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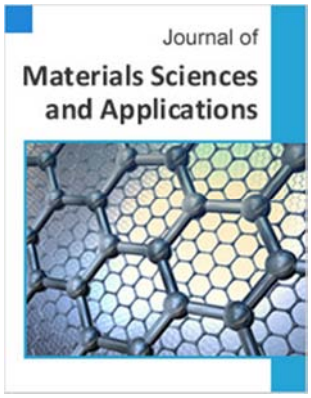

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Simulation of Transient Thermal Behaviors of the System Consisting of Aluminum Plate and Phase Change Material

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Abstract
In order to adjust operating temperature, the phase change materials (PCMs) are usually used by taking advantages of their ability of energy absorption or release during phase transition from solid state to liquid state or inverse process. In this paper, an energy system consisting of aluminum plate and phase change materials is studied for investigation of its transient thermal performance caused by phase change materials. To obtain its transient temperature response, the system is solved by using the finite element technique and then the sensitivity analysis of key material parameter of the PCM is carried out and its effect on the melting front of PCM at various time instants is determined to illustrate the phase change process of the PCM and its ability of adjusting temperature.

1. Introduction

The phase change materials (PCMs) are believed to have outstanding ability of releasing or absorbing thermal energy during melting or solidification processes, so that they are frequently considered to be used for sensible or latent thermal energy storage [1-3] in many applications such as energy saver building or green building materials [4, 5], high-efficient photovoltaic devices [6, 7], high-efficient compact heat sink [8, 9], and so on.

Due to complicated physical equations, the problems involving phase change are usually analyzed by numerical methods and experiments. Compared to experimental methods, numerical methods look more economic and efficient. For example, O'Neill developed the boundary integral formulation for nonlinear moving boundary phase change analysis [10]. Comini et al. established the finite element model for heat transfer in phase change materials [11]. Danaila et al. derived the fully-implicit Newton iterative method based on a finite-element formulation for the phase-change system [12]. Besides, the finite difference method was also used for phase change problems [13, 14]. Among these numerical methods for PCMs, the finite element simulation is most popular for its excellent feasibility and stability [15, 16]. One can obtain desired accuracy by proper mesh division in the computational domains including single or multiple materials

[17-19]. In this study, the paper establishes a two-dimensional transient thermal analysis of the Al/PCM system consisting of aluminum plate and phase change material by using the finite element method implemented by the software COMSOL®. By introducing proper module, the transient thermal behaviors of the system are investigated to predict the positions of melting front at various time instants. Also, the efficiency of the PCM for energy storage is assessed for potential practical applications.

The paper is organized as fellows. The computational model of the Al/PCM system consisting of aluminum plate and phase change material is given in Section 2, and numerical experiments are performed in Section 3. Finally, some concluding remarks are drawn in Section 4.

2. Computational Model

The physical problem to be solved in this study is depicted schematically in Figure 1, in which the PCM is perfectly attached to the right surface of the aluminum plate. The left surface of aluminum plate is heated through a constant hot temperature provided by an electric heater. Other surfaces of the system are assumed to be perfectly insulated. Additionally, the dashed line in the PCM approximately represents the melting front of the PCM during phase change, so within the left area of this dashed line, the PCM has been fully melted into liquid state, whilst the PCM keeps solid state within the right area of this line.

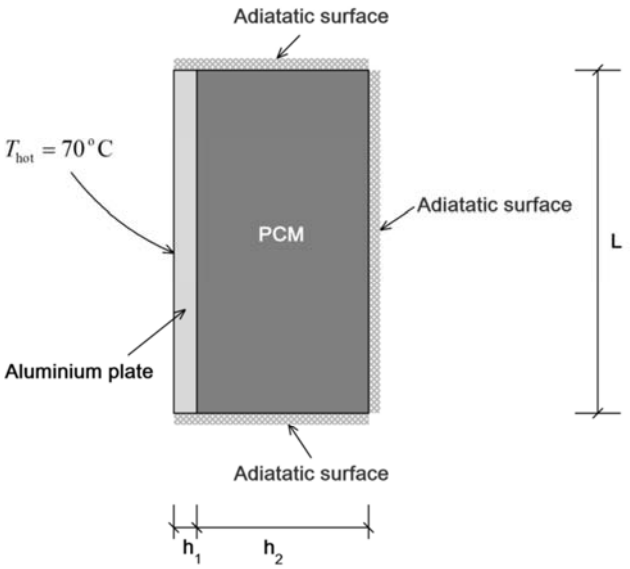


Figure 1. *Illustration of the two-dimensional system consisting of aluminum plate and PCM.*

