Thermal performance of ventilated solar collector with energy storage containing phase change material

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ABSTRACT

This paper presents a ventilated solar collector with energy storage of fins containing Phase Change Material (PCM) in the air cavity and investigates its thermal performance. The idea is to use PCM in combination with ventilation as a thermal controller of indoor environment and to consequently decrease the building energy consumption both in summer and winter time. The main parts of the solar collector are plate fins with small thickness containing PCM fitted into the ventilation cavity, which is a good way to compensate the low thermal conductivity of PCM. The solar collector can absorb large amount of solar energy because of the high latent capacity of PCM. The energy is supplied into the indoor environment by means of ventilation. The system can be integrated into the building envelopes such as windows for low-energy building.

This study starts with examining the discharge process of PCM fins by numerically investigating 9 cases of PCM fins in different fin thickness and air gap thickness in a transient 2D model. Then the charge process of PCM fins in consideration of solar radiation is studied in a time-dependent 3D model. The results show that for discharge process, a larger fin thickness and a smaller air gap thickness are good for the increase of total heat exchange amount of PCM fins during discharge process. However, when continuing to increase the fin thickness and keeping the air gap thickness fixed at 5 mm, the total heat exchange amount does not continue the increase trend. The fin thickness of 20 mm has the largest heat exchange amount and the largest utilization percentage. Mechanical ventilation is needed only in cases with air gap thickness as 5mm. The system has the potential to completely or partly substitute the air-conditioning and heating system and a big energy saving potential.

KEYWORDS

Low-energy building, ventilated solar collector, Phase Change Material, heating and cooling unit

1 INTRODUCTION

Building energy use is approximately 40% of the total energy use in Europe (Soares, Costa, Gaspar, & Santos, 2013). The main part of it is to cover the heating and cooling demand. In order to decrease this energy use and obtain higher energy efficiency, Thermal Energy Storage (TES) technics have been used in buildings. A novel idea of TES is to add Phase Change Materials (PCMs) to building elements and air conditioning systems, and this idea is gaining increasing interests in research as well as in the building market(Iten, Liu, & Shukla, 2016).

PCMs can store not only sensible heat energy but also latent heat energy, although the amount of sensible heat energy is much smaller in comparison with latent heat capacity(Akeiber et al., 2016). The heat been stored is much higher than the normal thermal mass applied in buildings. In addition, the temperature of PCMs will stay almost constant in the phase change period, which means the surface temperature of building envelope will not be too high, thus avoiding a high heat transfer (Osterman, Tyagi, Butala, Rahim, & Stritih, 2012), which is good for maintain indoor thermal comfort.

PCMs are well known of their advantages that can be perfectly applied in lightweight building façades(Fang, Tang, & Cao, 2014). Various kinds of PCMs can be used for thermal storage and thermal control for such building components. There are many studies about the PCMs integrated in opaque constructions, but limited research on integration in transparent materials and shading components. Michal et al. (Pomianowski, Heiselberg, & Lund Jensen, 2012) implemented PCMs in concrete and tested the performance of the hollow core deck made of this new material. The results show that there is a potential to apply PCMs in concrete elements. Hicham et al. (Karlsen, Heiselberg, Bryn, & Johra, 2016)(Heiselberg et al., 2013) put PCMs shading device into a double layer ventilated window and tested its efficiency. The results show that both shading and ventilation could improve the energy efficiency in comparison with the original non-ventilated ones. Diarce et al.(Diarce et al., 2013) put a PCM sheet into a ventilated façade, the thermal performance of such device was investigated in comparison with different traditional ventilation systems by means of simulation in Design Builder software. The results indicated that the implement of PCM sheet is advantage for prevent overheating problems. Alvaro et al.(De Gracia et al., 2013) put macro-encapsulated PCM into the ventilated façade and investigated its effect through different control strategies. The experimental results shows that free cooling during night is the most effective control strategy to decrease the indoor cooling load.

The basic principle of the ventilated solar collector with PCMs is to combine the advantages of solar energy capture and latent heat storage of PCMs. In the winter condition, the PCMs are charged by the solar energy in the daytime and discharged in the night (and during some of the daytime) by means of ventilation air. The building energy use is then diminished by this principle. The energy efficiency will be further improved if solar control strategies are taken into consideration in summer daytime.

