THERMAL ENERGY STORAGE IN PCM MELTING IN HORIZONTAL TUBE: NUMERICAL AND EXPERIMENTAL INVESTIGATIONS

AADMI MOUSSA¹, EL HAMMOUTH MIMOUN², KARKRI MUSTAPHA³, DOUDOU ABDELKADER⁴

¹Faculté pluridisciplinaire de Nadur,Selouane300, 62700, Maroc.
²Université Paris Est, CERTES, 61 avenue du General deGaulle94010Créteil, cedex, France
*(Corresponding author: moussa_aadmi@hotmail.com)

1. Introduction

Thermal energy storage plays an important role in some industrial applications, such as, solar thermal storage [1], center air conditioning [2], energy-saving building [3] and waste heat recovery system. Thermal energy storage systems are crucial for reducing dependency on fossil fuels and also for minimize CO₂ emissions [4]. Thermal energy storage can be accomplished either by using sensible heat storage or latent heat storage. Sensible heat storage has been used for centuries by builders to store/release passively thermal energy, but a much larger volume of material is required to store the same amount of energy in comparison to latent heat storage [5]. Latent heat storage is more attractive than sensible heat storage because of its high storage density with smaller temperature swing [6]. During melting or solidification processes, a phase change material (PCM) can effectively release or store a significant amount of latent heat. The temperature of a PCM can also be stably maintained during the latent heat transfer process. Therefore, a PCM is a very promising material choice in energy storage and thermal environmental control applications. Several methods of storing thermal energy for different temperature ranges have been discussed and reviewed [7].

The objective of this work consists in studying numerically and experimentally the thermal behavior of the melting process in a composite based on epoxy resin loaded with metal hollow tubes filled with phase change material (paraffin wax). Its properties used in the simulations, including the thermal conductivity and density in solid and liquid states, are based on a commercially available paraffin wax, which is manufactured to be used mainly in latent-heat-based heat storage systems. The thermophysical properties of the prepared composite phase change material have been characterized using transient hot plate apparatus. The results have shown that most important thermal properties of these composites at the solid and liquid states, like the “apparent” thermal conductivity, the heat storage capacity and the latent heat of fusion. These experimental results have been simulated using numerical Comsol® Multiphysics® 4.2a based models with success. The results of the experimental investigation compare favorably with the numerical results and thus serve to validate the numerical approach.

2.1 Experimental study

2.2 Sample preparation

In our experimental set-up, the matrix material is an epoxy resin of VANTICO Company. The Araldite® LY5052 is mixed to 38% weight of Aradur® 5052. This resin with a low viscosity (0.8 Pa.s at 23°C) is then placed under vacuum for about 40 minutes to remove the air bubbles before injection. The metallic hollow tubes (Goodfellow company) are placed in a mold (200 × 200 mm²) with an equidistant distribution of 2mm between the tubes (Fig. 1 (a-b-c-d)). To facilitate the release of the resin, a film of Teflon (PTFE) was stacked on the mold surface. Once the mold was closed and sealed, the resin is introduced from the injection gate at ambient temperature and under constant pressure. After characterization of these samples, all the tubes are filled with paraffin using a hermetic syringe with low diameter. Three configurations of samples were prepared under the same manufacturing conditions.

Fig.1: Manufacturing of epoxy resin/metallic hollow tubes composites. (a and b) positions of metallic tubes into a mold, (c) process of injection and (d) final phase of the sample.

2.3 Experimental device

For large size samples, testing using a noninvasive method for heat of fusion and specific heat determination is necessary. For this reason, a new hot plate apparatus was manufactured for the purpose of the presented investigation in order to be able to conduct dynamic thermal experiments. The proposed test bench for the parallelepiped-shape of composite provides temperature and heat flux measurements at the material borders. The tested sample is inserted between two horizontal exchanging aluminum plates. The various sensors are connected to a Labview® program adapted to measure temperature fluctuations and heat flux exchanged during fusion and solidification processes. Experimental data are recorded with regular and adjustable time steps (6 s). The lateral side faces are insulated by 50mm thickness of expanded polyethylene foam (PE) which reduces multidimensional heat transfer to a 1D problem.

