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Experimental study on the performance of RT 25 to be used as Ambient Energy Storage

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Abstract

The proposed experimental work intends to analyse the thermal performance of a TES unit incorporated into a ventilation system under different working conditions. The influences of the air inlet temperature and velocity on the air outlet temperature and heat transfer rate were investigated The air inlet temperature used for the solidification of RT25 were 10 °C, 12 °C and 14 °C and for the melting 34 °C, 36 °C and 38 °C. The selected air inlet velocities were the same for the melting and solidification process: 0.5 m/s, 1.4 m/s and 2.5 m/s. The results suggest that an increase of the air inlet velocity reduces linearly the temperature difference between the air inlet and outlet for the solidification process of the RT25. Contrary, for the melting of the RT25, increasing the air inlet velocity does not reduce the temperature difference linearly, increasing the air inlet temperature furthermore from 36 °C to 38 °C did not affect the melting time. The air inlet temperature plays a significant role on the melting process, reducing linearly the air inlet and outlet temperature difference and the heat transfer rate, however does not influence the solidification process, similar air inlet and outlet temperature difference and the heat transfer rate were obtained for all condition. Thus, air inlet velocity and air inlet temperature have to be carefully balanced to optimize the whole running cycle of both melting and solidification processes.

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Keywords: Thermal energy storage; Phase change material; Thermal performance; Paraffin RT25

1. Introduction

Thermal energy systems (TES) are a useful measure tool to store energy widely encountered in nature such as solar energy, geothermal energy and thermally stratified layers in oceans [1]. TES are advantageous to reduce the demand of heat and cold sources in different applications such as: cooling of heat and electrical engines, thermal protection of electronic devices, manufactory processes, thermal comfort in buildings and vehicles. Solar heat is a

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great source of energy since it's available free, clean and exhaustless, but only available during the day. On the other hand the storage of night coldness allows major savings for cooling applications. Common commercial phase change materials (PCM) used in free heating and cooling experiments are RT20, RT25 and RT27 supplied by Rubitherm [2] presenting melting temperatures around the acceptable comfort temperatures. Experiments carried out with these PCMs are presented in Butala and Stritih [3], Zalba et al. [4] and Dolado et al. [5] and reviewed in Iten and Liu [6]. Overall studies on rectangular PCM-air heat exchanger found that to determine the thermal performance, the most important parameters to be measured are the temperature of the inlet and outlet air and/or temperature across the PCM panels, inlet and outlet air flow rate/velocity and in some cases also the air humidity and air flowing resistance.

The present paper intends to evaluate the thermal performance of an air-PCM heat transfer unit using RT25 supplied by Rubitherm GmbH [2], i.e melting point at 25 °C, and to be used for different applications focusing on thermal comfort conditions.

2. Experimental setup

The experimental setup consists of an wood air duct , chosen due to its low thermal conductivity and aiming to reduce the heat losses to the surroundings. For the same purpose a 20 mm layer of insulation was fixed at the top of the ductwork to prevent the solar gains. The main air duct presents a length (L), width (W) and height (H) of 2.6 m, 0.25 m and 0.18m respectively. The air duct includes an air-PCM heat transfer unit and is coupled to heating/cooling unit, exhaust fan and to several measurements equipment as presented in Fig. 1.

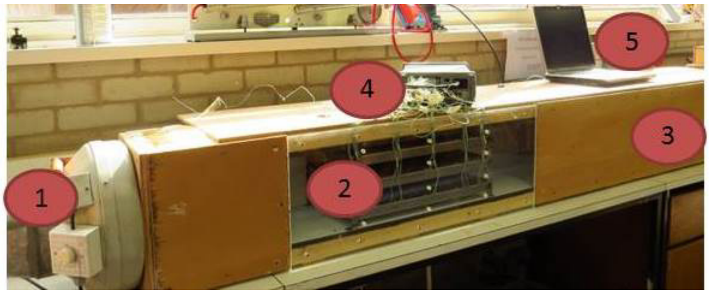

Fig. 1. Experimental Setup (1- Exhaust fan; 2- Air-PCM heat transfer; 3- Heating/Cooling unit; 4- Data acquisition; 5- PC)

Exhaust fan ①

The air is pulled through a centrifugal exhaust fan with electrical power and volumetric flow rate of 0.11 kW and 147 m3/h respectively. A variable speed device is coupled to the fan in order to vary the air inlet velocity between 1.25 m/s to 2.5 m/s.

