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Realization, test and modelling of honeycomb wallboards containing a Phase Change Material

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ABSTRACT

The present paper deals with the thermal study of honeycomb panels for short-term heat storage. Using honeycomb panels filled with Phase Change Materials (PCMs) allowed us to fulfil two criteria: enhancement of thermal conductivity and containment to avoid possible leaks. Paraffin whose thermal properties have been measured has been chosen as PCM. The response of the PCM panel to temperature variations was studied with a specific test bench. Temperature and flux measurements clearly showed a significant thermal inertia increase compared to samples filled with air and water. Modelling and numerical simulation have been carried out and validated with the experimental results.

1. Introduction

Energy storage has received growing attention since the last energy crises. It is a way to utilize energy more efficiently and to use clean and renewable energy (solar energy, wind energy, etc.) to reduce climate impact. A second benefit is to save energy in storing energy surplus when demand is low in order to use it in peak periods. In building applications, a third advantage is found in terms of thermal comfort if thermal storage is achieved with Phase Change Materials.

Thermal comfort is becoming an essential concern in modern buildings. In hot countries, the energy due to air conditioning represents an important part of the total energy consumption. Passive system could be an answer both in terms of comfort and energy savings. In mild climates, recent summer heat waves must incite architects, design engineers as well as users to consider the different possibilities to damp temperature peaks in order to insure a minimum comfort even in the absence of air conditioning. Using Phase Change Materials in building materials could be a way to maintain interior wall temperature at a temperature close to the phase-change temperature.

Using PCMs efficiently involves at less two conditions: (i) a mass adapted to the energy which must be stored/released and (ii) a thermal conductivity which allows heat to be transmitted throughout the whole material. The PCMs which can be employed in low temperature applications are essentially paraffins, salt and salt hydrates and fatty acids. These materials have a low thermal conductivity and when heated a part of the material can be a superheated liquid while another part remains solid. To obtain a solid–liquid mixture remaining at the constant fusion temperature, a way is to augment thermal conductivity by adding a controlled amount of a high conductivity material. This can be achieved in manufacturing a composite material with carbon fibres or another material, in impregnating metallic foams with PCMs or in adding conductive fins. This last technique is presented in this paper and it has been developed to build walls capable to store heat during a half-day and to release it during the night.

In the following sections, after a succinct bibliographical survey, we present the chosen enhancement technique viz. the employment of a honeycomb structure to create fins, the experimental test device of wall samples and the obtained results. A numerical simulation was carried out to interpret the experimental results. Conclusions are drawn on the possible optimization of honeycomb dimensions.

2. Selected bibliography

The low conductivity of a PCM (of the order of 0.2 W/m K for paraffin) impedes the thermal performance. For large volumes,

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Nomenclature

a	thermal diffusivity ($m^2\,s^{-1}$)
A	amplitude of the temperature sine variation (°C, K)
C_p	specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L	sample thickness (m)
t	time (s)
T	temperature (°C, K)
Greek characters	
φ	heat flux ($W\,m^{-2}$)
τ	period (s)
ρ	density ($kg\,m^{-3}$)
ω	angular frequency ($rad\,s^{-1}$)
Subscripts	
m	mean value
L	refers to sample thickness

