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Experimental research on a novel energy efficiency roof coupled with PCM and cool materials

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ABSTRACT

Phase change materials (PCM) and cool materials used in construction field cannot only effectively reduce buildings energy consumption, but also improve indoor thermal comfort and mitigate the urban heat island (UHI) condition. A novel energy efficiency roof coupled with PCM and cool materials has been conducted a field test in Tianjin of China. A kind of PCM-eutectic mixture was prepared, which was encapsulated in the polyethylene of raised temperature resistance (PE-RT) pipe, for using in building roofs. Thermal performances such as the roof surface temperatures and heat fluxes have been studied. The results indicated that, compared with reference rooms, the novel energy efficiency roof has shown good effect on decreasing the peaks of temperature and heat flux, which means that the influence of the outdoor circumstance on indoor environment has been weakened. In conclusion, it has been proved that the novel roof has good thermal insulation effect and energy efficiency potential.

1. Introduction and research background

Building energy consumption accounts for about 27% of society final energy consumption in China [1]. However, the proportion of energy consumption in using stage has been rise up from 10% in 1978 to 27% in 2003 and still remains growth state [2] and the Chinese government has taken many measures to deal with this situation [3]. Research has forecast that building energy consumption will be up to 1.089 billion ton standard coal in China [4] and building envelope parts consume about 57–77% of all the building energy consumption [5]. Compared with developed countries, the thermal performance of the building envelope and its energy saving properties were lower. Energy consumption per unit area of the exterior wall, the roof and the window in China are 2–5 times higher than that in developed countries, meanwhile, the energy saving potential of the building envelope can reach to 50–80% [4].

Solar radiation is the most important direct reason for the air conditioning energy consumption, which accounts for almost 40% electrical peak load in some large cities [6]. For single story building in summer, cooling load through the roof has the ratio of 36.7% in the whole building envelope cooling load [7], while for the multi-story building can reach to 8–10% [8]. Besides, research showed that air conditioning energy consumption can drop about 10% when the inner temperature decreased 1 °C [9]. Thus to enhance the thermal insulation of the roof cannot only improve the indoor thermal comfort, but also reduce the air conditioning load.

Phase change thermal storage technology can absorb or release the large amount latent heat during the melting or freezing process of PCM with a constant or near constant temperature, which makes the phase change technology being widely potential and has attracted lots of researchers [10,11]. Proper PCM selection and reliable encapsulation are important parts in this technology using, which also have achieved a great progress in recent years. PCM can be divided into two major categories of organic and inorganic depending on the different chemical properties [12] and the encapsulation method includes macro-encapsulation, microcapsules and other different techniques [13].

Many researchers have conducted numbers of experimental and simulation research on the effect of PCM used in the building envelope construction such as exterior wall, roof and floor Navarro et al. have studied several kinds of experiment systems using concrete core slab which contained PCM and the results showed that all of the systems can meet the charge and discharge cooling storage requirements well [14]. Bourdeau has studied two types passive thermal storage walls and came up to a conclusion that a phase change wall of 8.1 cm shows superior thermal performance than a 40 cm brick wall [15]. Peippo et al. have built and researched a passive solar house in USA and the results indicated that the optimal

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Nomenclature

$T_{air,out}$	The outdoor temperature (°C)
$T_{s,out}$	The outer surface temperature of the roof (°C)
Ts,in	The inner surface temperature of the roof (°C)
$T_{s,m}$	The contact surface temperature of the phase change layer and adhesive mortar layer (°C)
$q_{s,in}$	The inner surface heat flux of the roof (W/m^2)
c_p	Specific heat (J/kg K)
D	Diameter (mm)

Greek characters

δ	Thickness (mm)
ρ	Density (kg/m^3)
μ	Thermal storage coefficient (W/m^2 K)
λ	Thermal conductivity(W/m K)

phase change temperature should be higher 1–3 °C than the indoor average temperature [16]. Li et al. have simulated the effects of different roof factors on the performance of the room and found that the PCM roofs can delay peak temperature well [17]. Hashem et al. have studied the roof containing PCM and the results showed that this kind of roof can reduce the heat flux between 9% and 17.26% because of different variables in the experiment [18]. Zhou et al. has also studied the application effect of phase change plasterboard and form-stable phase change wall and found that the inner temperature fluctuation can reduce 46% and 56% respectively [19]. Kong et al. have proved that the PCM used in the inner surface of the exterior wall showed better thermal performance than that of the outer surface numerically [20]. Ayca et al. have investigated the effect of PCM used on a flat floor in Istanbul and found that a PCM thickness of 2 cm can meet the room requirements well [21].

Study on the cooling roof (CR) began in the United States in the 1980s, which mainly refers to the application of the cool materials on the roof. Because of low thermal conduction and highly efficient reflection against to the solar radiation of the CR roof, this technology cannot only improve the indoor thermal comfort and the service life of the roof, but also decrease the air conditioning load by means of reducing the temperature and heat transfer of the roof [22,23]. Also, large-scale application of this coating in cities can effectively reduce the UHI effect [24]. Similarly, Min et al. have studied the effect of a kind of shape stabilized PCM, which is produced by mixing of the PCM and cool painting, used as the roof materials and the test results indicated the good thermal performance of the materials on controlling UHI and lower air conditioning load in summer and winter [25]. Systematically, Santamouris et al. have reviewed several latest researches on advanced cool materials, including the application of cool materials on the roof and on the paving areas, integral application of the cool materials and PCM, as well as the thermochromic materials and the aging conditions, which is very instructive for researchers [26]. In another paper, Santamouris have studied research progress on the effect of reducing UHI due to reflective and green roof [27]. Pisello et al. have investigated an innovative cool roofing membrane combined with PCM. Meanwhile, the development and lab analysis about different kinds of prototyping materials have been performed by means of Differential Scanning Calorimetry (DSC) testing and other methods [28]. The energy performance of the green roofs and cool roofs has been discussed by the methods of simulation from the perspective of the UHI mitigation and energy needs of the building respectively [29]. Jo et al. have simulated the energy consumption in a building using cooling roof covered by the cool materials and the cooling roof showed observably energy-saving effect [30]. Akbari increased the cooling roof reflectivity from 0.26 to 0.72 and the results showed that the building energy consumption in summer decreased 0.5 kwh/day [31]. Guo et al. have performed field test on two identical rooms except for the heat-reflective insulation coating on one of the test room exterior wall surface. And the results indicated that the coating behaves better on reducing the temperature fluctuation of the exterior wall surface in summer [32]. Xiang et al. have reviewed the research progress of the reflective insulation coatings at home and abroad. Also, the insulation mechanism and influential factors have been discussed [33]. Tang et al. have carried out an annual simulation in Chong Qing and the results indicated that the cooling roof can increase the winter heating load while decrease the summer air conditioning load [34]. Shen et al. found that the inner surface temperature of the roof can be reduced up to 1.3–2.1 °C and the heat gain daytime 20% while the adverse effects in winter are negligible [35].

