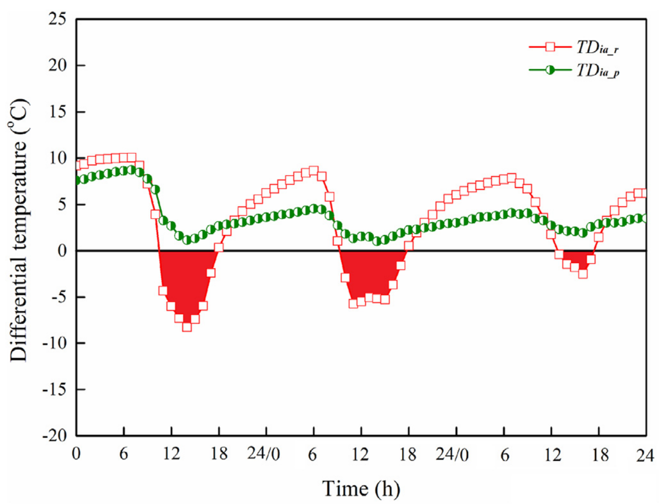

Fig. 9. The comparison between the TD_{ia} for the reference MH and the TD_{ia} for the PCM based MH.

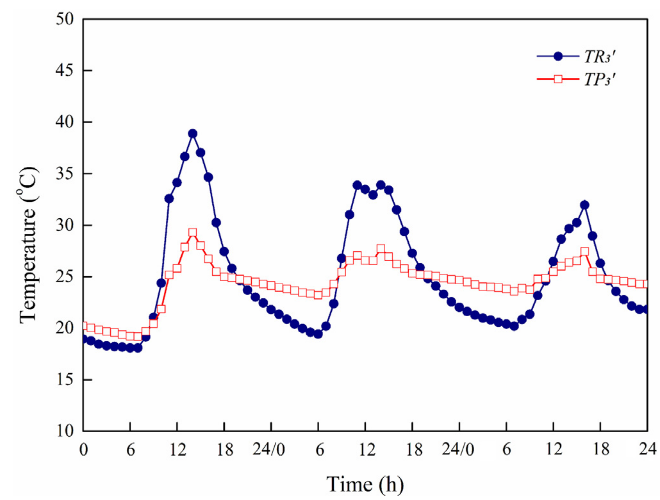

Fig. 11. Measured internal surface temperatures of the west walls of the reference MH and the PCM based MH.

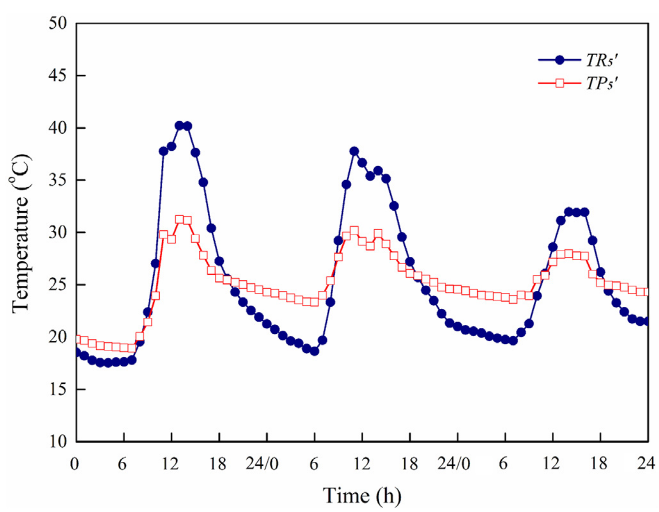

Fig. 10. Measured internal surface temperatures of the roofs of the reference MH and the PCM based MH.

difference in the reference MH, and TD_{ia_p} the temperature difference in the PCM based MH. A positive TD_{ia} suggested an acceptable indoor thermal environment, and vice versa. From Fig. 9, it can be seen that while TD_{ia_p} values remained positive throughout the three days, negative TD_{ia_r} values were present at 37% of the three days duration, mostly in the afternoons. This suggested that the use of PCM inside PTHs can help significantly improve the indoor thermal environment.