melting is first localized near the heat source and the melting zone moves slowly to the bulk. The liquid part near the source can be strongly superheated while the bulk remains in a solid state due to the slow propagation of heat flow. As a consequence the temperature of the material is no more constant. It is necessary to enhance the thermal conductivity of the PCM and distribute heat throughout the material to avoid, as far as possible, superheated zones. Several ways have been proposed and/or tested. The first way is to modify the material itself. It is realized by adding a higher conductivity material in the form of powder (Cu, Al, graphite, etc.). Siegel [1] concluded that even though an improvement in heat transfer happens there is a compensating effect due to the reduction in the volume fraction occupied by the PCM. Some authors have underlined the potential of PCM doped with nanoparticles (whose characteristic size is less than 50 nm) [2]. Another way is to embed the PCM inside a matrix to create a composite material. Several researchers have investigated materials consisting of a PCM embedded in a matrix of expanded graphite [3,4]. The thermal conductivity was strongly increased and it was concluded that the storage density can be 3 or 4 times that of water. Composite materials made of paraffin and compressed, expanded, natural graphite matrix seem to open new ways of development [5]. Insertion of carbon fibres or metallic fillings has led to important improvement in conductivity [6,7]. A third way is to impregnate porous materials with PCM. In the recent work of Siahpush et al. [8] a rather complete bibliography is done on the use of foam matrices made of different materials and with different shapes. In their own study with a copper matrix of 95% porosity they conclude that the effective conductivity was increased from 0.423 to 3.06 W/m K in strongly increasing the response time. Another way is to distribute heat with fins. Depending on applications and on heating or cooling process, several fin shapes can be used. For building and wallboard purposes, several criteria are defined (i) to augment the thermal inertia of the wall, (ii) to store heat during one half-day and to release it during the other half (iii) to maintain one wall surface to a constant temperature close to a comfort value. Use of PCM is a way to increase inertia and to maintain a constant temperature value. However, use PCMs adds another criterion: leaks of the liquid PCM must be prohibited. This can be obtained by creating a new material (composite [4,5,9] or gel) or in encapsulating the material. This last technique has been chosen in this work.

Several studies have shown that with a wallboard constituted of a panel filled with PCM the daily temperature variations are smoothed but over a whole day the attenuation is only between 2 and 5 °C [10]. This is essentially due to the superheating of the liquid PCM whose low conductivity does not allow heat to progress. We have tried different solutions to enhance the conductivity (carbon fibre filling or fins) but finally we have chosen honeycomb panels which can fulfil two criteria: enhancement of thermal conductivity and containment. This type of thermal management has already been used to investigate transient thermal control of electronic and avionics module [11–14] but to our knowledge it has been considered in only one work [15] for building applications.

It may be observed from the above bibliography that substantial amount of work has been reported on thermal management of electronic devices. The aim of this work is to characterize a structure for building applications and to validate a numerical simulation with the studied structure which would allow us to optimize the geometry.

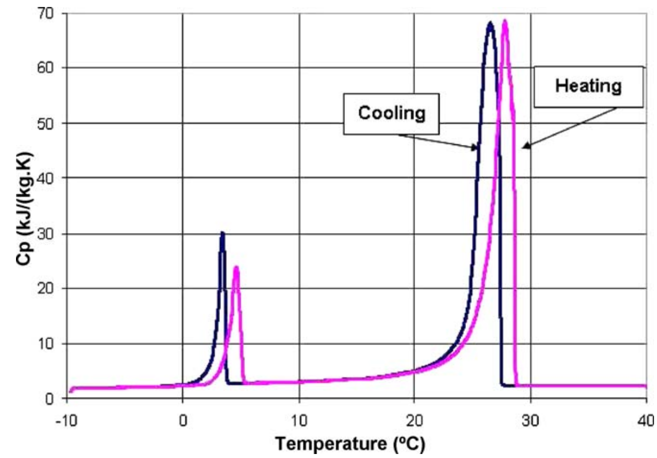

Fig. 1. Stored heat ($\sim C_p$) as a function of temperature measured by Differential Scanning Calorimetry (scanning rate, 0.05 K/min).

3. PCM characterization and wallboard realization

3.1. PCM choice and characterization

The adopted strategy for this study was the following:

- to choose a PCM allowing a comfort temperature about 25 °C,
- to measure thermophysical properties (specific heat capacity and thermal conductivity),
- to choose a mode of packaging and eventually to build construction component or a wallboard,
- to measure the response of the construction component or the wallboard to temperature variations,
- to validate modelling and numerical simulation with results obtained by measurements of the thermal response.

The chosen PCM was paraffin. These materials show a good storage density with respect to mass but their thermal conductivity is rather low. They do not react with most chemicals. Their compatibility with metals is very good. They have limited safety constraints, the main problem arising from their possible flammability. The used commercial product is LINPAR® 1820 which is a mixture of Tetradecane and Octadecane.

The stored heat as a function of temperature (nearly identical with specific heat capacity [16]) has been determined in the [−10 °C, 40 °C] interval in heating and cooling conditions (Fig. 1) with a SETARAM microcalorimeter. Measurements have been carried out in dynamic mode with a low scanning rate (0.05 K/min) to reduce deviation between peak top and temperature. It is shown that there is a shift between the two peaks (heating and cooling).

