Ventilation cooling/heating performance of a PCM enhanced ventilated window - an experimental study

Hu, Yue; Heiselberg, Per Kvols; Guo, Rui

Published in:
Energy and Buildings

DOI (link to publication from Publisher):
10.1016/j.enbuild.2020.109903

Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Hu, Y., Heiselberg, P. K., & Guo, R. (2020). Ventilation cooling/heating performance of a PCM enhanced ventilated window - an experimental study. *Energy and Buildings*, *214*(May), [109903]. https://doi.org/10.1016/j.enbuild.2020.109903

Energy & Buildings 214 (2020) 109903

Contents lists available at ScienceDirect

Energy & Buildings

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

Ventilation cooling/heating performance of a PCM enhanced ventilated window - an experimental study

Yue Hu*, Per Kvols Heiselberg, Rui Guo

Aalborg University, Division of Architectural Engineering, Department of Civil Engineering, Thomas Manns Vej 23, DK-9220 Aalborg Øst, Denmark

ARTICLE INFO

Article history:
Received 25 September 2019
Revised 12 February 2020
Accepted 24 February 2020
Available online 25 February 2020

Keywords:
Phase change material
Ventilated window
Night cooling application
Solar energy storage
Ventilation pre-cooling
Ventilation pre-heating

ABSTRACT

This paper presents a phase change material enhanced ventilated window (PCMVW) for both ventilation pre-cooling and pre-heating purposes. The PCM heat exchanger is used as a heat sink in the ventilation pre-cooling application and thermal energy storage in the ventilation pre-heating application. The paper presents a night cooling experiment and a solar energy storage experiment in order to investigate the thermal and energy performance of the PCMVW, and a ventilated window (VW) self-cooling experiment for overheating protection. Two VWs were tested in the façade lab in Aalborg (Denmark), and one of them is with PCM heat exchanger. The two windows were equipped with the same outdoor conditions and ventilation airflow. The experimental results show that for ventilation pre-cooling application with the PCM heat exchanger, the room inlet air temperature is by average 1.4 °C lower for 7 h during the daytime compared to the normal VW. The average energy saving is 0.7 MJ/day compared to a normal VW. The PCMVW cooling capacity is limited without advanced blinds control and system operation control. In ventilation pre-heating application, the PCM increases the inlet air temperature of the VW by 2.0 °C for 12 h. The average energy saving is 1.6 MJ/day compared to a normal VW. Buildings in a climate with high outdoor air temperature differences can benefit more from the PCMVW in ventilation pre-cooling application, but the pre-cooling ability is limited. While in ventilation pre-heating application the buildings in the climate with higher solar radiation levels has a higher energy performance. Moreover, the VW self-cooling application is more effective to decrease the overheating of the room than VW without self-cooling.

1. Introduction

Building energy for heating, cooling, and ventilation accounts for one-third of the total primary energy consumption in industrial countries and is becoming a major pollutant to the environment [1]. To sufficiently reduce the CO_2 emission, it is necessary to apply some innovative technologies and solutions, such as renewable energy applications. Among them, thermal energy storage (TES) is a promising way to store intermittent renewable energy for building energy supply. The TES can be sorted by sensible heat storage and latent heat storage. Phase change material (PCM) as TES has the advantage of high latent heat capacity and high energy storage density, due to a large amount of heat released/absorbed during the phase transition period. Some of the PCMs have the melting/freezing temperature near the thermal comfort temperature, which is good for building applications.

Researchers and engineers have done a lot of work for applying PCM in building systems, including passive applications and active applications. In passive applications, the PCM increases the thermal mass level and thermal inertia of the building or the building components. It is heated up or cooled down without any mechanical heating or cooling additions [2].

Passive applications include mixing PCM in constructions such as concrete [3,4], wall board [5], roof [6], floor [7], and so on. It has been proved to be effective with regards to achieving a better indoor climate and saving building energy. However, the PCM facilities for building applications are mostly limited to volume due to its low thermal conductivity. Caixia et al. [8] experimentally studied the application of moveable PCM thermal energy storage to disaster-relief prefabricated temporary houses during summer time. The results show that mobile PCM storage can decrease indoor air temperature by 3.2–3.6 °C. Later on, they built a

---

* Corresponding author.
E-mail address: hy@civil.aau.dk (Y. Hu).

https://doi.org/10.1016/j.enbuild.2020.109903

Nomenclature

Symbols

Cp_{air}	Specific heat capacity of the air [J/(kg•K)]
T	Temperature [°C]
t	Ventilation time [s]
q	Flowrate[m^3/h]
ρ_{air}	Air density [kg/m^3]
T_{inlet}	Inlet air temperature of the PCM heat exchanger [°C]
T_{outlet}	Outlet air temperature of the PCM heat exchanger [°C]
Q_1	Ventilation energy saving in night cooling application [MJ]
Q_2	Ventilation energy saving in solar energy storage application [MJ]
$T_{ref\ inlet}$	Inlet air temperature to the room from the reference window [°C]
$T_{PCMVW\ inlet}$	Inlet air temperature to the room from the PCMVW [°C]
r	Correlation coefficient
$\overline{T}_{night}$	Night time average outdoor air temperature [°C]
$\overline{T}_{day}$	Day time average outdoor air temperature [°C]
DT	Daytime and nighttime outdoor air temperature difference [°C]
U	Thermal transmittance
g	Total solar energy transmittance

HVAC	Heating, ventilation and air condition system
PCM	Phase change material
TES	Thermal energy storage
VW	Ventilated window
PCMVW	PCM enhanced ventilated window
Ref	Reference window(ventilated window)

numerical model to optimize the position and thickness of the PCM [9]. They discovered that the best design is to move the PCM to the outdoor during the night time for night cooling and bring it to the indoor room during the daytime, in order to decrease the indoor air temperature. The optimized PCM thickness of the PCM thermal storage is 20 mm. Memon et al. [10] tested a small-scaled concrete wall container with macro encapsulated PCM. The tests show that the PCM can reduce the indoor air temperature by 2.9 °C. Amir et al. [11] examined the performance of PCM in a residential building to improve its resiliency to extreme outdoor conditions in case of power outages. They determined that, for some climates, PCM can be beneficial for both energy saving and resiliency (24 h maximum temperature drop with respect to baseline building). The thickness of the PCM for the wall envelope in this application is 10 mm.

In active applications, the PCM is usually totally or partly heated up or cooled down by mechanically forced fluids such as air and water. An active application could be PCM in HVAC system [12], ventilated ceiling [13,14,15], double-skin façade [16], and other ventilation systems. The performance of active PCM applications is mostly higher than that of passive PCM applications. Mossafa et al. [17] studied a PCM-TES free cooling system for the ventilation pre-cooling purpose in summer. They conclude that the coefficient of performance (COP) of this facility can be as high as 7.63. Gonzalo et al. [18] evaluated a ventilation façade with PCM in the outer layer experimentally and numerically. The comparisons to the other conventional envelope show that the PCM increases the thermal inertia of the envelope and provides better thermal response. The authors suggested the necessity of optimization of the airflow rate design. Furthermore, they studied the thermal performance of the ventilated façade during severe winter conditions [19] and found that it increased the indoor temperature from 9 °C to 18 °C.

The ventilated window (VW) is originally designed for better thermal and energy performances of the ventilation system. The VW utilizes the hot air accumulated in the window cavity from transmission heat loss and solar radiation for heating purpose, and self-cooling by outdoor air for cooling purpose [20]. Several studies have investigated this matter numerically and experimentally. Jorge et al. [21] experimentally studied the pre-heating performance of the VW and found that it can increase the inlet air temperature by 6–12 °C. David et al. [22] studied the energy performance of the VW in a controlled climate and found the VW can decrease 10% of the heating demand. Tin-tai et al. [23] numerically studied the cooling and heating abilities of the VW in summer and winter respectively. They found that it is quite effective for both decreasing the cooling load and increasing the space heat gain in Hong Kong and Beijing.

In this study, the PCM adds additional thermal storage to the VW for cooling/heating purposes respectively. In ventilation preheating application, the PCM is cooled down from the ambient air by nighttime ventilation, and the cold PCM pre-cools the ventilated air during the daytime. In ventilation pre-heating application, the PCM stores solar energy during the daytime. It supplies pre-heated air to the VW when heating is demanded.

The PCM has the disadvantage of low thermal conductivity. In this study, the PCM heat exchanger is made by thin PCM plates (thickness = 0.0125 m), to compensate for this disadvantage. The distance between two PCM plates is set as 0.006 m; it is an optimized value for both the heat discharge/charge rate and the total thermal storage capacity of the PCM heat exchanger in both ventilation pre-cooling [24] and ventilation pre-heating [25] cases.

