Small thermal energy storage units filled with microencapsulated PCMs for building applications

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Abstract

Phase change materials (PCMs) can be used in buildings for thermal management and thermal energy storage purposes. This paper experimentally evaluates the heat transfer with conduction dominated solid-liquid phase-change through small thermal energy storage (TES) units with horizontal metallic fins emerging from vertical heated/cooled surfaces. The TES units are made up of a vertical stack of rectangular cavities filled with a paraffin-based microencapsulated PCM - the Micronal® DS 5001 X. The influence of the aspect ratio of the cavities and the influence of the boundary conditions imposed during both charging (melting of the PCM) and discharging (PCM solidification) experiments was analysed. The experimental results are intended to be used in the validation of numerical models. Furthermore, they allow to discuss how the TES units can be used to improve the thermal performance of some existing systems and to design/optimize new TES systems for buildings.

Keywords: *Building applications, Microencapsulated, Phase change materials (PCMs), Thermal energy storage (TES), TES units.*

Introduction

PCMs are materials that undergo melting/solidification at a nearly constant temperature. Therefore, they are very suitable for thermal management and TES applications. The incorporation of PCMs in buildings has been subject of great interest and much work has been developed worldwide, as reviewed by Soares *et al.* [1], Cabeza *et al*. [2] and Silva *et al.* [3].

It is known by now that commercial paraffin-waxes to be used as PCMs have typically low thermal conductivity, which can compromise the thermal performance of PCM-enhanced systems. The latent heat storage capacity in a complete melting cycle is proportional to the PCM mass while the PCM is melting. Similarly, the energy released is proportional to the PCM volume solidified during discharging. Consequently, low efficiency is achieved when the PCM melts or solidifies only partially. Therefore, for a specific application, the optimum combination of the PCM mass with the melting-peak temperature of the PCM (T_{mp}) have to be found, taking into account the structure of the PCM containment and the existence of any heat transfer enhancement technique to overcome the low thermal conductivity of the PCM.

The containment of PCMs in metallic rectangular-sectioned macrocapsules is a good technique to simultaneously solve the problem of liquid-leakage and improve the heat transfer to the PCM-bulk. Moreover, metallic fins can be incorporated within the container to accelerate the phase-change processes [4]. These PCM-filled macrocapsules can then be integrated in the design of new TES-systems such as bricks [5,6], shutters [7], window blinds [8-10], ventilated facades, etc. They can also be used for the thermal management of photovoltaic (PV) panels [11-14]. It has been claimed that the performance of these systems can be improved by placing a TES unit with PCMs on the PV panels back to reduce high operating temperatures [15,16].

As mentioned before, the existence of materials in the liquid phase, and the possible problem of liquid-leakage during the solid-liquid phase change processes (caused, for instance, by significant changes of pressure during phase change volume variations and by the eventual rupture of the TES unit container) can represent a constraint to foster the implementation of PCMs in building applications. The use of microencapsulated PCMs is very attractive for building applications as the PCM can be previously incorporated within microcapsules. At the end, the powder like material (Figure 1) can be mixed with other materials (such as mortars, concrete, gypsum, etc.), or it can be used to fill up specific containers. The main advantage of using TES units filled with microencapsulated PCMs is that the problem of liquid-leakage during manufacturing, assembling and operation can be significantly reduced. Moreover, any numerical modelling approach of the solid-liquid phase change processes becomes simpler since the influence of momentum and the advection terms in the energy conservation equation can be neglected.

Figure 1: Photographic view of the microencapsulated PCM used to fill up the TES units - Micronal® DS 5001 X

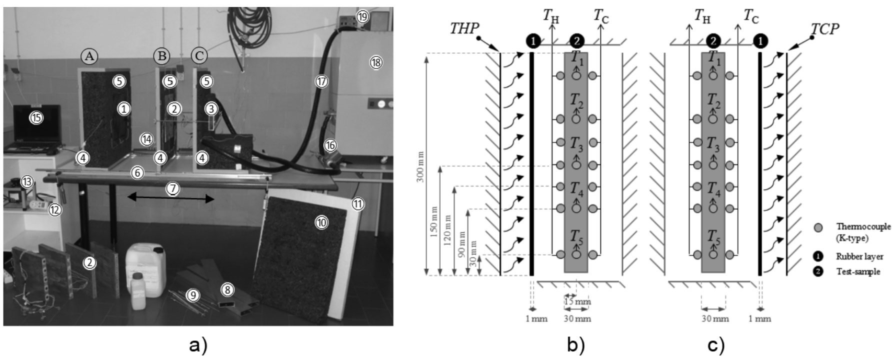
Recently, the authors have presented an experimental-setup to evaluate the transient heat-transfer through a vertical stack of rectangular cavities filled with different PCMs [17,18]. Indeed, this paper presents part of the results already published in refs. [17] and [18], considering the TES units filled with a paraffin-based microencapsulated PCM - the Micronal® DS 5001 X. The main goal of this study is to experimentally evaluate the influence of the aspect ratio of the cavities and the influence of the boundary conditions imposed during the experiments on the thermal performance of the TES unit.