Table 1
Measured values of physical properties.

	Heating	Cooling
Latent heat ($kJ\,kg^{-1}$)	170.1	168.1
Specific heat capacity peak temperature (°C)	27.9	26.6
	Solid	Liquid
Specific heat capacity ($J\,kg^{-1}\,K^{-1}$)	2560	2445
Thermal conductivity ($W\,m^{-1}\,K^{-1}$)	0.193	

This shift is probably due to subcooling before solidification. By integrating the measured curves the latent heat can be deduced and results are presented in Table 1.

Thermal conductivity has been measured by the hot-wire method far from the melting zones. At −5 °C thermal conductivity of the solid material was found to be 0.175 $W\,m^{-1}\,K^{-1}$. With our method we did not succeed to have coherent values at 30 or 40 °C due to convective effects and we have used the same value as for the solid material.

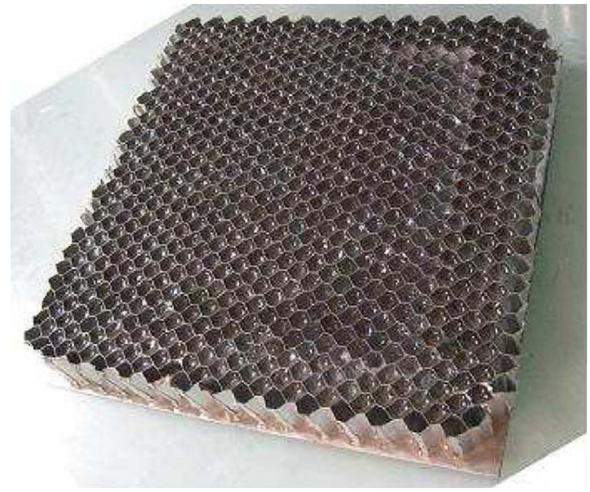

Fig. 2. Honeycomb panel sample filled with paraffin, before to stick the upper aluminium skin.

3.2. Hosting structure and wallboard realization

To enhance apparent thermal conductivity we have chosen to use aluminium fins under the form of honeycombs to ensure efficient heat conduction and good PCM incorporation. Commercial honeycomb panels were provided by SMCI [17]. Honeycombs were 2 cm deep, with a cell size of 6 mm and a cell wall thickness of 70 μm and after being carefully filled covered with a 1 mm thick aluminium sheet (Fig. 2) stuck on the honeycomb tips. Test samples with 15 cm × 15 cm dimension were realized together with a box of identical volume filled with water and another filled with air in order to compare their thermal responses to prescribed temperature boundary conditions.

4. Thermal characterization

4.1. Experimental set-up and instrumentation

The thermal response of panel samples has been tested on a specific test bench. The test loop has already been described in reference [18] and only some general characteristics are reminded. Tested panels are placed between two plate heat exchangers and the temperature can be imposed on each side of a panel or on one side, the other side being in contact with the ambient air or thermally insulated (Fig. 3). Water flows inside heat exchangers and its velocity is large enough to ensure a wall prescribed temperature. This was validated by measuring inlet/outlet water temperatures. Difference between the two temperatures was less than 0.3 °C.

The panel with the three test samples is shown in Figs. 4 and 5. In the present case, the panel is placed in close contact of only one heat exchanger (referred in the following as front side). On the back side, samples are embedded in polyurethane foam and the thermal insulation is completed with a Vacuum Isolating Panel (VIP).

Each sample was equipped with two thermofluxmeters (Captec [19]) which allows temperature and heat flux to be measured on each side of samples (Figs. 4 and 5). To avoid some deterioration of these thermofluxmeters when they are pressed against the plate of the heat exchanger a thin rubber foam layer is placed between the plates and the samples (Fig. 5). Data acquisition and temperature variation control were achieved with a Keithley Instruments module.