This paper experimentally studied the thermal and energy performances of the PCMVW for ventilation pre-heating and pre-cooling respectively. The study chose some main parameters that influence the thermal and energy performances of the PCMVW. Moreover, the annual energy-saving potential of this system with different control strategies in a building in different climate zones should be examined in modeling simulations, and this paper provided useful experimental data for model validation.

2. Experimental setup

Two windows are set up in the south wall of the façade lab. The lab is located on the top floor of the building and is in an open area with no obstructions from the surroundings. The PCM enhanced ventilated window (PCMVW) system is made by two parts: the PCM heat exchanger part and the VW part, see Fig. 1. The PCM heat exchanger is made by 62 parallel PCM plates (12.5 mm × 110 mm × 670 mm) in a wooden frame. The distance between the two plates is 6 mm. The PCM used in this experiment is paraffin wax (50%) absorbed in fiberboards. The total heat capacity of the PCM is 117 kJ/kg (10 °C - 30 °C), including the latent heat and sensible heat. The melting and freezing peaks are 21.5 °C and 20.7 °C respectively, as shown in Fig. 2. The specific heat of the PCM is 2.3 KJ/kg/ °C, the density of the PCM is 820 kg/m^3, and the thermal conductivity of the material is 0.18 W/m/ °C.

The outside of the heat exchanger is covered by a glass surface facing outdoor. The inner side of the heat exchanger is insulated by 30 mm wood fiber from the indoor room. The VW is made by a double panel glass (U = 1.1 W/m^2, g = 0.63) in the exterior and a single panel glass (U = 5.7 W/m^2, g = 0.79) in the interior. A 120 mm air cavity between the two glass panels is the path for the ventilated air. The reference window (Ref window) is with the same configuration as the VW in PCMVW system. The

Fig. 1. Experimental setup. The PCMVW in the left and the Reference window in the right.

PCM cooling performance is measured by comparing the temperature difference between the PCMVW system and the conventional VW (Ref window). In ventilation pre-cooling application, the PCM works as a heat sink during the night time. The relatively hot PCM is cooled down by the low-temperature outdoor air in the heat removal mode, as shown in Fig. 3(a). In the ventilation pre-cooling mode, which is mostly during the daytime, the hot outdoor air is ventilated through the cold PCM before ventilating into the room. In this way, the PCM provides pre-cooled air to the indoor HVAC systems, as shown in Fig. 3(b). During the test, the glass surface of the PCM heat exchanger is shaded by a 5 mm wooden board. For the PCMVW system, the ventilated air goes through both the PCM heat exchanger and the VW for the whole day and night, with 50 m^3/h ventilation flow rate. For the Ref window, the VW is ventilated for the whole day and night with the same airflow rate. The ventilation goes from the bottom of the VW, through the ventilated cavity to the indoor room. The flow rate chosen here is based on the ventilation rates for the residences category I recommended by EN 15251 [26] for a 1–2 persons' room.

In ventilation pre-heating application, the PCM works as thermal energy storage. In heat storage mode (Fig. 4(a)), the PCM stores solar energy during the daytime when solar radiation is available. The ventilation only goes through the VW. The air in the VW is heated up mainly by solar radiation. The ventilation of the window brings the hot air to the room so as to decrease the heat supply from the HVAC system and to decrease the heat loss from the window as well. In the ventilation pre-heating mode (Fig. 4(b)), the ventilation goes through both the PCM heat exchanger and the VW. The cold ambient air is heated up by the relatively hot PCM before supply to the indoor room. In this way, the PCM is providing pre-heated air to the indoor HVAC system. In this experiment, the PCM starts to provide heat to the ventilation at 18:30. Before 18:30, only the VW part of PCMVW system is used. The Ref window is ventilated through the VW part the whole day and night.

The VW self-cooling mode is operated when the indoor air temperature is too high for both ventilation pre-cooling and pre-heating cases. In this mode, the vents at the top and bottom of the VW are opened towards the outdoor in order to let the air

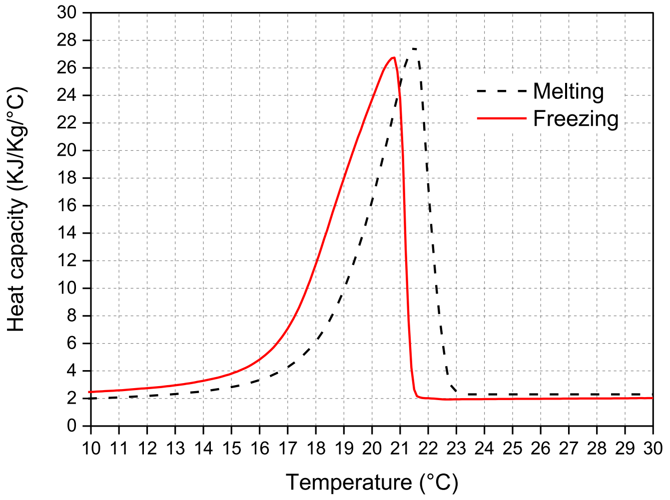
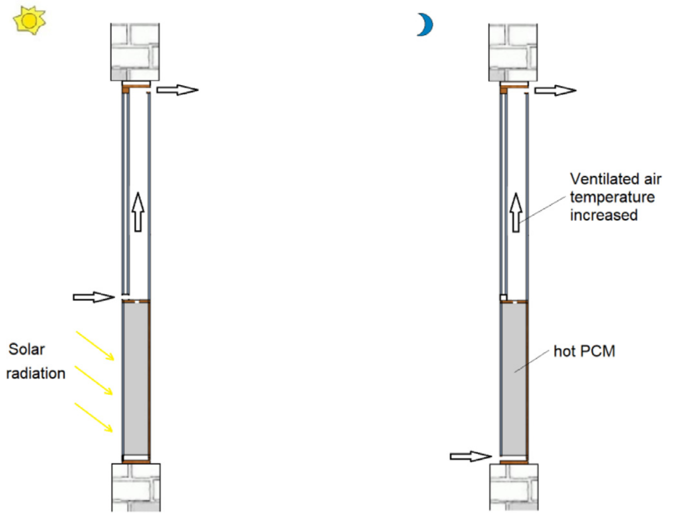


Fig. 2. Heat capacity of the PCM by DSC measurement under heating/cooling rate: 0.5 °C/min [24].



(a) **Heat storage mode**. (b) **Ventilation pre-heating mode.**

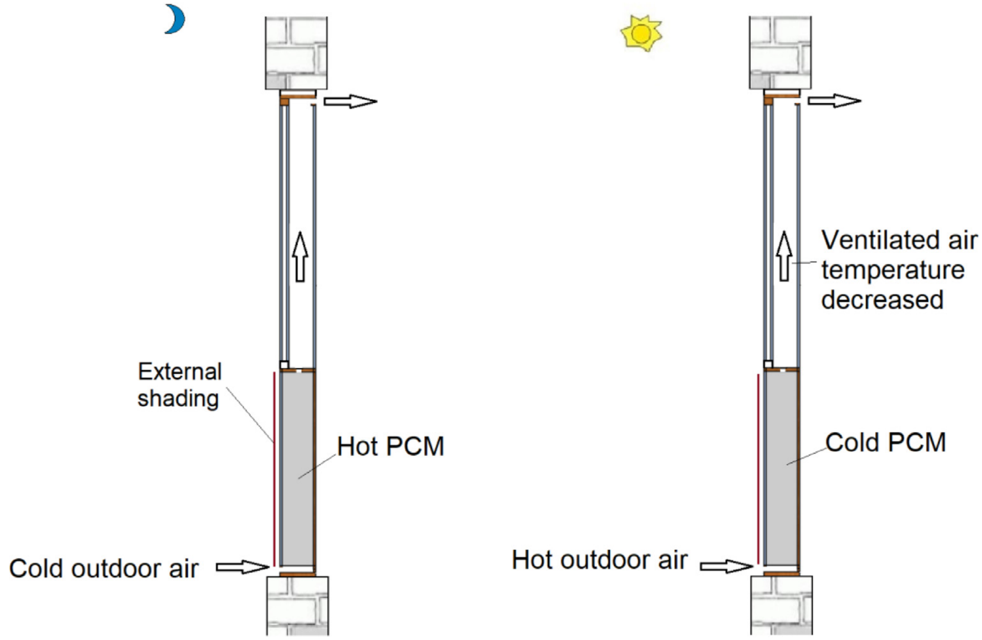
Fig. 4. Working principle of the PCMVW system in ventilation pre-heating application.

driven by natural ventilation and convection pass through the double window, see Fig. 5. It prevents overheating of the window by decreasing the temperature in the VW; thus it decreases the heat gain of the indoor environment from the window.