Furthermore, the temperatures of the internal surfaces of both MHs were also measured during the three days period and selected measured results for the roof and west wall are shown in Figs. 10 and 11, respectively. Fig. 10 shows the measured internal surface temperatures of roofs for both the reference MH (TR_5') and the PCM based MH (TP_5'). As seen, at the daytime of the three testing days, TP_5' was always lower than TR_5', and the difference between the two reached the largest in the afternoon during the three days. The highest of TR_5' was at 41 °C, but that of TP_5' was only at 31.5 °C on 12, June. Nonetheless, similar to the air temperature inside both MHs, TP_5' was always higher than TR_5' at nighttime, as PCM discharged the heat absorbed at daytime. Furthermore, Fig. 11 shows the measured internal surface temperatures of west walls for both the reference MH (TR_3') and the PCM based MH (TP_3'). Similar to those shown in Fig. 10, as seen in Fig. 11, TP_3' was lower than TR_3' at the daytime, and the difference between the two was increased in the afternoons of the three days. The highest value of TR_3' was 39.5 °C, but that of TP_3' was only at 29 °C on 12, June. However, at nighttime TP_3' was also always higher than TR_3'.

Therefore, from the results shown in Figs. 10 and 11, it can be seen that the use of PCMs in the PCM based MH can also help remarkably reduce its internal surface temperatures at daytime, which would consequently lead to a lower internal radiant temperature. A lower internal radiant temperature was certainly beneficial to achieving a better internal thermal environment. Nonetheless, a higher internal surface temperature at nighttime was counterproductive to a better internal thermal environment.

3.2. Experimental results of Design 2

Experiments using the full-scale PTH in the Design 2 were carried out in the summer of August and September, 2016, with two stages. In the first stage, the movable PESS was not placed inside the full-scale PTH, and in the second stage, the movable PESS was placed inside for experimental purpose. Also in the second stage, a room air conditioner was added to the full-scale experimental PTH and turned on at nighttime from 8:00 pm on the day prior to experiments to 8:00 am on the day of experiments, so as to charge the PESS for releasing the charged cooling energy at daytime for experimental purpose. During all experiments, doors and windows were closed with the windows further covered by sunshades, and there was no mechanical ventilation provided.

The measured indoor and outdoor air temperatures on the selected days for both stages are shown in Figs. 12 and 13, respectively. In Fig. 12, the measured outdoor air temperature and average indoor air temperature at Stage One, T_o and T_i, on a sunny day, and those at Stage Two, T_o' and T_i', on another sunny day, are shown. As seen, although on two different days, T_o and T_o' had similar hourly variation trends, with the starting and ending temperatures at around 26 °C and 32 °C, and the lowest and the highest temperatures at around 25 °C and 38 °C, respectively. For both days, the daily average outdoor air temperatures were at around 31 °C. On the other hand, the air temperature inside the full-scale experimental PTH in the first stage, T_i, was always higher than T_o, with the highest value of 42.5 °C at 1:00 pm. However, in the second stage, the air temperature inside the PTH from 0:00 am to 8:00 am was less than 20 °C due the operation of the air conditioner. As the air conditioner was turned off at 8:00 am, indoor air temperature, T_i, started to increase, and reached the highest at 38.1 °C,

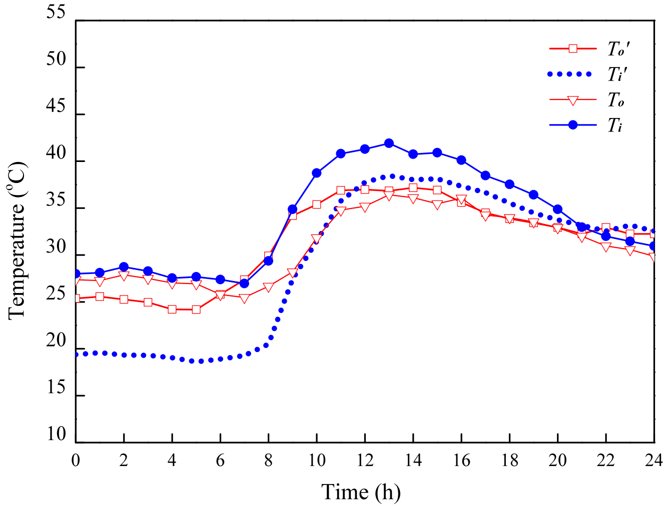

Fig. 12. Comparisons of indoor and outdoor air temperatures in selected sunny days.