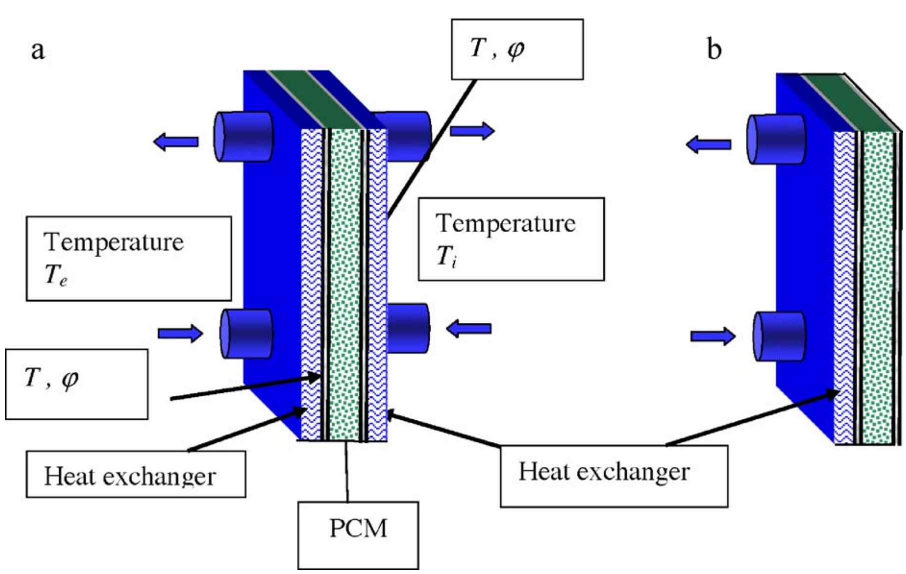

Fig. 3. Sketch of the experimental set-up: (a) both sides with imposed temperatures and (b) one side with an imposed temperature.

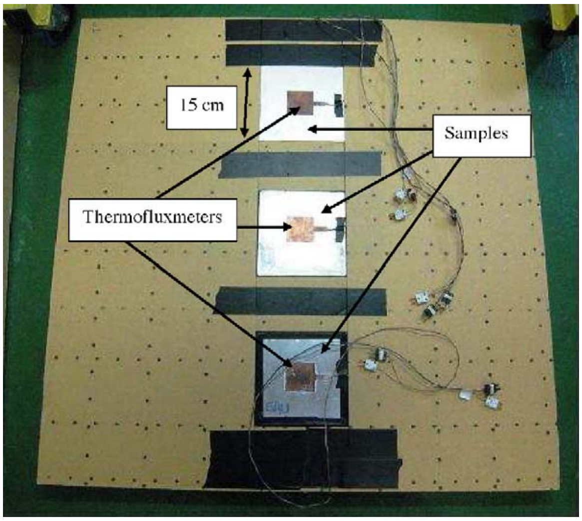

Fig. 4. The wall placed in the test loop. Three samples from up to down: empty (air), filled with PCM, filled with water.

4.2. Experimental procedure

A cyclic temperature variation (with a period of 24 h) was imposed on the front side of the samples. In the first test, temperature variation was linear (sawtooth) and comprised between 11 and 29 °C (Fig. 6). This test allowed us to easily detect any deviation of the front and back side temperatures with respect to a linear variation. In the second test a sinusoidal variation was imposed. Such a variation is more realistic compared to an ambient temperature variation.

4.3. Results and discussion

4.3.1. Thermal cycle with temperature linear variation

In Fig. 6 are presented the temperature variations on the back sides of the three samples (PCM, water, air) compared with the imposed linear temperature. The temperature curves of the air and water samples are linear too. The temperature curve of the air sample is not distinguishable from that of the heat exchanger temperature and for the water sample we observe a time lag of about 1500 s. If L is the thickness of samples, the time lag between the two sides is given by

$$t_L = \frac{L^2}{2a} \tag{1}$$

where a is the thermal diffusivity. For air it is about 9 s and for water 1400 s. These values are in agreement with the experimental data and also show that the samples are correctly thermally insulated. It can be observed that the surface temperature of the sample with PCM is no longer linear and present inflexion points, clearly indicating a thermal storage effect. The melting zone begins at temperatures between 15 and 20 °C in accordance with DSC curve. Solidification takes place at 27.5 °C, this value is slightly less than that observed in DSC. Far from the phase-change zones, a time lag can be evaluated. In liquid zone it is equals to 1140 s.