In this paper, fins containing PCM are chosen to fit in the ventilation cavity as a compensation to its low thermal conductivity and to increase heat transfer surface. Firstly, this paper presents the concept of ventilated solar collector in combination with PCM. Then the COMSOL Multiphysics program is used for the thermal performance of the ventilation cavity. The PCM fins are considered fully charged as initial condition and the discharge procedure is investigated.

2 MODELS AND METHODS

2.1 Concept of ventilated solar collector in combination with PCM

In this study, the development and design of the ventilated solar collector with PCM fins fitted in the air cavity is based on commercial product produced by the company Climawin, which produces a series of active ventilated solar collectors, but without PCM. Figure 1 shows the concept of ventilated solar collector with PCM.

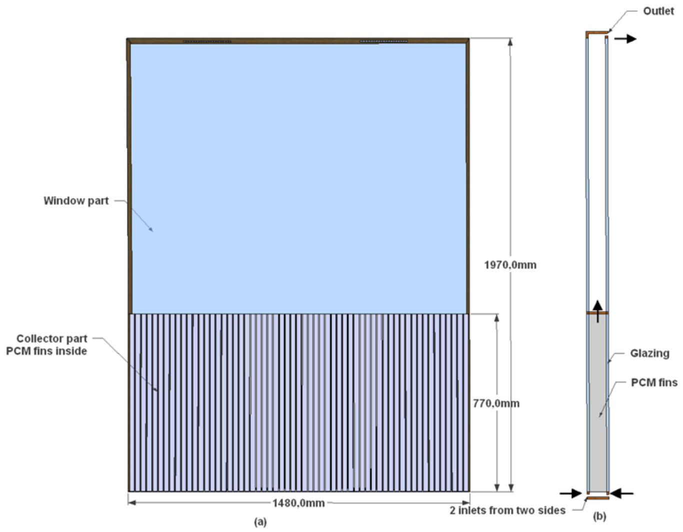


Figure 1: Ventilated façade with solar collector consist of PCM fins (a) Front view; (b) Side view

2.2 Thermal properties of PCM

The Paraffin wax with a phase transition at approximately 21.7 is chosen for this model. The main thermal properties of the PCM shown in Table 1 are provided by Energain DuPont(*DuPont^{TM}. (2007). Data Sheet - Measured Properties.*, n.d.).

Table 1:Thermal properties of paraffin wax (DSC method: 0.2 K/min; range of temperature: 5-30℃)

Thermal property	**Density(kg/m^3)**	**Thermal conductivity(W/(m·K))**	**Total heat storage capacity(kJ/kg)**	**Total latent heat(kJ/kg)**
Paraffin wax	1001.5	0.14	140	70

The specific heat has been measured experimentally at Artois University(Dû, Zalewski, Lassue, Dutil, & Rousse, 2012). The results are compared to the information provided by the manufacturer Energain including the total heat capacity and latent heat and they turned out to be in great consistency. The peak melting temperature is 20.0 ℃, and the peak freezing temperature is 15.4℃ according to the record. Figure 2 shows the experimental fictive heat capacity.

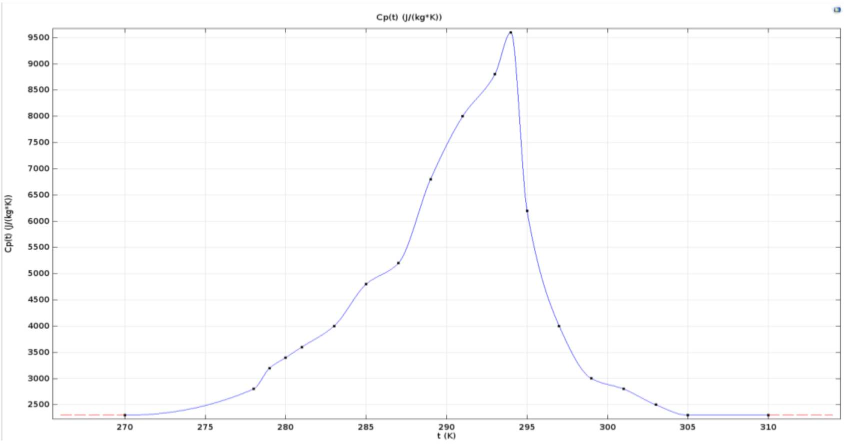


Figure 2: The fictive specific heat of PCM [20]