The ventilation of the two windows is provided by two fans for separate flow rate control, see Fig. 6. The total power of the fans is 93 W. The flow rate of the fans is measured and controlled by Lindab UltraLink FTCU.

The PCMVW system has three sets of valves in three different positions: at the bottom and the top of the PCM heat exchanger, and at the top of the VW, see Fig. 7. Each valve is controlled by a small motor with a specific ID that can be controlled by a computer, see Fig. 8. The power of each motor is 1.2 W. The valves control where the source air comes from. The Ref window has two sets of valves at the bottom and the top of the VW. The valves and motors are the same as in the PCMVW system.

180 type K thermocouples are used for temperature measurement. Fig. 7 shows a part of them. The measured temperature uncertainty is ± 0.15 °C. Three PCM plates and three air cavities between PCM plates are chosen for the temperature measurement in the PCM heat exchanger. A Kipp & Zonen CMP 22 pyranometer with ± 2% measurement uncertainty is used for outdoor solar radiation measurement. The temperature and radiation measurement data are collected by two Fluke Helios Plus 2287A data loggers. The log frequency is 10 s.



a. Heat removal mode. b. Ventilation pre-cooling mode.

Fig. 3. Working principle of the PCMVW system in ventilation pre-cooling application.

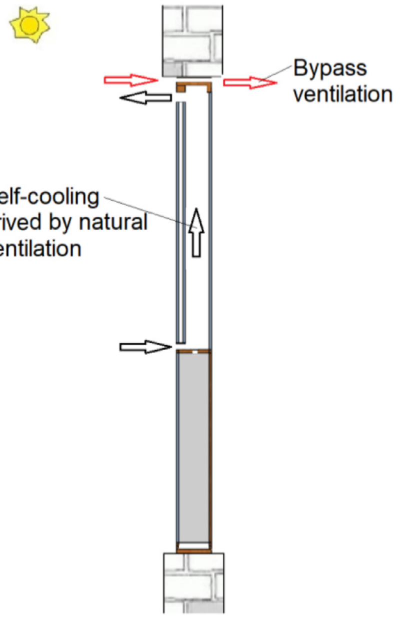


Fig. 5. Working principle of the VW self-cooling.

3. Results

3.1. Ventilation pre-cooling application

The experiment for ventilation pre-cooling application was operated from June 26–30 and July 12– 22, 2019, with 50 m^3/h airflow rate for both windows. The PCMVW system is ventilated through both the PCM heat exchanger and VW, while the Ref window is ventilated only through the VW. The purpose of this test is to determine the main parameters that influence the PCM thermal and energy performance, by analyzing the system as well as comparing it with the results from the Ref window. Figs. 9–11 show some of the measured results.

The PCM temperature has a periodic variation along with the fluctuation of the outdoor air temperature, as seen in Fig. 9. The PCM has a temperature drop during the night period and a temperature rise during the daytime. The $\overline{T}_{\text{night}}$ is defined as the average outdoor air temperature during the PCM heat removal mode. The$\overline{T}_{\text{day}}$ is defined as the average outdoor air temperature during the PCM ventilation pre-cooling mode. The DT is defined as $\overline{T}_{\text{day}}$ - $\overline{T}_{\text{night}}$. The outdoor air temperature difference varies from [1–12 °C].

Four indexes are defined to represent the PCM thermal and energy performances in ventilation pre-cooling application. These indexes are Heat removal amount, Ventilation energy saving amount, Inlet temperate decrease, and Cooling effect hours. The four indexes are chosen to compare the performance of the PCMVW to the reference VW in 3 aspects: the PCM thermal behavior, thermal and energy effect of the air system, and the system effective time. There are more indexes in literature, but they are all in the category of the aforementioned 3 aspects.

In the ventilation pre-cooling mode of the PCMVW system, the PCM cools down the ventilated air in the PCM unit. The air in the PCM unit has a temperature stratification, see Fig. 10. In this period, the inlet air temperature is the highest, and is close to the outdoor air temperature. The heat removal amount is calculated by the amount of heat removed from the ventilated air by the PCM, which can be calculated by the temperature drop of the ventilated air.

$$\text{Heat removal amount} = \int_{t} q\rho_{air}Cp_{air}(T_{inlet} - T_{outlet})dt \qquad (1)$$

Where t is the time period when PCM cools down the ventilated air in Fig. 10.

The ventilation inlet air temperature to the room is illustrated in Fig. 11. During the PCM ventilation pre-cooling mode, the inlet of the PCMVW system is lower than the Ref window. The PCM effective time is defined as the hours when the inlet air temperature of the PCMVW window is 0.5 °C lower than the Ref window, namely $T_{\text{ref inlet}}$- $T_{\text{PCMVW inlet}}$ > 0.5 °C. The inlet temperature decrease is the average value of $T_{\text{ref inlet}}$- $T_{\text{PCMVW inlet}}$ during the effective hours. The ventilation energy saving in ventilation pre-heating application is calculated by Eq. (2).

$$Q_1 = \int_{t'} q\rho_{air}Cp_{air}(T_{\text{refinlet}} - T_{\text{PCMVWinlet}})dt \qquad (2)$$

Fig. 6. The exhaust fans for the ventilation system.

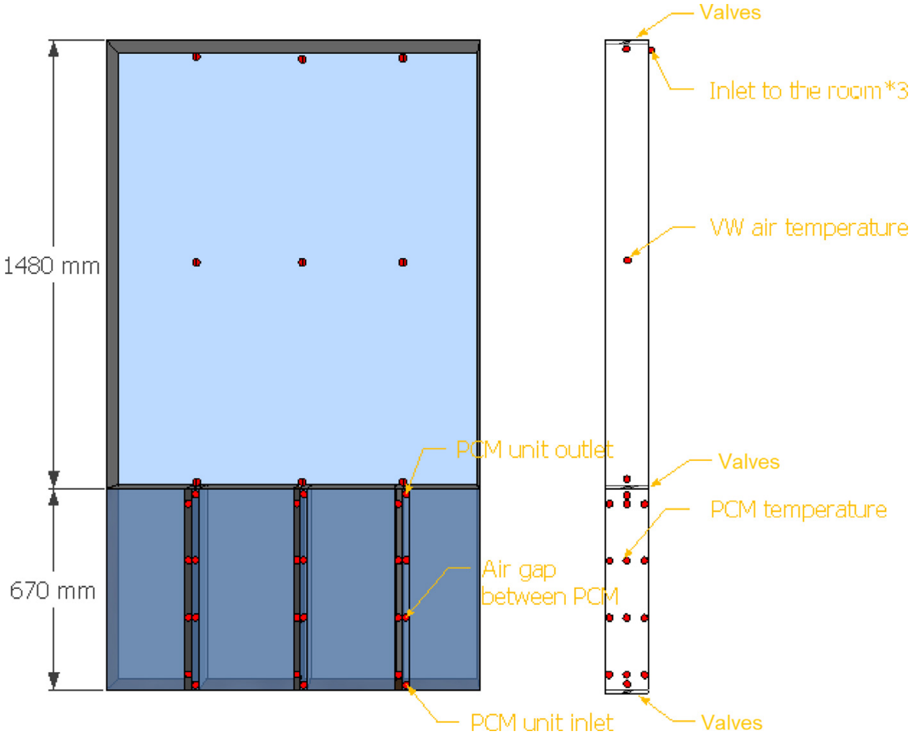


Fig. 7. Temperature measurement in the PCMVW system.

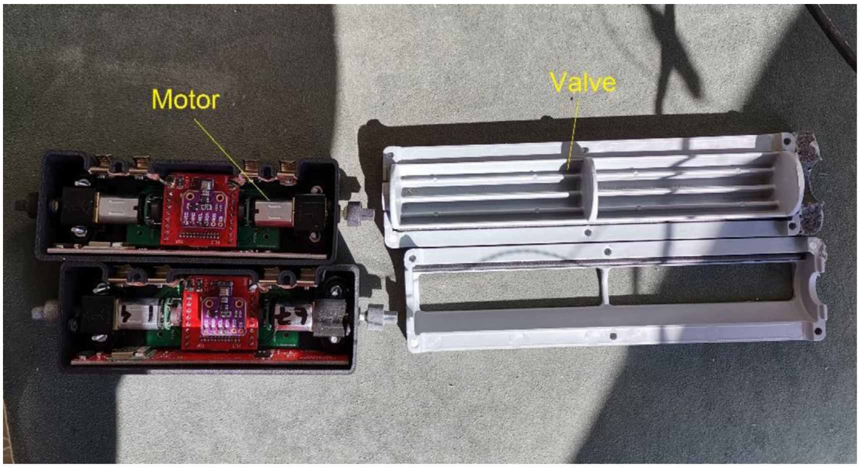


Fig. 8. Valves and motors for airflow direction control.