Air-PCM heat transfer unit ②

The air- PCM heat transfer unit is composed by three panels "filled" with RT25 into rectangular metallic plates and each panel is surrounded on the top and bottom by air channels. As there is no limitation in terms of application, the plates are arranged horizontally to reduce the air pressure drop and therefore reduce the required fan power. The air- PCM heat transfer unit is coupled downstream to a heating/cooling unit and upstream to an exhaust fan. Contrary to the researches carried out by Zivkovic and Fujii [5], Butala and Stritih [6] and Waqas and Kumar [7], three parallel plates have been arranged instead of a single panel to replicate the melting and solidification phenomena for the same conditions and to achieve converged results when comparing the three panels. Hence, unexpected anomalies can be easily identified when comparing the results obtained by the three panels. Table 1 presents the details about the air-PCM heat transfer unit.

Heating/Cooling Unit ③

The construction of the heating unit involved 4 electrical 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 operating temperatures are below 50 °C – lower than the wood fire point (300 ºC). Each electrical coil thermostat is connected to a adjust control unit enabling varying the temperature. The cooling unit corresponds to a portable air conditioner (Electro-Aire) with cooling capacity of 2.6 kW. The required cooling capacity is smaller than the heating capacity due to the round year ambient temperatures recorded in the laboratory where the testing is performed.

Table 1. Materials properties

Dimensions per panel	500 x 250 x 20 mm
PCM mass per panel	1.8 kg
Container mass per panel	1.8 kg
Phase change temperature	Melting: 20-25 °C Solidification: 18- 25 °C
Heat storage capacity per panel	370.8 kJ
Total heat storage capacity	1112.4 kJ

Measurement instrumentation④⑤

Temperature and velocity sensors are coupled at the entrance and exit of the air-PCM heat transfer unit to evaluate the overall performance of the system. The instrumentation used in this study includes: anemometer to measure the air velocity; thermocouples to measure air inlet/outlet temperatures, data acquisition unit to record the temperatures and connected to a PC. The air velocity is measured at the main air inlet and outlet at the location 1 and 2 respectively presented in Fig. 2 using an air velocity meter (TSI, model TA440A). The accuracy and resolution of the respective equipment is ±0.015 m/s and 0.01.4 m/s respectively. The chosen thermocouples are K-type provided by RS Components with accuracy of ± 1.5 °C and connected to the data logger. Position 1 was also used as the setup point where the air inlet velocities and temperatures were controlled and when desirable values were achieved, the experiment was started and recorded.

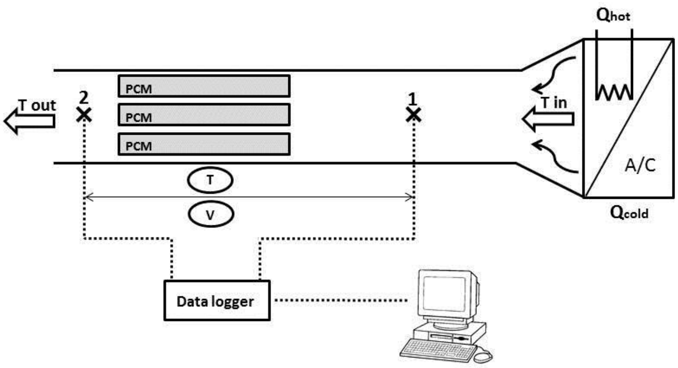

Fig. 2. Air temperature and velocity measurements points

The thermocouples were connected to a digital temperature recorder model 3470A by Agilent Technologies and included 2 cards to allow the connection of a maximum of 62 thermocouples. Provided software has been used to record temperature data in a database format with a personal computer. The temperature data have been recorded and stored at an interval of 10 Seconds.

The uncertainty of the experimental test can be calculated by using Eq. (1) [7].

$$U = \pm\sqrt{\left(\frac{\delta T_{TC}}{T_{TC}}\right)^2 + \left(\frac{\delta T_{DT}}{T_{DT}}\right)^2 + \left(\frac{\delta V}{V}\right)^2 + \left(\frac{\delta l}{l}\right)^2}\ x\ 100\% \quad (1)$$

The uncertainty of the experiment is calculated by Eq. (1). The total uncertainty is attributed to the inaccuracies for the temperature, data logger, velocity and thickness of the PCM container. The inaccuracies of the thermocouples, δT_{TC}, data acquisition instrument, δT_{DT}, air velocity, δV and thickness, δl are ± 0.3 °C (1.25 %), ± 0.5 °C (2.1 %), ± 0.015 m/s (1.5 %), and ± 0.1 mm (0.5 %) respectively. Thus, the experimental uncertainty is estimated at 5.4 % and it guarantees the credibility of experimental data.

