Experimental analysis of a PCM-Air heat exchanger for building cooling in hot-arid climates

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Abstract: The use of phase change materials as energy storage of cooling during the night-time to be retrieved during the hot daytime is one of the sustainable strategies for cooling buildings. In the present work, a modular PCM-air heat exchanger appropriate for buildings application in hot-arid regions has been investigated experimentally utilising commercial paraffin-based RT28HC PCM modules. The thermal performance of the proposed system has been investigated under various operating conditions for different PCM modules arrangement. The results confirmed that a compact design made of narrow PCM air flow channels has better thermal performance resulting in 10-14% reduction in the charging time, whilst this has a negligible impact on the comfort time during the discharging period. The results have shown that the proposed system design is capable of operating satisfactorily under the hot-arid climate conditions, and substantial energy savings are achievable.

Keywords: Thermal energy storage; Phase change material; Free cooling.

1. INTRODUCTION

In the hot-arid regions, the natural cooling available at night hours can be introduced into the building interior to provide instantaneous comfort and to be stored in an appropriate thermal energy storage (TES) medium for later use. This concept is referred to in the literature as the free cooling of buildings, which is much applicable for locations with a diurnal temperature variation larger than 12 K (Zalba et al., 2004, Waqas and Din, 2013).

TES systems play a key role in the incessant operation of the free cooling technology (Dincer and Dost, 1996). TES mechanisms are classified into sensible, latent and chemical storages or a combination of these (Sharma et al., 2009). Phase change materials (PCMs) has gained growing interest worldwide as efficient lightweight TES substances for building applications. PCMs have the advantage of a large energy density and possess an isothermal performance which makes these substances appropriate for maintaining the thermal comfort day and night (Pasupathy et al., 2008, Regin et al., 2008).

The utilisation of PCM as a specialised energy storage in the free cooling systems has launched since 2000 by Turnpenny et al. (2000, 2001). Recent development in this technology has been reported in several published reviews including (Thambidurai et al., 2015, Iten et al., 2016, Alizadeh and Sadrameli, 2016, Zeinelabdein et al., 2018). The majority of the studies emerged were carried out considering system application in moderate and continental climates. The results of free cooling systems applications under moderate summer conditions have shown a capability of lowering buildings cooling load and limiting the operation of air conditioning systems. On the other hand, regions with a high demand for cooling reaching almost eight months a year had got less attention and hence, published work is very rare.

In the present article, a comprehensive experimental investigation has been carried out. The study aims to evaluate the charging and discharging characteristics of a modular PCM energy storage for free cooling of buildings under hot-arid climate conditions through examining the impact of the PCM stacking arrangement under various inlet operating conditions.

2. SYSTEM DESCRIPTION

For free cooling of buildings, the PCM should be selected so the outlet air temperature from the system will be within the comfort zone during the discharging time, besides allowing rapid PCM solidification during the charging time (Yanbing et al., 2003, Arkar et al., 2007). The paraffin RT28HC with a transition temperature 27-29 °C produced by Rubitherm GmbH (RUBITHERM) has been selected as it is compatible with the charging ambient temperature and the thermal comfort range of 25.5-30 °C suggested by Merghani (2001) during summer months in Khartoum, a city with hot-arid climate located in Sudan. Specifications of the RT28HC PCM are presented in Table 1.

Table 1: Thermo-physical properties of the RT28HC PCM (RUBITHERM).

Property	Value
Phase change temperature	27-29 °C
Heat storage capacity (latent+sensible heat between 21 °C and 36 °C)	250 kJ/kg ± 7.5%
Specific heat (both phases)	2 kJ/kg K
Thermal Conductivity (both phases)	0.2 W/m K
Density (solid at 15 °C)	880 kg/m³
Density (liquid at 40 °C)	770 kg/m³

The laboratory system for free cooling of buildings consists of an arrangement of microencapsulated PCM modules placed inside an aluminium enclosure; an air circulating fan coupled with a variable speed controller; and ducting system components such as circular ducts, divergent, convergent and regulating dampers. The compact storage modules (CSM) filled with RT28-HC PCM which produced by Rubitherm were used in the TES system as shown in Figure 1a. The proposed TES unit comprises 16 modules, stacked horizontally over each other in eight parallel rows with two modules in each row. The total weight of the PCM utilised is approximately 8.8 kg. A rectangular aluminium enclosure 1.25 m (L) × 0.31 m (W) × 0.26 m (H) was fabricated to accommodate the entire arrangement of the PCM storage modules. The PCM modules arrangement inside the main container is illustrated in Figure 1b.