Experimental setup and procedure

Figure 2a shows the experimental setup which is presented in refs. [17] and [18]. It is composed by 3 main modules: the heating (A), the cooling (C) and the test-sample (B) modules. Modules A and C are both movable along a horizontal axis, allowing the implementation of charging and discharging cycles. The heating module holds the heat source fed by an electrical resistance – the hot-plate. The cooling module holds the heat exchanger fed by a thermo-regulated water flow – the cold-plate. The thermo-regulated water flow is ensured by a circulator pump coupled to a constant temperature water bath. The test-sample module has a fixed position and accommodates the TES unit filled with the microencapsulated PCM.

As described in refs. [17] and [18], before starting the charging cycle, the TES unit is pre-cooled at 13 ºC and the hot-plate is pre-heated at 55 ºC. The heating module is then moved towards the fixed test-sample module and, at the same time, the cooling module is replaced by a thermal insulation board. The heating module and the test-module are then tightly compressed against each other. The power level of the electrical resistance is kept constant during the experiment. When the temperature within the PCM-bulk reaches 55 ºC, the charging experiment is stopped, and a cooling experiment can start. The heating module is replaced by a thermal insulation board and, simultaneously, the cooling module is moved towards the test-sample module. Before starting the discharging cycle, the cold-plate is pre-cooled and then kept at the temperature selected for the experiment. The discharging experiment is stopped when the PCM-bulk temperature reaches the value specified on the thermostat of the cold water bath (T_{water}). A total of 6 charging and 9 discharging experiments were carried out by combining: (*i*) 3 TES units with different configurations (Figure 3); (*ii*) 2 heating loads during charging - power density values of about 378 and 756 W m^{-2}; and (*iii*) 3 cooling loads during discharging - T_{water} of about 14, 17 and 20 ºC. Each experiment was repeated thrice to check the repeatability of the results.

Nine K-type thermocouples are placed on each surface of the hot and cold plates (facing the test-sample module) for monitoring the temperature variation during the experiments. Twenty-one K-type thermocouples are also distributed on the front and back surfaces of the TES unit, respectively. Five K-type thermocouples are positioned on the mid-plane of the TES unit (inserted laterally at a depth of 150 mm). All the thermocouples were calibrated with an accuracy of ±0.1 ºC. Figures 2b and 2c show the sketch of the physical domain for the charging and discharging cycles, respectively. *THP* and *TCP* represent, respectively, the average temperature measured on the surfaces of the hot and cold plates facing the TES unit. T_H is the average temperature measured on the front surface of the TES unit (facing the heating module) and T_C is the average temperature measured on the back surface of the TES unit (facing the cooling module). *T* is the measured temperature of the PCM in the mid-plane of the TES unit. The subscripts 1 to 5 refer to the location of the thermocouples (from top to bottom). The data acquisition system is composed by 4 Pico® TC-08 thermocouple dataloggers connected to a computer and controlled by the PicoLog® data acquisition program. Data from all sensors are collected and stored at 30 s intervals. More details about the experimental setup, instrumentation and procedure can be found in refs. [17] and [18]. The thermophysical properties of the microencapsulated PCM-DS 5001 X can also be found in ref. [17].