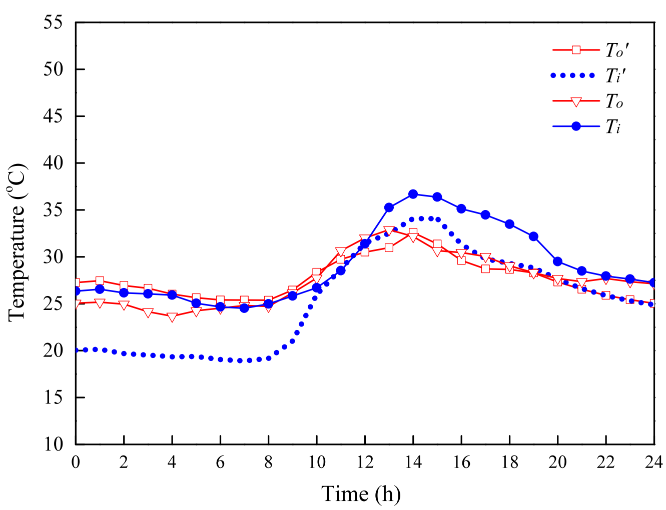

Fig. 13. Comparisons of indoor and outdoor air temperatures in selected cloudy days.

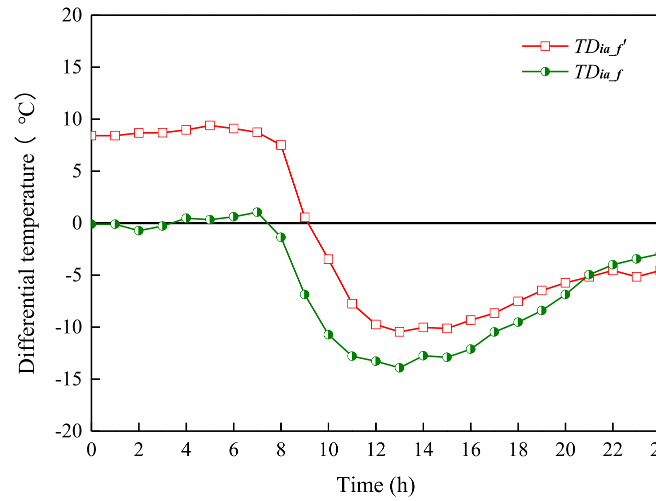

Fig. 14. The comparison between the TD_{ia} for the full-scale experimental PTH with and without PESS in the selected sunny days.

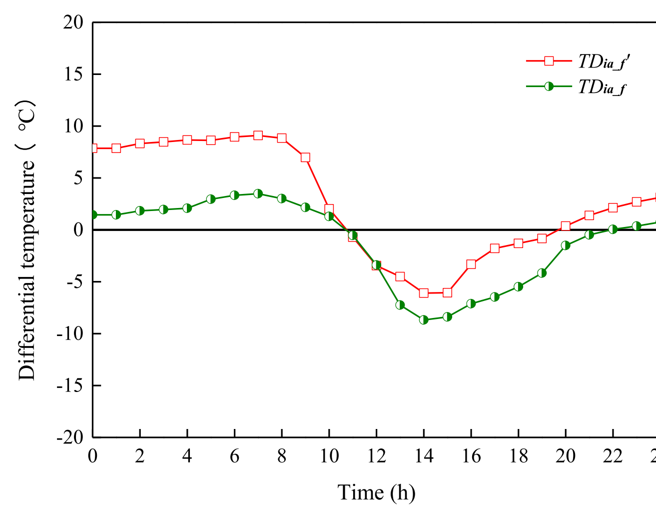

Fig. 15. The comparison between the TD_{ia} for the full-scale experimental PTH with and without PESS in the selected cloudy days.

also at around 1:00 pm. However, T_i' was consistently lower than T_i, at daytime, mainly due to the discharged cooling energy from the PESS. In addition, the average air temperature inside the full-scale experimental PTH from 10:00 am to 8:00 pm at Stage One was 3.2 °C higher than that at Stage Two. Furthermore, at 8:30 pm, T_i' started to over pass T_i, but the difference between T_i' and T_i was not as large as that in Design 1, due possibly to the difference in the amount of the cooling energy stored.

