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Experimental study of the heat transfer through a vertical stack of rectangular cavities filled with phase change materials

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HIGHLIGHTS

- Heat transfer through a vertical stack of rectangular cavities filled with PCMs.
- Experimental evaluation of the heat transfer during melting and solidification.
- Benchmarking results for validating numerical models.
- Discussion of which PCM type is better for building applications.
- Evaluating the effect of subcooling and natural convection during phase change.

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ABSTRACT

The heat transfer through a vertical stack of rectangular cavities filled with phase change materials (PCMs) is experimentally analysed in terms of both melting and solidification processes. This paper provides data that are useful for benchmarking and validation of numerical models that account for natural convection in the molten PCM. Two different PCMs are investigated: the free-form PCM-Rubitherm® RT 28 HC; and the microencapsulated PCM-Micronal® DS 5001 X. In terms of practical applications, the main goal is to discuss which PCM type is better for building applications. The time required for the melting and solidification fronts to reach the mid-plane of the cavities is presented as a function of the PCM type. During charging, the control-temperature value on the hot surface of the test-sample and the period of thermal-regulation are investigated. It is shown that the free PCM is preferable for the thermal control of vertical systems as both parameters are improved due to natural convection. The use of microencapsulated PCMs allows accelerating the charging process with almost no thermal stratification. However, in this case the control-temperature effect and the thermal-regulation period are both reduced. Regarding the discharging process, subcooling plays an important role during the solidification of the free PCM and its effect cannot be neglected when modelling.

1. Introduction

In the last years, the incorporation of PCMs in thermal energy storage (TES) applications has been a subject of great interest, and a significant number of extensive reviews on the topic can be found in the recent literature, reflecting the large amount of work that is being developed worldwide [1–26]. It is known by now that commercial paraffin waxes to be used as PCMs in passive TES applications for buildings have typically low thermal conductivity ($\sim$0.2 W m^{-1} K^{-1}), which can be problematic regarding the energy performance of these elements. The incorporation of fins of high-conductivity material within rectangular macrocapsules containing PCMs has been one of the techniques used to improve the heat transfer through the PCM bulk. These capsules can then be integrated in PCM-enhanced vertical envelope solutions such as PCM-concrete walls [27], PCM-bricks [28,29] and PCM-shutters [30]. They can also be used to take advantage of the off-peak electrical energy for indoor heating [31], to serve as vertical heat sinks [32] and to passively improve the energy performance of photovoltaics (PV/PCM systems) and solar panels (SP/PCM systems) [33–39] by controlling the operating temperature. For these reasons, solid–liquid phase change in

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Nomenclature

A	cavity aspect ratio (=H/L)
C_{eff}	overall heat storage capacity (J kg^{-1})
c_p	specific heat (J kg^{-1} K^{-1})
$E_{\mathrm{st,ex}}$	stored energy (experimentally calculated) (J)
$E_{\mathrm{st.th}}$	theoretical stored energy in the physical domain (J)
H	height of each individual cavity of the test-sample (m)
HF_1	average heat flux measured on the centre of the front surface of the test-sample (W m^{-2})
HF_2	average heat flux measured on the centre of the back surface of the test-sample (W m^{-2})
L	width of each individual cavity of the test-sample (m)
L_f	latent heat of fusion (kJ kg^{-1})
m	mass (kg)
S	area of the front and back surfaces of the test-sample (m^2)
T	temperature (°C)
T_C	average temperature of the surface of the test-sample facing the cold-plate (°C)
T_H	average temperature of the surface of the test-sample facing the hot-plate (°C)
TCP	average temperature measured on the surface of the cold-plate facing the test-sample (°C)
THP	average temperature measured on the surface of the hot-plate facing the test-sample (°C)
T_{mp}	melting peak temperature of the PCM (°C)
T_{reg}	control-temperature reached on the hot surface of the test-sample (°C)
T_{sp}	solidification temperature of the PCM (°C)
T^*_{sp}	lowest temperature reached by the PCM at the end of the sensible cooling due to the subcooling effect (°C)
T_{water}	temperature of the cooling water (°C)
t	time (s)
t_{cr}	time required for starting the crystallization process of the free PCM (s)
t_{liq}	time required for starting the solidification process of the microencapsulated PCM (s)
t_{m}	time required for complete melting of the PCM in the mid-plane of the test-sample (s)
t_{reg}	duration of the temperature control–thermal-regulation period (s)
t_{sc}	period during which subcooling occurs considering the free PCM (s)
t_{sol}	time required for solidifying all the PCM in the mid-plane of the cavities (s)
ΔT_{sc}	difference between T_{sp} and T^*_{sp}