Curves presented in Fig. 7 represent the temperature variations of the sample with PCM (full lines, temperature imposed by the heat exchanger, temperatures on the front side and the backside of the sample) and the flux on the front side (dotted line). It can be seen that during melting and solidification, curvature of the tem-

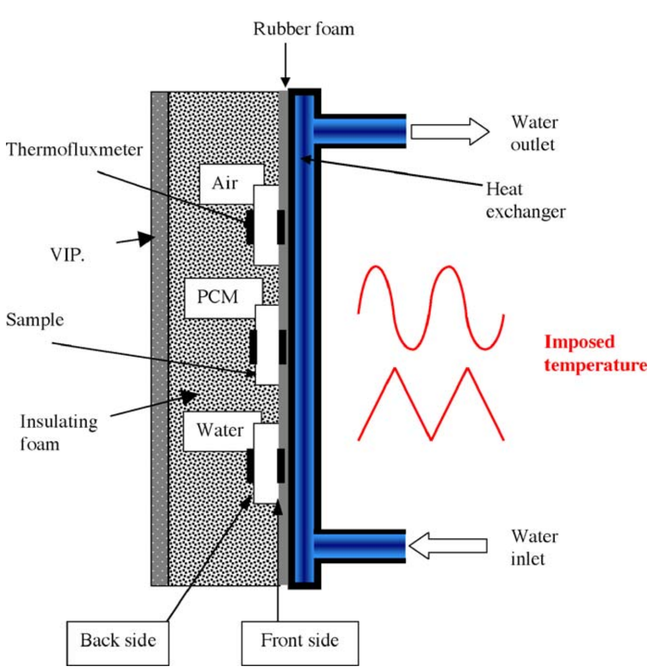

Fig. 5. Schematic of the test section with three samples and with temperature and flux sensors.

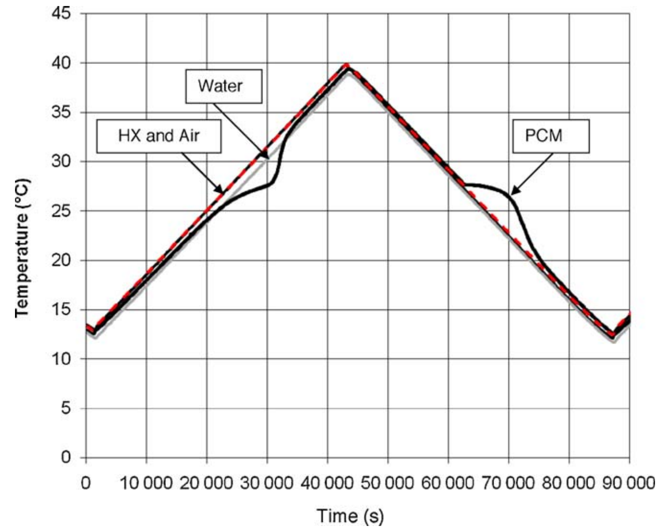

Fig. 6. Temperature variations on the back side of the empty sample (air – dotted line), the sample filled with water (water) and the honeycomb sample filled with PCM (PCM). Temperature of the heat exchanger (HX) is given for comparison.

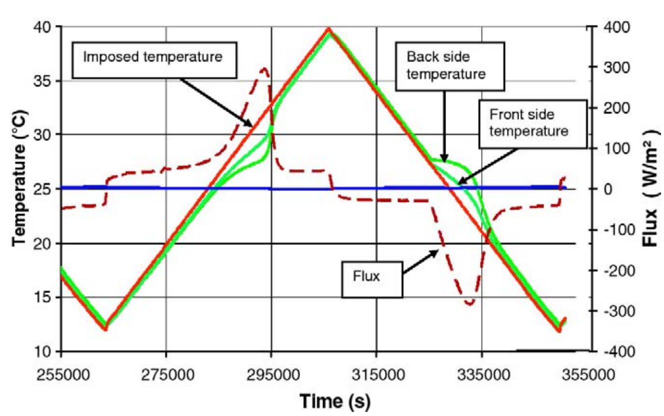

Fig. 7. Temperature (full lines) and flux (dotted line) variations of the PCM-filled honeycomb sample.