In the present study, both mass and thickness of the PCM were kept constant in all case studies, while the height of air passages between the PCM modules was varied in order to understand the impact of the TES compactness on the system thermal performance. Three different air channels heights were considered 10, 15, and 20 mm. The entire rig was thermally insulated to reduce the heat exchange with the surrounding environment.

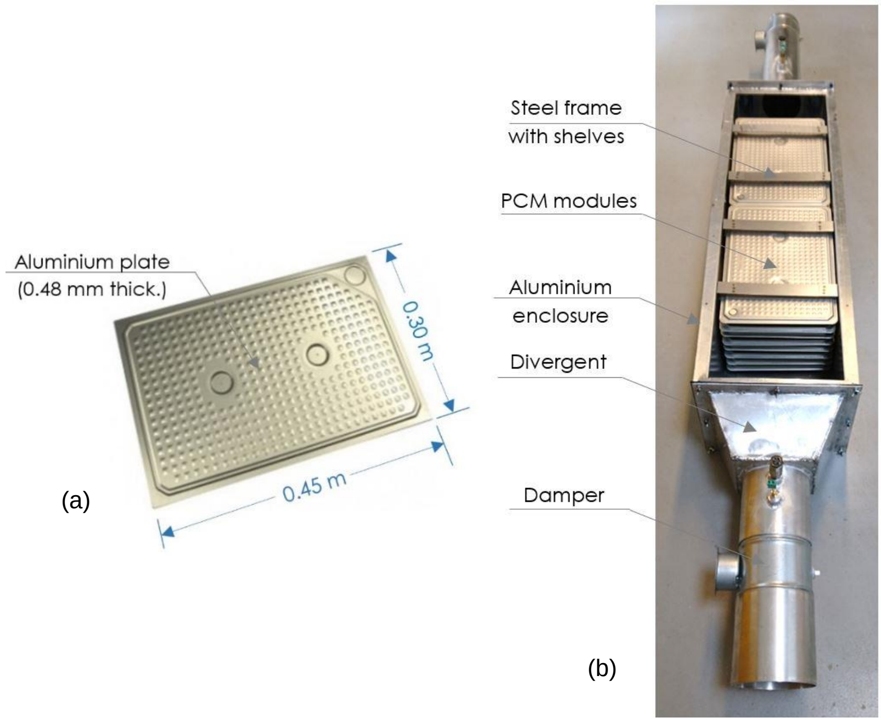
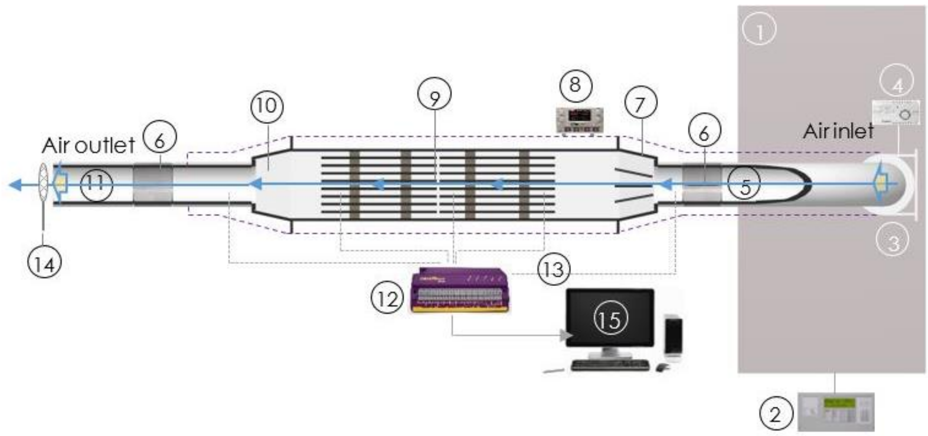


Figure 1: (a) The CSM unit produced by Rubitherm GmbH (RUBITHERM), (b) PCM modules arrangement.