In this paper, different effects are investigated and compared when PCM and cool materials are used in the building roof. A new type eutectic mixture PCM and PE-RT pipe encapsulation method will be introduced in this study. Three different roof construction rooms, including 1#, 2# and 3#, were carried out field test to analyze the heat transfer characteristic and energy efficiency effect. Finally, the comparable analysis of those three test rooms was conducted to further study the thermal performance of 3# roof.

2. Purpose of the study

Based on the above background, this research was performed upon previous studies on PCM and cool materials used in the building envelope by analyzing the thermal performance and energy-efficiency potential of the novel roof integrated with those two techniques. To achieve this aim, three full-scale tested rooms were built in Tianjin University. Meanwhile, relevant parameters such as the temperature and the heat flux of the roof have been recorded to analyze the energy efficiency of the roof. Therefore, the main purpose of this research is to study the energy-saving effect and indoor thermal comfort of the novel roof compared with the reference roofs.

3. Experimental procedure

3.1. Cool material

The tested rooms are located in Tianjin University in China with long hot days and short cool nights in summer. Referring to the relevant national standards, the ZS-221 type coating, produced by Beijing Zhi Sheng Wei Hua Chemical Co. Ltd. was chosen in the experiment. This coating is mainly composed of the acrylic emulsion, titanium dioxide and a small amount of the nano-hollow beads and additives and the main parameters are listed in Table 1.

3.2. Preparation of the PCM

Adequate melting and solidification temperature of the PCM can be obtained by the method of pre-test on the roof. As for the selection of the PCM, the single component of higher fatty alcohols exists multiple peak points in the solidification curve and the single component of saturated fatty acids is lack of suitable phase change temperature. Based on these considerations, a new type eutectic mixture has been prepared with the two materials, which shows stable property in the case of suitable selection of the binary mixtures proportion [36] and can eliminate the drawbacks when using the single component.

In this paper, the tetradecanol (TD) and the myristate (MA), both provided by the Tianjin Guangfu Fine Chemical Research Institute will be selected to compound the PCM used in the experiment. The

Table 1
Physical of the cool material.

Parameter	Value
Operating temperature range	−30 to 90 °C
Thermal conductivityλ	0.04 W/(mK)
Solar Reflectivity	0.85
Hemispherical emissivity	0.87
Condition in container	No lumps, no cohesion, showing a uniform state after stirring
Workability	Accessible after brushing the coating twice
Coating appearance	No pinhole, sagging, coating evenly
Drying time	1 h
Performance against the alkali	No abnormality after 48 h
Waterproofness	No abnormality after 96 h
Stability at low temperature	No clots, no coagulation and separation
Performance against thermal variable	No abnormality after 5 cycles
Washability	2000 times
Tensile strength	1.0 MPa
Elongation at break	439%
Water vapor transmission rate	16.6×10^{-8} g/(m^2 s Pa)

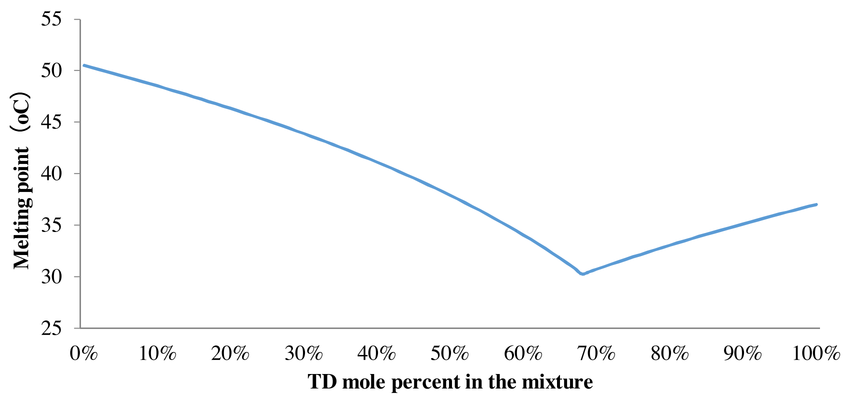

Fig. 1Melting point of different binary mixtures TD-MA proportion

Fig. 1. Melting point of different binary mixtures TD-MA proportion.

eutectic mixture PCM, TD-MA, has been successfully made with the TD (71.84 wt%) and the MA (28.16 wt%) based on the Schroeder equation [37], shown in Fig. 1 and the DSC test has been conducted for more precise proportion.

3.2.1. Thermal properties of the PCM

The thermal properties of the mixture PCM TD-MA were measured by DSC (204 F1 Phoenix by NETZSCH) with a heating rate of 1 °C/min in the interval (20 °C, 50 °C)of heating and cooling conditions, under a purified nitrogen atmosphere.

Table 2 shows the thermal performance of the TD-MA by DSC test. The latent heat reach up to 186J/g, and the melting peak temperature is 34.97 °C, which can meet the requirement of the thermal storage daytime. Also, the solidification peak temperature is 28.00 °C, which can meet the requirement of the thermal discharging at night. The melting temperature difference is 4.27 °C and the solidification temperature difference is 2.87 °C, which mean the PCM can charge and release the heat fast. In addition, the phase change process is stable and only one melting and freezing temperature can be found. To sum up, the TD-MA eutectic mixture can meet the requirements in this experiment well.

3.2.2. The encapsulation of the PCM

The encapsulation of the PCM is very important in the experiment. In this study, PE-RT pipe has been selected to package the PCM due to its good thermal performance, stability and long service life.

The PCM package unit is shown in Fig. 2. The unit was mainly composed of PE-RT pipe, a cap, an elbow and an exhaust vent hole. Both ends of the pipe were sealed with the caps, with one end reserving an exhaust vent hole. And all of the fittings are connected by the method of hot melt. Only the horizontal pipe was full of the PCM and the 10 cm vertical short pipe is used to be buffer space when the pressure in the pipe changes because of phase change process.

In order to verify whether the PE-RT pipe can be used to package the PCM, the sample unit full of PCM has been conducted per-test under outdoor natural circumstance. And there was no deformation between the melting and solidification process all the day with a small amount of gas exhausting from the hole, which indicates that the unit works well and can be used for the encapsulation.