Fig. 2: Experimental set-up
3. Numerical study

3.1. Model formulation

The composite with reinforcements PCM was seen like a periodic repetition of a Representative Volume Element (RVE). The RVE is composed of a conductive hollow tube filled with PCM (paraffin) of outer \( r_{ex} \) and inner \( r_{in} \) radius centered in a cavity of parallelepipedic dimensions 2a x 2a x 2b with \( a \approx b \) (Fig. 3). The boundary conditions at the edges of the representative volume element are of adiabatic type except at the upper and lower faces where temperature is prescribed with \( T_1 \) and \( T_2 \) respectively. The contact between the hollow tube and the PCM was considered perfect and the speed on the wall of the hollow tube is equal to zero (\( \bar{U} = \bar{0} \)). We will consider that the flow in the liquid phase is laminar, incompressible and Newtonian. We will neglect viscous dissipation. The physical properties of material will be considered constant in the two phases. The variation of volume, resulting from the phase change, is neglected. By taking into account the assumptions posed previously we can write the system equation (1-11), where the equation (2) translated the conservation of the mass, the equation (3) represent the conservation of the momentum, and the equations (1) and (4) the conservation of energy in matrix, hollow tube and PCM.

Heat equation in the solid phase (Matrix and Hollow tube):

\[
\rho_s C_p s \frac{\partial T}{\partial t} = \nabla (\lambda_s \nabla T) = \lambda_s \nabla^2 (T) \tag{1}
\]

Conservation equations in the PCM (liquid phase):

Conservation of mass \( \nabla \cdot U = 0 \) \tag{2}

Conservation of momentum \( \rho_p \frac{\partial U}{\partial t} + \rho_p (U \cdot \nabla U) = \nabla [ -p I + \mu_f (\nabla U + (\nabla U)^\top) ] + F_s + F_t \) \tag{3}

Energy conservation

\[
\rho_f C_p f \frac{\partial T}{\partial t} + \rho_p C_p f (U \cdot \nabla U) = \nabla (\lambda_f \nabla T) \tag{4}
\]

Where the volume force \( F_t \) must be added to the physics to simulate the buoyancy force giving rise to natural convection. The Boussinesq approximation is used to account for this buoyancy force, as follows:

\[
F_t = \rho_f \beta s (T - T_m) \tag{5}
\]

The impact of \( F_t \) is to dominate every other force terms in the momentum equations when the PCM is solid, speeding up the calculation and effectively forcing a trivial solution of \( u = 0 \) in the solid, is given by:

\[
F_s = -A \frac{f}{f} \tag{6}
\]

One of the classical models for the suppression speed is that of Darcy [8]:

\[
A (T) = C \left( \frac{6 - f (T)}{f (T)} \right)^{3/2} + b \tag{7}
\]

Where \( b = 0.001 \) is a small computational constant used to avoid division by zero, and \( C \) is a constant reflecting thermophysics of the melting front. This constant is a large number, usually \( 10^4 - 10^7 \). A value of \( C = 10^5 \) has been used in the literature [9], and \( f (T) \) is the liquid fraction during the phase-change which occurs over a range of temperatures \( T_i < T < T_f \), defined by the following relations [9]:

\[
f (T) = \begin{cases} 
0 & T < T_i, \\
\frac{T - T_i}{T_f - T_i} & T_i < T < T_f, 
\end{cases} \tag{8}
\]

To account for the change in thermal conductivity between the solid and the liquid phase of the PCM, a simple function \( \lambda_f (T) \) is created as shown in Eq. (4):

\[
\lambda_s (T) = \lambda_f (\lambda_s - \lambda_f) f (T) \tag{9}
\]

\( \lambda_f (T) \) is equal to \( \lambda_s \) for temperature lower than the melting point, and is equal to \( \lambda_f \) after melting. It decreases linearly from \( \lambda_s \) to \( \lambda_f \) over the melting temperature range \( \Delta T = T_f - T_i \).

\[
A (T) \text{ is first used to describe the viscosity function as follows:}
\]

\[
\mu_f (T) = \mu_f (1 + A (T)) \tag{10}
\]

where \( \mu_f \) is the liquid PCM viscosity. By the definition of \( A (T) \), the viscosity of the solid PCM is again pushed toward infinity. As the PCM changes phase to liquid, the value of \( A (T) \) diminishes to zero, making \( \mu_f (T) = \mu_f \). The method of the apparent heat capacity \( C_{pa} \) [10] comes to overcome this problem because at the time of the phase change, the release (or the absorption) of the latent heat \( L_f \) is taken into account by the increase in the \( C_{pa} \). The equations in each zone are defined by:

\[
C_{pa} = \begin{cases} 
\frac{1}{2} (C_{ps} + C_{pl}) + \frac{L_f}{\Delta T} & T_i < T < T_f, \\
C_{ps} & T_f < T < T_f \tag{11}
\end{cases}
\]

