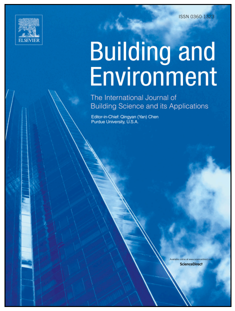
Experimental study on the thermal performance of air-PCM unit

Inten, M, Liu, S & Shukla, A

Original citation & hyperlink:
Inten, M, Liu, S & Shukla, A 2016, 'Experimental study on the thermal performance of air-PCM unit' Building and Environment, vol 105, pp. 128-139.
https://dx.doi.org/10.1016/j.buildenv.2016.05.035

DOI 10.1016/j.buildenv.2016.05.035
ISSN 0360-1323
ESSN 1873-684X
Publisher: Elsevier

Accepted Manuscript



Experimental study on the thermal performance of air-PCM unit

Muriel Iten, Shuli Liu, Ashish Shukla

PII: S0360-1323(16)30193-7

DOI: 10.1016/j.buildenv.2016.05.035

Reference: BAE 4509

To appear in: *Building and Environment*

Received Date: 5 January 2016

Revised Date: 26 May 2016

Accepted Date: 27 May 2016

Please cite this article as: Iten M, Liu S, Shukla A, Experimental study on the thermal performance of air-PCM unit, *Building and Environment* (2016), doi: 10.1016/j.buildenv.2016.05.035.

Experimental study on the thermal performance of air-PCM unit

Muriel Iten, Shuli Liu*, Ashish Shukla

School of Energy, Construction and Environment, Coventry University, Coventry, CV1 2HF, United Kingdom

Abstract

In the present research paper thermal performance of an air-phase change material (PCM) unit has been experimentally studied. The influences of the air inlet temperatures and velocities have been investigated on the charging/discharging time of the PCM panels, heating/cooling load and effectiveness over the phase transition. These parameters play a vital on determining thermal performance of an air-PCM unit. Air inlet temperatures of 34 °C, 36 °C and 38 °C and air inlet velocities of 0.6 m/s, 1.6 m/s and 2.5 m/s. have been studied. The increase of the air inlet velocity reduced the charging and discharging time, however not linearly. The time for the complete melting and solidification is substantially reduced when the velocity has been increased from 0.6 m/s to 1.6 m/s. The air inlet temperature has been proved to be most important factor affecting the discharging time. For lower air inlet velocity the cooling and heating loads achieve lower values but remain nearly constant over a longer period of time. The effectiveness reaches its highest values for the air inlet velocity of 0.6 m/s for the charging and discharging processes. It has been concluded that discharging time can be extended by reducing the air inlet velocity and making the technology more suitable for heating and cooling applications for the buildings. A simplified methodology is proposed for the analysis of the PCM charging and discharging process through the identification of the critical points as result of the heat transfer behaviour in the air- PCM unit.

Keywords: Air-PCM Unit, Phase change materials, Heat Exchanger, Charging/discharging

* Corresponding author. E-mail address: shuli.liu@coventry.ac.uk
Tel: +44 (0)24 7765 7822; Fax.: +44 (0) 2477658296

1. Introduction

Worldwide buildings account for 40% of total primary energy consumption contributing towards 30% of total annual greenhouse gas emissions [1]. The reduction of the energy consumption in buildings has been one of the priorities of the recent EU directives. The Energy Performance of Buildings Directive (EPBD) in 2002 requires all Member States of the EU to introduce a general framework and to set building energy codes based on the global building approach [2, 3]. In their work authors [4, 5] reported that the majority of the total primary energy requirements in the building was used for heating, ventilation and air-conditioning (HVAC).The necessity of improving the energy efficiency of the built environment results in the development of various techniques of better usage and conservation of energy for heating and cooling. Among various energy efficiency technologies and clean energy innovations free cooling in the building is getting increasing importance nowadays [6,7,8,9, 10].Phase change materials (PCMs) are characterized by a specific phase change (melting and solidifying) occurring at a temperature value or range due to latent heat [11]. Organic PCMs, such as paraffin, fatty acids and polyethylene glycol (PEG), are the most frequently used materials; they show good chemical stability, high latent heat and very limited supercooling [12]. Free cooling applications can be achieved by charging the PCM during night-time, i.e. solidification of the PCM in order to cool the inlet air by means of the discharging of the PCM i.e. melting of the PCM. Several important factors e.g. air temperature differential, air velocity/mass flow rate, ambient air inlet/outlet temperature and mass of the PCM are considered important in designing and studying an air-phase change material (PCM) experimental rig. An extensive review on the air-PCM-TES application for free cooling in buildings is reported in Iten et al. [13]. In Zalba et al. [6] a free cooling system corresponding to an air-PCM heat exchanger installation was designed and constructed to test the performance of such systems. Butala and Stritih [7] studied experimentally the energy saving in buildings with PCM cold storage. The air temperatures, heat fluxes and heat as a function of time are presented for different air velocities and inlet temperatures. Dolado et al. [8] investigated the influence of the air inlet temperature and air flow to test the thermal cycling of a real-scale air-PCM heat exchanger at ambient temperatures. Other referable studies are detailed in Iten and Liu [9] and it was found that the air inlet temperature and velocity are identified as the major factors for such systems. The investigation on the air temperature difference is presented in Iten and Liu [14]. It has been found that the air inlet temperature plays a significant role on the discharging process, increasing the air inlet and outlet temperature difference and the heat transfer rate when the inlet was increased from 34 °C to 36 °C, however does not influence the solidification process, similar air inlet and outlet temperature difference and the heat transfer rate were obtained for all conditions. Moreover the further increase of the air inlet velocity reduced the air temperature difference for both processes. A detailed experimental study considering the major impact factors free cooling applications using air-PCM unit will be critically analysed, enabling researchers to select suitable performance and design parameters of such systems. The present study will aim the melting and solidification times of the PCM panels, the potential cooling/heating load and effectiveness for variable air inlet temperatures and velocities. For that purpose, several temperature measuring thermocouples were used to measure the temperatures along the PCM panel. Current research paper will analyse aforesaid factors with respect to charging/discharging times of the PCM panels and to the air temperature differences in order to understand how these variables can be adjusted to design and optimize a real scale case unit for the free cooling of buildings. To summarise, this paper will establish experimental findings on i) charging/discharging time of TES, ii) heating/cooling load in charging (discharging) process and iii) effectiveness over the phase change process. Moreover, this paper details a simplified methodology to monitor the PCM temperature within the panels by identifying the critical points. This will save significant time as well as avoid inaccuracies that can result from assuming the average temperature of the panel for the analysis of the complete charging and discharging of the PCMs.

2. Research design – methodology

The design and construction of a small scale prototype of an air-PCM unit has been carried out to investigate the influence of the air inlet temperature and velocity on three main output parameters namely charging/discharging time of the PCM, cooling/heating load and effectiveness over the phase change as presented in Fig. 1.