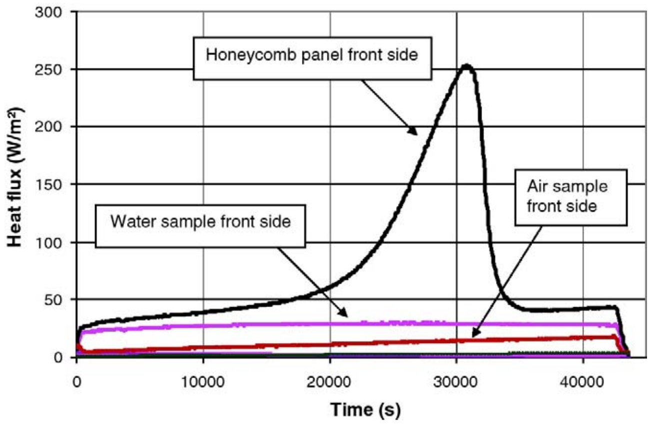

Fig. 8. Heat fluxes measured at the front sides of the three samples (PCM, water, air) during sample heating. Fluxes measured at the back sides are nearly zero.

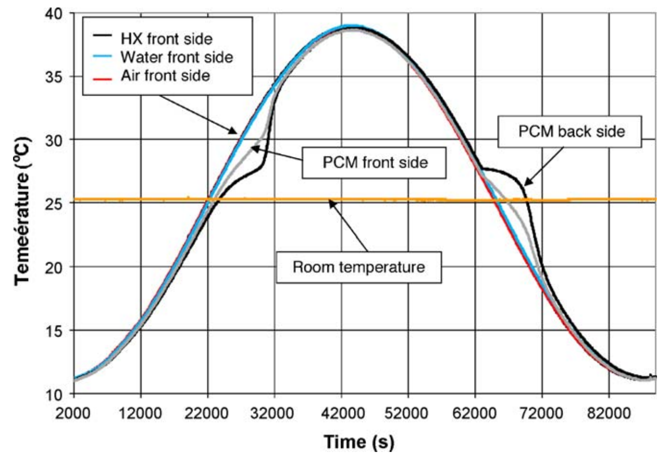

Fig. 9. Temperature variation for sinusoidal cycle. Pure sine curves are for imposed temperature, and front side temperatures of water and air samples.

perature curve on front side is less pronounced than that on back side. The plate of the heat exchanger should impose its temperature on the front side whereas the phase-change process controls the temperature variation on the back side. However, due to thermal resistance of the rubber foam layer inserted between the heat exchanger plate and the sample, the temperature measured on the front side does not follow exactly the imposed temperature and a shallow "shoulder" is observed.

Fig. 8 shows flux variations as a function of temperature and the phase-change process is clearly reflected by the flux peak accompanying temperature shoulders. The nearly constant level before and after the peak is a measurement of the sensible heat. The stored/released thermal energy can be calculated by integration of the flux peak. Results are given in Table 2. Found values are in agreement with those calculated with latent heat which are 2891.7 kJ m^{-2} (heating) and 2857.7 kJ m^{-2} (cooling).

In order to compare the storage capability of the honeycomb panel with PCM with storage by sensible heat, we have reported in Fig. 8, the fluxes measured for the three samples (Air, water, PCM). Heat stored is given by integration, and results given in Table 2 clearly show that the sample containing PCM is able to store about 3 times more energy than the sample containing water.

4.3.2. Thermal cycle with temperature sinusoidal variation

To simulate daily ambient temperatures, a sinusoidal variation was imposed to the plate heat exchanger:

$$T(t) = T_m + A \sin \omega t \quad (2)$$

where T_m is the mean temperature (T_m = 25 °C), A the amplitude (A = 14 °C) and ω the angular frequency equals to

$$\omega = \frac{2\pi}{\tau} \quad (3)$$

τ being the period (τ = 24 h).

Thermal responses of the three samples are reported in Fig. 9. As already seen with the linear variation, temperature curves of the PCM honeycomb panel present "shoulders" in the zones of phase change. We can observe superheating of the liquid paraffin as in the previous experiment due to a too low quantity of paraffin. However one of the objectives of these experiments is to provide data to validate a numerical simulation program in order to optimize honeycomb panels and paraffin amount.

Table 2
Energy stored by the samples deduced from the flux curves.

