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Experimental Study on the Dynamic Heat Transfer Characteristics of Triple-pane PCM-filled Window

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Abstract

In order to reduce the heat transferred into the indoor environment in the discharge period of PCM and to reduce the overheating risk after the PCM has melted completely, the TW+PCM is proposed. Paraffin MG29 is filled in the TW+PCM. The comparative experiment of the TW+PCM, the DW+PCM in the sunny summer day and rainy summer day is conducted. The thermal properties of the TW+PCM are obtained. The results of the experiment show that in the representative sunny summer day, the peak temperature on the interior surface of the TW+PCM is reduced by 2.7℃, and the heat entered the building through the TW+PCM is reduced by 16.6%, comparing with the DW+PCM. The TW+PCM plays a significant role in decreasing the peak temperature and peak heat flux on the interior surface and reducing the heat entered the building through the TW+PCM. It also shows a good performance on the delay of peak-temperature time, the same with the DW+PCM. In the representative rainy summer day, the TW+PCM has a good performance of reducing the temperature fluctuation of the interior surface and the heat transferred through the TW+PCM, but it is unsatisfactory to reduce the peak heat flux on the interior surface and delaying the peak temperature.

Keywords - PCM-filled window; overheating; comparative experiment; temperature decrement factor; energy saving efficiency

Abbreviations

PCM	phase change material	FCU	fan coil unit
TW+PCM	triple-pane PCM-filled window		
DW+PCM	double-pane PCM-filled window		
HW	hollow glass window		

Nomenclature

φ_{PCM}	temperature time lag of the TW+PCM comparing with the DW+PCM
$\tau_{PCM,max}$	time of the interior surface maximum temperature of the TW+PCM
$\tau_{air,max}$	time of the interior surface maximum temperature of the DW+PCM
$t_{PCM,max}$	the maximum temperature on the interior surface of the TW+PCM in the temperature waves

$t_{PCM,min}$	the minimum temperature on the interior surface of the TW+PCM in the temperature waves
$t_{air,max}$	the maximum temperature on the interior surface of the the DW+PCM in the temperature waves
$t_{air,min}$	the minimum temperature on the interior surface of the the DW+PCM in the temperature waves
η	energy saving rate of the TW+PCM comparing with the DW+PCM
$Q_{i,PCM}$	the heat transferred through the TW+PCM
$Q_{i,air}$	the heat transferred through the DW+PCM
q_i	the interior surface heat flux of the TW+PCM or the DW+PCM
α_i	the interior surface composite heat transfer coefficient of the TW+PCM or the DW+PCM
$t_{g,i}$	temperature on the interior surface of the TW+PCM or the DW+PCM
$t_{a,i}$	temperature of the indoor air
I	solar radiation in vertical plane
σ	solar transmittance of the TW+PCM or the DW+PCM
Q_i	specific cumulative heat transferred through the TW+PCM or the DW+PCM
Q_H	power of the electric heater in testing chamber
Q_F	power of the fan in the FCU in testing chamber
Q_C	cooling capacity provided by the FCU in testing chamber
c_w	specific heat capacity the circulating water in the FCU
ρ_w	density of the circulating water
G_w	volume flow rate of the circulating water
$t_{w,o}$	outlet water temperature of the FCU in testing chamber
$t_{w,i}$	inlet water temperature of the FCU in testing chamber

1. Introduction

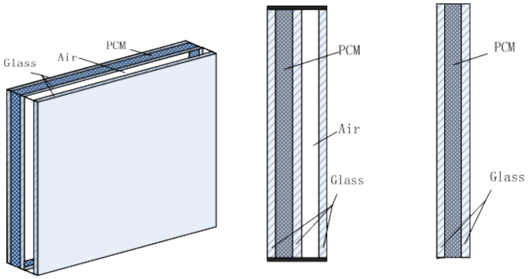
International Energy Agency indicated that the building energy consumption accounted for 31% of the total primary energy consumption in China in 2007 [1]. In the hot summer and cold winter area of China, energy consumption of the building envelope accounted for 60%~80% of the total energy consumption in buildings, and the energy consumption through the window accounted for 30% of the energy consumption of the building envelope [2]. It played an important role on the building energy conservation to improve the thermal performance of window.