3. Experimental procedure

The experimental setup was built to determine and evaluate the outlet temperature and heat transfer rate under different air velocities and at different air inlet temperatures as displayed in Fig. 3. The experimental procedures involved therefore different conditions for the air inlet temperature and velocity as presented in Table 1.

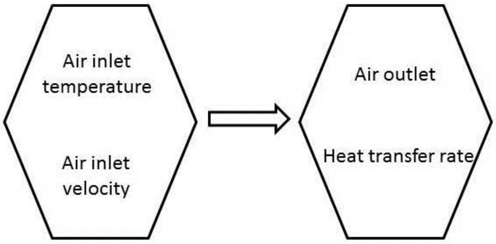

Fig. 3. Parameters to be evaluated in the experimental study

In the melting process, hot air at a higher temperature than the PCM melting temperature and at a constant flow rate flows through the air-PCM heat transfer unit in order to melt the PCM. The process is continued until the three PCM panels reach 30 °C – beyond the melting temperature of RT25. In the solidification process, cold air at a lower temperature than the PCM solidification temperature and at a constant flow rate flows through the air-PCM heat transfer unit until it solidifies the PCM. The process is continued until the PCM panels reach 14 °C– beyond the solidification temperature.

For Mediterranean countries, namely Portugal, typical daily ambient temperature profiles during summer are presented in Fig 4. The solidification process of the PCM takes place during night time between 10 and 16 ºC while the melting process of the PCM is expected during day time when the ambient temperature reaches over 30 ºC. The experimental operation conditions specific in the temperatures were selected according to these figures and presented in Table 2.

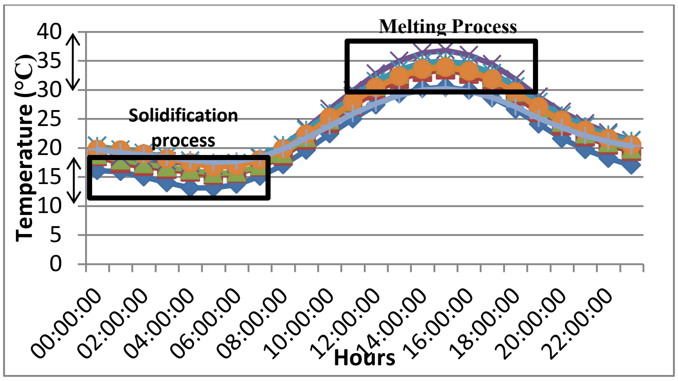

Fig. 4. Typical temperature profiles for the summer in Castelo Branco, Portugal (Solterm, 2006)

Table 2. Experimental procedures

Experiment		Air inlet temperature	Air inlet velocity
Influence of air inlet velocity	Melting Process	38 °C	0.5 m/s 1.4 m/s 2.5 m/s
	Solidification Process	10 °C	0.5 m/s 1.4 m/s 2.5 m/s
Influence of air inlet temperature	Melting Process	34 °C 36 °C 38 °C	1.4 m/s
	Solidification Process	10 °C 12 °C 14 °C	

4. Results and Discussion

In this section the experimental results for the experimental procedures detailed in Table 2 are presented.

4.1. Influence of air inlet velocity on melting of the PCM

The influence of the air inlet velocity is analysed by choosing three different air velocities as listed in Table 2 but keeping the temperature constant. For melting the air inlet temperature is fixed at 38 °C and the influence of the air velocity analysed by varying the velocity from a minimum of 0.5 m/s, 1.4 m/s and maximum of 2.5 m/s. The initial temperature of the whole systems was at 14 °C.

- Air outlet temperatur

The influence of the air inlet velocity on the air outlet temperature is evaluated by fixing the air inlet temperature at 38 °C and varying the velocity from 0.5 m/s, 1.4 m/s to 2.5 m/s and displayed in Fig. 5. The melting process was carried out until the air inlet and outlet from the air-PCM heat transfer unit reached the same temperature. The temperature difference between the air inlet and air outlet is represented as ΔT_1, ΔT_2 and ΔT_3 for 0.5 m/s, 1.4 m/s and 2.5 m/s respectively. From Fig 4 it is also possible to identify the time indicting the complete of PCM melting, when the air outlet reaches the air inlet temperature, represented as t_1, t_2 and t_3 for 0.5 m/s, 1.4 m/s and 2.5 m/s respectively.