In Fig. 13, the measured T_o and T_i at Stage One on a cloudy day, and the measured T_o' and T_i' at Stage Two, also on another cloudy day, are shown. As seen, although on two different days, T_o and T_o' had similar hourly variation trends, with the starting and ending temperatures at around 26 °C and 29 °C, and the lowest and the highest temperatures at around 25 °C and 32 °C, respectively. The daily average outdoor air temperatures were at around 27.6 °C on both days. On the other hand, at Stage One, since there was no direct solar heat gain, the air temperature inside the full-scale experimental PTH, T_i, was not as high as that on a sunny day, but stayed higher than T_o from 12:00 pm onwards. At Stage Two, after the air conditioner was turned off at 8:00 am, indoor air temperature, T_i', started to increase, but unlike that in Stage One, stayed consistently lower than T_i after 12:00 pm to the end of the day. This was because the experiment was carried out on a cloudy day and the internal loads were smaller than those in Stage One. However, the cooling energy provided by the air conditioner to charge the PESS was the same on both days, so that there was an adequate amount of cooling energy to maintain a lower T_i' to the end of the experimental day. In addition, the average air temperature inside the full-scale experimental PTH from 10:00 am to 8:00 pm at Stage One was 3.6 °C higher than that at Stage Two.

Therefore, as seen from Figs. 12 and 13, the use of the movable PESS helped lower the air temperatures inside the full-scale experimental PTH at daytime on both a sunny day and a cloudy day, thus providing an improved thermal environment inside the full-scale experimental PTH in summer.

For evaluating the thermal conditions inside the full-scale PTH, similar to those for the MH based experiments reported in Design1, the index of TD_{ia} was also used. Hence TD_{ia_f} ' was for the temperature difference in the full-scale PTH with PESS, and TD_{ia_f} in the full-scale PTH without PESS. Figs. 14 and 15 show the TD_{ia} values for the full-scale PTH experiments on the selected sunny days and cloudy days, respectively. From Fig. 14, it can be seen that the total area for the negative TD_{ia_f} values was larger than that for TD_{ia_f} ' from 10:00 am to 8:00 pm in sunny days. In Fig. 15, it also can be seen that the total area for the negative of TD_{ia_f} values was also larger than that for TD_{ia_f} ' from 10:00 am to 8:00 pm in cloudy days. These suggested that the use of PCM inside full-scale PTH also helped improve the thermal environment inside the full-scale PTH.

4. Discussions

In Section 3, the experimental results for both the Designs of applying PCMs to disaster relief PTHs for improving their internal thermal environments in summer are reported. Although the results demonstrated that the use of PCM based thermal energy storage in PTHs can, to a certain extent, help improve their indoor thermal environment inside both MHs and the full-scale PTH, a number of related issues should be carefully considered, as follows.

4.1. The research approach

In this study, two different Designs for applying PCMs to PTHs were used. In Design 1, two model PTHs were used, with 2.5 kg PCMs applying to one of the model PTHs. In Design 2, a full-scale PTH was used, using 148.8 kg PCMs. Although the sizes of the PTHs and the amounts of the PCMs used in the two Designs were different, the ratio of the amount of the PCMs used in Design 1 to that in Design 2 was the same as the ratio of the space volume in Design 1 to that in Design 2. Furthermore, the studies with the two designs were not carried out at the same time, with the study for Design 1 undertaken first. The study result for Design 1 suggested that the use of PCMs could help improve the thermal comfort level in disaster-relief PTHs effectively at daytime. At nighttime, the experimental results, however, demonstrated that the air temperature inside the PCM based MH was 3 °C higher than that inside the reference MH. Hence, the design of a movable PCM based energy storage system, or Design 2, was proposed and implemented. The experimental results from the study for Design 2 demonstrated that the movable PESS may be effectively used to help eliminate the negative effect of the PCMs inside PTHs at nighttime and could also be practically applied to PTHs used for disaster relief reconstructions.

4.2. Energy sources for charging of PCM

In the current experiments with full-scale PTH in Design 2, an air conditioner was used to provide cooling energy to charge the PCM at nighttime. The air conditioner was turned on from 8:00 pm on the day prior to experiments for 12 h. Such an arrangement was purely for the purpose of the current experimental work. However, in Design 1, no additional measures of providing cooling source for charging the PCM. Hence, it becomes essential that a suitable source of cooling energy for charging the PCM should be made available. One of potential energy sources is due to the diurnal charge in outdoor air temperature. For instance, in Qinghai Province, Tibet Autonomous Region and Xinjiang Uygur Autonomous Region of western China, in summer, the outdoor air temperature difference between day and night is on average at 12 °C. For certain locations such as Yinchuan and Kashi, the days whose nighttime temperature of lower than 16 °C and daytime temperature of greater than 29 °C account for 87% of the total number of days in summer [22]. In the current study, when carrying out experiments with MHs in Design 1, there were no additional measures for providing cooling sources for charging the PCM. However, the diurnal changes in outdoor air temperature in June in Chengdu city was large, with the lowest outdoor air temperature at 17 °C, so that certain cooling energy was available for charging the PCM.