3.3. Description of the test rooms

Three test rooms were respectively built with PCM roof (1#), the CR roof (2#), which means the roof was covered by the cool materials and the other one with PCM and coating simultaneously (the PCR roof, 3#) shown in Figs. 4–6. In addition, the specification (2 m × 2 m × 2.4 m) and orientation of those three test rooms were all the same except the roof construction, as well as no interference on each other. The PCR roof (3#) was composed of roof base layer, waterproof layer, adhesive mortar layer, phase change layer, cracking mortar layer and reflective coating layer from the inside to the outside successively. And Fig. 2 shows the arrangement of the PE-RT pipe on the roof. The main construction of the wall was perforated brick with a dimension of 240 mm × 115 mm × 90 mm. The basic construction of the roof was composed of glass-fiber cement polystyrene core, which included 12.5 mm glass-fiber cement,

Table 2
the properties of the TD-MA (71.84:28.16) mixture.

TD-MA	The start point (°C)	The end point (°C)	Temperature difference (°C)	Peak temperature (°C)	Latent heat (J/g)
Melting	31.83	36.1	4.27	34.97	183.00
Solidification	29.51	26.64	2.87	28.00	186.00

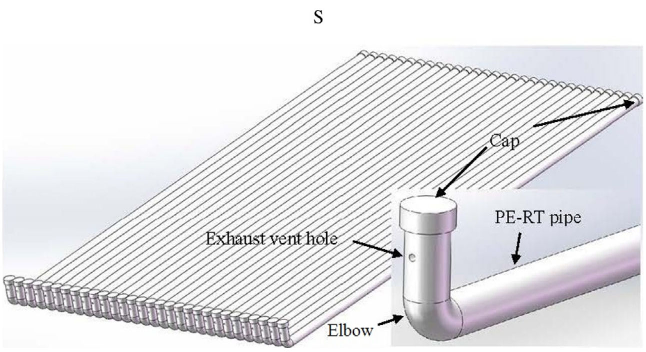

Fig. 2. The schematic diagram of the PCM storage unit.

Fig. 3. The picture of the test room.

Table 3
the thermal parameter and thickness of the room envelope.

Material type	δ	ρ	c_p	μ	λ
	mm	kg/m^3	J/(kg K)	W/(m^2 K)	W/(m K)
Crack-resistance mortar	20.00	1600.00	1050.00	10.12	0.81
Extrusion plastic board	50.00	32.00	1500.00	0.32	0.03
Adhesive mortar	10.00	1500.00	1050.00	9.44	0.76
Perforated brick	240.00	1269.00	1050.00	7.92	0.54
Plaster layer	10.00	1500.00	1050.00	10.12	0.81
Polystyrene board	90.00	200.00	1070.00	0.36	0.04
Glass-fiber cement	12.50	2500.00	920.00	7.37	0.69

90 mm polystyrene board and 12.5 mm glass-fiber cement. There was a plastic-steel door of 1800 mm × 800 mm with the glass area 0.72 m^2 in the southern wall and a window of 800 mm × 500 mm in the northern wall. Also, since the focus of the experiment was to test the roof performance, 50 mm extrusion plastic board was installed on the outer surface of the wall to weaken the influence of the wall. Fig. 3 shows the picture of the test room. The thermal parameters of the envelope are shown in Table 3.

3.4. The equipment and test points distribution of experiment

The study is intended to compare the thermal performance of those three different test rooms, i.e. 1#, 2# and 3#. Experimental time was from 0:00 on August 8th, 2014 to 0:00 on August 12, 2014 with the test interval of 1 min and the following data analysis smallest time unit is 10 min. To reduce the impact of the external factors on the indoor environment during the experiment, the doors, windows of the test rooms are kept closed.

The test content of this experiment mainly included the roof thermal performance and the indoor and outdoor climate parameters.

The roof thermal parameters and the indoor parameters mainly include each surface temperature and the heat flow of the roof.

The outdoor climate parameters composed of solar radiation intensity, the outdoor air dry bulb temperature and the relative humidity were tested and recorded.

3.4.1. Equipment of the experiment

The equipment of the experiment mainly included the thermocouples, solar thermal radiometer, data logger, temperature and humidity self-recording instrument and the heat flux meter. All of the test equipment have been calibrated in order to make sure the accuracy of the data. The Table 4 shows the parameters of the test equipment.

3.4.2. Distribution of the thermocouples

As shown in Fig. 7, the thermocouples were distributed on the inner surface of the outer wall. The thermocouples to test the inner air temperature, which was shadowed by tinfoil to avoid the environmental radiation, were arranged from the ground 0.6 m, 1.2 m, 1.8 m respectively as shown in Fig. 7. And heat flux meter was arranged on the inner surface of the roof. The measure points distribution of the experiment room construction layers are shown in Fig. 8, which indicate that five thermocouples were arranged evenly on the surface of every layers. And the A–C points representative the layers where the thermocouples were distributed.

4. Results and discussion

4.1. Comparison on 2# and 3# rooms

Fig. 9 shows the test location of the $T_{air,out}$, $T_{s,out}$, $T_{s,in}$, $T_{s,m}$,and $q_{s,in}$. Figs. 10 and 11 show the temperature variation curves (1# and 3#) with the test time. It can be found that the surrounding temperature can meet the requirement of melting and freezing for PCM well. In the dotted portion, obvious damping and delay of the $T_{s,m}$ and $T_{s,out}$ can be found, which can prove the evident effect of the phase change layer to absorb the heat from the roof surface daytime and to release at night when the outdoor temperature is low relatively. It can be drawn from the test data that, for room 1#, the maximum peak difference between the $T_{s,m}$ and $T_{s,out}$ reached up to 12.22 °C, the average peak difference 9.95 °C, the maximum time delay 320 min and the average 230 min. For room 3#, the maximum peak difference between the $T_{s,out}$ and the $T_{s,m}$ can be up to 6.03 °C, the average peak difference 4.86 °C, the maximum time delay 270 min and the average 222 min respectively. These test results illustrate fully that the phase change layer (16 mm thick) can