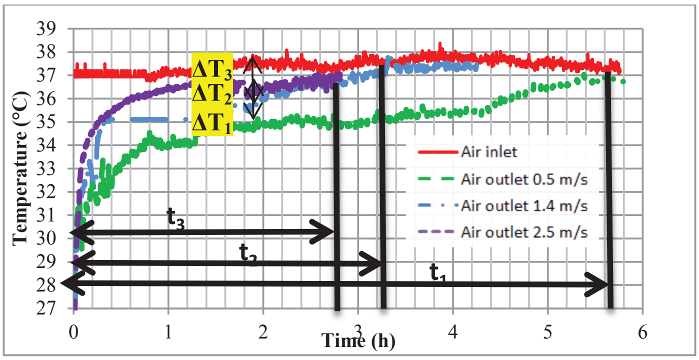

Fig.5. Influence of the air inlet velocity on the air outlet temperature (melting process)

From Fig. 5 it is possible to visualize three stages, first one corresponding a temperature increase from the initial temperature approx.14 °C until the experiment temperatures (35 ºC), secondly the air outlet became relatively constant when air is transferring the heat to the PCM and increasing its latent heat and at last air outlet increases sharply showing the end of latent heat exchange and turning into sensible heat. Fig. 5 shows that increasing the air inlet velocity decreases the melting time period of the PCM. The melting of the PCM panels took approx. 2.8 h (t_3), approx. 3.4 h (t_2) and approx. 5.8h (t_1), for 1.4 m/s, 2.5 m/s and 0.5 m/s respectively. Consequently increasing the air inlet temperature form 0.5 to 1.4 m/s allowed the major time reduction for the melting of the whole PCM. Also, increasing the air inlet velocity decreases the temperature difference between the air inlet and air outlet temperatures. It is observed that for air inlet velocity of 2.5 m/s an average temperature difference of 0.8 °C (ΔT_3) is registered. For 1.4 m/s the average temperature difference reaches 2 °C (ΔT_2). For an air inlet velocity of 0.5 m/s the average temperature difference corresponds to 3 °C (ΔT_1).

- Heat transfer rate

Heat transfer rate between air and PCM during the melting and solidification process was calculated using the measured values of the air temperature at the inlet and outlet of the air-PCM heat transfer unit and according to

$$\dot{q}_{melting} = \rho_{air}\dot{m}_{air}c_{p,air}\left(T_{air,in} - T_{air,out}\right) \quad (2)$$

Where, $\dot{q}_{melting}$ is the heat transfer rate in J/s, $\dot{m}_{air}$ the volumetric air flow rate in m^3/s, $c_{p,air}$ the specific heat of the air (J/kg.°C) and $T_{air,in}$, $T_{air,out}$ the air inlet and outlet temperatures in °C, respectively.

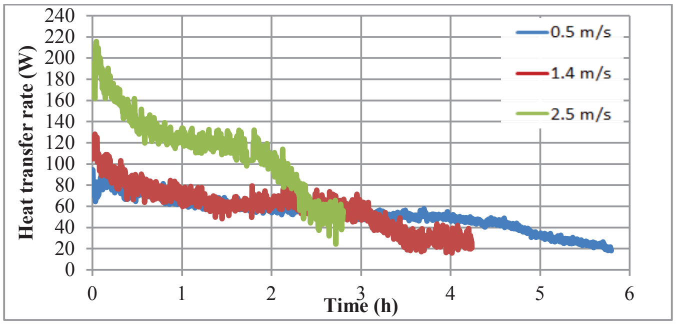

Fig.6. Influence of the air inlet velocity on the heat transfer rate (melting process)

At higher air inlet velocity the heat flux achieves higher values but reaches the minimum value in a short time period (Fig. 6), showing that melting process of the PCM completes earlier with a higher air inlet velocity. On the other hand for lower air inlet velocity the heat transfer rate is lower however stays above the minimum value for a longer period of time.

4.2. Influence of the air inlet velocity on the solidification of PCM

For the solidification process the air temperature is fixed at 10 °C and the influence of the air velocity is analysed by varying the velocity from a minimum of 0.5 m/s to1.4 m/s and then maximum of 2.5 m/s. The initial temperature of the whole systems was 30 °C, the ambient temperature was 20 °C and the air inlet temperature was 10 °C. The transient temperatures for the different velocities are presented in Fig. 6.

- Air outlet temperature

The temperature difference between the air inlet and air outlet are represented as ΔT_1, ΔT_2 and ΔT_3 for 0.5 m/s, 1.4 m/s and 2.5 m/s respectively in Fig.7. It also identifies the period of time for the air outlet temperature to reach the air inlet temperature, t_1, t_2 and t_3 for 0.5 m/s, 1.4 m/s and 2.5 m/s respectively.