Subscripts

Al	aluminium
i,f	initial and final times considered for calculating the stored energy during charging
l	liquid
PCM	phase change material
s	solid
1,…,5	vertical position of the thermocouples in the mid-plane of the container (from top to bottom)

rectangular cavities is of great interest either from the theoretical point of view or for the development of new TES systems.

Several experimental and numerical studies have been devoted to evaluate the effect of natural convection in vertical rectangular cavities filled with free PCMs [32–37,40–47]. The term "free" means that the macrocapsule is the only way of containment in order to avoid liquid leakages. Therefore, the molten paraffin can move freely inside the cavity due to buoyancy forces. On the other hand, microencapsulated PCMs can also be chosen to fill up the internally finned cavities. In this case, the migration of the PCM within the enclosure due to the buoyancy forces may be considered negligible. Typically, considering vertical applications, horizontal fins are added to the vertical heated/cooled walls of the cavity to provide additional heat transfer surface in the TES system. These units are different from those commonly used in electronic devices mainly in what concerns the orientation of both the enclosure and fins. In recent years, different PCM-based heat sinks with vertical fins emerging from top and bottom heated surfaces have been extensively studied [48–53]. However, since the heat transfer mechanisms during the phase change processes depend on the configuration and orientation of both system and fins, the main findings regarding the influence of natural convection in the molten PCM within these heat sinks can only be carefully applied to vertical building applications.

The most important findings about the natural convection inside rectangular fins-enhanced enclosures filled with commercial paraffin waxes for vertical building applications are pointed out in the recent literature related with the thermal control of PV/PCM and SP/PCM systems [33–35,37]. It has been claimed that the performance of these panels can be improved by placing a PCM-fins-enhanced latent-heat storage unit on the panels back to passively lower the high operating temperature of the systems. Some of these studies were recently reviewed by Du et al. [54]. Hasan et al. [55] also reviewed the main advantages and disadvantages of different thermal control techniques for building integrated PV including the one with PCMs.

One of the first numerical models of a PV/PCM system that has been validated with realistic experimental conditions, for identically sized geometries, was proposed by Huang et al. [33]. The same two fins PV/PCM geometry was considered in the numerical study carried out by Biwole et al. [34]. For validation purposes, these authors compared the numerical results (isotherms and velocity fields) to those obtained from experiments. They found that adding a PCM-fins-enhanced capsule on the back of the solar panel can maintain the operating temperature below 40 °C for 80 min under a constant solar radiation of 1000 W m^{-2}. The same temperature was reached by the panel without PCM after only 5 min. The authors also pointed out that adding high-conductivity fins accelerates the phase-transition, as well as the attenuation of the operating temperature. Huang et al. [35] evaluated the impact of different internal fins-arrangements (number, dimension and shape) on the heat transfer processes with phase change. For a macrocapsule filled with the free-form PCM-RT 25 and a certain fins arrangement, these authors found that during melting the temperature rise of the PV/PCM system can be reduced by more than 30 °C when compared with the data of a single flat aluminium plate. Huang et al. [36] developed a 3D numerical model to simulate the temperature rise of a PV/PCM system and the results were compared with those obtained from using a previously developed and experimentally validated 2D finite-volume heat transfer model. They found that the 2D model can reflect correctly the 3D model predictions for simple line-axis systems. Huang et al. [37] carried out an experimental study for evaluating the effect of natural convection on the molten PCM and PCM crystalline segregation by considering different systems enhanced with internal fins. They found that although the metal fins can improve the heat