Where *t'* is the PCM effective time.

The correlation coefficient r between two variables x and y measure their linear association. Given a pair of variables $\{(x_1,y_1), \bullet\bullet\bullet(x_i,y_i), \bullet\bullet\bullet(x_n,y_n)\}$,

$$r = \frac{\sum_{i=1}^{n}(x_i-\overline{x})(y_i-\overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\overline{x})^2}\sqrt{\sum_{i=1}^{n}(y_i-\overline{y})^2}} \tag{3}$$

Where n is the sample size, and

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n}x_i \qquad \overline{y} = \frac{1}{n}\sum_{i=1}^{n}y_i \tag{4}$$

$-1 \le r \le 1$. $r = 0$ indicates there is no linear correlation between x and y. $r = 1$ is total positive linear correlation and $r = -1$ is total negative correlation.

Table 1 shows the correlation coefficient between the outdoor environment and the PCM thermal and energy performance when $q = 50$ m^3/h. The DT has the strongest correlation with all four indexes. It indicates that the day and night temperature difference has the highest influence on PCM thermal and energy performance.$\overline{T}_{\mathrm{night}}$ has a negative correlation with the four indexes. While$\overline{T}_{\mathrm{day}}$ has a positive correlation with the four indexes.

The Heat removal amount, Ventilation energy saving amount, and Inlet temperate decrease are in positive linear relation with DT, see Fig. 12. Compare Fig. 12(a) and (b), the heat removal amount, and ventilation energy saving are both increasing along with the increase of the DT. The ventilation energy saving is much smaller than the PCM heat removal amount, due to the heat gain

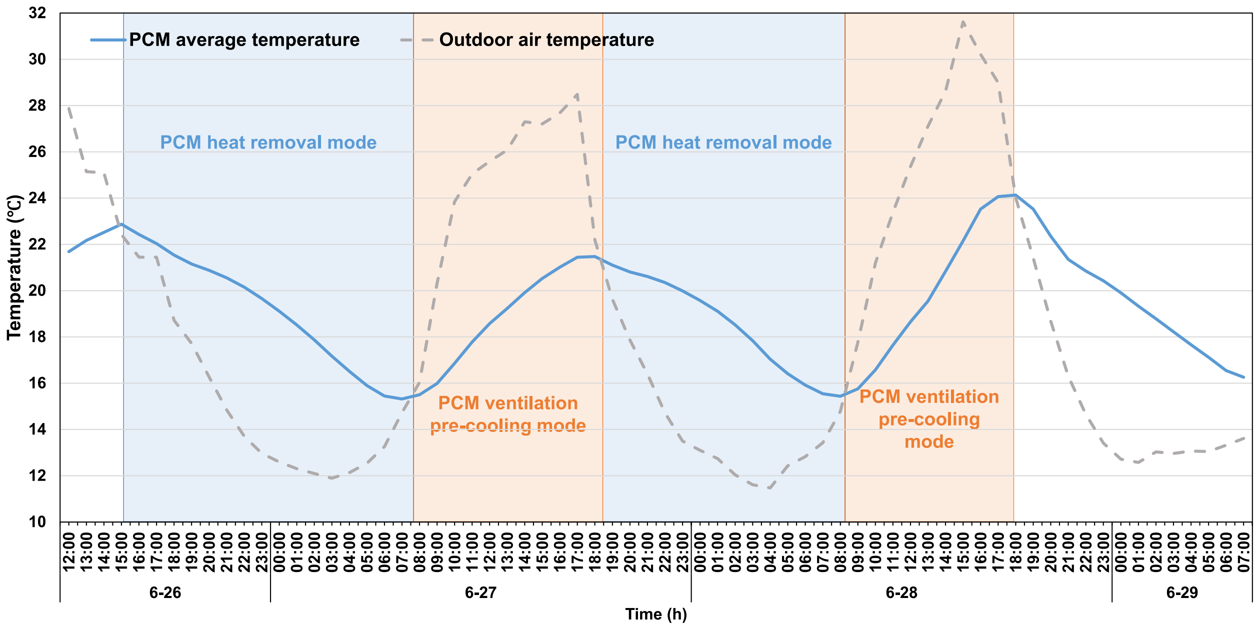


Fig. 9. The average PCM temperature in function with outdoor air temperature.

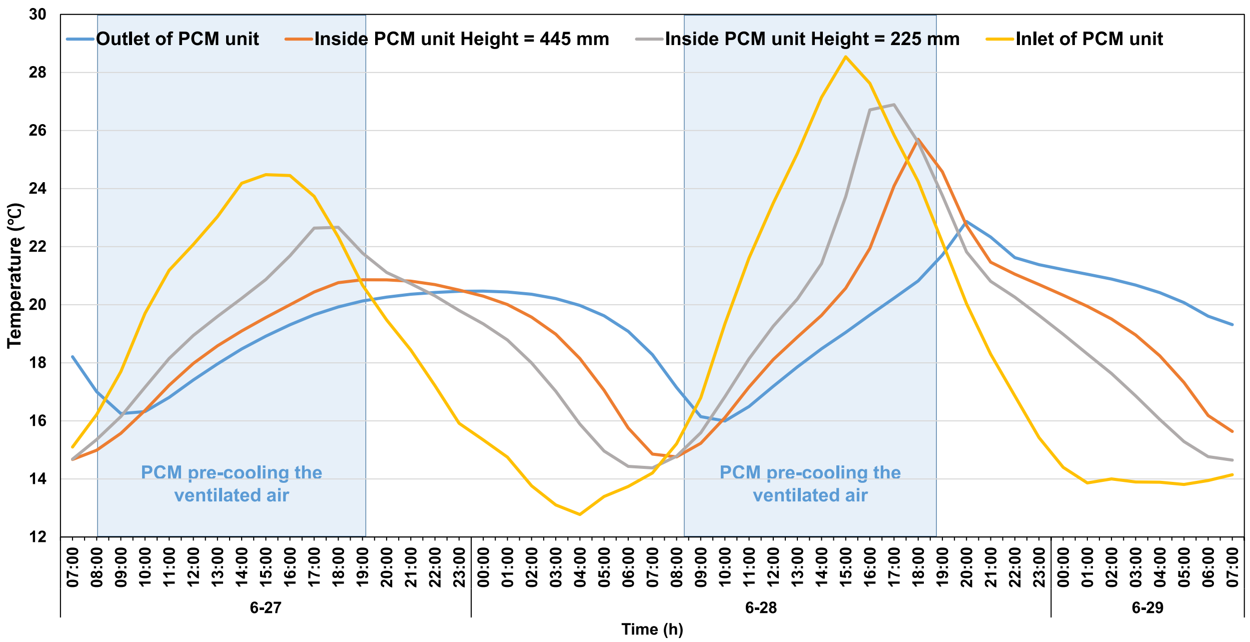


Fig. 10. Air temperature in the PCM unit.

Table 1
Correlation coefficient between the outdoor climate and the PCM thermal and energy performance in ventilation pre-cooling application.

Correlation coefficient (*r*)	Heat removal amount	Ventilation energy saving	Inlet temperate decrease	Cooling effect hours
$\overline{T}_{night}$ -$\overline{T}_{day}$ (DT)	0.91	0.92	0.95	0.55
$\overline{T}_{night}$	−0.58	−0.48	−0.47	−0.33
$\overline{T}_{day}$	0.51	0.61	0.65	0.32

from the VW part. The average heat removal amount is 2.0 MJ per day and the average ventilation energy saving compared to normal VW is 0.7 MJ per day. Fig. 12(c) shows the linear fit of room average inlet temperature decrease in relation to DT. It has the best linear fit. The PCM is effective to provide an inlet temperature decrease for all the tested days. The average inlet temperature decrease is 1.4 °C. Fig. 12(d) shows the correlation between the cooling effect hours and DT. The linear correlation is not strong in this case. For all the measured days, the deviation of the cooling effect hours is not big. The average cooling effect hours is 7.0 h. The PCM is effective in providing pre-cooled air for a long time during the daytime.