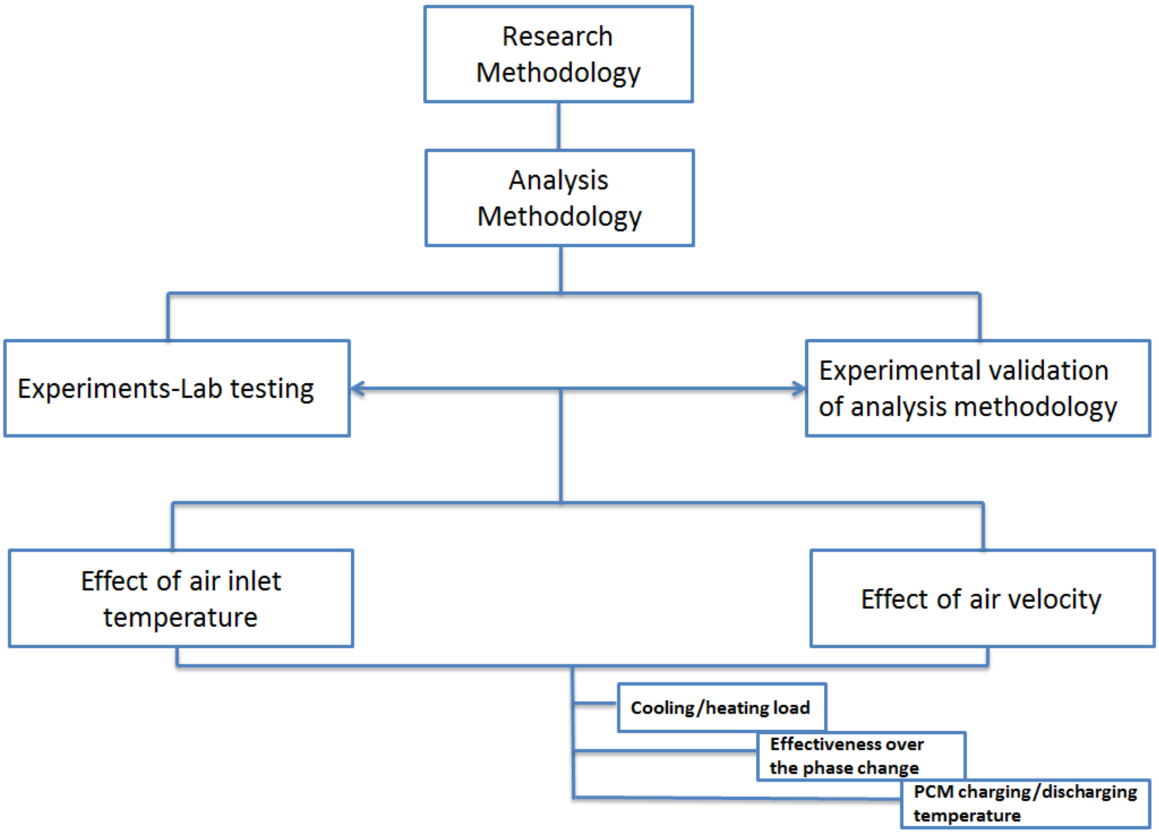


Fig. 1. Research methodology

2.1 Analysis methodology

To estimate the charging and discharging time, a total of 15 thermocouples have been fixed in each panel to understand the temperature variations along the panels. The analysis can be simplified however, by identifying the critical points. These critical points correspond to the last points from the inlet where melting or solidification take place assuring that these points fully melt or solidify, the entire panel is assumed completely charged or discharged. In order to identify these critical points, Fig. 2 presents three scenarios (1, 2 and 3) of a single panel containing the PCM completely solidified and in contact with a heat source.

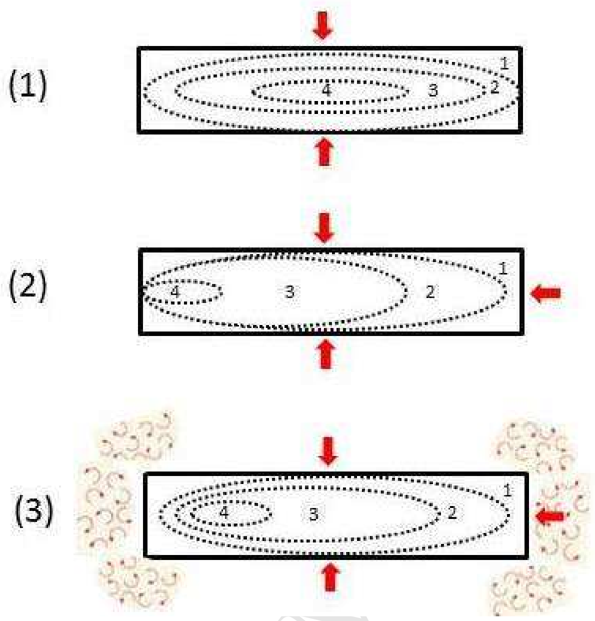


Fig. 2. Melting process of single PCM panel in contact with heat source

For all scenarios over the time that the PCM start to melt with associated liquid fraction; the increase of the liquid fraction is identified by the interfaces numbered from 1 to 4. For scenario 1, the panel is heated from the top and bottom and over time the liquid fraction increases from interface 1 to 4. In this case, the melting fractions increase symmetrically. The last part that melted is at the centre of the panel and delimited by interface 4. For scenario 2, the panel is heated from the top and bottom and also from the right end. The melted fraction is increased symmetrically in the vertical direction. However, for the horizontal direction a higher rate of melting fraction is noted at the right end as it is closer to the heat source. Over time the interface moves from 1 to 4 and it is observed that the left end is the last part that melted, represented by interface 4. Scenario 3 represents the current experiment, similar to the previous case however the heat source is from the convection of hot heat transfer fluid

(HTF) surrounding the panel. Hence, additionally to the previous case, the left and right ends are surrounded by a high convective heat coefficient of the surrounded HTF benefiting the heat transfer at these last two ends. Therefore the melting of the last part is not expected to occur at the left end, but between the centre and the left end.

3. Design of the air-PCM heat transfer unit

Several PCMs are discussed on the literature [9, 15, 16]. As stated in Iten and Shuli's research [9], the selection of the PCM is dependent on many factors including the melting point, cost, energy density for thermal energy storage, availability, suitability for the application. For the present air-PCM unit, paraffin was considered due to the following reasons: available in several commercial types; low cost; compatibility with metals; excellent thermal stability and match with the thermal energy storage density. Several paraffins are available on the market, however suitable melting temperature should be selected for the appropriate application. For the cooling of buildings, RSECE [17] and ASHRAE [18] suggest indoor temperatures within 23-26 °C in order to achieve the thermal comfort of occupants. A commercial paraffin RT25 [19] with phase change temperature from 23 °C to 25 °C has been determined to fulfil the comfort temperatures. The thermophysical properties of the selected paraffin were provided by the manufacturer and listed in Table 1.

Table 1
RT25 properties [19]

PCM	Melting Temperature (ºC)	Density (kg/m^3)		Specific heat (kJ/kg ºC)		Thermal conductivity (W/m ºC)		Latent heat (kJ/kg)
		Solid	Liquid	Solid	Liquid	Solid	Liquid	
RT25	23-25	880	760	2000		0.2		148000

The commercial paraffin RT25 is a mixture of compounds and therefore the melting occurs across a range of temperature: 23-25 °C. For the present study the RT25 has been assumed to be completely discharged at 25 °C and completely charged at 23 °C. Air is considered as the working fluid for ventilation application. There are three typical options for the selection of the shape of the encapsulation: plates, cylinders and spheres [8]. Plates are selected due to the advantages such as: uniformity of the PCM thickness and therefore, of the phase change process; melting and freezing process on a plate surface is symmetric in relation to all sides of the plates; heat transfer in the PCM can be controlled with selected thickness of the encapsulation; high ration area/volume storage; less pressure drop in the air; simplicity of the manufacturing process and versatility of handling (transportation, installation and maintenance); applicability to various applications and easy to control the PCM thickness which is a crucial design factor influencing the melting and solidification time. Rectangular containers were also selected in similar applications due to their much shorter melting time (half) than the cylindrical container of the same volume and heat transfer [20]. In Iten and Liu [9], the corrosion of the PCMs and compatibility with the container was discussed; plastic materials were not recommended to be in contact with organic compounds i.e. paraffins. In that sense, metallic containers were chosen to assure the compatibly with the paraffins and also to enhance the heat transfer between the air and the PCM panels [21]. Several experimental tests on rectangular air-PCM heat exchangers have been reported in Iten and Shuli [9]. For the present study, the chosen PCM thickness was 0.02 m (H_{panel}) as it was presented as one of the most suitable dimensions for air-PCM units [22, 23, 24, 25, 26, 27] (Fig. 3). Halawa and Saman [27] stated that if the mass of the PCM and the thickness of the panel were constant, the other two dimensions (width and length) do not play an important role in the heat transfer. Thus, the chosen length and width of the panels were fixed on 0.5 m and 0.25 m respectively meeting the requirements of a small prototype scale (Fig. 3). The dimensions of the rectangular air channels corresponded to $L_{channel}$ x $W_{channel}$ x $H_{channel}$ in which L is the same length as the PCM panels (L_{panel}), W is the same as the width of the PCM panels (W_{panel}) and $H_{channel}$ is the air gap height. Different air gap heights have been investigated for rectangular air-PCM units: 0.05 m [27, 28], 0.01 m [29], 0.08 m and 0.016 m [30, 31], 0.02 m [32] and 0.035 m [33]. Too small dimension will make the construction delicate, and the number of panels will have to be increased leading to a higher pressure drop across the unit.

Thus, for the present study an air gap of 0.02 m for each PCM panel has been chosen (Fig. 3). The experimental setup includes an arrangement of three PCM panels and to fulfil the 0.02 m air gap for the top and bottom of each panel, the middle air gaps height correspond to 0.04 m. Specification of the TES systems dimensions are listed in Table 2. The air-PCM heat transfer unit was inserted in rectangular air duct built in wood with thickness of 0.01m.