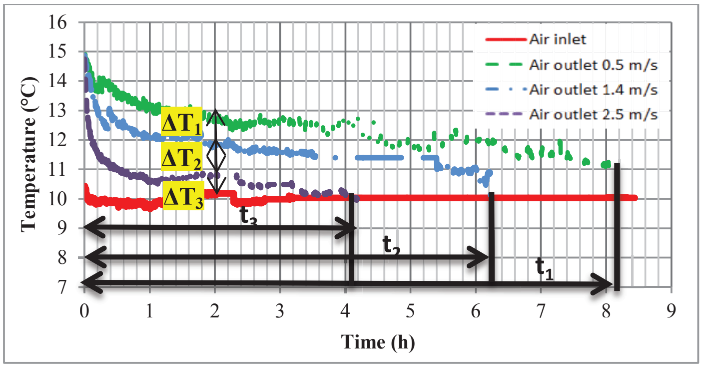

Fig.7. Influence of the air inlet velocity on the air outlet temperature (solidification)

From Fig. 7 it is observed that for the solidification process of the PCM, increasing the air inlet velocity decreases the temperature difference between the air inlet and air outlet temperatures, ΔT and also the time at which they become the same. For instance for 0.5 m/s the temperature difference, ΔT_1 varies from 1 to 3°C along 8 hours, however for a higher air inlet velocity of 2.5 m/s, ΔT_2 reduces to an average of 0.5 °C. Contrary to the melting process as observed from Fig. 7, for the solidification process, the sensible cooling after complete solidification process decreases smoothly over a certain period of time and therefore after the solidification process is complete it takes an extra time for the outlet temperature to reach the air inlet temperature. The increase of the air inlet velocity also decreases the solidification time of the PCM panels. The solidification of the PCM panels took approx. 4.2 h (t_3), approx. 6.2 h (t_2) and over 8 h (t_1), for 2.5 m/s, 1.4 m/s and 0.5 m/s respectively. Consequently increasing the air inlet velocity decreases linearly the solidification time.

- Heat transfer rate

Heat transfer rate between air and PCM during the melting and solidification process was calculated using the measured values of the air temperature at the inlet and outlet of the air-PCM heat transfer unit using the below equation:

$$\dot{q}_{melting} = \rho_{air}\dot{m}_{air}c_{p,air}\left(T_{air,out} - T_{air,in}\right) \tag{3}$$

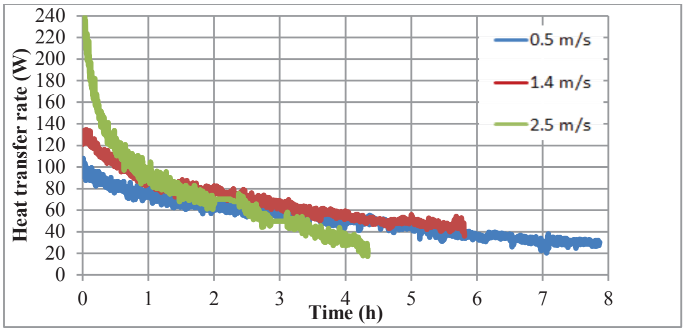

Fig. 8. Influence of the air inlet velocity on the heat transfer rate (solidification process)

Observation from Fig. 8 illustrate that at a higher air inlet velocity the heat flux reaches the minimum value in a short time period, showing that solidification of the PCM has completed quicker at a higher air inlet velocity. It can be concluded that more heat was extracted at higher air inlet velocity compared to lower air inlet velocity within 8 hours of the solidification process. Moreover, at higher inlet velocity the storage was solidified in a shorter period comparing to the lower air inlet velocity.

For both melting and solidification process it is observed that the heat transfer rates are identical for air inlet velocity of 0.5 m/s and 1.4 m/s and higher for an air inlet velocity of 2.5 m/s.

Table 3 and 4 summarize the influence of the air inlet velocity on the melting and solidification process.