3. EXPERIMENT SETUP

The experiments have been carried out in a laboratory environment where an environmental chamber was used to simulate the climate conditions of the hot-arid regions. A schematic diagram of the experiment setup is illustrated in Figure 2. When air temperature and humidity inside the chamber (1) reach the required values set using the chamber control panel (2), the axial fan (3) is used to blow the controlled air from the chamber at a given flow rate regulated by the fan speed controller (4) through the connected insulated duct. The air circulates through a connected divergent with air guides (7) to the main duct which contains the PCM modules (9). The air extracts or adds heat to the PCM based on the operating mode (charging or discharging) before exiting the system through the outlet aperture (11) to the surrounding space. The measuring instruments used in the experiments included thermocouples for temperature measurement at the inlet, outlet and the surrounding space; anemometers for air flow, and a data taker for data acquisition and recording.



1	Environmental Chamber	6	Damper	11	Outlet aperture
2	Chamber control panel	7	Divergent	12	Data logger
3	Axial fan	8	Power supply unit	13	Thermocouples
4	Fan controller	9	PCM storage unit	14	Anemometer
5	Insulated flexible duct	10	Convergent	15	Personal PC

Figure 2: A schematic of the experiment setup.

In the experiments, a range of inlet air temperatures and air flow rates have been investigated for both charging and discharging phases. Each test was performed considering steady inlet air temperature and flow rate throughout the entire test period. The charging air temperature has been selected based on the prevalent ambient temperature during summer nights in Khartoum. Three inlet temperatures have been selected; 21 and 23 °C to simulate charging during the transitional months (March and April), and 25 °C for charging during the overheated months (May-October). On the other hand, the adopted inlet air temperatures in the discharging phase are based on the average daytime room temperature obtained for a typical room under moderate and hot summer of Khartoum using DesignBuilder simulation software. The tested operating conditions are presented in Table 2.

Table 2: Operating conditions for the charging and discharging processes

	PCM initial temp.	Inlet air temp.	Air flow rate
Charging tests	34 °C	21, 23, and 25 °C	30, 50, and 70 L/s
Discharging tests	22 °C	32, 36, and 40 °C	7, 16, and 25 L/s

4. RESULTS AND DISCUSSION

This section analyses and discusses the results of PCM charging and discharging processes for free cooling of buildings. It assesses the impact of air channels height under various inlet air conditions on the thermal performance of the TES system.

4.1. PCM charging performance

During the charging mode, the cold air was drawn from the environmental chamber with constant temperature and flow rate over the PCM modules via a fan connected between them. The flowing air allowed heat removal from the liquid PCM which changed its state gradually to solid. The charging tests were carried out until the whole PCM solidification is achieved.

Figure 3 compares the outlet air temperature and the heat transfer rate for the three tested cases at the inlet air temperature of 23 °C and the air flow rate of 70 L/s. It is noticed that the outlet air temperature in the case of the smaller channels height arrangement was higher during the initial half of the charging period and lower during the latter period than the larger channels height arrangement (Figure 3a). The TES system with a smaller channels height exhibited a higher cooling rate during the phase change period compared to that of larger channels height (Figure 3b). This is attributed to the enhanced heat transfer rate yielded by air velocity increase inside the narrow channels, leading to a faster solidification time. Moreover, it is clear that a longer solidification time is required with larger air flow channels. At inlet air temperature 23 °C and air flow rate 70 L/s, the solidification periods for cases A, B, and C were 5.6, 5.2, and 4.8 hours, respectively, with the narrow channels achieving faster solidification.