A series of studies related to the energy conservation in transparent envelope were conducted. The vanadium dioxide thermochromic glass window [3], the double-glazed window with fluid channel [4] and the near-infrared electrochromic glass window [5] were studied. As an effective and economical way to reduce the energy consumption, the DW+PCM was also put forward. It was proposed originally for cold climate conditions and it was also applicable in warm region[6]. Ismail and Henriquez [7] [8] studied the overall coefficient of heat transfer, the solar heat gain coefficient and the shading coefficient of the DW+PCM by numerical and experimental investigations. The optical properties of the DW+PCM (RT27) were researched by Gowreesunker [9] by the T-history method and spectrophotometry principles. The thermal performance of DW+PCM (CaCl2 • 6H2O) on the condition of simulative heat source was researched by Qing Luo [10]. The DW+PCM which was applied in a humid subtropical climate area was investigated by Francesco Goia [11] [12] [13]. The heat transferred through the DW+PCM was calculated and the thermal comfort of the indoor environment was evaluated, the shading and heat insulation effects of the DW+PCM were significant in high solar radiation. The DW+PCM (sodium sulfate decahydrate) applied in the hot summer and cold winter area of China was investigated by Li et al.[14]. It was concluded that the heat transferred though DW+PCM decreased 39.5% compared with HW in sunny summer day, and the thermal insulation and load shifting effects of DW+PCM was unsatisfactory in the other typical days.

According to the literature review, the DW+PCM has a good thermal performance of saving building energy consumption. However, further improvement should be done as for the two problems about DW+PCM below: (1) Since PCM's thermal conductivity is higher than air's, the overall thermal conductivity of DW+PCM is higher than that of conventional double-pane window. As a result, when the PCM has melted completely because of strong solar radiation in summer daytime , the interior surface temperature of DW+PCM will rise to a high value (overheating phenomenon), which will enlarge the fluctuation range of indoor temperature. (2) PCM will release the unnecessary heat into the indoor environment during the discharge period of PCM (the period of PCM releasing the latent heat which is absorbed in daytime) in summer night, which will increase the air conditioning load indoors. A configuration of TW+PCM is proposed to solve these problems. It contained two cavities, the outer cavity is filled with PCM and the inner one is filled with air. Compared with DW+PCM, this configuration has an air cavity in addition, which can increase the holistic thermal resistance of itself. As a result, it can reduce the heat exchanged by convection between the outdoor and indoor environment, and consequently avoiding the interior surface temperature of the window rising excessively after the PCM has melted completely. Also, the heat transferred into the room during the discharge period of PCM can be reduced. Based on the above theories, an experiment about the dynamic thermal properties and energy saving performance of the TW+PCM in the sunny summer day and rainy summer day is conducted.

2. The Structure of the TW+PCM

2.1. The Test Structure of the TW+PCM



(a) Structure of the TW+PCM

(b) Structure of the DW+PCM

Fig. 1. Structure comparison of the two kinds of windows

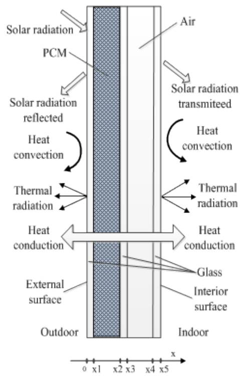


Fig. 2 Heat transfer process of the TW+PCM

The TW+PCM are 0.5 meters long, 0.5 meters wide and 0.043 meters thick. Specifically, each pane of glass is 0.005 meters thick, the outer PCM cavity and inner air cavity are both 0.014 meters thick. In order to obtain the thermal performance of the TW+PCM, a comparative experiment of the TW+PCM and DW+PCM is conducted. As a control-group window, the length and width of the DW+PCM are the same with the TW+PCM's. Each pane of glass of the DW+PCM is also 0.005 meters thick. And the DW+PCM have the same thickness of PCM cavity with TW+PCM, which means the masses of the PCMs filled in these two configurations are the same. Structure comparison of the two kinds of windows is shown in Fig. 1. Since the thermal performance of sodium sulfate decahydrate was unstable [14], paraffin MG29 is selected in this experimental research. Thermo-physical properties of the related materials are shown in Table 1.