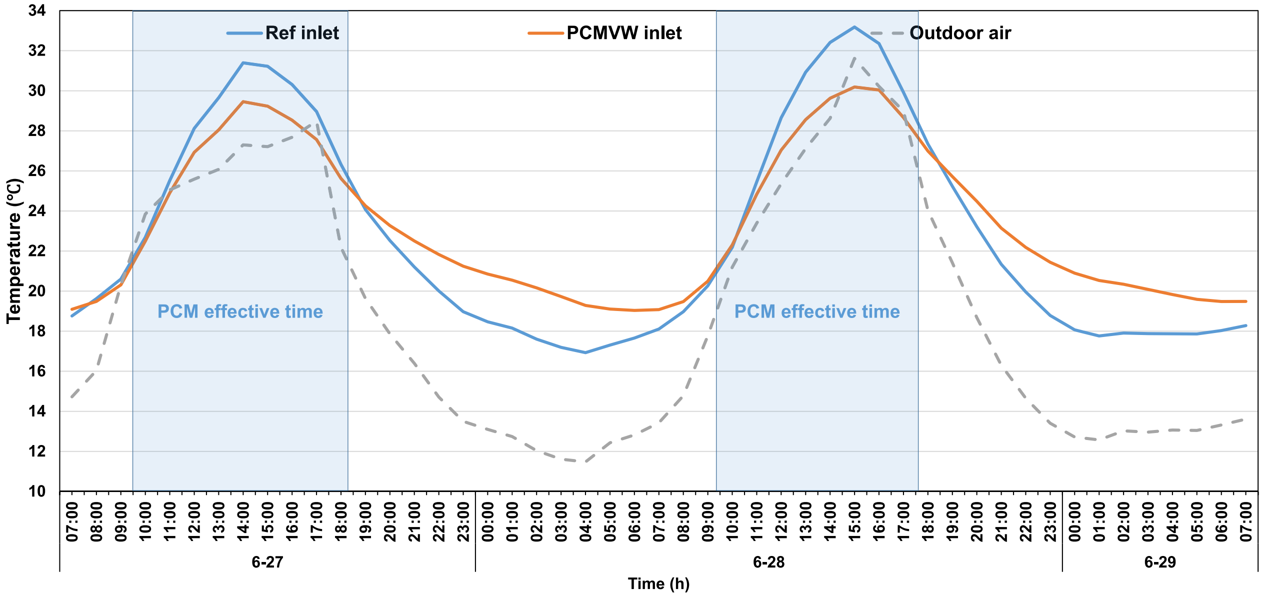


Fig. 11. The room inlet air temperature for both windows.

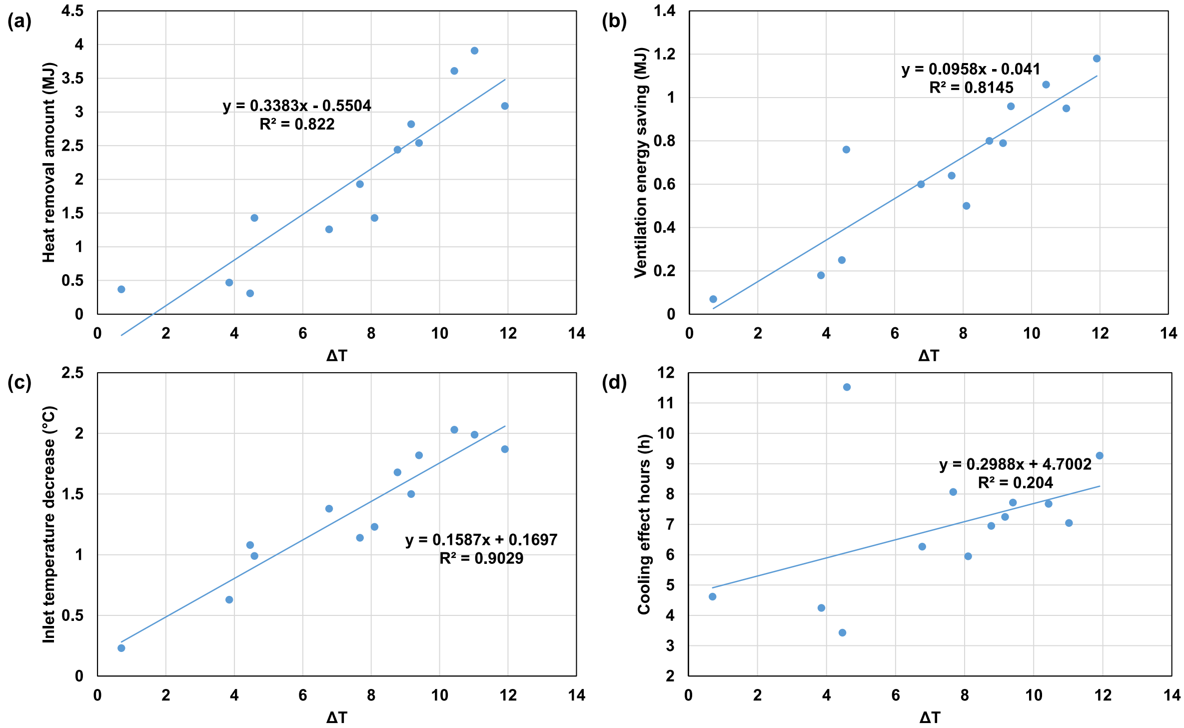


Fig. 12. The daily PCM thermal and energy performance as functions of DT: (a) heat removal amount as a function of DT, (b) ventilation energy saving as a function of DT, (c) inlet temperature decrease as a function of DT and (d) cooling effect hours as a function of DT. R^2 is the variation of the measured date from the prediction functions.

The cooling performance of the PCMVW system is based on a comparison with a normal VW. For both systems, the performance is limited by the solar heat gain in the VW. Consequently, the inlet air temperature presented in Fig. 11 is similar or even higher than the outdoor air temperature.

3.2. Solar energy storage application

The solar energy storage experiment was done on July 2–July 12, 2019. The time of the heat storage mode is set as 8:30–18:30, when both windows are ventilated only through the VW. The time of ventilation pre-heating mode is set as 18:30–8:30 the next day, when the PCMVW system ventilates through both PCM heat exchanger and VW, while the Ref window ventilates through VW. Fig. 13 shows the measured outdoor weather condition and the PCM temperature. The solar radiation level is the total solar radiation (both direct and diffuse) received by the south wall. It is calculated by the daily integration of the solar radiation per square meter surface. The solar radiation level is within the range [3–18 W/m^2] and the nighttime outdoor air temperature within the range [11–17 °C]. The daily outdoor air temperature varies from [12.5–20.5 °C].

Similar to the ventilation pre-cooling application, four indexes are defined to represent the PCM thermal and energy performance for ventilation pre-heating application. These indexes are Heat storage amount, Ventilation energy saving amount, Inlet

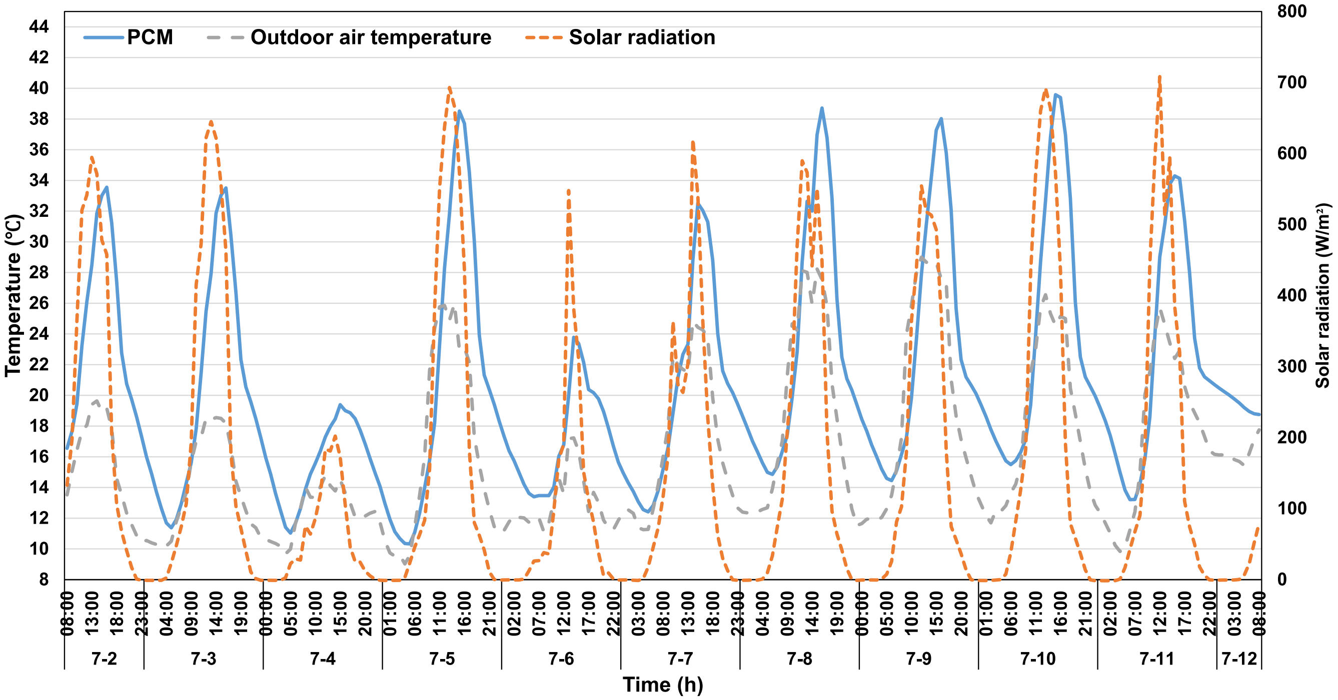


Fig. 13. The measured weather condition and PCM average temperature.