3.2. Temperature evolution

Fig. 4 presents the results of the simulation at different times during the heating process of a composite filled with PCM cylindrical. This simulation corresponds to the heating from the temperature \( T_i \) and \( T_2 = 15^\circ C \) to the temperature \( T_f \) and \( T_2 = 50^\circ C \), at which the node is maintained afterward. Fig. 4 shows the isothermal colorized in longitudinal section in the middle of the sample. We can see the effect of the heating process at the top and the bottom of the internal volume on the phase change front radial progress. The heat induces a deformation of the upper and the lower face of the front during the first instants of the storage steps (Fig. 4). Furthermore, it is appears from this figure that the shape of the solid-liquid interface is greatly defined and the distribution of the temperature remains symmetrical in the interval [0s, 4950s]. After one observes a variation of the solid interface/liquid has box of the effect of the
natural convection and the force of buoyancy. One can see from the figure that the solid phase typically descends. This result is in very good agreement with the literature.

Fig. 4: Evolution of the melting front propagation.

4. Comparison between numerical and experimental results

The numerical simulations were carried out by using the above mentioned thermophysical properties and the measured temperatures ($T_1$, $T_2$) like boundary conditions in order to study the thermal behavior of the composites charged with paraffin. Figs. 5-6 present, respectively, the evolution of heat flux measured and calculated in solid phase (15°C-20°C) and in the liquid phase (40°C-50°C). It is also noticed that according to the imposed ramp temperature, the flow evolves very quickly at the beginning of recording and then to a zero value which corresponds in a new state of balance obtained at the end of the test. Fig. 7 presents similar results for the transition from the solid to the liquid phase (15–50°C).

The objective of this test is to follow the process of fusion (solid-liquid) of paraffin numerically and to highlight the contribution of RT27 in terms of energy storage. It can be observed that the heat stored is much more important than sensible heat transfer when a phase change occurs. This confirms the interest of latent heat storage. As shown in Figs. 5-6, the experimental and simulated results present good agreement up to the phase change front detection. During the solid-liquid phase heat period, the experimental and simulated heat flux present little deviations. The difference seems due to the difficulty, in the experiment, to control with a very good precision the measured temperatures and heat flux.

Another reason is the effect of the pressure on the melting point of RT27 in the cylindrical. Increase in pressure increases the melting point; this is because increase in pressure opposes expansion. We suppose, increasing of the internal pressure of RT27 Nevertheless, all the experimental and simulated curves join together at the same time at the end of the process. Therefore, the overall agreement between the experiments and simulations was considered fair, and the model was used for complementary studies. The results were found to be satisfactory and provided values of thermophysical properties of sample S1 are listed in Table 1. The difference between the measured and the numericals thermophysical properties lies between 0.041% and 7.30%.

Fig. 5: Evolution of temperature and flow on the two faces of the sample (S1) for a ramp (15–20°C)

Fig. 6: Evolution of temperature and flow on the two faces of the sample (S1) for a ramp(40-50°C)

Table 1. Thermophysical properties of composites S1.

<table>
<thead>
<tr>
<th>Thermophysical properties</th>
<th>Sample (S1)</th>
<th>simulation</th>
<th>Error(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensible heat (solid) [J/g]</td>
<td>13.933</td>
<td>13.925</td>
<td>0.016</td>
</tr>
<tr>
<td>Sensible heat (liquid) [J/g]</td>
<td>19.476</td>
<td>19.359</td>
<td>0.638</td>
</tr>
<tr>
<td>Heat capacity (solid) [J/g K]</td>
<td>1.41</td>
<td>1.412</td>
<td>0.014</td>
</tr>
<tr>
<td>Heat capacity (liquid) [J/g K]</td>
<td>0.568</td>
<td>0.912</td>
<td>57.85</td>
</tr>
<tr>
<td>Latent heat [J/g]</td>
<td>14.856</td>
<td>15.290</td>
<td>2.808</td>
</tr>
<tr>
<td>Total stored heat [J/g]</td>
<td>48.247</td>
<td>48.227</td>
<td>0.041</td>
</tr>
</tbody>
</table>

Conclusions

In this contribution, thermal investigation of new phase change materials based on Epoxy resin/copper tube/ paraffin wax have been studied. Heat capacity and ability to store of thermal energy of PCMs have been measured by home-made equipment, Transient Hot Guarded Plane Method (THGP). Phase change materials were able to store and release thermal energy by changing the temperature above and below melting point of paraffin wax. Moreover, repeatability of storing and releasing of thermal energy have been demonstrated. The heat transfer characteristics of the melting process inside composites have been investigated numerically and the results have been compared with the experimental results. The results provide conclusive evidence of the role played by natural convection, contact melting and the phase change temperature range on the heat transfer.