Table 1. Thermo-physical properties of the related materials

Material	Density $/kg \cdot m^{-3}$	Specific heat capacity $/kJ \cdot kg^{-1} \cdot K^{-1}$	Latent heat $/kJ \cdot kg^{-1}$	Thermal conductivity $/W \cdot m^{-1} \cdot K^{-1}$	Melting temperature $/ ^{o}C$
paraffin (MG29)	850	2.23	205	0.21	27-29
air	1.1644	1.0064	-	0.0264	-
glass	2500	0.79	-	0.76	-

Heat transfer process of the TW+PCM configuration is presented in Fig. 2. The solar radiation reaching the glass surface is divided into three parts: reflected radiation, absorbed radiation and transmitted radiation. The heat transfer process with the combination of thermal radiation and convection takes place on the surface of the windows.

2.3. Evaluation Parameters

In this paper, temperature time lag and temperature decrement factor are used to evaluate the dynamic thermal performance of the TW+PCM and DW+PCM, and the energy saving rate is used to evaluate the thermal insulation performance of the above windows.

Temperature time lag is the phase difference of the temperature waves on the interior surfaces of the TW+PCM and the DW+PCM, which is calculated by (1). Temperature decrement factor is the ratio of the temperature waves on the interior surfaces of the amplitude of the TW+PCM and the DW+PCM, which can be calculated by (2). If the temperature time lag is high and temperature decrement factor is low, the thermal performance of building envelope is satisfactory.

$$\varphi_{PCM} = \tau_{\mathrm{PCM,max}} - \tau_{\mathrm{air,max}} \tag{1}$$

$$f_{PCM} = \frac{t_{PCM,\max} - t_{PCM,\min}}{t_{air,\max} - t_{air,\min}} \tag{2}$$

Where φ_{PCM} is the temperature time lag of the TW+PCM comparing with the DW+PCM, $\tau_{PCM,max}$ and $\tau_{air,max}$ are the time of the interior surface maximum temperature of the TW+PCM and the DW+PCM in the temperature waves respectively, f_{PCM} is the temperature decrement factor of the TW+PCM comparing with the DW+PCM, $t_{PCM,max}$ and $t_{PCM,min}$ are the maximum and minimum temperature on the interior surface of the TW+PCM in the temperature waves respectively, and $t_{air,max}$ and $t_{air,min}$ are the maximum and minimum temperature on the interior surface of the the DW+PCM in the temperature waves respectively.

The energy saving rate is defined as the proportional reduction between the heat transferred into the building through the DW+PCM and the heat transferred into the building through the TW+PCM, as shown in (3). The heat flux on the interior surfaces of the TW+PCM or the DW+PCM is calculated by (4). The heat transferred through the TW+PCM and DW+PCM is calculated by (5).

$$\eta = \frac{Q_{i,air} - Q_{i,PCM}}{Q_{i,air}} \tag{3}$$

$$q_i = \alpha_i (t_{\mathrm{g},i} - t_{a,i}) + \sigma \cdot I \tag{4}$$

$$Q_i = \int q_i \cdot d\tau = \int \alpha_i (t_{g,i} - t_{a,i}) \cdot d\tau + \int \sigma \cdot I \cdot d\tau \tag{5}$$

Where $Q_{i,PCM}$ and $Q_{i,air}$ are the heat transferred through the TW+PCM and the DW+PCM respectively, η is the energy saving rate of the TW+PCM comparing with the DW+PCM, q_i is the interior surface heat flux of the TW+PCM or the DW+PCM, α_i is the interior surface composite heat transfer coefficient of the TW+PCM or the DW+PCM, $t_{g,i}$ is the temperature on the interior surface of the TW+PCM or the DW+PCM, $t_{a,i}$ is the temperature of the indoor air, I is the solar radiation in vertical plane, σ is the solar transmittance of the TW+PCM or the DW+PCM, Q_i is the specific cumulative heat transferred through the TW+PCM or the DW+PCM.