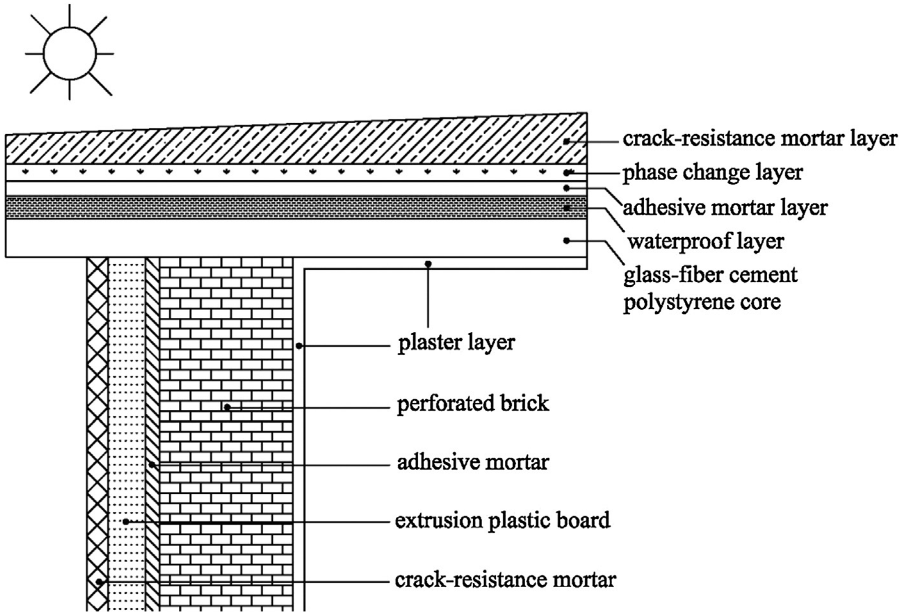

Fig. 4. The structure of the PCM roof (1#).

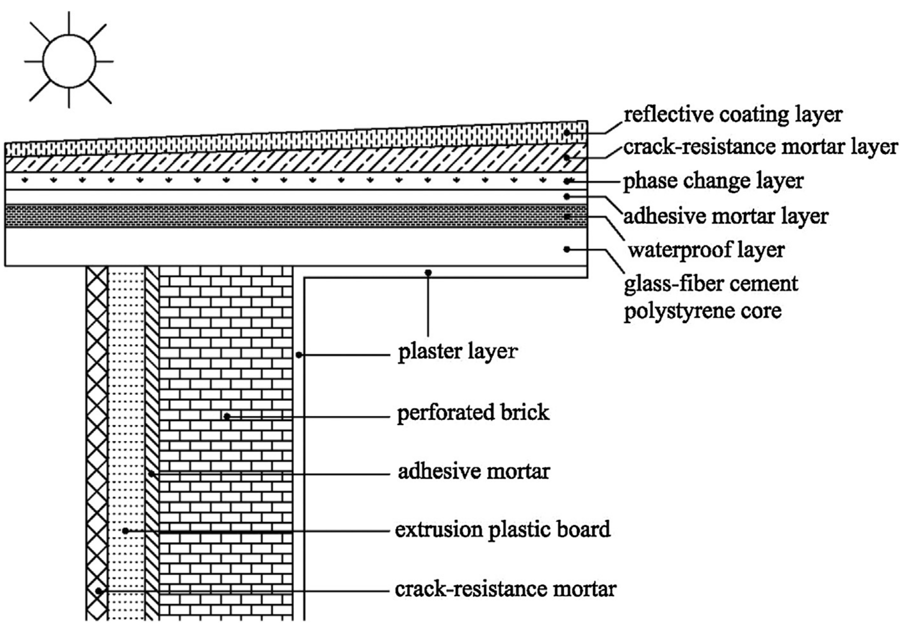

Fig. 5. The structure of the CR roof (2#).

Table 4
the parameter of the test equipment.

Equipment	Type	Accuracy	Manufacturers	Remark
Thermocouples	T	±0.2 °C	/	1 mm of the D
Temperature and humidity self-recording instrument	HOBO U10-003	±0.54 °C±3.5% RH	ONSET	−20 to 70 °C25–75%
Solar thermal radiometer	HOBO H21-002	±10 W/m^2	ONSET	0–1280 W/m^2
Data logger	34972A	/	Agilent	3sets
Heat flux meter	RLJ-10050C	15 W/m^2 mv^{-1}	Beijing Ju Jing Hong	50 × 100 × 2.6 mm

increase the thermal inertia of the building envelope construction and decrease the negative influence around.

Fig. 12 shows the $T_{s,out}$ of three test rooms. The difference of the room 2# and 3# is the phase change layer. And the $T_{s,out}$ variation curves of the room 3# is more smoothly than that of 2# because of the phase change layer. The main reason for this phenomenon is the effect of the PCM to absorb the heat from the roof daytime and release the heat to the roof at night, which increase the $T_{s,out}$ to some extent.

Table 5 shows that the average difference between peak and valley is 17.7 °C (2#) and 14.72 °C (3#) with a difference of 2.98 °C, which reaches up to the max of 5.27 °C on August 11.

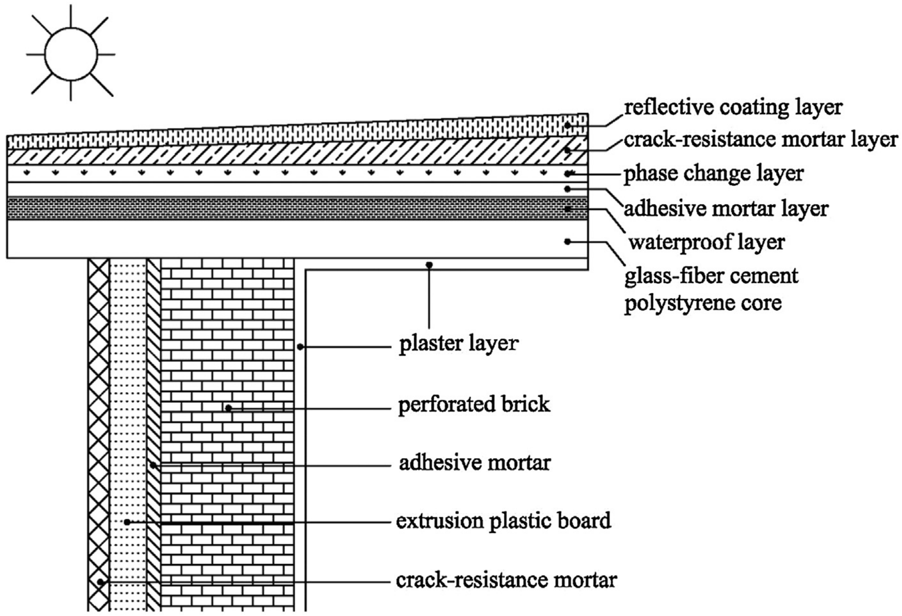

Fig. 6. The structure of the PCR roof (3#).