Stored energy during heating	
PCM	2841 kJ m^{-2}
Water	835 kJ m^{-2}
Air	284 kJ m^{-2}

5. Numerical approach

For sake of simplicity, the modelling approach restricts to an elementary prismatic region (Fig. 10): a hexagonal Al-honeycomb cell completely filled with PCM and delimited by the aluminium top and bottom sheets of the sandwich structure. The rubber foam placed on the front side between the heat exchanger and the sample is also represented. The presence of this low conductivity thickness plays an important role in the difference between the temperature imposed by the heat exchanger and the temperature measured on the front side, at the level of the aluminium sheet. On the back side, the two insulating layers of PU foam and Vacuum Insulated Panel (VIP) are not described. They are implicitly taken into account in the mode by an insulation boundary condition.

The geometrical parameters are the cell depth, the cell size and the thickness of the aluminium cell walls, the Al sheet thickness and the rubber foam thickness. Taking into account the geometrical symmetries of the structure leads to model only half of the whole assembly. One of the difficulties of meshing such a structure is to deal with sizes of different order of magnitude. The cell size is about some millimetres high whereas the cell wall size is about few tens of micrometres thick. This difficulty has been overcome by describing the honeycomb cell walls with a so-called "highly con-

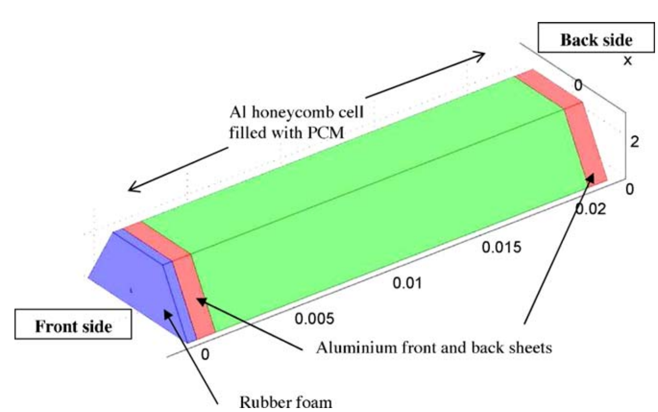

Fig. 10. Structure for the finite element modelling. Half of an aluminium hexagonal cell filled with PCM is represented with aluminium sheets of both sides. Rubber foam is placed on the front side.

Table 3
Numerical values used for the finite element simulation.

Physical properties	Al	Rubber foam
Density (kg m^{-3})	2700	134
Thermal conductivity (W m^{-1} K^{-1})	160	0.055
Specific heat capacity (J kg^{-1} K^{-1})	900	1500

Geometrical parameters	Value (mm)
Honeycomb depth	20
Cell size	6
Cell wall thickness	0.07
Front and back Al sheet thickness	1
Rubber foam thickness	0.5

ductive layer", a special element available in the COMSOL package [20]. This allows an appreciable gain of degrees of freedom in such a 3D calculation.

The only heat transfer mode considered is conduction, even during the melting or solidification processes. Natural convection effects at the solid–liquid interface are neglected, as already discussed in [14]. The governing equation considered here is classical energy balance equation, in absence of heat source:

$$\rho C_p \frac{\partial T}{\partial t} + div\left(-k\vec{\nabla}T\right) = 0, \quad (4)$$

with ρ, C_p, k respectively the density, the specific heat and the thermal conductivity of the different materials in the structure. A Dirichlet boundary condition is imposed on the front side, corresponding to the external cyclic temperature variation imposed by the heat exchanger, either linear or sinusoidal, as shown in Fig. 5. An insulated boundary condition is imposed on the back side. The other lateral boundary conditions reflect the symmetry of the structure.

A finite element procedure has been used to solve this 3D transient and heterogeneous problem (COMSOL Multiphysics® software). Different kinds of numerical approaches for modelling the phase change problem exist. The effective heat capacity method is used here. It consists in explicitly taking into account the temperature dependence of the heat capacity of the PCM, as appearing in Fig. 1. The different geometrical and material parameters used in the simulation are summarized in Table 3. It is worth noticing that the effective thermal conductivity corresponding to the elements referred as "conductive layer" must be taken lower than the aluminium thermal conductivity. Indeed, the process leading to the sandwich structure implies to glue the two Al sheets on the Al honeycomb. This glue acts as a weak link in term of thermal conductivity of the whole metallic structure. A value of 50 W m^{-1} K^{-1} has been taken for this effective thermal conductivity.