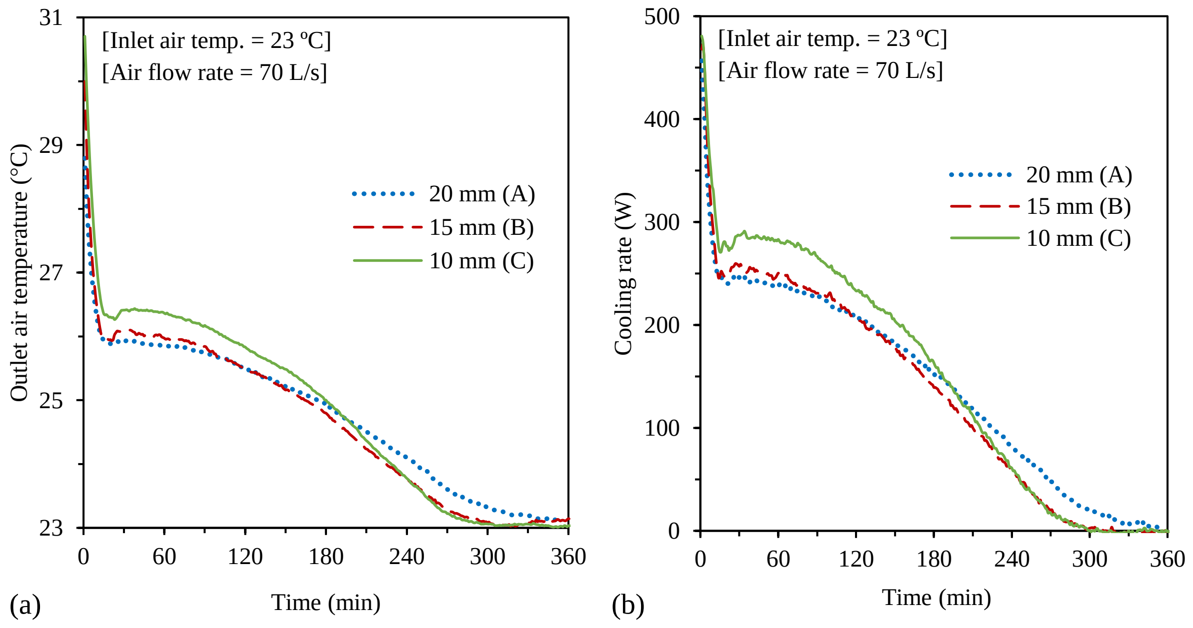


Figure 3: Impact of air channels height on PCM charging; (a) variation of the outlet air temperature (b) variation of the PCM cooling rate.

The charging time for the three TES arrangements under the adopted operating conditions is presented in Figure 4. It can be clearly seen that the increase of PCM charging time with the air channels height is varied according to charging inlet air temperature. For the considered range of inlet temperatures (32-40 °C), minimising the air channels height from 20 to 10 mm accelerated the melting time by 11-14%, when the air flow rate was 70 L/s (Figure 4a). On the other hand, the delay in the PCM charging with the air channels height increase is also varied depending on the air flow rate. However, the variations are generally small. For the considered range of air flow rates (30-70 L/s), the reduction in the PCM charging period was in the range 10-14% when lessening the air channels height from 20 to 10 mm, at the inlet air temperature 23 °C (Figure 4b).