2.3 Model description

The air cavity of ventilated solar collector is of 1.31 m in height, 1.06 m in width and 0.075 mm in depth. The PCM fins are fixed in the air cavity vertically. The inlet is in the bottom of the air cavity while the outlet is in the top. The optimizations of the thickness of PCM fins as well as the distance between fins are based on the simulation conducted in the COMSOL Multiphysics program. The ventilation cavity is simplified to a 2D model and only a section of the fin with air path. The PCM fins are supposed to fill the whole ventilation cavity so a length of 1.31 m is chosen for all the fins in this program.

3 DISCHARGE PROCESS OF PCM FINS

3.1 Boundary conditions and equations

Some assumptions are made to investigate the discharge process of the PCM fins.

a. The airflow rate is chosen as 106 m^3 /h at which condition the air states in the air path are all laminar flow.
b. The inlet air temperature is defined as 273.15K to simplify the simulation.
c. The physics condition of the model is defined as conjugate heat transfer, with conjugation of heat transfer and laminar flow.
d. The PCM fins are considered as fully charged with an initial temperature of 300.15K.
e. The vertical boundaries are defined as symmetric as they almost face the same sections.
f. The simulations are from 0s to 18000 s with a time step of 10 s.

The boundary conditions are the same for all simulation models in order to insure the comparable results. Symmetry boundary condition is considered for simplification of the calculation as seen in Figure 3.

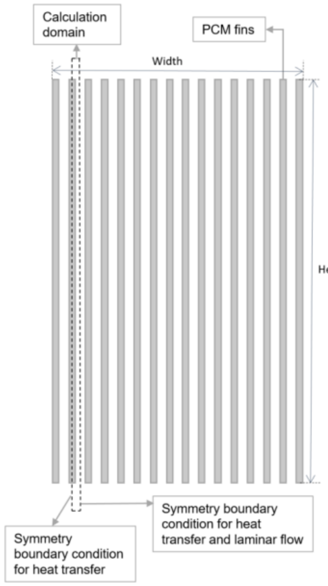


Figure 3: Calculation domain in COMSOL model

The Non-Isothermal Flow and Conjugate Heat Transfer interfaces contain the fully compressible formulation of the continuity equation and momentum equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \tag{1}$$

$$\rho \frac{\partial u}{\partial t} + \rho u \cdot \nabla u = -\nabla p + \nabla \cdot (\mu \left(\nabla u + (\nabla u)^T \right) - \frac{2}{3} \mu (\nabla \cdot u) I) + F \tag{2}$$

Where
ρ is the density (kg/m3)
u is the velocity vector (m/s)
p is pressure (Pa)
μ is the dynamic viscosity (Pa·s)
F is the body force vector (N/m3)

For heat equation,

$$\rho C_p \left(\frac{\partial T}{\partial t} + (u \cdot \nabla) T \right) = -(\nabla \cdot q) + \tau : S - \frac{T}{\rho} \frac{\partial \rho}{\partial T}\bigg|_p \left(\frac{\partial p}{\partial t} + (u \cdot \nabla) p \right) + Q \tag{3}$$

Where
C_p is the specific heat capacity at constant pressure (J/(kgK))
T is absolute temperature (K)
q is the heat flux by conduction (W/m2)
τ is the viscous stress tensor (Pa)
S is the strain-rate tensor (1/s)
Q contains heat sources other than viscous heating (W/m3)

For heat transfer in PCM:

$$\rho C_p \frac{\partial T}{\partial t} = -\left(\nabla \cdot q\right) - T\frac{\partial E}{\partial t} + Q \tag{4}$$

where **E** is the elastic contribution to entropy (J/(m^3·K))

3.2 Results

When cold air goes through the gaps between the fins from below, the PCM in the lower part of the fins melt first and faster than in the upper part. The cold air is heated and temperature increases along the vertical length. Heat transfers from the hot PCM fins to the inlet air, in which progress the PCM is discharged.