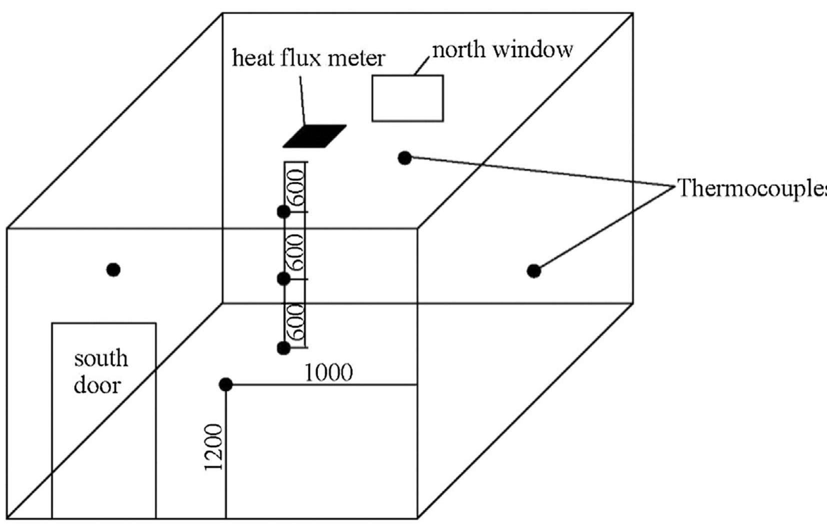

Fig. 7. The test points diagram schematic diagram of the outer wall surface, inner air and the roof heat flux.

Table 5
comparison on the peak and valley difference of three test room $T_{s,out}$.

Date	Peak and valley difference of the $T_{s,out}$ (°C)			The difference value (°C)	
	1#	2#	3#	1# and 3#	2# and 3#
August 8	16.69	15.78	13.93	2.76	1.85
August 9	17.10	16.15	13.90	3.20	2.25
August 10	19.51	18.94	15.22	4.29	3.72
August 11	21.38	20.32	15.05	6.33	5.27
August 12	18.81	17.33	15.49	3.32	1.84
Average	18.70	17.70	14.72	3.98	2.98

Table 6
comparison of the $T_{s,in}$ peak of three test rooms.

Date	Peak of $T_{s,in}$ (°C)			Peak difference (°C)		Delay (min)	
	1#	2#	3#	1# and 3#	2# and 3#	1# and 3#	2# and 3#
August 8	28.10	28.38	27.84	0.26	0.54	20	150
August 9	28.30	28.56	28.05	0.24	0.50	50	190
August 10	28.68	29.07	28.39	0.30	0.69	10	60
August 11	29.23	29.71	28.97	0.26	0.74	30	110
August 12	29.15	29.36	28.95	0.20	0.41	10	100
Average	/	/	/	0.26	0.58	24	122

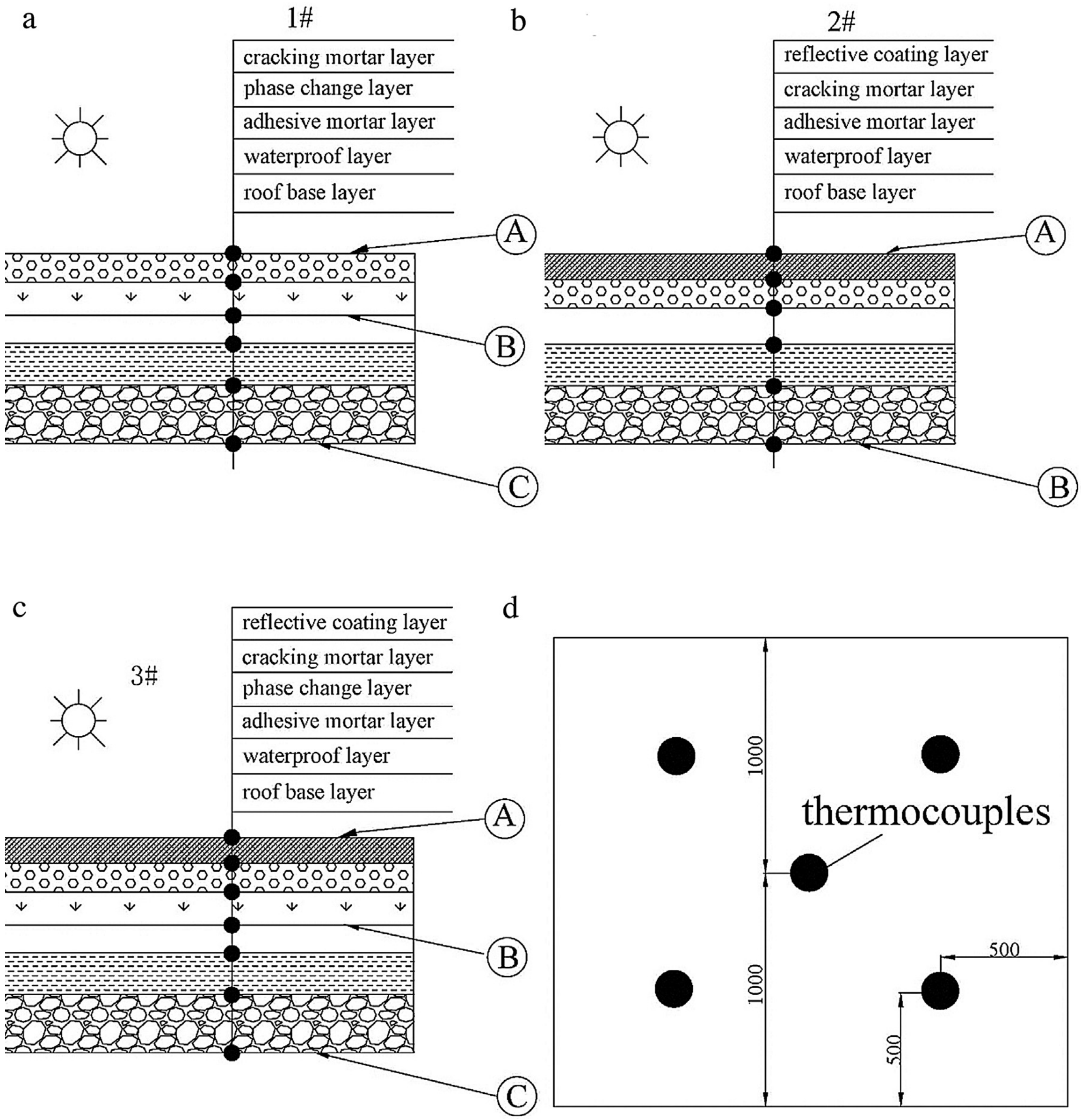

Fig. 8. The test points diagram schematic diagram of roof construction layer: a(1#), b(2#), c(3#), d (the test points distribution of the construction layer).