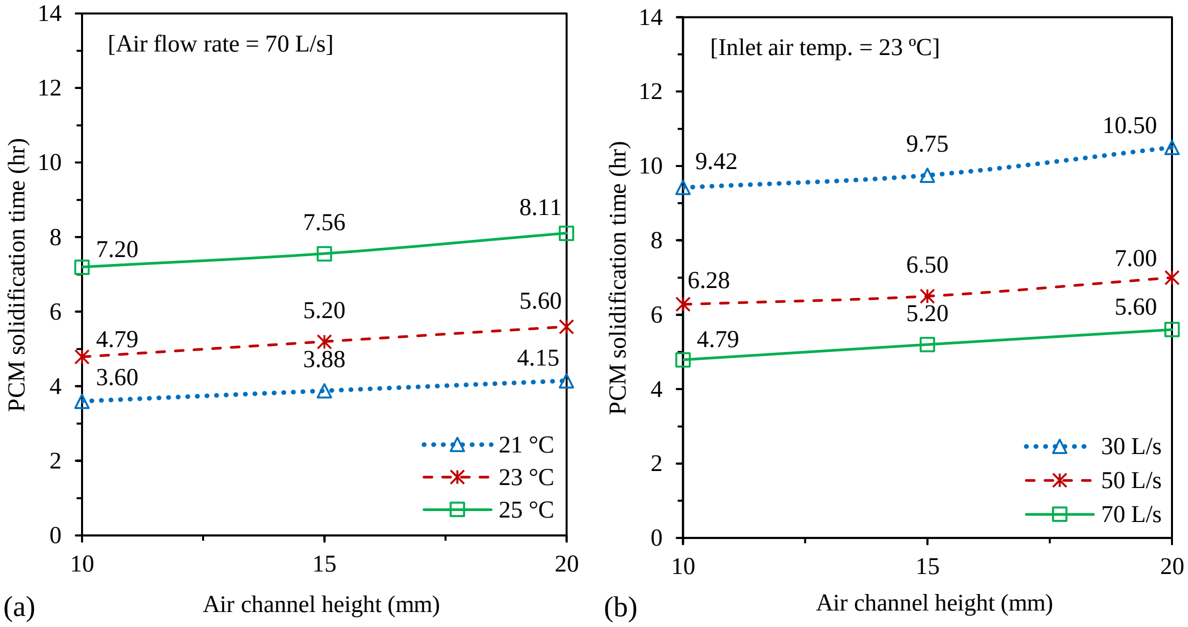


Figure 4: Sensitivity of PCM solidification time to the air channels height under various (a) inlet air temperatures, and (b) air flow rates.

In brief, narrow air flow channels are highly desirable for achieving quicker PCM solidification during the charging phase. The negative impact is that narrow channels may induce high-pressure drop and hence, higher fan power requirements. But, overall, a compact PCM-air heat exchanger is more efficient in achieving an effective free energy storage.

4.2. PCM discharging performance

During the discharging mode, a fan was used to draw the hot air from the environmental chamber with a constant temperature and flow rate over the PCM modules. The flowing air added heat to the solid PCM which changed its state gradually to liquid. The discharging tests were carried out until the whole PCM turned into liquid. The discharging performance was evaluated based on the time required to achieve complete melting of the PCM. The period in which the system is able to provide thermal comfort in buildings under hot-arid regions was also assessed.

Figure 5 compares the outlet air temperature and the cooling rate for the three tested cases when the inlet air temperature was 36 °C and the air flow rate was 16 L/s. It is observed that the smaller the air channels height the cooler the outlet air temperature will be during the initial half of the discharging period. This was due to the higher heat transfer rate caused by the enhanced air velocity inside the narrower channels compared to the wider ones. The situation reverses after a certain period of time, so the cold extraction from the PCM was lower in the case of the smaller channels height design, and hence, the outlet temperature increases more sharply resulting in a faster PCM melting. This occurred because the temperature difference between the PCM and the discharging air has gradually dropped with the time.