3. Experimental System

In order to investigate the dynamic heat transfer characteristics of the TW+PCM in the sunny summer day and the rainy summer day, a comparative experiment is conducted in this paper. The control-group window is DW+PCM. According to the experimental data，the thermal performance of the TW+PCM in summer days is evaluated.

3.1. Experimental Setup

The experimental setup is located in Nanjing of China (32.03N, 118.46E) which belongs to the hot-summer and cold-winter zone.The experimental devices consist of two identical experimental chambers, as is shown in Fig. 3. The experimental chamber A and the experimental chamber B are used to test the dynamic heat transfer properties of the TW+PCM and the DW+PCM respectively. Both of the chambers are made up of the polyurethane sandwich insulation panels. Each experimental chamber is composed of a testing chamber inside and a guarded chamber outside, as is shown in Fig. 4. The testing chamber and the guarded chamber share the same south panel, and there is a widow frame in this south pane to install the TW+PCM or the DW+PCM. The size of the window frame is 1m×1m. In order to highlight the energy saving effect, four TW+PCMs with the size of 0.5m×0.5m are installed in the window frame of experimental chamber A comparing with the same area of the DW+PCM installed in the experimental chamber B.

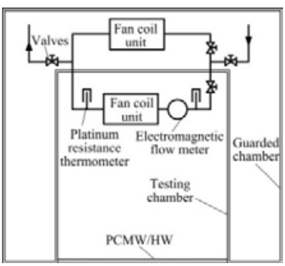


Fig. 4. Internal structure of the experimental chambers

Fig. 3. Picture of experimental chambers

Each testing chamber and each guarded chamber has installed a FCU which comes with an electric heater. The chilled water is supplied to the FCUs by an air-source heat pump water chiller/heater unit. In summer, the water chiller unit supply chilled water to the FCUs to provide cooling capacity. Meanwhile, the electric heaters supply heat to the testing chambers and guarded chambers. The power of the electric heaters can be regulated successively according to the indoor temperature, which aims to keep the indoor temperature of testing chambers and their corresponding guarded chambers be the same.

3.2. Data Measurement

In the process of the experiment, the interior surface temperature and heat flux of interior surface of the TW+PCM and the DW+PCM need to be collected. Since the thermal performance of the windows is influenced by the outdoor air temperature and the solar radiation intensity on the south vertical surface, these two data should also be collected. All the above data can be collected by the measuring instruments directly.The major parameters of the measuring instruments are presented in Table 2.

Table 2. Main parameters of the experimental measuring instruments

Parameter	Instrument	Instrument model	Range	Accuracy
Temperature (surface)	Thermocouple	Omega/T	-200~350 ^{o}C	0.4 ^{o}C
Temperature (water)	Platinum resistance thermometer	PT100	-200~400 ^{o}C	0.05 ^{o}C
Temperature (outdoor air)	Meteorological station	Davis/06162C	-40~65 ^{o}C	0.5 ^{o}C
Flow	Electromagnetic flow meter	Zhonghuan Tig/LDTH-10B	0~2.8 $m^3 \cdot h^{-1}$	0.5%
Power	Digital power meter	Yokogawa/WT230	0~12 kW	0.1%
Heat flux (surface)	Heat flux sensor	gSKIN	-150~150 $kW \cdot m^{-2}$	3%
Solar radiation	Solar spectral radiometer	Jinzhou Sunshine	0~1400 $W \cdot m^{-2}$	2%

The heat transferred into building through the above windows also needs to be obtained. In order to obtain it, the following data should be collected according to the energy conservation of the testing chamber: the inlet temperature and the outlet temperature of the circulating water in the FCU in testing chamber, the volume flow rate the of the circulating water, the power of the electric heater and the fan in the FCU. There will be no heat transferred through the polyurethane sandwich insulation panel between the guarded chamber and testing chamber when the guarded chamber and testing chamber were set at the same temperature, so the heat transferred only through the TW+PCM or the DW+PCM between the testing chamber and the external environment. Therefore, the heat transferred through the TW+PCM and the DW+PCM can be calculated by energy conservation equation of the testing chamber as shown in (6).