Fig. 13 and Table 6 show the $T_{s,in}$ test results of three rooms. And about the 2# and 3# rooms, the average peak difference of the $T_{s,in}$ is 0.58 °C, the maximum 0.74 °C, average time delay 122 min and the maximum 190 min, which can prove that the PCR roof behaves better on damping and time delay effect than the other.

The roof heat flux test results of three rooms can be seen from Fig. 14 and obvious time delay of the heat flux can be found. The peak of the $T_{air,out}$ takes place around 13:00, the $q_{s,in}$ of the 2# and 3# around 16:00 and 20:00 respectively. The $q_{s,in}$ of the 3# is slightly larger than that of 2# and the $q_{s,in}$ slope of the 3# is slower than that of the 2# because of the heat released from the phase change process. Table 7 shows that during the test period, the maximum peak $q_{s,in}$ difference between 2# and 3# room is 3.80 W/m^2 (on Aug. 11), the average $q_{s,in}$ difference 2.85 W/m^2, the maximum time delay 340 min and the average time delay 230 min, which prove that the PCM can reduce the heat into the room and delay the heat flux peak evidently.

In addition, the heat into the room through the roof can be calculated by means of plus of the heat flux one day and is shown in Fig. 15. About the 2# and 3# rooms, indeed, the application of the PCM on the 3# can reduce the indoor thermal load apparently. Compared with the room 2#, the heat into the room 3# through the roof can reduce at most 67.31 kJ (on Aug. 10), average 47.45 kJ, the percentage reduction of heat transfer up to 14.68% (on Aug. 10) and the average 10.62%. Taking into account that ventilation method can be used to eliminate the heat into the room because of the PCM solidification process, the PCR roof holds great energy saving potential.

Similarly but more extensively, given that insufficient research that only one latent heat condition being tested in this paper, investigation on the effects of different values to the room can be found in Ref. [17,38]. Li et al. have analyzed the numerical results of three kinds of case, with the latent heat 138 kJ, 188 kJ, 238 kJ and the results have shown that the PCM latent heat has slight effects on the temperature and heat flux of the roof surface, which still more noticeable with the increasing value of the latent heat [17]. In another paper studying on the effect of the PCM roof on the energy saving rate of the room, the author has simulated the conditions of different melting temperature and latent heat capacity ranging from 21.3 °C to 51.3 °C and 30 kJ to 150 kJ respectively. The results

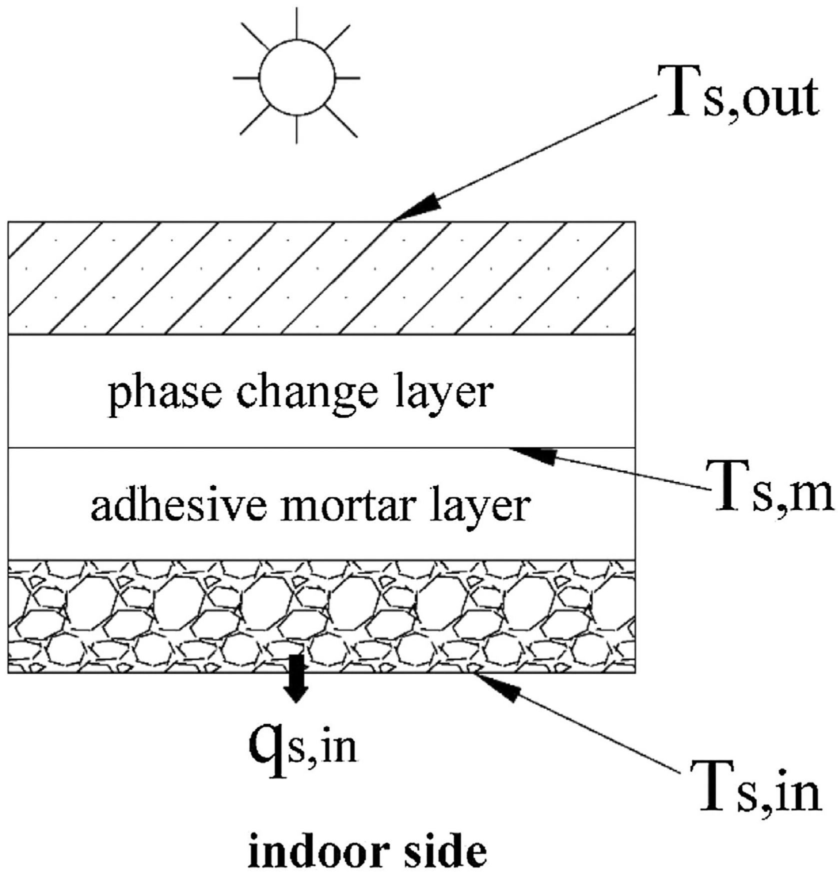

Fig. 9. The diagram schematic of the roof measure points.

Table 7
comparison of the peak heat flux and delay of three test rooms.

Date	Peak $q_{s,\,in}$ (W/m^2)			Difference of the peak (W/m^2)		Time delay (min)	
	1#	2#	3#	1#and 3#	2# and 3#	1#and 3#	2# and 3#
August 8	6.55	7.70	5.44	1.11	2.25	50	250
August 9	6.68	7.88	5.49	1.19	2.39	90	240
August 10	7.22	9.19	5.55	1.67	3.64	10	110
August 11	6.96	9.54	5.74	1.21	3.80	60	340
August 12	6.64	7.61	5.44	1.2	2.17	10	210
Average	/	/	/	1.28	2.85	52	230

Table 8
comparison of the peak $T_{s,out}$ of 1# and 3#.

Date	Peak $T_{s,out}$ of the 1# (°C)	Peak $T_{s,out}$ of the 3# (°C)	Peak difference of the $T_{s,out}$ (°C)
August 8	39.74	35.28	4.45
August 9	41.01	36.20	4.81
August 10	43.51	37.78	5.73
August 11	47.60	39.47	8.13
August 12	43.95	38.26	5.69
Average	/	/	5.76

showed that the energy saving rate increased with the latent heat capacity [38]. From the results of previous study, a conclusion can be made that the thermal inertia of the building envelop can be increased resulting from the application of PCM with higher latent heat, which means that the inner environment of the building suffer little influence from surroundings. In terms of this study, TD-MA holds relative higher latent heat (183 kJ/kg in the melting process) used in building field [39–41] and cost effective, which means that the energy saving efficient was noticeable compared with other PCM with lower latent heat, while opposite under the higher latent heat PCM conditions to some extent.