At first fin depth as 0.075 m is chosen. There are 9 cases to be investigated as listed in Table 2. The airflow rate is chosen as constant for all the cases, which means the air velocity in the gaps between fins would be different. The total fin surface area and total PCM volume for different cases are also different. Those factors have an interaction influence to the performance of the ventilated solar collector.

Table 2: Analysis conditions for discharge process of PCM fins

Case	Fin thickness (mm)	Air gap thickness (mm)	Fin number	Fin depth (mm)	Air flow rate (m³/h)	Air velocity in gap (m/s)	Total fin surface area (m²)	Total PCM volume(m³)
1	5	5	106			0.75	22.30	0.052
2	5	10	70			0.56	14.73	0.034
3	5	15	53			0.50	11.15	0.026
4	10	5	70			1.11	15.69	0.069
5	10	10	53	75	106	0.75	11.88	0.052
6	10	15	42			0.62	9.42	0.041
7	15	5	53			1.50	12.62	0.078
8	15	10	42			0.93	10.00	0.062
9	15	15	35			0.76	7.86	0.052

Figure 4 and Figure 5 show the average air temperature of outlet for different cases. As shown in Figure 4, for the same air gap thickness, outlet air temperature of fin thickness of 5 mm reaches the inlet air temperature faster than in the other cases. Nevertheless, the larger the fin thickness, the more stable the outlet air temperature due to the larger total PCM volume, which contributes to more heat being stored. As seen in Figure 5, for the same fin thickness, air gap thickness of 5 mm has the higher heat exchange rate and air gap thickness of 15 mm has the lower air change rate compared to other cases. Meanwhile, air gap thickness of 5 mm has the highest outlet average temperature compared to other cases.

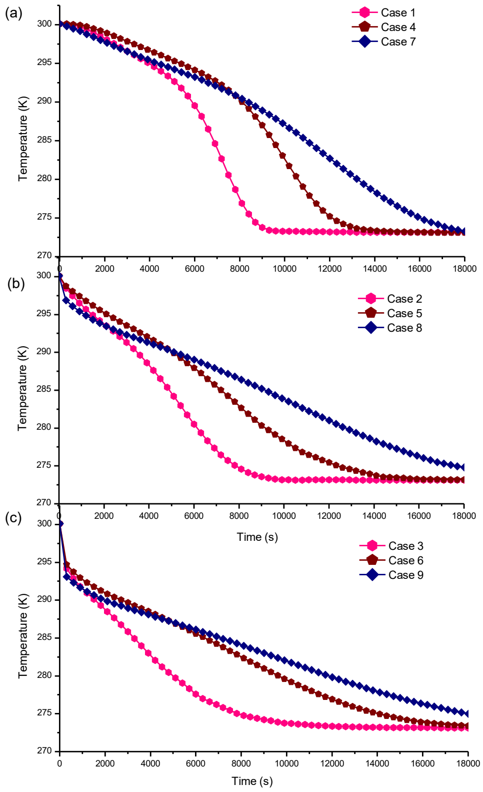


Figure 4: Outlet air temperature of fins with same air gap thickness (a) air gap thickness=5 mm; (b) air gap thickness=10 mm; (c) air gap thickness=15 mm.