$$Q_{\mathrm{i}} = Q_{\mathrm{C}} - Q_{\mathrm{H}} - Q_{\mathrm{F}} = c_{\mathrm{w}} \cdot \rho_{\mathrm{w}} \cdot G_{\mathrm{w}} \cdot (t_{\mathrm{w,o}} - t_{\mathrm{w,i}}) - (Q_{\mathrm{H}} + Q_{\mathrm{F}}) \tag{6}$$

Where Q_i is the heat transferred through the TW+PCM and DW+PCM, Q_H is the power of the electric heater in testing chamber, Q_F is the power of the fan in the FCU in testing chamber, Q_C is the cooling capacity provided by the FCU in testing chamber, c_w, ρ_w and G_w are the specific heat capacity, the density and the volume flow rate of the circulating water in the FCU in testing chamber respectively, $t_{w,o}$ and $t_{w,i}$ are the outlet and inlet water temperature of the FCU in testing chamber respectively.

3.3. Error Analysis of the Experiment

According to principle of experiment measurement, the error analysis of the experiment is analyzed. As is shown in Table 2, the measurement accuracy of the interior surface temperature of the TW+PCM and the DW+PCM is ±0.4 ^{o}C, and the relative error of the heat flux on the interior surface of the above windows which is measured by the heat flux sensor is less than 3%. These two kinds of data are accurate and reliable. The relative accuracy of the electromagnetic flow meter is 0.5%, while the accuracy of the inlet and outlet water temperature of the FCU in testing chamber is 0.05 ^{o}C, and the temperature difference between the inlet and outlet water temperature of the FCU in testing chamber is about 5 ^{o}C. So the relative error of the cooling capacity (Q_C) is 2.5% by calculating. The relative accuracy of the digital power meter is 0.1%, while the power of the fan in the FCU in testing chamber is about 30 W; the power of the electric heater in the FCU in testing chamber is about 200 W; the cooling capacity provided by the FCU in testing chamber is about 400 W. The relative error of the heat transferred through the TW+PCM and the DW+PCM is 5.9% by calculating according to (7). The error analysis indicates that the results of this experimental system are satisfactory.

$$\left(\frac{\Delta Q_{\mathrm{i}}}{Q_{\mathrm{i}}}\right) = \left(\frac{Q_{\mathrm{C}}}{(Q_{\mathrm{C}} - (Q_{\mathrm{H}} + Q_{\mathrm{F}}))} \cdot \left|\frac{\Delta Q_{\mathrm{C}}}{Q_{\mathrm{C}}}\right| - \frac{Q_{\mathrm{H}} + Q_{\mathrm{F}}}{(Q_{\mathrm{C}} - (Q_{\mathrm{H}} + Q_{\mathrm{F}}))} \cdot \left|\frac{\Delta(Q_{\mathrm{H}} + Q_{\mathrm{F}})}{(Q_{\mathrm{H}} + Q_{\mathrm{F}})}\right|\right) \tag{7}$$

4. Experimental Results

The comparative experiment of the TW+PCM and the DW+PCM is conducted from September 6 of 2015 to September 13 of 2015. All kinds of data have been collected every 2 seconds. The weather condition of September 7 and September 11 belong to the weather condition of typical sunny summer day and typical rainy summer day respectively. The experimental data of the two days are selected for further processing. Specifically, take the average of two day's outdoor air temperature and solar radiation intensity on the south vertical surface every 30 minutes, while the temperature and heat flux on the interior surface of the TW+PCM and DW+PCM are averaged every 30 minutes.