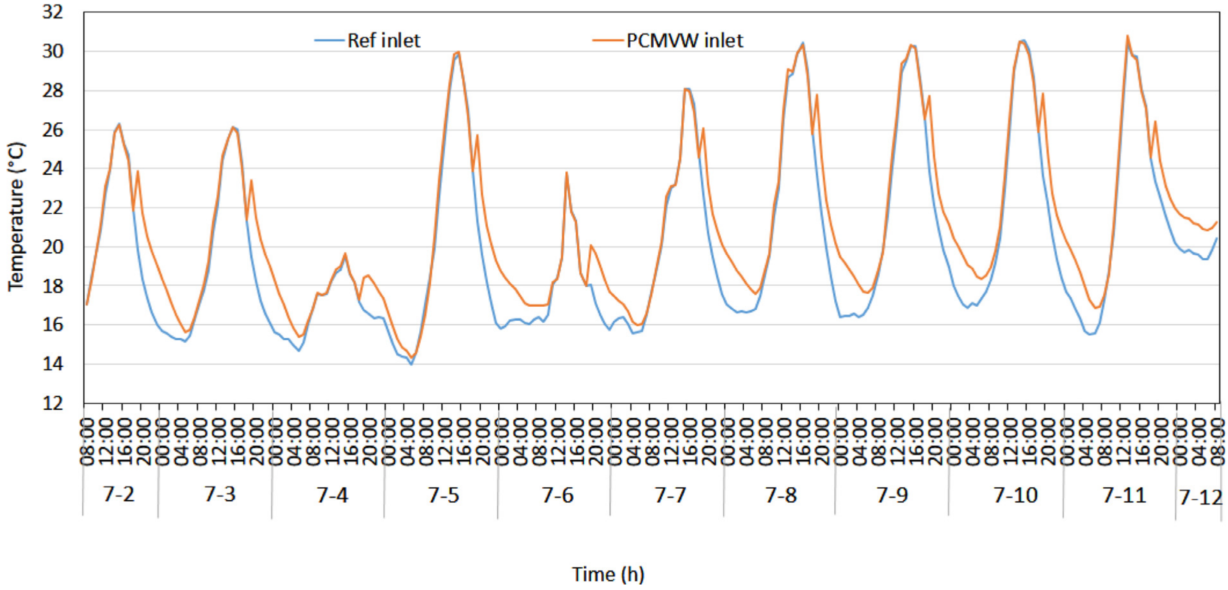


Fig. 14. Room ventilation inlet air temperature.

temperature increase, and Heating effect hours. The PCM heat storage amount is defined by the PCM temperature rise until 18:30. This section will later on investigate the correlations with the solar radiation and outdoor air temperature.

Fig. 14 shows the room ventilation inlet air temperature. The inlet air temperature of the PCMVW window is higher than the Ref window for most of the time during the ventilation pre-heating mode. The ventilation energy saving amount in ventilation pre-heating application is defined as:

$$Q_2 = \int_{t''} q\rho_{air} Cp_{air}(T_{\mathrm{PCMVWinlet}} - T_{\mathrm{refinlet}})dt \qquad (5)$$

t ''- Ventilation pre-heating time.

$q = 50\ \mathrm{m}^3/\mathrm{h}$.

The inlet temperature increase is the average of$(T_{\mathrm{PCMVWinlet}} - T_{\mathrm{refinlet}})$in ventilation pre-heating mode. The heating effect hours are the hours when $T_{\mathrm{PCMVW\ inlet}}$ - $T_{\mathrm{ref\ inlet}}$ > 0.5 °C.

Table 2 shows the correlation coefficient between the outdoor climate and the PCM thermal and energy performance in ventilation pre-heating application. Solar radiation has the strongest correlation with ventilation energy saving, PCM heat storage amount, and room inlet temperature increase, while nighttime outdoor air average temperature has the strongest correlation with Heating effect hours.

Fig. 15 shows the daily PCM thermal and energy performance as functions of solar radiation and nighttime average outdoor air temperature. Fig. 15(a) shows the linear correlation between the PCM

Table 2
Correlation coefficient between the outdoor climate and the PCM thermal and energy performance in ventilation pre-cooling application.

Correlation coefficient (r)	Ventilation energy saving	PCM heat storage amount	Inlet temperature increase	Heating effect hours
Solar radiation	0.94	0.94	0.88	0.43
$\overline{T}_{\text{day}}$	0.81	0.69	0.54	0.74
$\overline{T}_{\text{night}}$	0.25	0.35	−0.07	0.81
DT	0.88	0.68	0.70	0.54

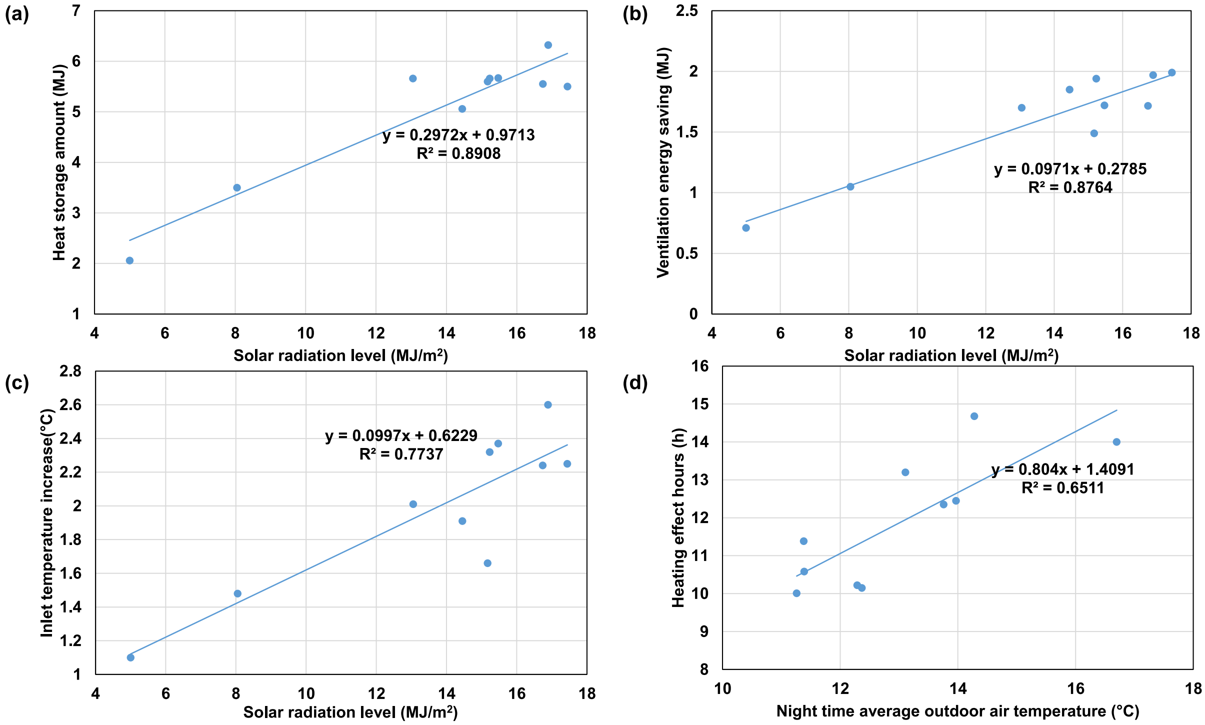


Fig. 15. The daily PCM thermal and energy performance as functions of solar radiation and nighttime average outdoor air temperature: (a) heat removal amount as function of solar radiation level, (b) ventilation energy saving as function of solar radiation level, (c) inlet temperature increase as function of solar radiation level and (d) heating effect hours as function of nighttime average outdoor air temperature.

heat storage amount and the solar radiation level. The higher the received solar radiation, the larger the heat storage amount. The average heat storage amount is 5.1 MJ per day. Fig. 15(b) shows the linear correlation between ventilation energy saving and the solar radiation level. It has a similar trend as the PCM heat storage amount, except for the fact that ventilation energy saving is much smaller than the heat storage amount. The average ventilation energy saving is 1.6 MJ per day. Fig. 15(c) indicates the daily average inlet temperature increase in relation to solar radiation level. It shows the same positive linear correlation. The PCM is effective in providing an inlet temperature increase for all the tested cases. The lowest inlet temperature increase is 1.1 °C for the worst tested scenario. The average inlet temperature increase is 2.0 °C. The best linear fit for heating effect hours is with the night time average outdoor air temperature, see Fig. 15(d). The cooling effect hours for all the tested days are high. The average cooling effect hours is 11.9 h per day. The PCM is effective in providing pre-heated air in long enough period during the night, even in the days when the solar radiation level is relatively low.