Table 2
Specification of the air-PCM TES system

Internal height of the PCM panels (H_{panel})	0.02 m
PCM encapsulation thickness (steel plate)	0.003 m
Air channels height ($H_{channel}$)	0.02 m 0.04 m
Length of the PCM panels (L_{panel})	0.5 m
Width of the PCM panels (W_{panel})	0.25 m
Air duct thickness (wood layers)	0.01 m
Total internal height of the air – PCM TES unit (H_{total})	0.198 m

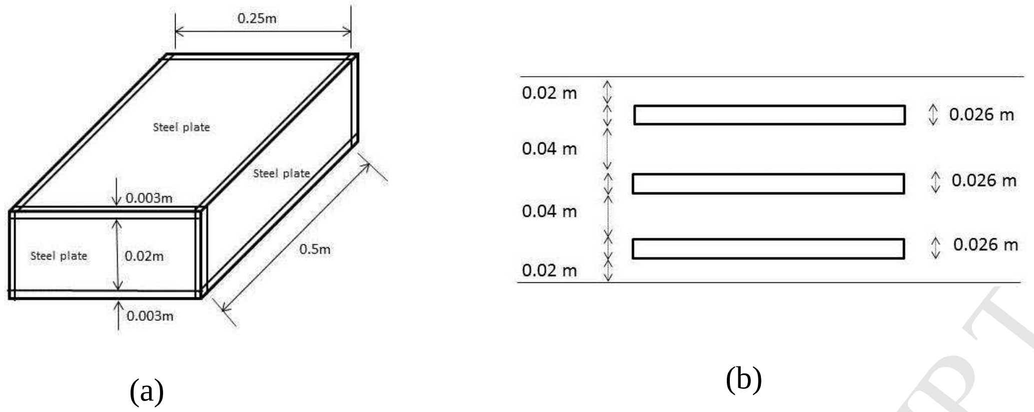


Fig. 3. PCM panel and air gap dimensions (a) single PCM panel dimensions (b) PCM panels and air channel heights arrangement

Each panel with an internal volume of 0.0025 m^3 is filled to the top with a liquid PCM in order to prevent any overflow due to volume expansion corresponding to a total mass of 1.8 kg per panel. Fig. 4. displays a photographic view of the panels filled with PCM and Table 3 the specifications of the respective panels.

Table 3
PCM panels specifications

Panel internal volume	0.0025 m^3
PCM mass	1.8 kg
Panel mass	1.8 kg
Total mass per panel	3.6 kg

Fig. 4. Mass and volume of PCM panels

From the literature review it was possible to characterize the selected PCM as well as to select the most appropriate dimensions for the air-PCM heat transfer unit.

4. Experimental setup

The experimental setup consists of an air duct made from wood due to its low thermal conductivity, aiming to reduce the heat losses to the surroundings. The main air duct presents a length (L), width (W) and height (H) of 2.2 m, 0.25 m and 0.218 m respectively. The air duct includes an air-PCM heat transfer unit coupled to a heating/cooling unit, exhaust fan and to a range of measuring equipment as presented in Fig. 5. A photographic view of the experimental setup is also presented in Fig. 5.

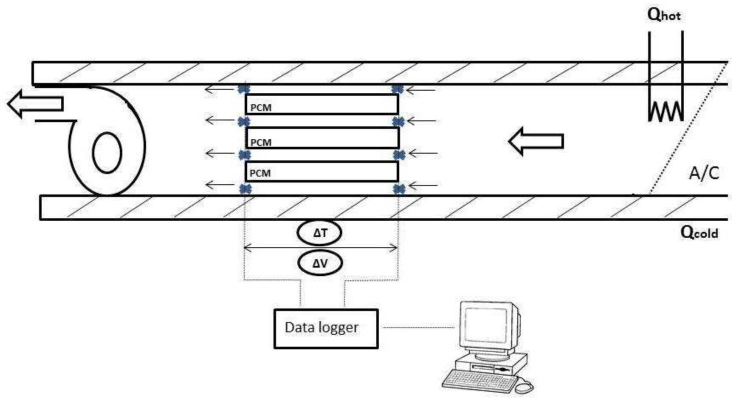
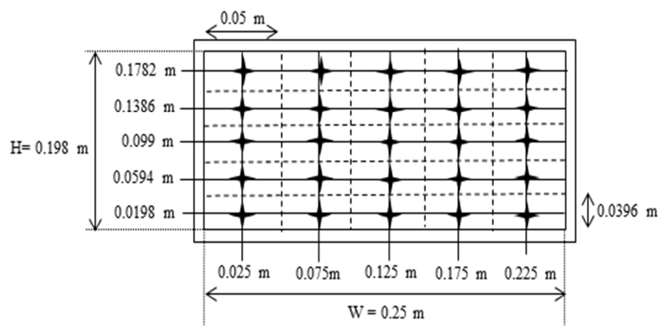


Fig.5. Experimental Setup

The air is pulled through a centrifugal exhaust fan with an electrical power and volumetric flow rate of 0.11 kW and 147 m^3/h, respectively. Varying the air velocity plays a very important role in the heat transfer between the air and the PCM panels to be analysed in this experiment. A variable speed device is coupled to the exhaust fan in order to vary the air inlet velocity. The air velocity at the main air duct can be varied from 0.6 m/s until 2.5 m/s as used for the experimental proposes and further described in section 4. An air- PCM heat transfer unit is composed by three panels "filled" with RT25 PCM into rectangular plate and each panel is surrounded on the top and bottom by air channels. As there is no limitation in terms of space or a particular application, the plates are arranged horizontally to reduce the pressure drop and the electrical consumption of the fan. The air- PCM heat transfer unit was coupled downstream to a heating/cooling unit on one side and an exhaust fan on another side. Contrary to Butala and Stritih [7], Zivkovic and Fujii [20] and Waqas and Kumar [34], three parallel plates have been arranged instead of a single panel in order to replicate the melting and solidification phenomena for the same conditions and to achieve converged results when comparing the three panels. In other words, unexpected anomalies can be easily identified when comparing the results obtained by the three panels.

The construction of the heating unit involve four electrical heating coils (2.5 kW, 2 kW, 2 kW, 2 kW) enclosed into a metal tube structure and connected to a wood box. The safety issues are guaranteed as the electric coils did not increase the temperature beyond 80 °C a lower temperature than the conventional wood burning temperature of 250 °C. Each electrical coil thermostat, except for the 2.5 kW coil with two thermostats, are connected to an adjust control, allowing six different setting temperatures. The cooling unit corresponds to a portable air conditioner (Electro-Aire) with a cooling capacity of 2.6 kW. The instrumentation used in this study includes an anemometer for the air velocity measurement and thermocouples for the PCM temperature measurements and a data acquisition system to record the temperatures. The air velocity was measured at the inlet of the air duct at 25 points (Fig. 6) as suggested in ASHRAE [35] and TSI [36] using an air velocity meter (TSI, model TA440A). The chosen thermocouples were K-type provided by RS Components.

Anemometer (TSI)



Air velocity measuring points for rectangular duct traverse

Fig. 6 Air velocity measurement

The temperatures are measured along each PCM panel (15 thermocouples for each PCM panel) as presented in Fig. 7. All of them were located at the centre of the panel as the panel presents a minimum height of 0.02 m and no significant variation was expected along the height. The thermocouples were connected to a digital temperature recorder model 3470A by

Agilent Technologies, UK. The provided software has been used to record the temperature data in a database format with a personal computer. Time steps of 10 seconds were used for temperature monitoring.

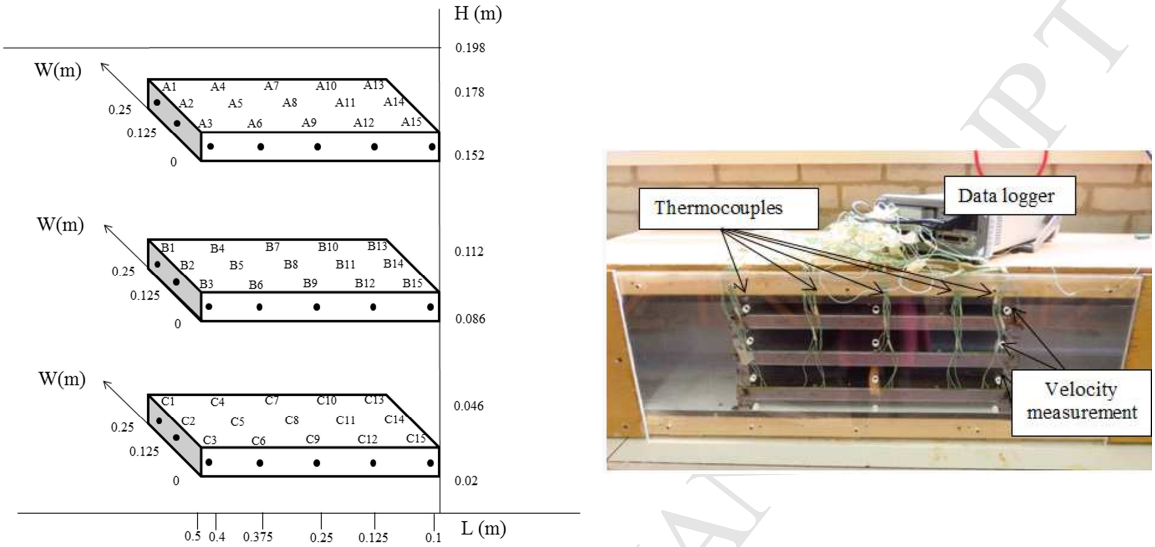


Fig. 7. Schematic view of the thermocouples distribution

Table 4
Instrumentation for experimental study and their technical information

Variable	Instrument	Model/Brand	Measurement range	Sensitivity	Quantity
Air velocity	Air flow meter	TA440A/ TSI	0 – 30 m/s	± 0.001 m/s	1
PCM/air temperatures	Thermocouples	K-type / RS Components	-50 °C – 1100 °C	±0.1 ºC	55
	Data logger	3470A/ Agilent Technologies	-100 °C to 1200 °C	±0.1 ºC	1