4.2. Comparison on 1# and 3# rooms

The difference between the 1# and 3# rooms is the cool materials layer existing on the room 3#. Compared with room 1#, $T_{s,out}$

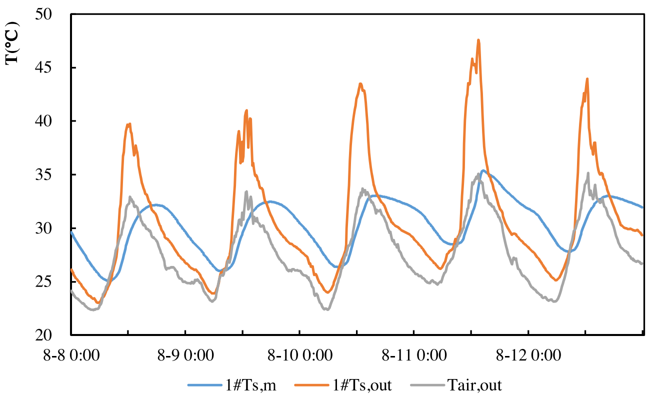

Fig. 10. Comparison of the $T_{s,out}$ and the $T_{s,m}$ (1#, PCM room).

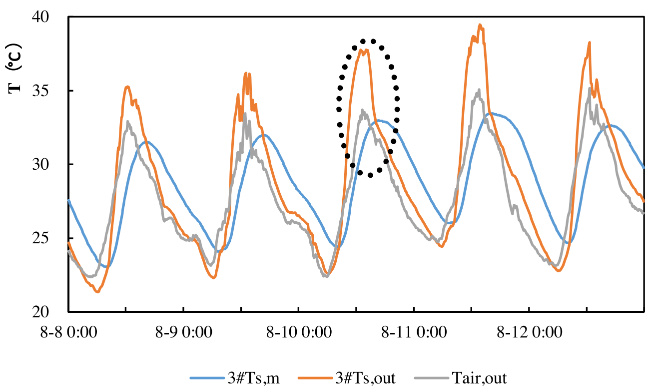

Fig. 11. Comparison of the $T_{s,out}$ and the $T_{s,m}$ (3#, PCR room).

reduction of room 3# can be found in Fig. 12 and the cooling effect of the coating is noticeable in the case of strong solar radiation intensity and conversely weak, which can prove the close relation between the coating and the solar radiation. The reason for this phenomenon is that, in the daytime, the reflective effect of the coating can decrease the surface temperature by reducing the heat absorption of the roof. At night even though the same condition that the coating (3#) and the adhesive mortar (1#) release the heat accumulated daytime with the close hemispherical emissivity, the PCR (3#) release less heat because of the coating insulation effect daytime.

Table 8 shows that the average peak difference of the $T_{s,out}$ (1# and 3#) is about 5.76 °C and the maximum up to 8.13 °C (on Aug. 11) with a tiny time delay, which indicate that the good cooling effect of the coating.

The comparison of $T_{s,in}$ can be found in Table 6. The average peak difference of the $T_{s,in}$ between the 3# and 1# is 0.26 °C, the maximum 0.3 °C, average time delay 24 min and the maximum 50 min, which can prove that the coating cannot delay the roof temperature fluctuation effectively.

As shown in Table 7, compared with room 1#, the $q_{s,in}$ of the 3# exists damping but not apparently time delay because of the reflective effect and poor thermal inertia of the coating. The maximum $q_{s,in}$ difference between the 1# and 3# is 1.67 W/m^2 (on Aug. 10) and the average difference 1.28 W/m^2, which indicate that the cool materials can reduce the heat flux into the room but no obviously time delay.

About the heat into the room through the roof as shown in Fig. 15, room 3# reduced 24.60 kJ at most (5.92%), and average 16.78 kJ (4.07%) compared with room 1#, which indicate that the cool materials can reduce the indoor thermal load but the effect is limited.

Studies on the impact of cool roofs coating with different albedo cool materials can be found in Ref. [42–45]. Garg et al. have investigated the test results of two school buildings with the roof albedo 0.4 and 0.6 respectively from March 2014 till May 2014 in India. The test results showed that the temperature of the outer surface, inner surface of the roof and the indoor air all showed some temperature reduction, which basically were consistent with the conclusions of this study [42]. Generally, different performance of roof sensible reflective including 0.3, 0.5, 0.7 and 0.86 have been simulated and the results indicated that a high roof reflectance (0.86) can greatly reduce the roof surface temperature about 26 °C compared with traditional roof (0.3) [43]. Zhang et al. have studied the effect of different solar reflectance from 0 to 1 and the results show that the inner temperature decrease when the application of higher reflective coatings [44]. Antonaia et al. have investigated several different materials with the reflectance varying from 0.05 to 0.84 and the similar conclusion has been achieved. From the previous research, a conclusion similar with the latent heat of PCM can be made that the energy saving performance holds a positive correlation with the solar reflectance of the coatings [45]. From the point of view of this article, the solar reflectivity value of cool materials was 0.85, which was relatively higher in China market compared with Ref. [46,47] and was close to the latest generation about 0.88 [48]. It can be predictably that the energy saving efficiency of this cool materials was outstanding and it will decrease when the application of the lower solar reflectivity coating while be opposite on the condition of higher solar reflectivity to some extent.

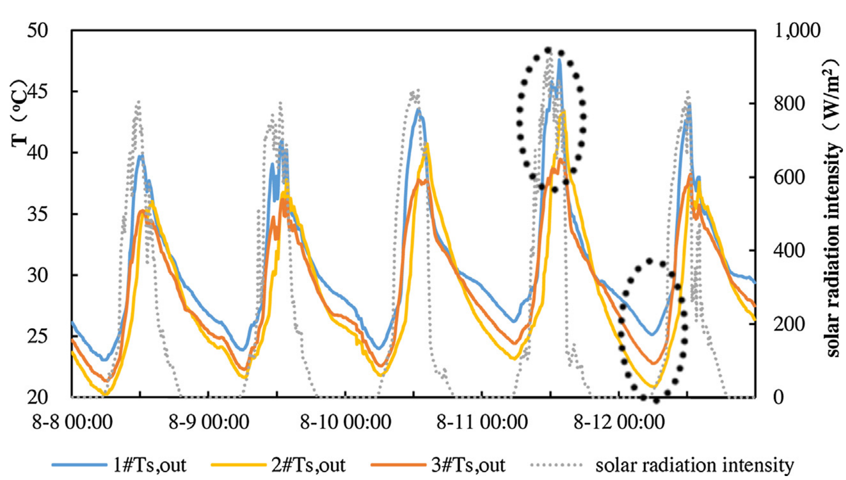

Fig. 12. Comparison of the $T_{s,out}$ of three test rooms.