3.3. *Ventilated window self-cooling application*

The VW self-cooling mode and its thermal performance to reduce heat gain through the widow are tested, in conditions without shading. Two double windows, one with self-cooling, one without self-cooling are tested. For the one with self-cooling, the vents in the bottom and top of the VW are open towards the outdoor environment. All vents are turned off for the double window without self-cooling. It works as a double-skin façade. The convection air force pushes out the hot air inside the double window. Natural ventilation also occurs when there is wind pressure on the exterior surface. The self-cooling performance is evaluated by measuring the surface temperature of the double window in the period 7th August- 13th August. This section provides the main results.

Fig. 16 shows the surface temperature of the two double windows without shading. The external surface temperature in Fig. 16(a) shows a small difference for both double windows with and without self-cooling. The internal surface temperature for the two double windows are showing different levels of discrepancies, see Fig. 16(b)–(d). The bottom of the internal surface temperature of the window with self-cooling is on average 1.1 °C lower without self-cooling. The top of the internal surface has an average 0.8 °C temperature difference between the two windows. The middle of the internal surface shows the lowest discrepancy, which is 0.4 °C. It indicates that natural ventilation, which is driven by wind pressure, dominates the air ventilation in the double window. In average, the window with self-cooling control can reduce the glass surface temperature by 0.8 °C.

The effect of VW self-cooling application is very limited in the presented experiment. In fact, it is more related to outdoor weather conditions, such as wind direction and wind speed. It is not stable due to the unstable outdoor weather conditions. The VW self-cooling application has to be operated in combination with

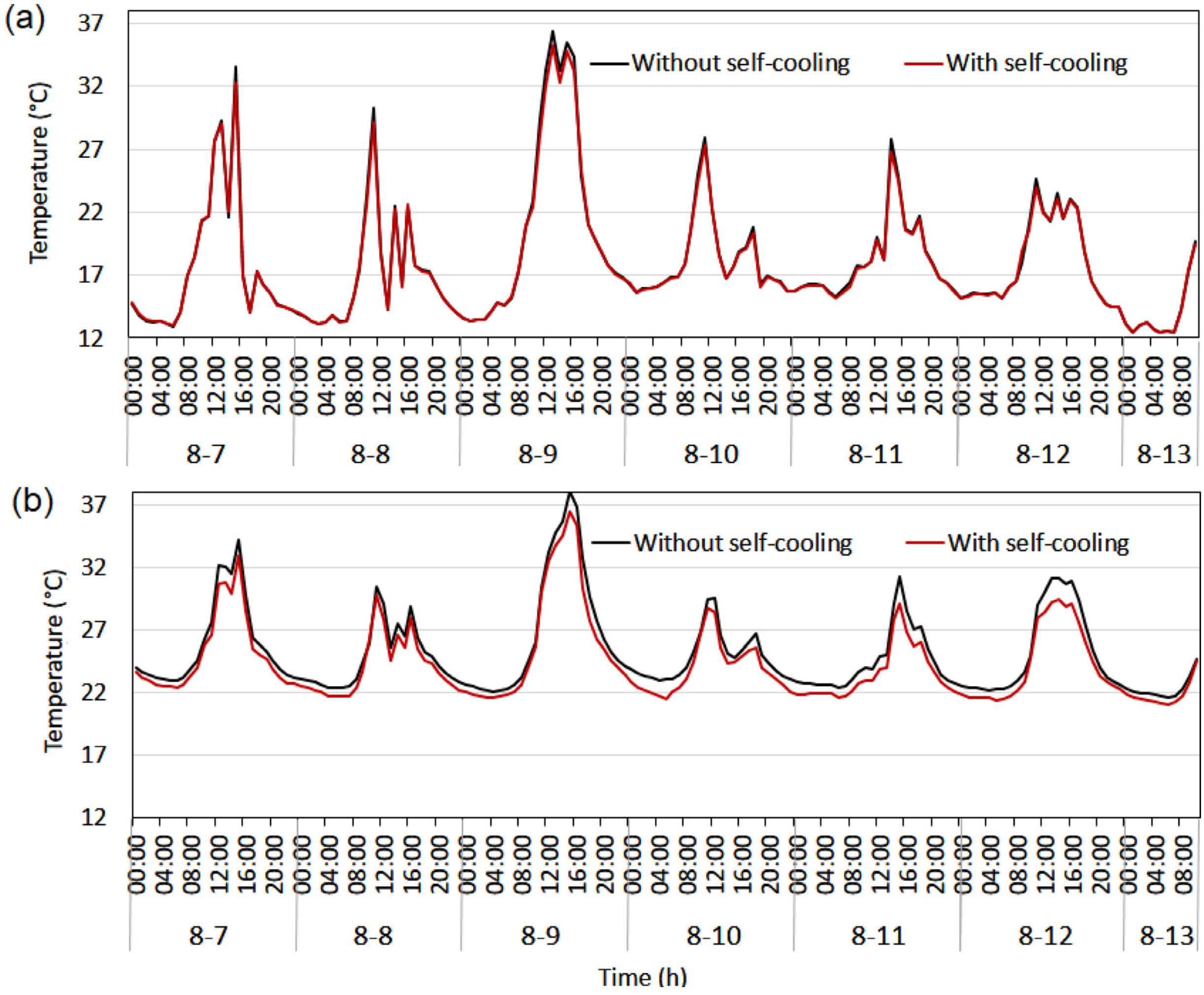


Fig. 16. (a) external surface temperature, (b) internal surface temperature of the two double windows with and without shading.

other PCMVW control strategies to potentially decrease the indoor heat load.

4. Conclusions

This paper experimentally studied a phase change material enhanced ventilated window (PCMVW) and its thermal and energy performance in both ventilation pre-cooling application and ventilation pre-heating application. In ventilation pre-cooling application, the PCM works as a heat sink. The material is cooled down by night ventilation. The cold PCM cools down the ventilation during the daytime. In ventilation pre-heating application, the PCM works as thermal energy storage for solar energy during the daytime and releases the heat for ventilation pre-heating during night time or when ventilation pre-heating is needed. The PCM adds additional thermal energy to the VW. The VW has a self-cooling mode so as to reduce the heat gain through the window when the indoor air temperature is too high. The PCM thermal and energy performance is valued by heat removal/heat storage amount, ventilation energy saving amount, inlet temperature decrease/increase and cooling/heating effect hours.

The experimental setup includes the PCMVW and a Ref window. The Ref window is a VW that has the same configuration as the PCMVW system. The PCM thermal and energy performances are calculated by analyzing the PCM condition as well as comparing the ventilated air conditions with the Ref window. This work presents three different experiments for night cooling, solar energy storage, and double window self-cooling effect.

The night cooling experiment results show that with the PCM heat exchanger, the room inlet air temperature is by average 1.4 °C lower in 7.0 h than the normal VW. The average ventilation energy saving compared to a normal VW is 0.7 MJ/day for the tested period. It is also found that the daily outdoor air temperature difference has the highest influence on the thermal and energy performance. Buildings in a climate with high daily outdoor air temperature differences can benefit more from the PCMVW system in ventilation pre-cooling application. However, the pre-cooling effect of the PCMVW is limited.

The conclusion of the solar energy storage experiment results is that the PCM heat exchanger can increase the inlet air temperature of the VW by 2.0 °C for 12.0 h. The average ventilation energy saving is 1.6 MJ/day compared with a normal VW. The solar radiation level affects the heat storage amount, ventilation energy saving amount, and the inlet air temperature the most. The heating effect hours are more influenced by nighttime outdoor air temperatures, but the overall heating effect hours are quite high even with the lowest night time average outdoor air temperature. Buildings in a climate with higher solar radiation levels can benefit more from the PCMVW system in ventilation pre-heating application. The VW self-cooling experiment demonstrated that the self-cooling mode of the VW can reduce the glass surface temperature by an average of 0.8 °C.