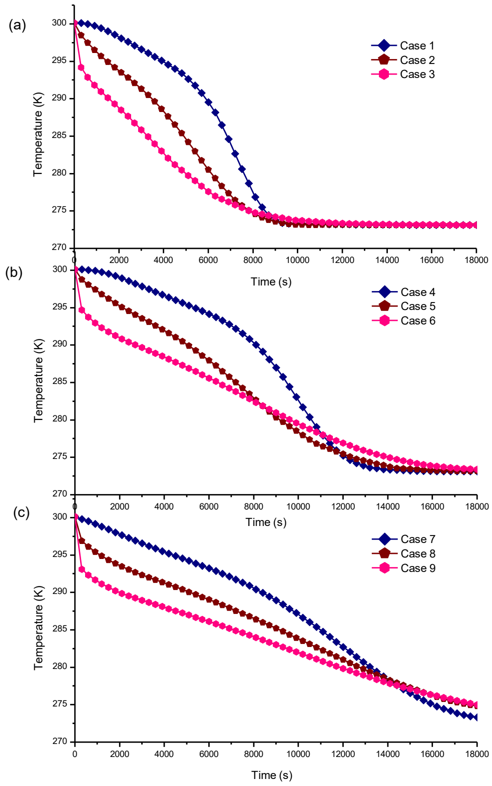


Figure 5: Outlet air temperature of fins with same fin thickness (a) fin thickness=5 mm; (b) fin thickness=10 mm; (c) fin thickness=15 mm.

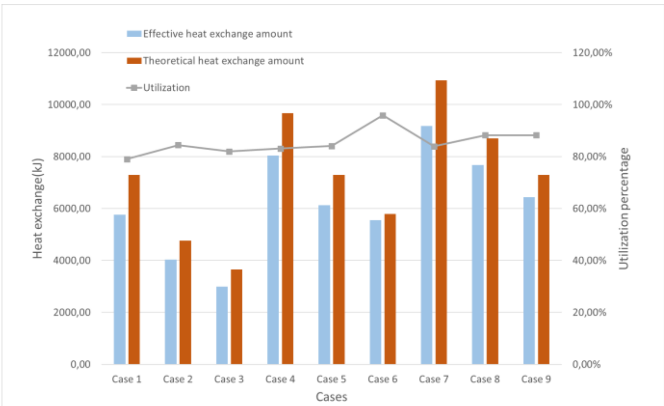


Figure 6:Total heat exchange amount between inlet air and PCM fins for 9 cases

Figure 6 presents the total heat exchange amount for different cases. There is a similar pattern shown as the average outlet air temperature, which is in connection with total PCM volume. The comparison of effective heat exchange amount and theoretical heat exchange amount shows that case 6 has the largest PCM utilization percentage. Cases 1, 5, 9 have the same theoretical heat exchange amount but PCM utilization percentage is increasing.

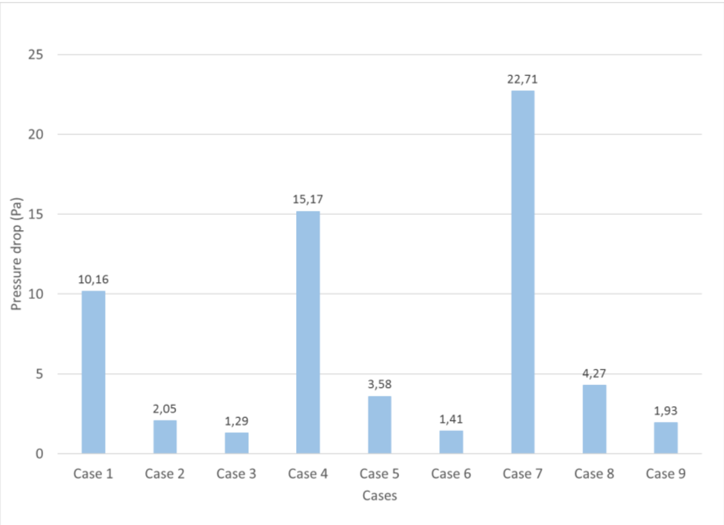
Table 3 shows the correlations of fin thickness and air gap thickness to other factors.

Table 3: The correlations of fin thickness and air gap thickness to other factors

	Number of fins	Air velocity	Surface area	Total PCM amount	Heat exchange rate	Discharge time	Total heat exchange amount
Fin thickness	-	+	-	+	-	+	+
Air gap thickness	-	-	-	-	+	-	-

As shown in table 3, when the fin thickness increases, the heat exchange rate decreases and the discharge time increases consequently. Nevertheless, the total heat exchange rate increases, and the outlet air temperatures are more stable as seen in Figure 4. The total heat exchange amount is more directly in connection with the total PCM volume, which means a larger fin thickness and a smaller air gap thickness. So it can be concluded that a larger fin thickness and a smaller air gap thickness are good for discharge process of PCM fins. However, cases 5-9 could not be fully discharged in 5 hours. Case 4 has the second total heat exchange amount and a relatively short discharge time, which means 10 mm fin thickness and 5 mm air gap thickness is the optimized size of the PCM ventilation unit.
Figure7 (a) shows the pressure loss of ventilation cavity is shown in, and Figure7 (b) shows the fan energy consumption for the 18000 s considering the fan efficiency as 0.7. Cases 1, 4, 7 are used for mechanical ventilation and other cases are suited for nature ventilation.