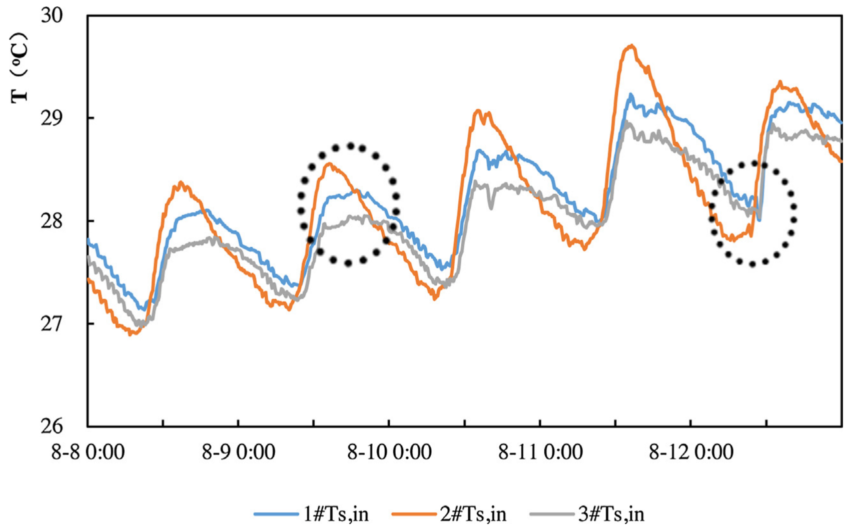

Fig. 13. Comparison of the $T_{s,in}$ (three test rooms).

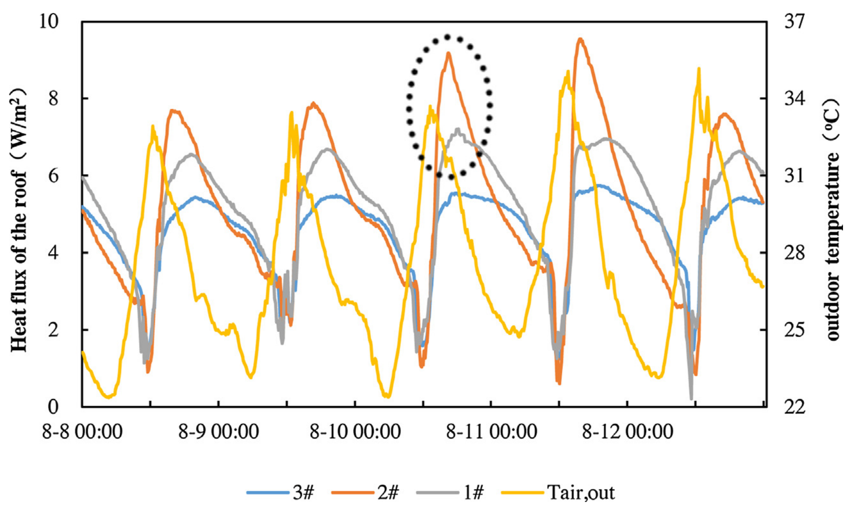

Fig. 14. Comparison of the heat flux (three test rooms).

4.3. *Comprehensive analysis of the three rooms*

In conclusion, the $T_{s,out}$ comparison of three rooms can be found in Fig. 12. In the daytime, the $T_{s,out}$ of three rooms can be listed as follows in the order of high to low: 1# > 2# > 3# because of the cooling effect of the coating (2# and 3#) and the thermal storage of the phase change effect (1# and 3#). At night, the $T_{s,out}$ of three rooms can be listed as follows in the order of high to low: 1# > 3# > 2#. The daily average temperature difference of the $T_{s,out}$ between peak and valley of three rooms can be listed as follows in the order of high to low: 1#(18.70 °C) > 2#(17.70 °C) > 3#(14.72 °C). In summary, the thermal insulation of the PCR roof (3#) is superior to the others.

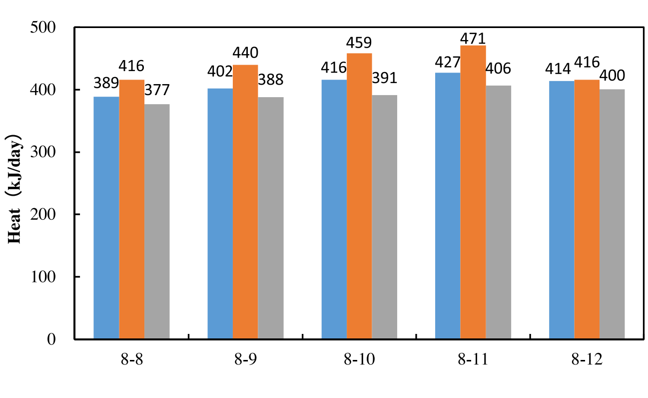

Fig. 15. Comparison of the heat into the room through the roof (three test rooms).

Fig. 13 shows the $T_{s,in}$ test results of three rooms. The $T_{s,in}$ fluctuation of the PCM roof (1#) and PCR roof (3#) is more smooth than the CR roof (2#) and there exists the time delay condition. In the daytime, the $T_{s,in}$ of three rooms can be listed as follows in the order of high to low: 2# > 1# > 3# and at night, the $T_{s,in}$ of three rooms can be listed as follows in the order of high to low: 1# > 3# > 2# because of the integrated effect of phase change thermal storage effect and the coating reflective effect.

According the above analysis, the energy saving efficiency holds positive correlation with the latent heat of PCM and solar reflectivity of the cool materials respectively. On the other hand, the PCM and the cool materials do not have any other reactions or negative interaction. The energy saving performance of the roof will be better compared with the lower latent heat and solar reflectivity while opposite if higher latent heat PCM and solar reflectivity cool materials were used.

5. Conclusion

In this paper, a novel energy efficiency roof coupled with PCM and cool materials, which aims to lower the air conditioning load, has been introduced and performed full-scale field test. Comparative analyses on surface temperatures and heat fluxes have been conducted.

The test results have indicated that the PCR roof shows better thermal insulation and thermal inertia performance compared with CR roof and the application of the cool materials on the PCM roof can evidently reduce the outer surface temperature of the roof. Those conclusions have confirmed that this novel energy efficiency roof can suppress the influence from the outer environment effectively and improve the indoor thermal environment. Furthermore, the application of the PCR roof can reduce the heating and air conditioning load of the building evidently. However, further work also should be done, such as, the research of the PCR on the different climate regions, the optimum design scheme of the PCR roof and the cool materials, including the using effects of different PCM latent heat capacity and the reflectance of the cool materials. In addition, in light of the ventilation at night can eliminate the heat accumulated in the daytime, the integrated application effect of the ventilation and the PCR roof also can be further studied.

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