For both ventilation pre-cooling and ventilation pre-heating applications, the PCM heat removal/storage amounts are much higher than the ventilation energy saving. This is because the ventilation goes through the double window part before it is supplied to the indoor room, and the heat loss/gain from the double window is quite high. Even in such cases, the PCM still provides pre-cooled/pre-heated air with long effect time to the room. The thermal and energy performance of PCMVW system can be further improved by two methods: 1. Develop some new control strategies that the ventilation goes from the PCM unit directly to the indoor room. 2. Add solar reflect/absorb curtain in the VW. Those can be done by numerical modeling in future works.

Different ventilation airflow rates can affect thermal and energy performances. However, it is less applicable in experiments than in models to achieve exactly the same boundary conditions. The examination of different control strategies to combine PCM unit ventilation, double window self-cooling, and reflect/absorb curtain is more complicated to fulfill in experiments. The control strategies in building level can be more complicated by involving the indoor environment. Different control strategies should be developed considering both PCM condition and indoor air temperature setpoint.

Declaration of Competing Interest

None.

CRediT authorship contribution statement

Yue Hu: Conceptualization, Data curation, Investigation, Methodology, Writing - original draft, Writing - review & editing. **Per Kvols Heiselberg:** Conceptualization, Funding acquisition, Supervision, Writing - review & editing. **Rui Guo:** Visualization, Writing - review & editing.

Acknowledgements

The authors gratefully acknowledge the EU Horizon 2020 research and innovation program under grant agreement NO. 768576 (ReCO2ST) and the Chinese Scholarship Council(CSC No. 201606050118).

Reference

[1] P. Heiselberg, H. Brohus, A. Hesselholt, H. Rasmussen, E. Seinre, S Thomas, Application of sensitivity analysis in design of sustainable buildings, Renew. Energy 34 (2009) 2030–2036, doi:10.1016/J.RENENE.2009.02.016.

[2] M. Pomianowski, P. Heiselberg, Y Zhang, Review of thermal energy storage technologies based on PCM application in buildings, Energy Build. 67 (2013) 56–69, doi:10.1016/j.enbuild.2013.08.006.

[3] M. Pomianowski, P. Heiselberg, R.L. Jensen, R Lund Jensen, Dynamic heat storage and cooling capacity of a concrete deck with PCM and thermally activated building system, Energy Build. 53 (2012) 96–107, doi:10.1016/j.enbuild.2012.07.007.

[4] M. Pomianowski, P. Heiselberg, R.L Jensen, Full-scale investigation of the dynamic heat storage of concrete decks with PCM and enhanced heat transfer surface area, Energy Build. 59 (2013) 287–300, doi:10.1016/j.enbuild.2012.12.013.

[5] F. Kuznik, J. Virgone, Experimental investigation of wallboard containing phase change material: data for validation of numerical modeling, Energy Build. 41 (2009) 561–570, doi:10.1016/J.ENBUILD.2008.11.022.

[6] A. De Gracia, L. Navarro, A. Castell, L.F. Cabeza, L.F Cabeza, Numerical study on the thermal performance of a ventilated facade with PCM, Appl. Therm. Eng. 61 (2013) 372–380, doi:10.1016/j.applthermaleng.2013.07.035.

[7] X. Jin, X. Zhang, Thermal analysis of a double layer phase change material floor, Appl. Therm. Eng. 31 (2011) 1576–1581, doi:10.1016/j.applthermaleng.2011.01.023.

[8] C. Wang, X. Huang, S. Deng, E. Long, J Niu, An experimental study on applying PCMs to disaster-relief prefabricated temporary houses for improving internal thermal environment in summer, Energy Build. 179 (2018) 301–310, doi:10.1016/J.ENBUILD.2018.09.028.

[9] C. Wang, S. Deng, J. Niu, E Long, A numerical study on optimizing the designs of applying PCMs to a disaster-relief prefabricated temporary-house (PTH) to improve its summer daytime indoor thermal environment, Energy 181 (2019) 239–249, doi:10.1016/J.ENERGY.2019.05.165.

[10] S.A. Memon, H.Z. Cui, H. Zhang, F Xing, Utilization of macro encapsulated phase change materials for the development of thermal energy storage and structural lightweight aggregate concrete, Appl. Energy 139 (2015) 43–55, doi:10.1016/J.APENERGY.2014.11.022.

[11] A. Baniassadi, D.J. Sailor, H.J Bryan, Effectiveness of phase change materials for improving the resiliency of residential buildings to extreme thermal conditions, Sol. Energy 188 (2019) 190–199, doi:10.1016/J.SOLENER.2019.06.011.

[12] M. Yamaha, S. Misaki, The evaluation of peak shaving by a thermal storage system using phase-change materials in air distribution systems, HVAC&R Res. 12 (2006) 861–869, doi:10.1080/10789669.2006.10391213.

[13] K. Yanbing, J. Yi, Z Yinping, Modeling and experimental study on an innovative passive cooling system—NVP system, Energy Build. 35 (2003) 417–425, doi:10.1016/S0378-7788(02)00141-X.

[14] X. Wang, J. Niu, Performance of cooled-ceiling operating with MPCM slurry, Energy Convers. Manage. 50 (2009) 583–591, doi:10.1016/J.ENCONMAN.2008.10.021.

[15] T. Kondo, S. Iwamoto, Research on thermal storage using rock wool PCM ceiling board, ASHRAE Trans. (2006) 526–531.

[16] A. De Gracia, L. Navarro, A. Castell, L.F Cabeza, Energy performance of a ventilated double skin facade with PCM under different climates, Energy Build. 91 (2015) 37–42, doi:10.1016/j.enbuild.2015.01.011.

[17] A.H. Mosaffa, C.A. Infante Ferreira, M.A. Rosen, F Talati, Thermal performance optimization of free cooling systems using enhanced latent heat thermal storage unit, Appl. Therm. Eng. 59 (2013) 473–479, doi:10.1016/J.APPLTHERMALENG.2013.06.011.

[18] G. Diarce, A. Urresti, A. García-Romero, A. Delgado, A. Erkoreka, C. Escudero, et al., Ventilated active façades with PCM, Appl. Energy 109 (2013) 530–537, doi:10.1016/j.apenergy.2013.01.032.

[19] A. De Gracia, L. Navarro, A. Castell, Ruiz-Pardo Á, S. Alvárez, L.F Cabeza, Experimental study of a ventilated facade with PCM during winter period, Energy Build. 58 (2013) 324–332, doi:10.1016/j.enbuild.2012.10.026.

[20] M. Liu, P.K. Heiselberg, O.K. Larsen, L. Mortensen, J Rose, Investigation of different configurations of a ventilated window to optimize both energy efficiency and thermal comfort, Energy Procedia 132 (2017) 478–483, doi:10.1016/j.egypro.2017.09.660.

[21] J.S. Carlos, H. Corvacho, P.D. Silva, J.P Castro-Gomes, Real climate experimental study of two double window systems with preheating of ventilation air, Energy Build. 42 (2010) 928–934.

[22] D. Appelfeld, S. Svendsen, Experimental analysis of energy performance of a ventilated window for heat recovery under controlled conditions, Energy Build. 43 (2011) 3200–3207, doi:10.1016/J.ENBUILD.2011.08.018.

[23] T. Chow, Z. Lin, K. Fong, L. Chan, M He, Thermal performance of natural airflow window in subtropical and temperate climate zones – a comparative study, Energy Convers. Manage. 50 (2009) 1884–1890, doi:10.1016/J.ENCONMAN.2009.04.028.

[24] Y. Hu, P.K. Heiselberg, A new ventilated window with PCM heat exchanger – performance analysis and design optimization, Energy Build. (2018), doi:10.1016/J.ENBUILD.2018.03.060.

[25] Y. Hu, P.K. Heiselberg, H. Johra, R Guo, Experimental and numerical study of a PCM solar air heat exchanger and its ventilation preheating effectiveness, Renew. Energy (2019) 145 Under review, doi:10.1016/J.RENENE.2019.05.115.

[26] E.N. 15251, Indoor environmental input parameters for design and assessment of energy performance of buildings – addressing indoor air quality, thermal environment, lighting and acoustics, Eur. Comm. Stand. 3 (2007) 1–52, doi:10.1520/E2019-03R13.Copyright.