The PCM and air temperatures and air velocities are measured with appropriate instruments clarified in Table 4. The uncertainty of the experiment is calculated by Eq. (1) [37].

$$U = \pm\sqrt{\left(\frac{\Delta T_{TC}}{T_{TC}}\right)_{PCM}^{2} + \left(\frac{\Delta T_{TC}}{T_{TC}}\right)_{air}^{2} + \left(\frac{\Delta V}{V}\right)^{2}} \times 100\% \quad (1)$$

The uncertainty is first estimated separately based on the sensitivity values specified in Table 4. Because the sensitivity of thermocouples and the data logger are set at ± 0.1 °C, the reading errors for PCM and air temperature measurements are assumed as ±0.2 °C (ΔT_{TC}). The sensitivity of the anemometer used in measuring the velocity of the air is ±0.001 m/s and reading errors are ±0.001 m/s (ΔV) respectively. The maximum uncertainties reached for each parameter are summarized in Table 5. The total uncertainty is obtained by applying Eq. (1) for the uncertainties listed in Table 5. Thus, the experimental uncertainty is estimated at 2.1 % and it guarantees the credibility of the experimental data.

Table 5
Experimental uncertainty

Parameter	Equipment	Uncertainty
PCM temperature	K-type thermocouples (ΔT_{TC}) Data logger (ΔT_{DT})	1.3%
Air temperature	K-type thermocouples (ΔT_{TC}) Data logger (ΔT_{DT})	1.6 %
Air velocity	Anemometer (ΔV)	0.16 %

Section 4 allowed identifying all the components and measuring devices to carry on the experimental testing. Moreover, the experimental uncertainty was specified and determined based on the selected equipment.

5. Experimental procedure

The experimental procedure has involved the charging and discharging of the panels for different air inlet velocity and temperature conditions (Table 6). The charging and discharging processes have corresponded to the solidification and melting of the PCM panels respectively. In the discharging process, hot air flowed at a constant flow rate through the air-

PCM heat transfer unit in order to melt the PCM panels. The process has been continued until the PCM reached 30 °C, beyond the melting temperature of 25 °C. In the charging process, cold air at a lower temperature than the PCM solidification temperature has been supplied at a constant flow rate until the whole PCM temperature has been below 23 °C. Air inlet temperatures from 30 to 38 °C and 12 to 18°C have been selected for the study of the discharging and charging processes respectively. These values are based on typical daily temperatures observed in the Mediterranean countries. Furthermore, air inlet velocities of 0.6 to 2.5 m/s have been chosen to fit with a domestic exhaust fan and accurately varied with a variable speed device.

Table 6
Experimental procedures

<table>
<tr><th colspan="2">Experiment</th><th>Air inlet temperature (°C)</th><th>Air inlet velocity (m/s)</th><th>Air mass flow rate (kg/s)</th></tr>
<tr><td rowspan="6">Variable inlet velocity</td><td rowspan="3">Discharging process</td><td rowspan="3">38</td><td>0.6</td><td>0.036</td></tr>
<tr><td>1.6</td><td>0.097</td></tr>
<tr><td>2.5</td><td>0.152</td></tr>
<tr><td rowspan="3">Charging process</td><td rowspan="3">12</td><td>0.6</td><td>0.036</td></tr>
<tr><td>1.6</td><td>0.097</td></tr>
<tr><td>2.5</td><td>0.152</td></tr>
<tr><td rowspan="6">Variable air inlet temperature</td><td rowspan="3">Discharging process</td><td>30</td><td rowspan="6">1.6</td><td rowspan="6">0.097</td></tr>
<tr><td>34</td></tr>
<tr><td>38</td></tr>
<tr><td rowspan="3">Charging process</td><td>12</td></tr>
<tr><td>16</td></tr>
<tr><td>18</td></tr>
</table>

The initial conditions and the air inlet conditions have been setup according to the real climatic conditions observed in Mediterranean countries. This will allow to approximate the experimental results to real conditions and achieve a more realistic outcome on the thermal performance of an air- PCM unit for free cooling of buildings.

6. Results and discussion

For present research paper results and discussions are divided into two main parts; validation of analysis methodology followed up by experimental results.

6.1 Validation of Research methodology

The analogy presented in Fig. 2 is confirmed experimentally and shown in Fig. 8. The complete charging and discharging time for each panel is assumed with respect to thermocouples A5, B5 and C5. Also, by comparing these three thermocouples it is observed that the complete melting time of the bottom panel – C5 takes slightly longer when compared with the top panel- A5 and the middle panel - B5 (Fig. 2). The more reasonable explanation for this slight discrepancy is related to a minimal thermal buoyancy effect that has occurred in the experimental apparatus benefiting the upper panels.

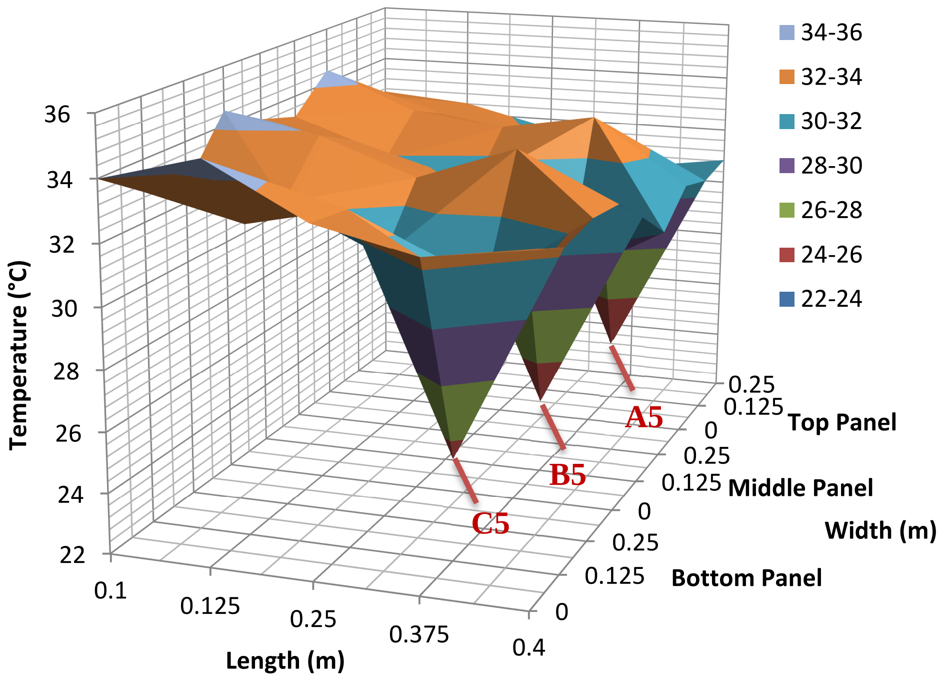


Fig.8. Temperature profile across the PCM Panel

This paper presents a simplified approach to investigate the complete charging and discharging of the PCM temperatures. It reduces the analysis time, as the analysis is carried on a single PCM, and it reduces the inaccuracies that may occur if for instance the average temperature of all thermocouples is assumed.

6.2 Experimental results

The influence of the air inlet velocity on the discharging time has been analysed for three velocity variations of 0.6 m/s, 1.6 m/s and 2.5 m/s for the inlet temperature of 38 °C (Table 6). Following the analogy presented in Fig. 2 and Fig. 8, the complete charging and discharging time for each panel has been assumed with respect to thermocouple C5.