A - Movable heating module
B - Fixed test module
C - Movable cooling module

① - Hot-plate
② - TES unit
③ - Cold-plate
④ - Rigid iron skeleton of the modules
⑤ - Thermal insulation boundary - cork
⑥ - Rails for linear motion
⑦ - Linear motion of the heating/cooling modules
⑧ - Accessories for joining the modules
⑨ - Threaded rods and nuts
⑩ - Thermal insulation layer - cork
⑪ - Thermal insulation layer - XPS
⑫ - Digital wattmeter
⑬ - Variac (*Lübcke Vario*)
⑭ - Pico® USB TC-08 thermocouple data logger
⑮ - PicoLog® data acquisition program
⑯ - Circulator pump *Grundfos* UPE 25-60
⑰ - Water circulation - insulated flow
⑱ - Therm. bath *Heto Lab Equipment* DBT KB21
⑲ - Controller *Heto Lab Equipment* DBT 200

Figure 2: a) Photographic view of the experimental setup described in refs. [17] and [18]. Physical domain of the 1-single cavity TES-unit during b) charging and c) discharging

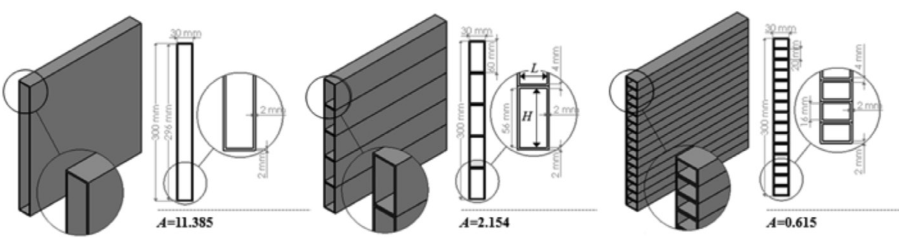


Figure 3: Sketch and dimensions of the 3 TES units used in the experiments: a) 1-single cavity (A = 11.385); b) 5-cavities (A = 2.154); c) 15-cavities (A = 0.615)

Results and discussion

Figures 4a shows the evolution of the measured temperatures during charging of the 1-single cavity TES unit for the 34 W power level of the electrical resistance. Two main inflection points can be observed on the time evolution of the measured temperatures in the PCM domain. The first inflection is observed after the initial temperature increase, when the temperature reaches the melting-peak temperature of the PCM. The second inflection is observed when the heat is no longer absorbed by the melting process; from this moment on, the temperature of the PCM rises sharply while the temperature on both surfaces of the TES unit also increases at a higher rate. Therefore, 3 different phases can be identified during the charging process: (*i*) solid (sensible heating); (*ii*) solid/liquid phase change (latent heat), and (*iii*) liquid (sensible heating). The experimental results also show that conduction is the predominant mechanism of heat transfer, therefore no significant thermal stratification is observed in the PCM domain. The evolution of the measured temperatures during the other experiments carried out in the parametric study can be found in ref. [18].

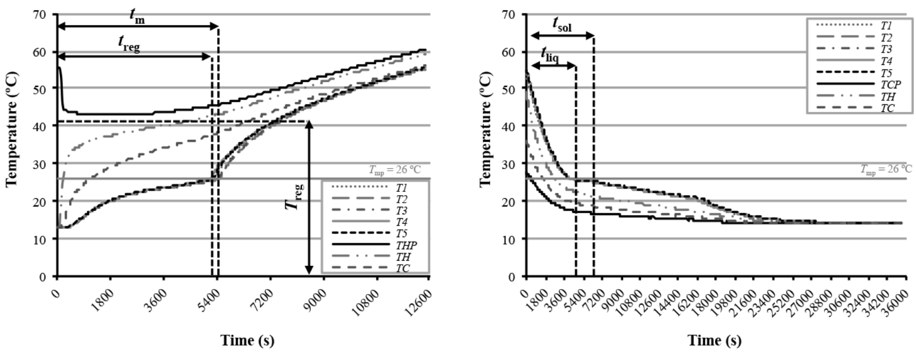


Figure 4: Evolution of the average measured temperatures for the 1-single cavity TES unit during a) the 34 W power level charging cycle and (b) the discharging cycle with Twater = 14 °C

Three parameters are defined to characterize the charging cycle and to evaluate the thermal performance of the TES unit: t_m is the time required for complete melting the PCM in the mid-plane of the TES unit, t_{reg} is the thermal-regulation period achieved, and T_{reg} is the value of the control-temperature reached on the hot surface of the TES unit. Table 1 shows the results of the parametric study carried out to evaluate the thermal performance of the TES unit considering different configurations of it and different power levels during charging.

Table 1: Evaluation of the thermal performance of the TES unit during charging - parametric study.