4.2. Weather Conditions of the Summer Days

The outdoor air temperature and solar radiation intensity on the south vertical surface in the sunny summer day and rainy summer day are shown in Fig. 6 and Fig. 7 respectively. The highest and lowest outdoor air temperatures of September 7 are 30.3 ^{o}C and 21.2 ^{o}C respectively. The same terms of September 11 are 28.5 ^{o}C and 20.3 ^{o}C respectively. The maximum solar radiation intensity on the south vertical surface in September 7 and September 11 are 483 W·m^{-2} and 157 W·m^{-2} respectively.

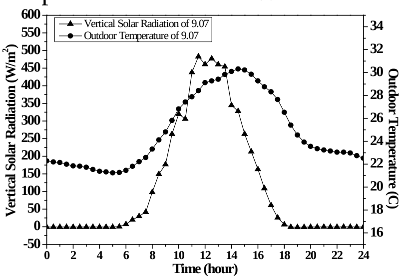


Fig.6. Outdoor air temperature and solar radiation intensity on the south vertical surface in the sunny summer day

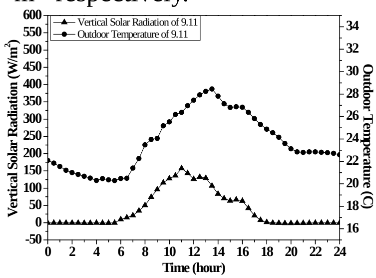


Fig.7. Outdoor air temperature and solar radiation intensity on the south vertical surface in the rainy summer day

4.3. Experimental Results in Sunny Summer Day

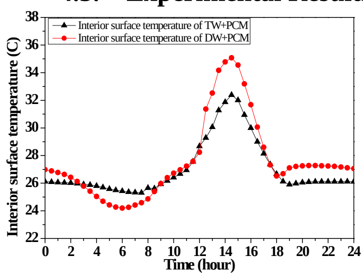


Fig. 8. The temperature on the interior surface of the TW+PCM and DW+PCM in the sunny summer day

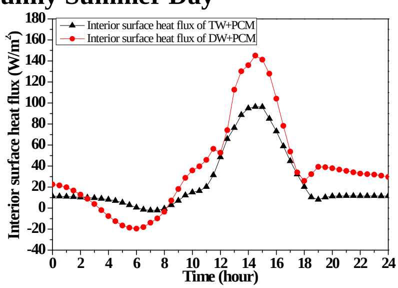


Fig. 9. The heat flux on the interior surface of the TW+PCM and DW+PCM in the sunny summer day

The temperature and heat flux on the interior surface of the TW+PCM and the DW+PCM in the sunny summer day are plotted in Fig. 8 and Fig.9 respectively. The calculation results of the evaluation parameters of the

TW+PCM and in the typical sunny summer day are presented in Table 3.As is shown in Fig. 8 and Table 3, the peak temperature on the interior surface of the TW+PCM is 2.7 ^{o}C lower than the DW+PCM, and the temperature time lag and temperature decrement factor of the TW+PCM are 0 h and 0.65 respectively comparing with the DW+PCM in the sunny summer day. Fig.8 indicates that the peak heat flux on the interior surface of the TW+PCM is 48.8 W·m^{-2} lower than that of the DW+PCM. The heat transferred though the TW+PCM is reduced by 16.6% comparing with the DW+PCM according to the result in Table 3 which is calculated by (3).

The heat gain of the TW+PCM significantly reduces because PCM absorbs the intense solar radiation and releases the heat to outdoor cold air during the night. Therefore, the use of the TW+PCM can mitigate the temperature fluctuation of indoor air. On the other hand, as the TW+PCM is equipped with an air cavity additionally comparing with the DW+PCM, which increases the thermal resistance of the TW+PCM, the quantity of heat convection through window after the PCM has melted completely (about 14:00) is reduced. As a result, the peak temperature on the interior surface of the TW+PCM gets a reduction. In addition, the TW+PCM and the DW+PCM have the similar time lag of the peak temperature on the interior surface, because the mass of the PCM and the thickness of the PCM cavities of the two configurations are the same.