Table 3. Summary of the air inlet velocity influence on the average air outlet temperature

	0.5 m/s	1.4 m/s	2.5 m/s
	ΔT_1	ΔT_2	ΔT_3
Melting (T= 38°C)	2.5 °C	1.5 °C	1 °C
Solidification (T= 10°C)	3 °C	2 °C	0.8 °C

Table 4. Summary of the air inlet velocity influence on average heat transfer rate

	0.5 m/s	1.4 m/s	2.5 m/s
Melting (T= 38°C)	60 J/s	60 J/s	120 J/s
Solidification (T= 10°C)	60 J/s	60 J/s	120 J/s

The results show that for melting process increasing the air inlet velocity from 0.5 m/s to 1.4 m/s reduces the melting time nearly in 2h and increasing the velocity to 2.5 m/s leads to similar melting time. For the solidification increasing the velocity from 0.5 m/s to 1.4 m/s reduced the melting time in 2 hours, although the melting time was reduced in another hours for the velocity of 2.5 m/s. From these results the optimum air inlet velocity corresponds to 1.4 m/s and therefore it is selected as the velocity to be used for the next analysis: air inlet temperature influence on the melting and solidification time.

4.3. Influence of air inlet temperature on melting of the PCM

For the air inlet temperature influence study, the air velocity is fixed at 1.4 m/s and the air temperature is analysed by varying the air inlet temperature from 34 °C, 36 °C to 38 °C. The initial temperature of the whole systems was at 14 °C, the ambient temperature was at 20 °C. The transient temperatures for the different temperatures are presented in Fig. 9-11.

- Air outlet temperature

The temperature difference between the air inlet and air outlet are represented as ΔT_1, ΔT_2 and ΔT_3 for 34 °C, 36 °C and 38 °C respectively. It also identifies the period of time for the air outlet temperature to reach the air inlet temperature, t_1, t_2 and t_3 for 34 °C, 36 °C and 38 °C respectively.

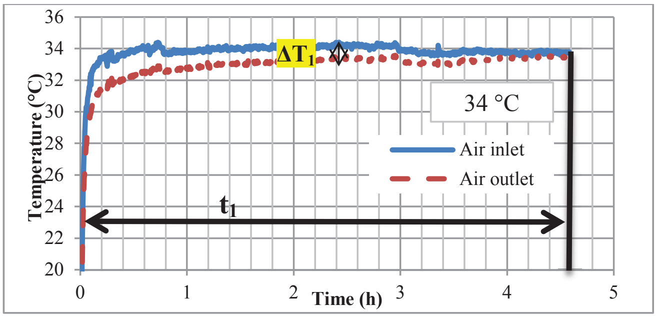

Fig. 9. Influence of the air inlet temperature (34 °C) on the air outlet temperature

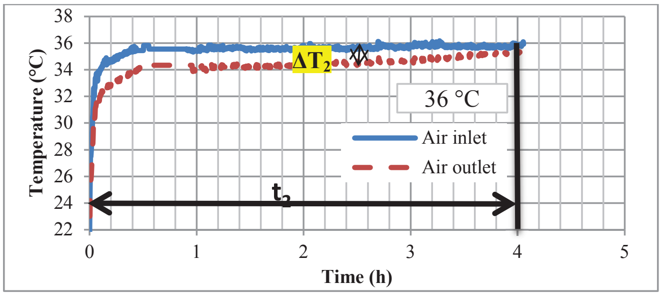

Fig. 10. Influence of the air inlet temperature (36 °C) on the air outlet temperature

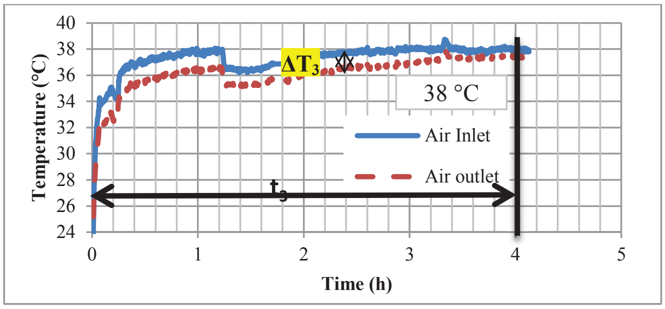

Fig. 11. Influence of the air inlet temperature (38°C) on the air outlet temperature

Fig. 9-11 represent the temperature difference ΔT_1, ΔT_2 and ΔT_3 for air inlet temperature of 34 °C, 36 °C and 38°C, respectively. For any case, the temperature difference remains nearly constant representing the phase transformation process of the PCM afterwards is becomes nearly zero representing the end of the melting process.

Overall, it is observed that for the melting process of the PCM, increasing the air inlet temperature from 34 °C to 36 °C increased the temperature difference from ΔT_1=1°C to ΔT_2= 1.5 °C. However a nonlinear relation is observed as an increase in the air inlet temperature from 36°C to 38°C did not increase the temperature difference any further. On the other hand, increasing the air inlet temperature decreases the period of time that it takes for the air outlet to reach the air inlet temperature, translating the melting time (t_1, t_2 and t_3). The melting process was complete after approx. 4 h for 36 °C and 38 °C (t_2, t_3) and 4.5 h for 34 °C. This is due the fact that 34 °C is closer to the PCM melting point, requiring more time for the complete melting of the PCM panels.