6.2.1 Influence of the air inlet velocity

(i) Charging/discharging time

For the phase change process the air temperature has been fixed at 38 °C (discharging process) and 12 °C (charging process) and the influence of the air velocity is analysed through varying the velocity from 0.6 m/s, 1.6 m/s and 2.5 m/s. The initial temperature of the whole system has been at 16 °C (discharging process) and 30 °C (charging process) and the average ambient temperature has been at 19 °C. The transient PCM temperatures for the different conditions are presented in Fig. 9 and Fig. 10. The black line represents the melting temperature, i.e. temperature at which the phase change is completed and the PCM is entirely liquid (25 °C) and solid (23 °C). The period of time for the PCM to increase its initial temperature until it reaches the melting temperature represented by t_1, t_2 and t_3 for 0.6 m/s, 1.6 m/s and 2.5 m/s respectively.

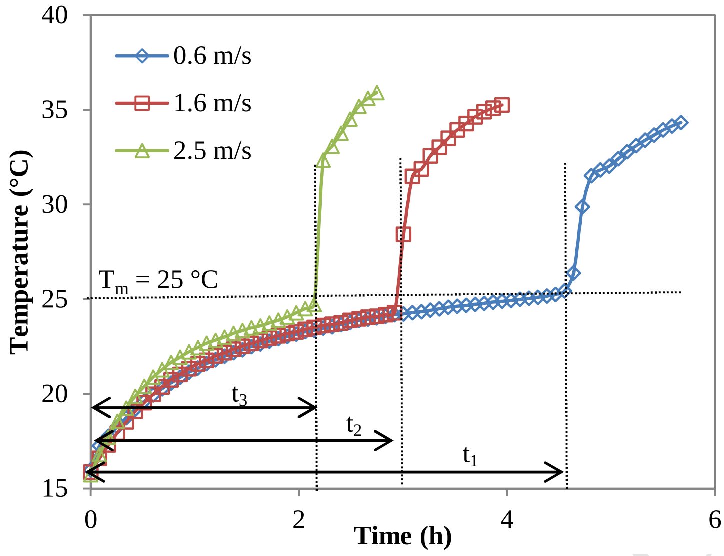


Fig.9. Influence of air inlet velocity on the PCM discharging process

From Fig. 9 it is observed that firstly the PCM temperature increases very rapidly (sensible heating) followed by a slow temperature increase from 23 °C to 25 °C (phase change). Afterwards the PCM temperature rises very sharply meeting the air inlet temperature (38 °C) in a very short period of time (sensible heating). Overall, it is possible to visualise that increasing the air inlet velocity decreases the time for the PCM panels to be completely discharged. However this decrease of the discharging time is not proportional. For instance increasing the air inlet velocity from 0.6 m/s (t_1) to 1.6 m/s (t_2) significantly reduces the melting time approximately 1.6 h, however, a further increasing to 2.5 m/s reduces the time only by 0.8h.

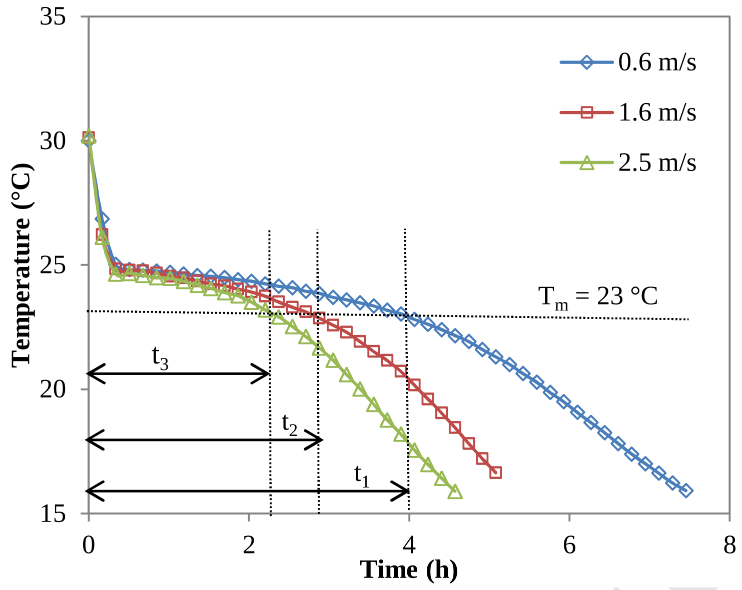


Fig.10. Influence of air inlet velocity on the PCM charging process

For the velocity of 0.6 m/s, 1.6 m/s and 2.5 m/s, the complete phase change takes 4h (t_1), 2.8h (t_2) and 2.3h (t_3) respectively. Through increasing the air inlet velocity from 0.6 m/s to 1.6 m/s the solidification time is reduced by over 1h. Increasing the velocity further to 2.5 m/s decreases the time in nearly half an hour. The charging time reaches approximately half magnitude for the second increment (1.6 m/s to 2.5 m/s) compared to the first increment (0.6 m/s to 1.6 m/s) of the air velocity. Further increase in the air inlet velocity will not reduce significantly the charging time; instead a lower temperature may be required for that purpose. Waqas and Kumar [34] also stated that if the air inlet temperature is not below the subcooling temperature of the PCM the charging process would not be effective.

Table 7 summarizes the influence of the air inlet velocity on the charging and discharging time identified as t_1, t_2 and t_3 in Fig. 9 (for the discharging process) and Fig. 10 (for the charging process) with an constant air inlet temperature of 38 °C and 12 °C for the discharging and charging process, respectively.

Table 7

Summary of the air inlet velocity influence on the charging and discharging process

	0.6 m/s (t_1)	1.6 m/s (t_2)	2.5 m/s (t_3)

Discharging process (T= 38°C)	4.6h	3h	2.2h
Charging process (T= 12°C)	4h	2.8h	2.3h

From Table 7, comparing the overall time for the charging and discharging processes, it can be seen that for the selected air inlet temperatures of any air inlet velocities the discharging process takes slightly longer than the solidification process ≈ 0.5h. Overall, it is observed that the charging and discharging processes are strongly influenced by the air inlet velocity similar to findings from other researchers [6, 34]. For both the charging and discharging process, it is concluded that increasing the air velocity from 0.6 m/s to 1.6 m/s significantly reduces the phase change time, hence 1.6 m/s is selected as the air inlet velocity to be used for the following analysis: air inlet temperature influence on the charging and discharging time.

(ii) Cooling/heating load and effectiveness over the phase change

During the discharging process of the PCM panels, air is cooled down to corresponding to a certain cooling load (Q_c). The cooling load during the discharging process is calculated using the measured values of the air temperature at the inlet and outlet of the air-PCM heat transfer unit

$$Q_c = \int_0^t m_{air}\, c_{p,air}(T_{in} - T_{out})\, dt$$

(2)

Where T_{in} and T_{out} correspond to the air inlet and outlet temperatures respectively for each time step, t. While the PCM panels are charged (solidification), the air is heated up and the heating load during the process is determined as follows:

$$Q_h = \int_0^t m_{air}\, c_{p,air}(T_{out} - T_{in})\, dt$$

(3)

Where T_{in} and T_{out} correspond to the air inlet and outlet temperatures respectively for each time step, t. The effectiveness over the phase change process can be determined by the average inlet and outlet temperature during the process [33]. This parameter gives an indication of the performance of the effectiveness.

$$\varepsilon = \frac{T_{in} - T_{out}}{T_{in} - T_{m,PCM}}$$

(4)

The Eq. (4) formulation is adapted from the theoretical (general) heat exchanger temperature transfer efficiency with the phase change material taken as the ideal outflow temperature [38]. Fig. 11 and Fig. 12 display the cooling load and effectiveness of the discharging and charging processes respectively for different air inlet velocities.