Table 3. Evaluation parameters of the TW+PCM and the DW+PCM

Weather conditions		Sunny summer day	Rainy summer day
Peak temperature time of the TW+PCM /h		14.5	14
Peak temperature time of the DW+PCM /h		14.5	14
Peak temperature time lag φ_{PCM} /h		0	0
Temperature on the interior surface of the TW+PCM	Max/℃	32.38	26.42
	Min/℃	25.31	24.54
Temperature on the interior surface of the DW+PCM	Max/℃	35.07	27.15
	Min/℃	24.19	23.34
temperature decrement factor f_{PCM}		0.65	0.49
Energy saving rate η		16.6%	14.7%

4.4. Experimental Results in Rainy Summer Day

The temperature and the heat flux on the interior surface of the TW+PCM and DW+PCM in the rainy summer day are plotted in Fig. 10 and Fig.11 respectively. The calculation results of the evaluation parameters of the TW+PCM in the rainy summer day are presented in Table 3. As is shown in Fig. 10 and Table 3, the peak temperature on the interior surface of the TW+PCM is 0.74 ^{o}C lower than the DW+PCM, and the temperature time lag and temperature decrement factor of the TW+PCM are 0 h and 0.49 respectively comparing with the DW+PCM in the rainy summer day.

Fig.8 indicates that the peak heat flux on the interior surface of the TW+PCM is 25 W·m^{-2} lower than that of the DW+PCM. The heat transferred though the TW+PCM is reduced by 14.7% comparing with the DW+PCM according to the results in Table 3.

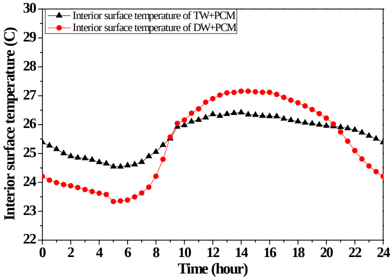


Fig. 10. The temperature on the interior surface of the TW+PCM and DW+PCM in the rainy summer day

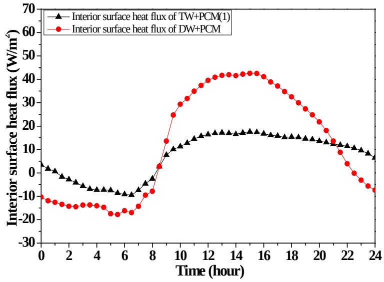


Fig. 11. The heat flux on the interior surface of the TW+PCM and DW+PCM in the rainy summer day

The solar radiation absorbed by the TW+PCM in rainy summer day is significantly less than the solar radiation absorbed by the TW+PCM in sunny summer day because of the weak solar radiation outdoors. Therefore, the temperature on the interior surface of the TW+PCM has a slight reduction comparing with the DW+PCM, and the delay of the peak temperature on the interior surface is not obvious. On the other hand, the heat transferred through the TW+PCM is reduced comparing with the DW+PCM, because the TW is equipped with an air cavity additionally, which increases the thermal resistance of the TW+PCM.

5. Conclusions

A comparative experiment is conducted in this paper to investigate the dynamic heat transfer characteristics of the TW+PCM in the sunny summer day and the rainy summer day. It consists of the TW+PCM and the DW+PCM. The experimental principle, experimental setup and measuring instruments are introduced in detail. The conclusions are as follows:

(1) In the representative sunny summer day, the temperature on the interior surface of the TW is 2.7 ^{o}C lower than that of the DW+PCM, and the heat transferred into room through the TW+PCM is reduced by 16.6% comparing with the DW+PCM. The TW+PCM plays a significant role in decreasing the peak temperature and peak heat flux of the interior surface and reducing the heat entered the building through the TW+PCM, and it shows a good performance on the delay of peak-temperature time, the same with the DW+PCM configuration. It can adjust the peak load of the air conditioning system and save the air-conditioning energy consumption.

(2) In the representative rainy summer day, the TW+PCM has a good performance on reducing the temperature fluctuation of the interior surface and the heat entered through the TW+PCM, but it is unsatisfactory to

reduce the peak heat flux on the interior surface and delaying the peak temperature.

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