(a)



(b)

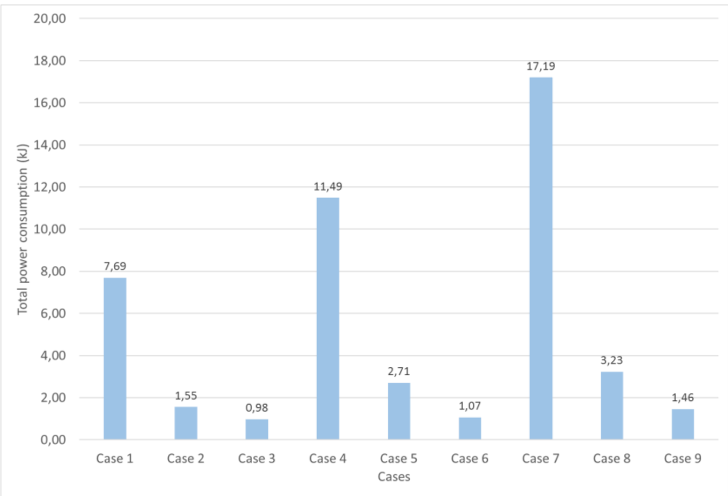


Figure 7:Pressure loss and total fan energy consumption of ventilation cavity (a) Results for different groups; (b) Total fan energy consumption for 5 hrs.

Two more cases are investigated to further evaluate the influence of fin thickness to the total heat exchange amount. As shown in Table 4, the air gap thickness is fixed at 5 mm and fin thickness increased from 15 mm to 25 mm. Figure 8 shows the outlet air temperature, and the heat exchange rate of the discharge process tends to be in two stages. In the first stage, the heat exchange rate is mainly influenced by total surface area of fins. Case 7 has the largest fin surface area and heat exchange rate. In the second stage, the heat exchange rate is mainly influenced by the total PCM volume. Case 11 has the largest total PCM storage volume and heat exchange rate. The discharge time of the two cases are more than 5 hours. Figure 9 shows the total heat exchange amount, and the fin thickness of 20 mm has the largest heat exchange amount. The effective value of heat exchange amount is compared with the theoretical value. It turns out that the largest utilization percentage of PCM is a fin thickness of 20 mm.

Table 4: Analysis conditions for discharge process of PCM fins

Case	Fin thickness (mm)	Air gap thickness (mm)	Fin depth (mm)	Air flow rate (m^3/h)	Air velocity in gap (m/s)	Total fin surface area (m^2)	Total PCM volume(m^3)
7	15	5			1.50	12.62	0.078
10	20	5	75	106	1.78	10.58	0.083
11	25	5			2.12	9.30	0.086