The simulation allows the spatial distribution of temperature to be followed in the structure during the 24 h of the cyclic imposed variation. In Fig. 11 is displayed the propagation of the melting front in the symmetry plane of the structure as a function of time in the range [20,000 s; 30,000 s], corresponding to the phase-change domain. The contribution of the fins to the heat transfer is clearly evidenced, even with the lower effective conductivity chosen for the honeycomb structure.

In Fig. 12 are shown front side and back side temperature evolutions (measured on the Al sheets), displaying a very good agreement with experimental results. The curvature of temperature curves is well retrieved during melting and solidification, with a difference between front side and back side values. This effect would be more or less pronounced considering respectively lower or higher values of the effective thermal conductivity. With the fair agreement between the experimental results and the numerical simulation, it can be considered that the model is validated.

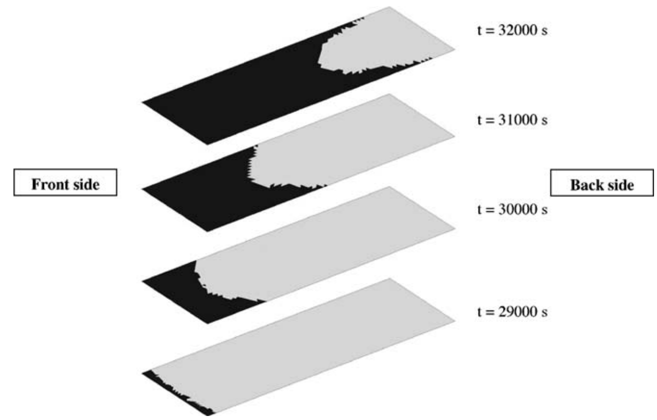

Fig. 11. Melting front propagation within the PCM in the symmetry plane of a honeycomb, for the time range [29,000:32,000 s]. In black, the liquid zone.

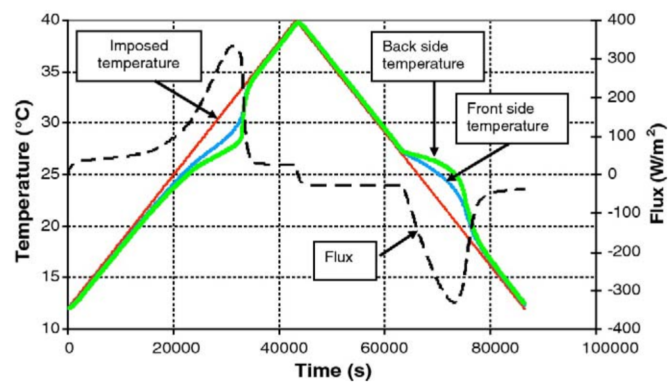

Fig. 12. Numerical prediction for temperature (full lines) and flux (dotted line) variations of the PCM-filled honeycomb sample.

6. Conclusion

Growing of energy needs impose the development of systems which accumulate energy during a time of surplus and release it at time when it is needed. Use of PCM is a way to store thermal energy in reducing the material volume and in building applications to choose the phase-change temperature to reach a thermal comfort temperature. The PCM must be selected such as its phase-change point and its physical properties enable complete melting or solidification. However, when a PCM with the right phase-change temperature is chosen its thermal conductivity may not to be adapted to complete melting of the material. Using fins allow us to adapt the apparent thermal conductivity to an efficient use of the material. We have chosen to use honeycombs as fins because this configuration allows a large surface area in contact with the PCM. Paraffin with melting temperature about 27 °C was used as PCM and was incorporated in aluminium honeycomb panels. Samples were submitted to periodic variations of temperatures (24 h periods, from 11 °C to 39 °C) on one side while insulated on the other side. Heat fluxes and temperatures were measured on each side to study thermal response of samples. A numerical simulation was carried out with COMSOL Multiphysics® in order to interpret experiments and to optimize honeycomb and panel dimensions according to applications. Experiments show the efficiency of latent heat storage and the experimental curves are well represented by numerical simulations. Work in progress will consider the numerical model validated here as an optimization tool for the design of PCM hosting structure. It will be in particular of great importance to derive the optimum choice in term of honeycomb material and geometrical properties in order to maximize the stored energy for a given set of boundary conditions.

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