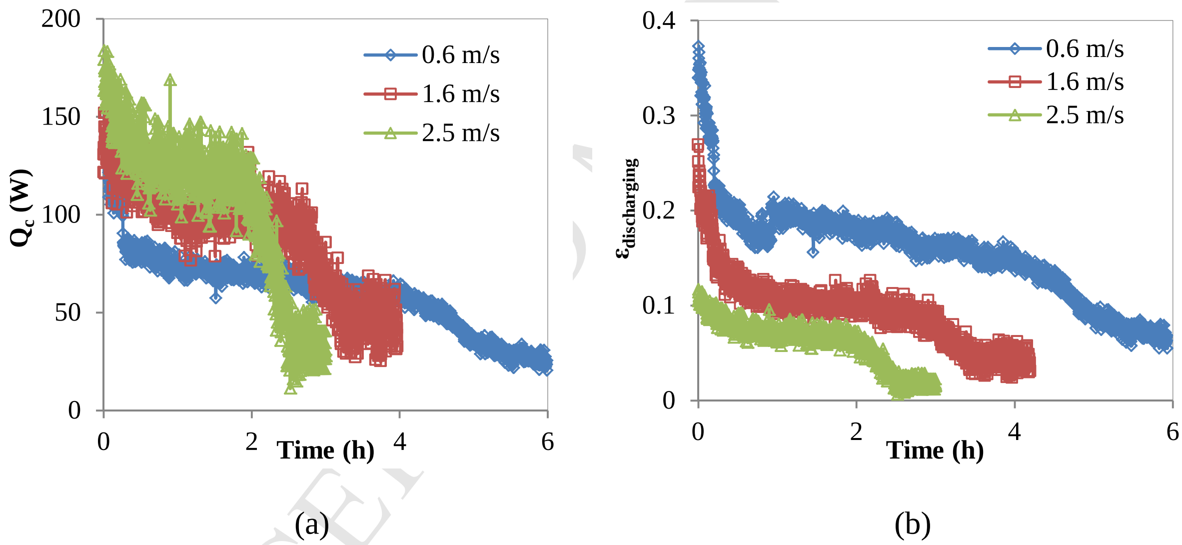


Fig.11. Influence of the air inlet velocity on the (a) cooling load and (b) effectiveness for the discharging process

Generally for all air inlet velocities during the first hours, a high cooling load has been observed related to the air sensible cooling (i.e. PCM sensible heating) followed by a nearly constant load during the phase change followed again by air sensible cooling (i.e. PCM sensible heating) that drastically reduces the cooling load. Fig. 11 shows that at a higher air inlet velocity, the cooling load achieves higher values but reaches the minimum value in a shorter time period, showing and confirming that the discharging process of the PCM has been completed earlier at a higher air inlet velocity. On the other hand for lower air inlet velocities, the cooling load (Q_c) reaches lower values. However, it stays above the minimum value for a longer period of time. An average cooling load corresponds to 70 W, 110 W and 130 W for air velocities of 0.6m/s, 1.6 m/s and 2.5m/s respectively for designed test rig. Overall the effectiveness of the discharging process range between 0.18 and 0.08. Higher effectiveness has been achieved for lower air inlet velocity due to the longer contact time of the PCM with the air.

For, a lower velocity, the panels are in contact with the air source for longer enhancing the transfer process and hence the air temperature difference directly proportional to the effectiveness.

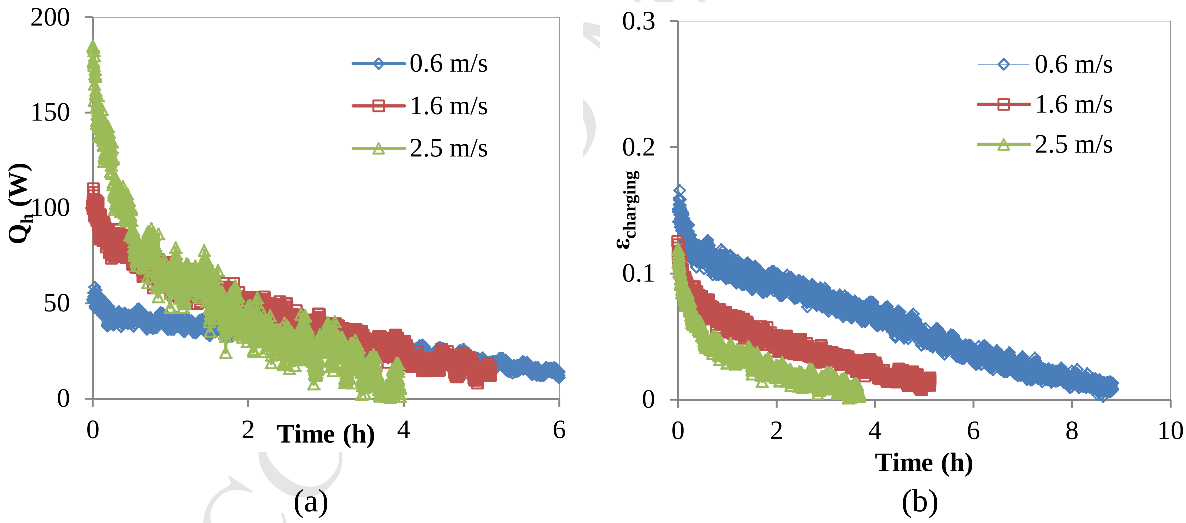


Fig.12. Influence of the air inlet velocity on the (a) heating load and (b) the effectiveness for the charging process (Q_h)

As for the cooling load, for the heating load it is observed that the for higher air inlet velocities the heating load reached the minimum value in a shorter period of time, translating to a quicker charging time of the panels. Lower air inlet velocity translates lower heating load. However, it remains nearly constant over 8h. The average heating load corresponds to

30 W, 40 W and 50 W to air velocity of 0.6m/s, 1.6 m/s and 2.5m/s respectively. For both of the processes load was increased for an increasing air inlet velocity as also stated in Mosaffa et al. [39].The charging process has been represented by an effectiveness ranging between 0.1 and 0.05. As for the discharging process, the air inlet velocity is decreased the effectiveness over the phase change has been increased. Overall, the effectiveness is higher for discharging than for the charging process. This is due to the higher air temperature difference achieved. For the selected temperatures, the discharging process presents higher temperature difference translating to a higher effectiveness.

6.2.2 Influence of the air inlet temperature

(i) Charging and discharging time

For the phase change process the air temperature has been fixed at 1.6 m/s and the influence of the air temperature is analysed through varying the temperatures from 30 °C, 34 °C to 38 °C for the discharging process and from 12 °C, 16 °C to 18 °C for the charging process. The initial temperature of the whole system has been set at 16 °C (discharging process) and 30 °C (charging process) and the average ambient temperature is at 19 °C. The transient PCM temperatures for the different conditions are presented in Fig. 13 and Fig. 14.

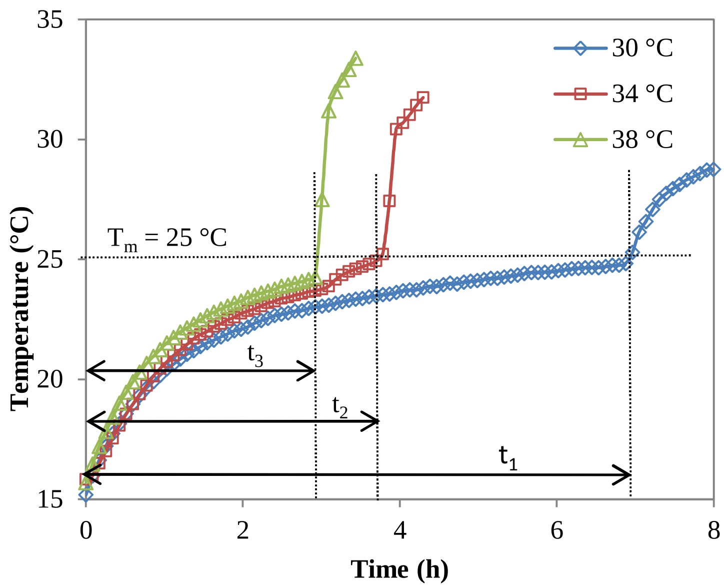


Fig.13. Influence of air inlet temperature on the PCM discharging process

Fig. 13 shows that for the minimum inlet temperature (30 °C) the melting process took around 6.9h. This time is reduced by three hours for the inlet temperature of 34 °C and it is reduced by only 0.8h for the maximum temperature of 38 °C. The results suggest that increasing the air inlet temperature from 30 °C to 34°C significantly affects the discharging time. Increasing further to 38 °C reduces the time in 0.8h. In all cases, after the discharging is completed, the PCM temperature increases very sharply to meet the air inlet temperature (heat source input) in a very short period of time.