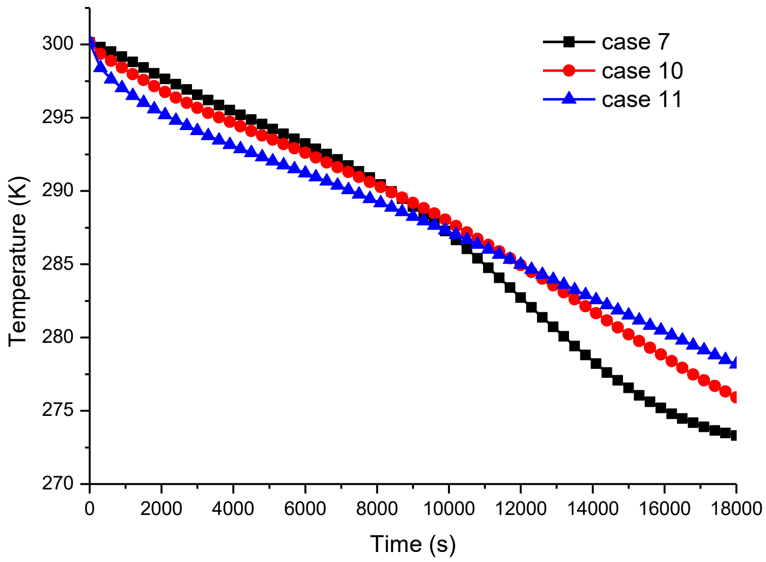


Figure 8: Outlet air temperature with air gap thickness as 5 mm

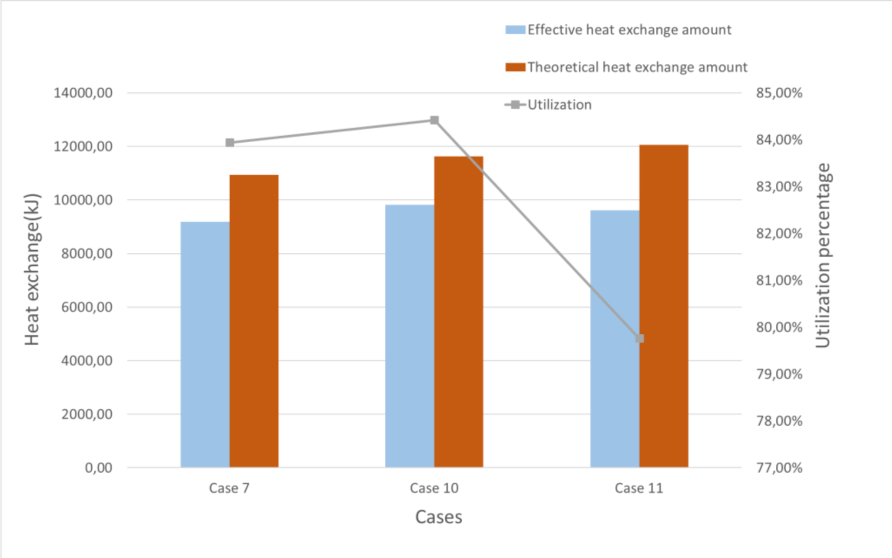


Figure 9: Total heat exchange amount between inlet air and PCM fins

4 CONCLUSION AND DISCUSSION

This paper propositions a ventilated solar collector with fins containing Phase Change Material (PCM) in the air cavity. The discharge and charge process of PCM fins are analysed and the thermal performance of the PCM fins in the air cavity are investigated. The main conclusions are as listed below.

1. For the discharge process, the heat exchange rate is in proportion to the total fin surface area while total heat storage amount is in proportion to the total PCM volume. The larger the fin thickness, the more stable the outlet air temperature.
2. The heat exchange rate of discharge process tends to be in two stages. In the first stage, the heat exchange rate is mainly influenced by total surface area of fins. In the second stage, the heat exchange rate is mainly influenced by the total PCM volume. A greater fin thickness and a smaller air gap thickness are good for the increase of total heat exchange amount of PCM fins during the discharge process.
3. Considering the discharge time, cases 5-9 cannot be fully discharged in 5 hours while case 4 has a high total heat exchange amount and a relatively short discharge time, which makes 10 mm fin thickness and 5 mm air gap thickness the optimized size of a PCM fin device.
4. However, when increasing the fin thickness and air gap thickness fixed at 5 mm, the total heat exchange amount does not continue the increase trend. The fin thickness of 20 mm has the largest heat exchange amount and the largest utilization percentage.
5. Pressure drop and energy consumption results show that mechanical ventilation should be considered when the air gap thickness is 5 mm. For other cases nature ventilation would be sufficient.

There is more work to be done for the system. Firstly, the inlet air temperature should be taken directly from outdoor environment. Thus the real outdoor environment should be taken into account for the further simulation work. What is more, the charge and discharge process should be investigated consecutively to get an overall evaluation of the thermal behaviour of the device. Last but not least, the system should be installed into a building site to further study the effect of the thermal behaviour of indoor environment and control strategies during different seasons.

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