- Heat transfer rate

Heat transfer rate between air and PCM during the melting and solidification process was calculated using the measured values of the air temperature at the inlet and outlet of the air-PCM heat transfer unit. The heat transfer rate between the air and the PCM during the melting process is determined from Eq. 2.

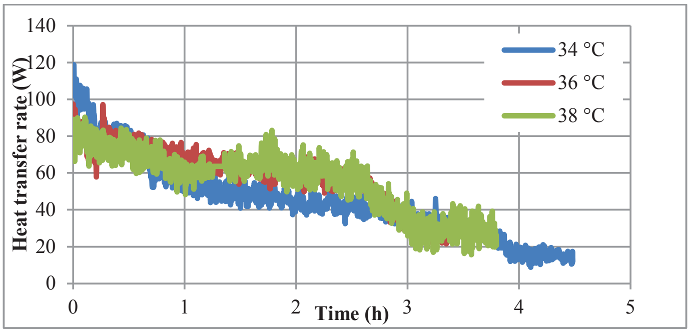

Fig. 12. Influence of the air inlet temperature on the heat transfer rate (melting process)

the heat transfer rates are similar for the air inlet temperature of 36 °C T and 38 °C and lower for an air inlet of 34 °C (Fig. 12). For a higher air inlet temperature the heat flux reaches the minimum value in a short time period, showing that melting process of the PCM has been completed earlier at higher air inlet temperature. On the other hand for lower air inlet temperature the heat transfer rate is lower however stays above the minimum value for a longer period of time.

4.4. *Influence of air inlet temperature on solidification of the PCM*

For the solidification process the air velocity is fixed at 1.4 m/s and the influence of the air temperature is analysed by varying the air temperature from 10 °C, 12°C to 14 °C. The initial temperature of the whole systems was at 30 °C and the ambient temperature was at 20 °C. The transient temperatures for the different temperatures are presented in Fig. 13-15.

- Air outlet temperature

The temperature difference between the air inlet and air outlet are represented as ΔT_1, ΔT_2 and ΔT_3 for 10 °C, 12 °C and 14 °C respectively. It identifies the period of time for the air outlet temperature to reach the air inlet temperature, t_1, t_2 and t_3 for 10 °C, 12 °C and 14 °C respectively.

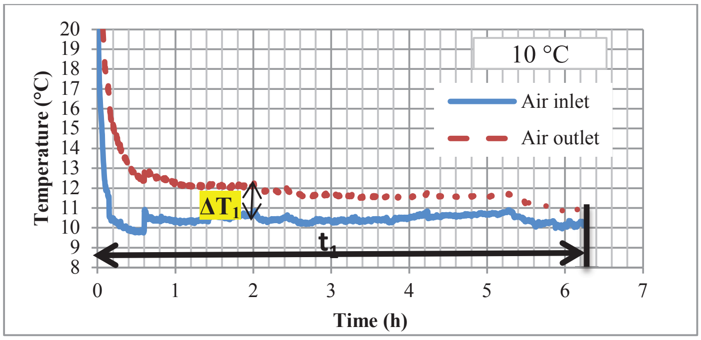

Fig.13. Influence of the air inlet temperature (10 °C) on the air outlet temperature

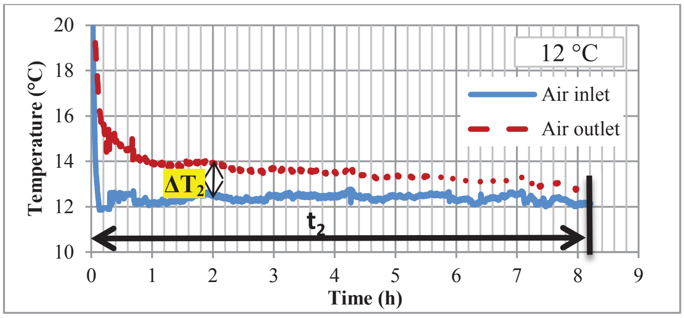

Fig.14. Influence of the air inlet temperature (12 °C) on the air outlet temperature