Power level	Aspect ratio	t_m (s)	t_{reg} (s)	T_{reg} (°C)
34 W	*A* = 11.385	5460	5250	42.7
	A = 2.154	4890	4740	40.0
	A = 0.615	3660	3030	32.9
68 W	*A* = 11.385	4230	3780	51.7
	A = 2.154	3840	2970	45.8
	A = 0.615	2910	2400	36.8

Results show that adding fins, by increasing the number of cavities, increases the heat transfer rate to the PCM-bulk by conduction, reducing the values of T_{reg}, t_m and t_{reg}. Therefore, adding fins is unquestionably a good technique to speed up the melting process of the PCM. The melting process is also very influenced by the imposed power level. As expected, for the same configuration of the TES unit, the greater the power level, the shorter the time required to completely melt the PCM in the mid-plane of the TES unit and, likewise, the thermal-regulation period. Regarding building applications, if the TES units are intended to be used for TES applications, for instance to reduce the time required for complete melting the PCM in a TES system, more fins should be added to increase the heat transfer rate to the PCM-bulk. This is the case of PCM-enhanced TES systems designed to store solar thermal energy during a specific period of the day, as the higher the volume of melted PCM, the higher the energy stored in the system. However, it should be remarked that the higher the number of fins, the heavier the system, which can be problematic for some vertical building applications. Moreover, the higher the number of fins, the lower the volume of PCM, which means that less energy will be stored during the charging cycle. On the other hand, if the TES units are to be used for thermal management purposes, the number of fins should be reduced in order to improve the thermal-regulation period. However, it should be remarked that the higher the number of fins, the lower the value of the control-temperature reached on the hot surface of the TES unit, which can also be very interesting for thermal management purposes. Therefore, a compromise should be attained for each potential application. Regarding building applications, these TES units can be used, for instance, for the thermo-regulation of PCM-enhanced PV panels.

Figure 4b shows the evolution of the measured temperatures during discharging of the 1-single cavity TES unit with the cooling water temperature set to 14 ºC. The results also show 3 different phases during the discharging cycle: (*i*) liquid (sensible heating); (*ii*) liquid/solid phase change (latent heat), and (*iii*) solid (sensible heating). Initially, the measured temperatures decrease rather steeply. When the temperature in the PCM domain drops to the solidification temperature of the PCM, the decrease of the measured variables slows down as the latent heat is released. After some time, a slow cooling brings the thermocouples to the temperature of the cooling water.

Two parameters are defined for characterizing the discharging process: t_{liq} is time required for starting the solidification process and t_{sol} is the time required for solidifying all the PCM in the mid-plane of the TES unit. Table 2 shows the results of the parametric study carried out to evaluate the thermal performance of the TES unit during discharging by considering different values of the temperature of the cooling water, and different configurations of the TES unit. The results show that adding fins is unquestionably a good technique for improving the release of the stored energy by enhancing the solidification rate during the discharging process. Therefore, the higher the number of cavities, the lower the time required for solidifying all the PCM in the mid-plane of the TES unit. Regarding building applications, this feature is particular interesting for PCM-enhanced systems where it is crucial to reduce the time required for complete discharging the system. Systems designed to store solar thermal energy during the day to be discharged during the night are a good example of this sort of applications.

Table 2: Evaluation of the thermal performance of the TES unit during discharging - parametric study.

T_{water}	Aspect ratio	t_{liq} (s)	t_{sol} (s)
14 ºC	A = 11.385	4260	6120
	A = 2.154	4020	4740
	A = 0.615	3090	4170
17 ºC	A = 11.385	4980	6540
	A = 2.154	4590	5580
	A = 0.615	3600	4980
20 ºC	A = 11.385	5580	8370
	A = 2.154	5310	7020
	A = 0.615	4560	6390

Conclusion

This work aimed at experimentally evaluating the heat transfer through small TES units filled with a paraffin-based microencapsulated PCM – the Micronal® DS 5001 X. These TES units are intended to be used in thermal management and TES applications. They can also be integrated in the design of PCM-enhanced systems to improve the energy performance of buildings. A parametric study was carried out to evaluate how the charging and discharging cycles are influenced by the configuration of the TES unit (aspect ratio of the rectangular cavities) and by the boundary conditions imposed during the experiments. The results achieved give relevant contributions to the present knowledge in the study of the conduction-dominated heat transfer with solid–liquid phase-change through rectangular cavities filled with microencapsulated PCMs. Indeed, the experimental results are intended to be used in the validation of numerical models, which can be used to optimize the configuration of PCM-enhanced TES systems in a cost- and time-effective way.

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