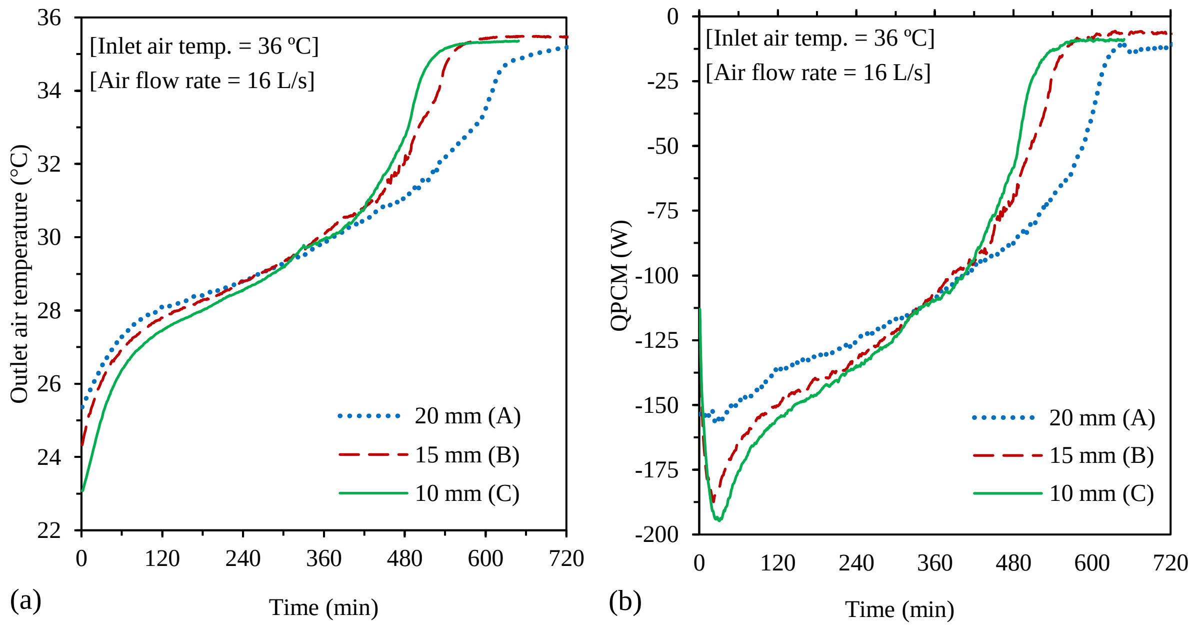


Figure 5: Impact of air channels height on PCM discharging; (a) variation of the outlet air temperature (b) variation of the PCM heating rate.

The melting time and the corresponding comfort level duration achieved are illustrated in Figure 6 and Figure 7, respectively, for the three cases under the tested conditions. It is obvious that the time required for the complete PCM melting and the comfort period prolonged with the air channels height.

As shown in Figure 6a, the increase in the melting time with the air channels height rise varies based on the discharging air temperature. It was higher at the low inlet air temperatures compared to the high temperatures. For instance, increasing the height of the air channels from 10 to 20 mm prolonged the melting time by 26-20% at inlet air temperatures 32-40 °C, respectively, when the air flow rate was 16 L/s. On the other hand, as shown in Figure 6b, the melting time varied with the augment of air channels height depending on the air flow rate. The melting time increase was higher at low air flow rates compared to the high flow rates. As an illustration, with air channels height increase from 10 to 20 mm, the melting time extended by approximately 28-25% for the air flow rates 7-25 L/s, respectively, when the inlet air temperature was 36 °C.

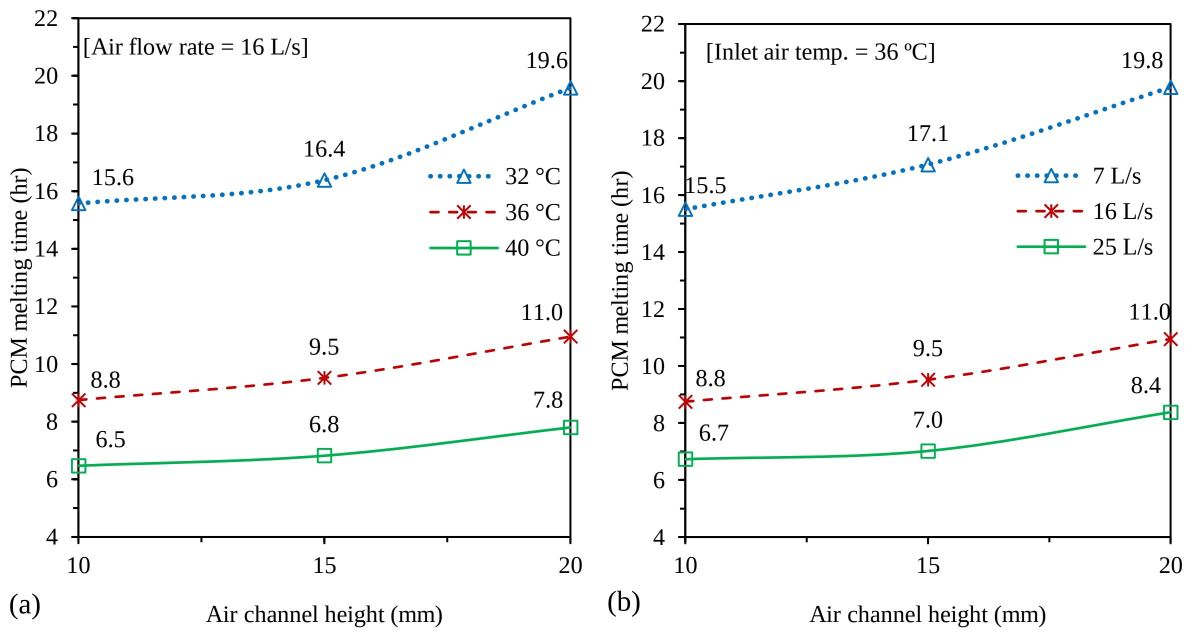


Figure 6: Sensitivity of PCM melting time to the air channels height under various (a) inlet air temperatures, and (b) air flow rates.