It may be however argued that in certain places with a large outdoor air temperature difference between daytime and nighttime, the use of nighttime ventilation may help improve the thermal comfort inside PTHs during nighttime and provide cooling energy to charge those permanently installed PCMs. However, the use of nighttime ventilation may actually have the following disadvantages: (a) additional fan energy consumption is required; (b) with PCM placed indoor, the amount of cooling energy charged can be less than placed outdoor since the indoor air temperature and the temperatures of internal surfaces of a PTH may be higher; (c) it is not possible to use the additional cooling energy due to sky radiation at nighttime to charge PCMs if placed indoor with nighttime ventilation. Furthermore, if the outdoor air temperature is very low, while directly using nighttime ventilation may effectively charge the PCMs placed indoor, it may also cause thermal discomfort for PTHs' occupants at nighttime.

4.3. Comparison between the two Designs

In this study, two different designs of applying PCMs were experimentally evaluated. In Design 1, a PCM layer of 20 mm thick was fixed to the internal surfaces of the PCM based MH. Since the PCM layer was at a fixed place, while it can be charged with cooling energy at nighttime, it can also be charged with heat energy at daytime, in particular in the afternoons, so that the resulted air temperatures and internal surface temperature inside the PCM based MH at nighttime during the experimental period (except the indoor air temperature on the first night) were both higher than those in the reference MH. Since PCM was fixed indoor, at a higher indoor air temperature at nighttime, it can only absorb less cooling energy to be discharged at daytime for lowering down the indoor air temperature. This may hence be seen as an inadequacy in Design 1. However, in Design 2, the PESS was designed as being movable. Therefore, it can be moved from indoor to outdoor, so that the PCM after absorbing the heat in the afternoons can release heat to a colder outdoor air at nighttime. Consequently, both a lower indoor air temperature may be resulted in and more cooling energy can be charged to the PCM at a lower outdoor air temperature. Hence, a movable PCM-based energy storage system design should be preferred when applying PCMs to disaster-relief PTHs for improving their indoor thermal environment in summer.

4.4. The amount of PCM used

It is obvious that the more PCM is used, the greater improvement in indoor thermal environment can be made. In the current experiments using the full-scale PTH in Design 2, a total of 148.8 kg PCM was used and helped reduce averaged daytime indoor air temperature from 10:00 am to 8:00 pm from 39.3 °C at Stage One to 36.1 °C at Stage Two on sunny days, and from 33.7 °C to 30.1 °C on cloudy days. In order to achieve an experimental improvement in the thermal environment inside PTHs, proper sizing of the PESS should be carefully carried out, taking into account a number of factors such as locations and climates, thermal loads in PTHs, thermal properties of PCM, etc.

On the other hand, the amount of PCM used would affect the cost of applying PESS in PTHs. In the current experiments using the full-scale PTH, the total cost of the movable PESS with 148.8 kg PCMs was at RMB 1200, which was 11.6% of the cost for a full-scale PTH. However, the cost of actual application can be remarkably lower if PESSs are massively produced. Furthermore, the cost of a PESS appears comparable to that of an electrical driven basic room air conditioner. However, using room air conditioners is not possible for disaster-relief PTHs, as usually there will only be limited essential power supply for disaster relief over a long period of time.