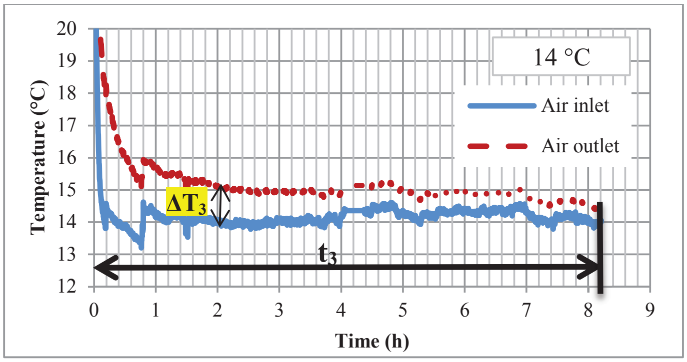

Fig.15. Influence of the air inlet temperature (14 °C) on the air outlet temperature

It is observed that for the solidification, decreasing the air inlet temperature does not decreases the temperature difference between the air inlet and air outlet, same temperature difference was recognized ΔT_1= ΔT_2= ΔT_3= 1.2 °C. Hence, the air inlet temperature does not affect the solidification process for the temperature range considered in the analysis. The solidification process was assumed to complete after approx. 8.2 h for air inlet temperature of 12 °C and 14 °C (t_2, t_3) and approx. 6.2 h for 10 °C (t_1). This is due to the fact that 10 °C is further away from the PCM melting point and hence less time is required to complete the solidification of the PCM panels.

- Heat transfer rate

The heat transfer rate between the air and PCM during the melting process is determined from Eq. 3

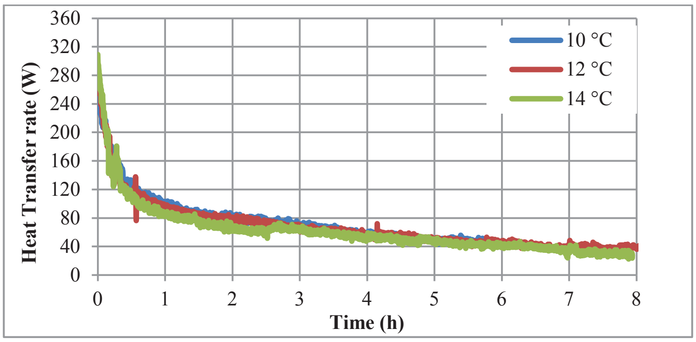

Fig. 16. Influence of the air inlet temperature on the heat transfer rate (melting process)

Observation from Fig. 16 illustrates that the heat flux is identical for any air inlet temperature with average value of approx. 60 J/s and the minimum value associated to the same temperature difference ΔT achieved for the different conditions. Table 5 and 6 summarize the influence of the air inlet temperature on the melting and solidification process.

Table 5- Summary of the air inlet temperature influence on the average air outlet temperature

	34 °C (ΔT_1)	36 °C (ΔT_2)	38° (ΔT_3)
Melting (V= 1.4 m/s)	1 °C	1.5 °C	1.5 °C
	10 °C (ΔT_1)	12 °C (ΔT_2)	14 °C (ΔT_3)
Solidification (V= 1.4 m/s)	1.2°C	1.2 °C	1.2 °C

Table 6- Summary of the air inlet temperature influence on average heat transfer rate

	34 °C	36 °C	38°
Melting (V= 1.4 m/s)	40 J/s	60 J/s	60 J/s
	10 °C	12 °C	14 °C
Solidification (V= 1.4 m/s)	60 J/s	60 J/s	60J/s

5. Conclusion

An experiment investigation of a small prototype of air-PCM TES united was carried out. The influence of the air inlet velocity and temperature on the air inlet and air outlet temperature difference and heat transfer rate, conclusions has been drawn. The main findings of the experimental study are as follows:

The most parameter affecting the melting of the PCM is the air inlet velocity, increasing the air inlet velocity decreases the melting time however not linearly. For instance increasing the air inlet velocity from 0.5 m/s to 1.4 m/s the melting time in approx. 2 h was reduced, however increasing furthermore to 2.5 m/s, the melting time was reduced only in 0.4h. The air inlet temperature did also influence the melting time however increasing the air inlet from 36 °C to 38 °C did not affected the melting time, air outlet temperature or the heat transfer rate.

The solidification of PCM was only influenced by the air inlet velocity. Increasing the air inlet velocity linearly decreased the solidification time, an increase of 0.5 m/s to 1.4 m/s reduced the process in 2 h and further increasing to 2.5 m/s reduced the process in another 2 h. The temperature difference between the air inlet and outlet decreased also linearly in approx. 1 °C. The inlet air temperature did not influence the solidification process, in fact the melting time, air outlet temperature and heat transfer rate were similar for all the tested conditions.

References

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