Figure 7 clearly indicates that the variation in the comfort period for the three tested PCM modules arrangements was very slight under all tested conditions. This is evident in Figure 5, where the outlet air temperature curves met at the maximum comfort temperature of 30 °C. At the given temperature, the variation in the comfort time was less than 7% in all cases, however, except for the case when the air flow rate was 25 L/s (Figure 7b), at which the configuration C exhibited a longer comfort time by nearly 20% compared to the other arrangements. This is because the initial temperature of the PCM was lower by almost a 2-K in case C at the beginning of the discharging process.

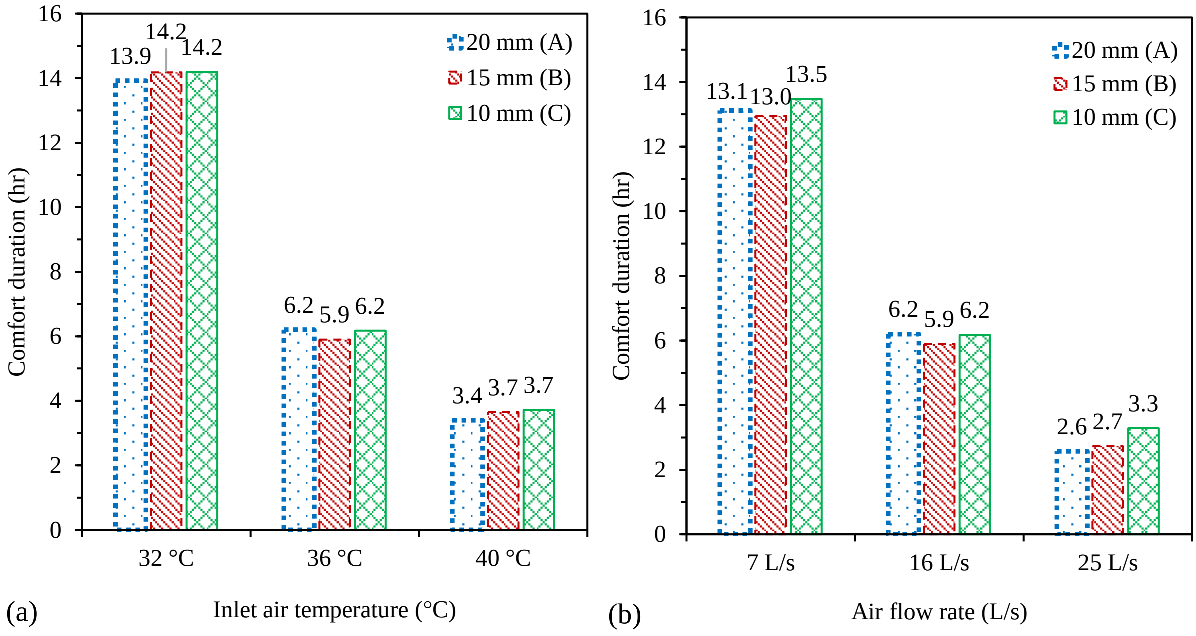


Figure 7: Influence of air channels height on the comfort level period under various (a) inlet air temperatures, and (b) air flow rates.

Significantly, it appears under the current TES configurations and the PCM transition temperature range that the distance between the PCM modules has a great impact on the complete discharge of the PCM cooling and a negligible impact on the comfort level duration.

5. CONCLUSION

An experimental investigation of a PCM-air heat exchanger for free cooling of building under hot-arid climate conditions was carried out. The PCM charging and discharging performance were investigated under various inlet operating conditions for different arrangements of PCM modules with varying air flow channels.

Optimising the distance between the PCM panels is an important aspect to enhance the system performance. Narrow air channels result in a higher cooling accumulation and hence, shorter solidification time during the charging process. On the other hand, a system with wider air channels provides a slower melting rate during the discharging process, whereas, comfort durations are not affected by the height of the air channel. Consequently, a compact TES design with a smaller air channels height is appropriate for both transition phases.

The results have demonstrated that the proposed TES system is capable of meeting building cooling requirements under some hot-arid climate conditions, and thus, has a potential to minimise the operation hours and energy use of the conventional air conditioning systems.

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