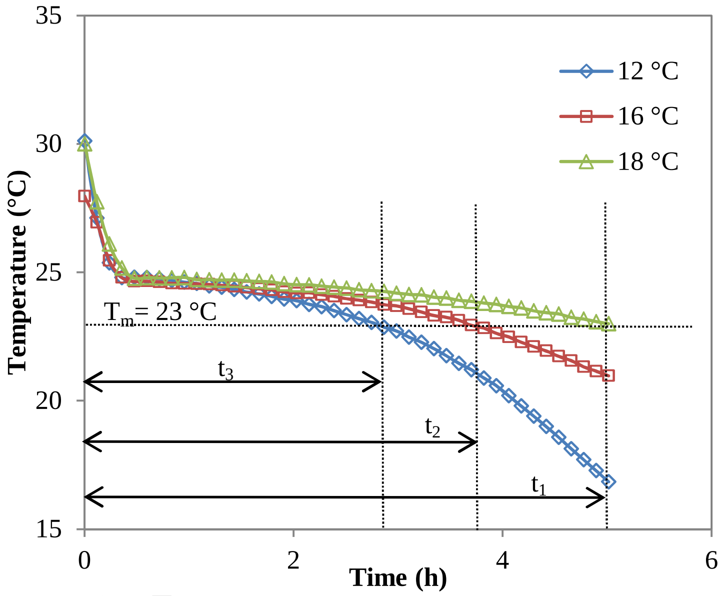


Fig.14. Influence of air inlet temperature on the PCM charging process

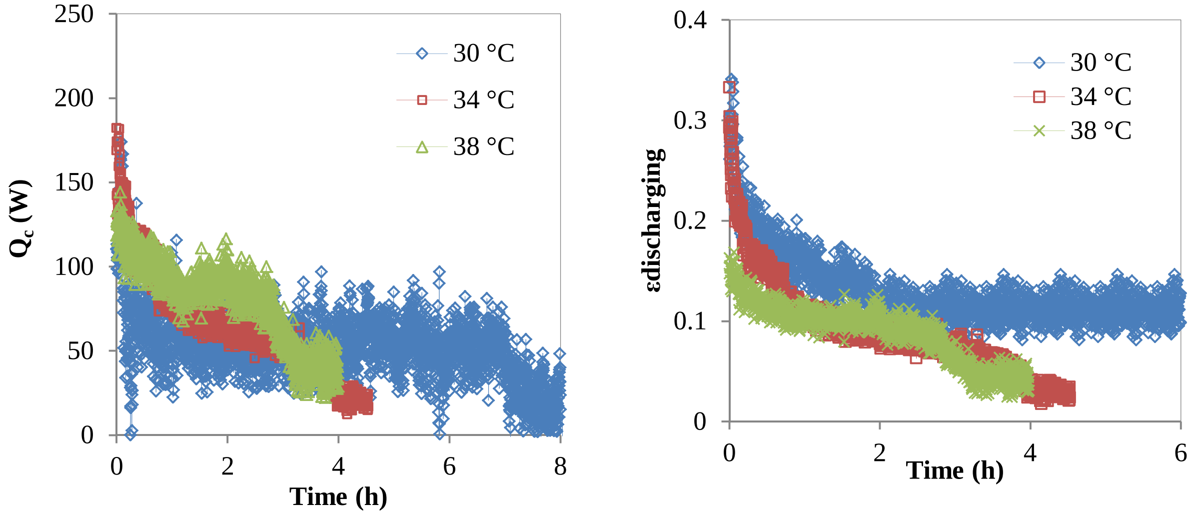
It can be seen in Fig. 14, the charging time is short for lower air inlet temperatures and his reduction is proportional. Reducing the air inlet temperature from 18 °C to 14 °C decreases the charging time by an hour and the further decreasing of the temperature to 12 °C decreases the process by another hour. Table 8 summarizes the charging and discharging times identified as t_1, t_2 and t_3 as in Fig. 13 (for the discharging process) and Fig. 14 (for the charging process) for a constant air inlet velocity of 0.6 m/s. Confirming the similar findings from Zalba et al. [6] that the air inlet temperature plays a major role in the discharging time.

Table 8
Summary of the air inlet temperature influence on discharging and charging time

	30 °C (t_1)	34 °C (t_2)	38 °C (t_3)
Discharging process (V= 1.6 m/s)	6.9h	3.8h	3h
	12 °C (t_1)	16 °C (t_2)	18 °C (t_3)
Charging process (V= 1.6 m/s)	2.8h	3.8h	4.8h

(ii) Cooling/heating load and effectiveness over the phase change

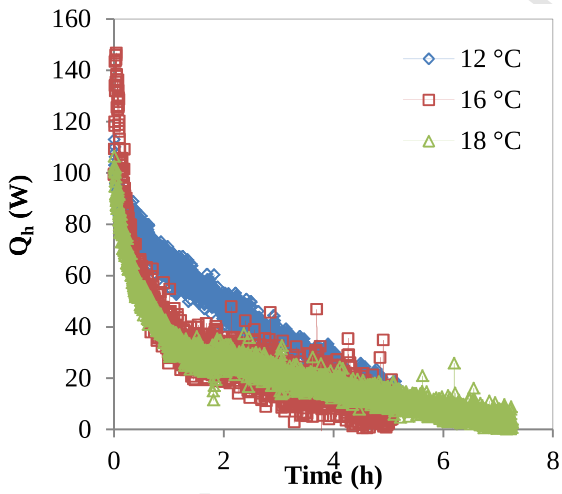
The cooling and heating loads of the PCM during the charging and discharging processes have been calculated using Eq. (2) and Eq. (3) and displayed at Fig. 15 and Fig.16.



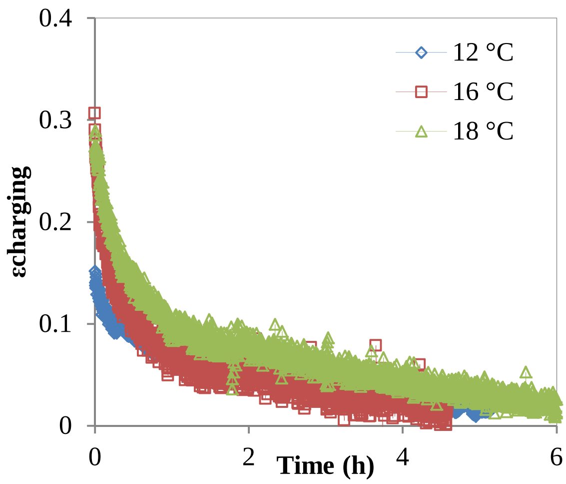
(a) (b)

Fig.15. Influence of the air inlet temperature on the (a) cooling load and (b) effectiveness for discharging process

The cooling load remains at approximately 80 W for an air inlet temperature of 38 °C, dropping to a minimum value after 3h. This drop is associated with the end of the phase change. For 34 °C, the cooling load keeps at approximately 60 W, and then reduces after 3.8h. At last for air inlet of 30 °C the cooling load maintains at 50 W till 6.8h. Overall, for a higher air inlet temperature, the heat flux reaches the minimum value in a short time period, showing that the discharging process of the PCM has been completed earlier at higher air inlet temperatures. On the other hand, for lower air inlet temperatures, the heat transfer rate obtains lower values. However, it stays above the minimum value of 50 W for a longer period of time. The average effectiveness over the phase change has been calculated for the discharging and charging process through Eq. (4) and displayed in Fig. 15 and Fig. 16. From Fig. 15, the average effectiveness ranged between 0.17 and 0.09 for the discharging process. The highest value is registered for the air inlet temperature of 30 °C followed by inlet of 34°C and 38 °C. This is due to the temperature difference between the air inlet temperature and the discharging temperature represented in the nominator of Eq. (4).



(a)



(b)

Fig.16. Influence of the air inlet temperature on the (a) heating load and (b) effectiveness for charging process

Similar heating loads have been observed for 16 °C and 18 °C (30 W) due to the similar air temperature difference. This figure rises slightly for an air inlet temperature of 12 °C to 50 W, but it diminishes drastically after 2.5h due to the end of the phase change and becomes approximate to the other two curves. The effectiveness of the lower air inlet temperature is highest during the discharging process. For higher inlet temperatures, greater effectiveness has been achieved for the charging process. For the charging process (Fig. 16) the average effectiveness register a higher value for an air inlet temperature of 18 °C and is reduced for the lower air inlet temperatures. Again, this is because of the temperature difference between the air inlet and the melting temperature of the PCM.

The influence of the air inlet temperature and velocity on the PCM charging/discharging time, heating/cooling load and effectiveness is presented and discussed and summarised in the following section.

7. Conclusions

Both the charging and discharging processes are influenced by the air inlet velocity. It has been observed that for the selected temperatures, the increase of the air inlet velocity would reduce the charging and discharging time. However, this reduction is more significant when the velocity has increased from 0.6 m/s to 1.6 m/s. The air inlet temperature has been proved to be the most important parameter affecting the discharging time. The discharging time would be reduced when the air inlet temperature is increased from 30 °C to 34 °C. However, the charging time presents a linear reduction with the decrease of the air inlet temperature. The cooling load associated with the discharging of the PCM panels is in the average of 70 W, 110 W and 130 W for an air inlet temperature of 38 °C and air inlet velocities of 0.6 m/s, 1.6 m/s and 2.5 m/s respectively. The heating load related to the charging of the PCM panels achieves 30 W, 40 W and 50 W for the velocities of 0.6 m/s, 1.6 m/s and 2.5 m/s respectively. The cooling load (i.e. the discharging process) decreases for lower air inlet temperatures corresponding to 50 W and 60 W and 80 for 30 °C, 34 °C and 38 °C respectively. The heating load (i.e. charging process) keeps the same for 16 °C (30 W) and 18 °C (30 W) increasing slightly for 12 °C (50 W). For the higher velocity the cooling and heating load reaches the higher values but drops sharply as the phase change of the PCM has been completely finished. Although for the lower air inlet velocity both the heating and cooling loads achieves lower values, they remain nearly constant over a longer period of time due to the longer phase change time. The effectiveness reaches its highest values for a velocity of 0.6 m/s for both the charging and discharging processes benefiting from a longer contact between the air and the PCM panels.