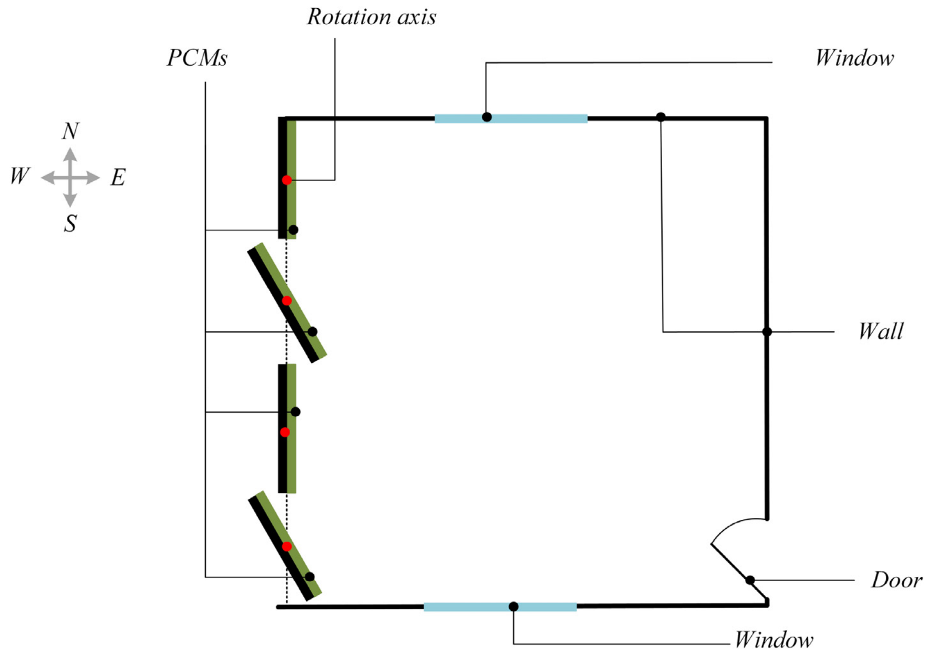

Fig. 16. A proposed practical design of a movable PESS in future PTHs.

4.5. A proposed practical design of a PESS for future PTHs

From the experimental investigations, it was obvious that when applying the movable PESS to PTHs, the use of the movable PESS could improve the thermal environment inside the PTHs. However, the practical design of a movable PESS in a future disaster relief temporary house will be certainly a key issue for its future wide application. One of practical designs can be that PCMs may be attached to the envelopes of a PTH during its prefabrication. The envelopes with PCMs attached may be divided into several pieces and each piece can be rotated along its axis, thus providing a convenient way to move PCMs from indoor to outdoor, as shown schematically in Fig. 16. Such a movable PESS can be massively produced and conveniently used.

5. Conclusions

This paper reports an experimental study on applying PCM to disaster-relief PTHs for improving their internal thermal environment inside in summer. Two different designs of applying PCMs to PTHs were examined. In Design 1, PCM was fixed to the internal surfaces of the PCM based MH, but a movable PESS was used in Design 2. The experimental results for Design 1 demonstrated that in summer, the use of PCM helped reduce not only indoor air temperature, but also internal surface temperature at daytime when solar radiation was present. In Design 2, the use of the mobile PESS with a total charge of 148.8 kg PCM helped reduce average daytime indoor air temperature from 10:00 am to 8:00 pm by 3.2 °C on sunny experimental days and by 3.6 °C on cloudy experimental days. The experimental results from both Designs demonstrated that the use of PCM can help improve thermal environment inside PTHs at daytime in summer. However, the comparison between the two Designs suggested that, since outdoor air at a lower temperature at nighttime may be the only cooling energy source for charging the PCM, using a movable PCM based energy storage system was preferred. This was because a movable system can be moved to outdoor at nighttime to absorb more cooling energy from outdoor air at a lower temperature, but not to lead to a relatively higher indoor air temperature.

However, the use of PCM in PTH is subject to the availability of cooling energy source for charging the PCM. Given the nature of disaster relief, it is not practical to use electrical-based means to charge the PCM. However, supported by the result of the comparison of the two Designs, especially during the nighttime, the cooling energy of outdoor environment due to diurnal charge of outdoor air temperature may potentially be used for charging the PCM at nighttime. Furthermore, to achieve a suitable balance between the cost of a PESS and the level of thermal environment improvement inside a disaster-relief PTH, the PESS must be properly sized. Additionally, the practical design of the movable PCMs in a future disaster relief PTHs should also be considered for the future wide application of the PTHs.

Conflict of interest statement

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the manuscript submitted.

Acknowledgements

The authors gratefully acknowledge the financial supports from the Hong Kong Polytechnic University, Hong Kong Jockey Club (No. 2016YFC0700400), and Sichuan University (No. 51478280). In addition, the support by the National Key Research and Development Program of China (No. 2016YFC0700400) and the National Natural Science Foundation of China (No. 51478280) are acknowledged.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbuild.2018.09.028.

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