Free cooling applications that rely on the daytime and night-time temperature differences face two challenges, the charging of the PCM over a short period of time (overnight) and the discharging of the PCM during the daytime. These results suggest that the further increase of the air inlet velocity will not reduce the charging time. Instead, a lower temperature will be required for that purpose. Therefore, to accomplish the required charging time, the PCM thermophysical properties (namely the melting temperatures) need to be considered taking into account the night-time temperature profile. For the discharging time, it could be extended over a certain period of time by reducing the air inlet velocity even for higher air inlet temperature. Hence, it is crucial to carefully balance the air inlet velocity to achieve the desirable charging/discharging time and also to achieve the intended air temperature difference.

References

[1] Buildings and Climate Change. A Summary for Decision-Makers, UNEP's Sustainable Buildings & Climate Initiative (SBCI) 987-92-807-3064-7 (2009).

[2] J. Laustsen, Energy Efficiency Requirements in Building Codes, Energy Efficiency Policies for New Buildings (IEA Information paper) (2008).

[3] E. Annunziata, M. Frey, F. Rizzi, Towards nearly zero-energy buildings: the state-of-art of national regulations in Europe, Energy 57 (2013) 125-133.

[4] K.W. Wan Kevin, H.W. Li Danny, L. Dalong, C. Lam Joseph, Future trends of building heating and cooling loads and energy consumption in different climates, Building and Environment 46 (1) (2011) 223-234.

[5] A.G. Kwok, N.B. Rajkovich, Addressing climate change in comfort standards, Building and Environment 45(1) (2010) 18-22.

[6] B. Zalba, J. Marin, L. Cabeza, H. Mehling, Free cooling of buildings with phase change materials, Int J of Refrigeration 27 (2004) 839-849.

[7] Li Yongcai, Liu Shuli, Shukla A, Experimental analysis on use of thermal conductivity enhancers (TCEs) for solar chimney applications with energy storage layer, Energy and Buildings 16 (2016) 35-44.

[8] P. Dolado, A. Lazaro, J.M. Marin, B. Zalba, Characterization of melting a in a real PCM-air heat exchanger: Numerical model and experimental validation, Energy Convers Mgmt 52 (2011) 1890-1907.

[9] M. Iten, S. Liu, A work procedure of utilising PCM as thermal storage systems based on air-TES systems, Energy Conversion and Management 77 (2014) 608-627.

[10] Y. Zhang, G. Zhou, K. Lin, Q. Zhang and H. Di, Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook, Building and Environment 42 (2007) 2197-2209.

[11] I. Mandilaras, M. Stamatiadou, D. Katsourinis, G. Zannis and M. Founti, Experimental thermal characterization of a Mediterranean residential building with PCM gypsum board walls, Building and Environment 61 (2013) 93-103.

[12] G. Evola, L. Marletta, F. Sicurella, A methodlogy for investigating the effectiveness of PCM wallboards for summer thermal comfort in buildings, Building and Environment 59 (2013) 517-527.

[13] M. Iten, S. Liu and A. Shukla, A review on the air-PCM-TES application for free cooling and heating in the buildings 61 (2016) 175-186.

[14] M. Iten, S. Liu, Experimental study on the performance of RT25 to be used as Ambient Energy Storage, Energy Procedia 70 (2015) 229-240.

[15] V. Raj, R. Velraj, Review on free cooling of buildings using phase change materials, Renewable and Sustainable Energy Reviews 14 (2010) 2819-2829.

[16] L. Cabeza, A. Castell, C. Barreneche, A. Gracia, A. Fernández, Materials used as a PCM in thermal energy storage in buildings: A review, Renewable and Sustainable Energy Reviews 15 (2011) 1675-1695.

[17] RSECE. Decreto de Lei nº 79/2006, Regulamento dos Sistemas Energéticos e de Climatização dos Edifícios, Portugal (2006).

[18] ASHRAE. Handbook of Fundamentals, American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc. Atlanta, GA, (2001).

[19] Rubitherm Technologies GmbH. Available from http://www.rubitherm.de/, (2015).

[20] B. Zivkovic, I.Fujii, An analysis of isothermal phase change material within rectangular and cylindrical containers, Solar Energy 70 (2001) 51–6.

[21] K. Ismail, J.R.Henrıquez, Numerical and experimental study of spherical capsules packed bed latent heat storage system, Applied Thermal Engineering 22 (2002) 1705–16.

[22] A. Laouadi, M. Lacroix, Thermal performance of a latent heat energy storage ventilated panel for electric load management, Int J Heat Mass 42 (1999) 275-286.

[23] S. Vakilaltojjar, W.Saman, Analysis and modelling of a phase change storage system for air conditioning applications, Applied Thermal Engineering 21 (2001) 249-263.

[24] P.D. Silva, L.C. Gonçalves, L. Pires, Transient behaviour of a latent-heat thermal-energy store: numerical and experimental studies, Appl Energy 73 (2002) 83-98.

[25] B. Liu, P. Majumdar, Numerical Simulation of Phase Change Heat Transfer in PCM-Encapsultaed Heat Sinks, In: The 18th IEEE Semi-Therm Symposium (2006).

[26] N.A.M. Amin, F. Bruno, M. Belusko, Optimisation of a phase change thermal storage system, In: World Academy of Science, Engineering and Technology 56 (2009) 765–769.

[27] E. Halawa, W. Saman, Thermal performance analysis of a phase change thermal storage unit for space heating, Renewable Energy 36 (2011) 259-264.

[28] W. Saman, F. Bruno, E. Halawa, Thermal performance of PCM thermal storage unit for a roof integrated solar heating system, Solar Energy 78 (2005) 341-349.

[29] P. Dolado, Almacenamiento térmico de energía mediante cambio de fase. Diseño y modelizacíon de quipos de almacenamiento para intercambio de calor con aire. Ph.D. Thesis, Departamento de Ingeniería Mecánica, University Zaragoza, Spain (2011).

[30] B.L. Gowreesunker, Phase change thermal energy storage for the thermal control of large thermally lightweight indoor spaces, PhD Thesis, Brunel University, UK (2013).

[31] E. Osterman, K. Hagel, C. Rathgeber, V. Butala, U.Stritih, Parametrical analysis of latent heat and cold storage for heating and cooling of rooms, Applied Thermal Engineering 84 (2015) 138- 149.

[32] P. Charvát, L. Klimes, M. Ostry, Numerical and experimental investigation of a PCM-based thermal storage unit for solar air systems, Energy and Buildings 68 (2014) 488-497.

[33] E. Osterman, V. Butala, U. Stritih, Room heat exchanger with PCM as a thermal accumulation for heating and cooling of buildings. 11th REHVA World Congress and the 8th International Conference on IAQVEC, Prague, Czech Republic (2013).

[34] A. Waqas, S. Kumar, Thermal performance of Latent Heat Storage for Free Cooling of Buildings in a Dry and Hot Climate: An Experimental Study, Energy and Buildings 43 (2011) 2621-2630

[35] ASHRAE. Handbook of Fundamentals, American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., Atlanta (1993).

[36] TSI. Available from http://www.tsi.com/uploadedFiles/_Site_Root/Products/Literature/Manuals/flow_and_pressure.pdf (2015).

[37] D. Zhou, C.Y. Zhao, Experimental investigations on heat transfer in phase change materials (PCMs) embedded in porous materials, Appl. Therm. Eng. 31 (2011) 970-977.

[38] J.N.W. Chiu, V. Martin, Multistage latent heat cold thermal energy storage design analysis, Applied Energy 112 (2013) 1438-1445.

[39] A.H. Mosaffa, C.A. Infante Ferreira, F. Talati, and M.A. Rosen. Thermal performance of a multiple PCM thermal storage unit for free cooling. Energy Conversion and Management 67 (2013): 1-7.

Highlights

- Present research paper investigates thermal performance of an air-phase change material (PCM) unit.
- Air inlet temperatures and velocities play a vital on determining thermal performance of an air-PCM unit.
- The increase of the air inlet velocity reduced the charging and discharging time, however not linearly.
- The time for the complete melting and solidification is substantially reduced when the velocity has been increased from 0.6 m/s to 1.6 m/s.