Referred to the Cartesian coordinate system, the transient heat conduction equation at point $\mathbf{x}$ is written as [20]

$$\rho c_p \frac{\partial T(\mathbf{x},t)}{\partial t} = \nabla \cdot \left[k \nabla T(\mathbf{x},t)\right] + Q \tag{1}$$

where $\rho(\mathrm{kgm^{-3}})$, $c_p(\mathrm{Jkg^{-1}K^{-1}})$, $k(\mathrm{Wm^{-1}K^{-1}})$ are material density, mass heat capacity at constant pressure, and thermal conductivity, respectively. $T(\mathrm{K})$ is the temperature, and $Q(\mathrm{Wm^{-3}})$ is an interior heat source per unit volume. t is the time variable. In the study, the interior heat source is set as zero.

In the aluminum plate, the material properties for heat transfer are given by

$$\rho = \rho_{\mathrm{al}}, \quad k = k_{\mathrm{al}}, \quad c_p = c_{p\mathrm{al}} \tag{2}$$

while in the PCM, the effective heat capacity technique is introduced and the related material thermal properties are taken as

$$k = \begin{cases} k_{solid} & \text{for solid state} \\ k_{liquid} & \text{for liquid state} \end{cases} \tag{3}$$

$$c_p = \begin{cases} c_{psolid} & \text{for solid state} \\ c_{pm} & \text{for melting zone} \\ c_{pliquid} & \text{for liquid state} \end{cases} \tag{4}$$

In Eq. (4), the modified mass heat capacity c_{pm} in the melting zone where the solid and liquid states exist together can be calculated using the melting temperature range ΔT_m and the latent heat of fusion L_m for the PCM, i.e.

$$c_{pm} = \frac{L_m}{\Delta T_m} \tag{5}$$

Besides, in the two-dimensional Al/PCM system shown in Figure 1, the initial temperature of the aluminum plate and the PCM is assumed to be same as that of the environmental temperature T_0, that is

$$T(\mathbf{x}, t=0) = T_0 \tag{6}$$

For the need of computation, the material properties of the PCM, RT25 here [21], and the aluminum [20] in the Al/PCM system are tabulated in Table 1.

Table 1. *Material thermophysical properties of PCM and Aluminum.*

Property		PCM	Aluminium
Density $\rho(\mathrm{kgm^{-3}})$	Solid	785	2675
	Liquid	749	/
Mass heat capacity	Solid	1800	903
$c_p(\mathrm{Jkg^{-1}K^{-1}})$	Liquid	2400	/
Thermal conductivity	Solid	0.19	211
$k(\mathrm{Wm^{-1}K^{-1}})$	Liquid	0.18	/
Melting temperature $T_m(\mathrm{K})$		299.75	/
Latent heat of fusion $L_m(\mathrm{Jkg^{-1}})$		232000	/

In the practical simulation, the constant temperature, i.e. $T_{hot} = 70℃$, is applied on the left surface of the system since $t > 0$. Clearly, it will cause a temperature discontinuity at the

starting time $t = 0$. To fix this, a smoothed step temperature function which increases from T_0 to T_{hot} in 0.1s is introduced, as shown in Figure 2, in which the environment temperature is taken as 20℃. In addition, the thicknesses of the aluminum plate and the PCM are taken as 4mm and 20mm, respectively, and the heights of them are all 40mm.

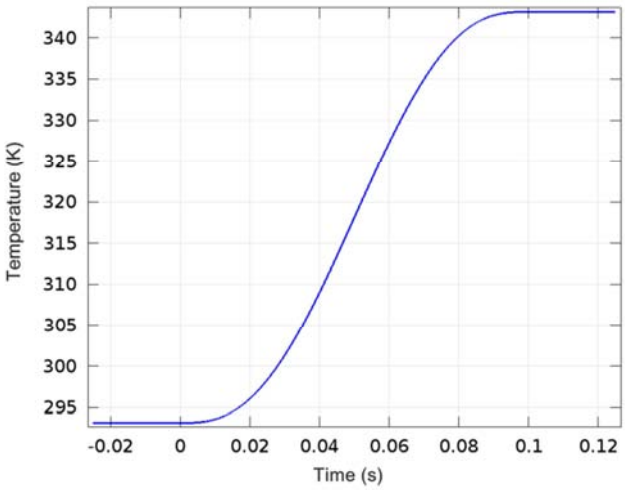


Figure 2. *Smoothed constant temperature constraint.*

3. Numerical Results and Discussions

The thermal storage model is solved by the finite element method implemented by COMSOL®, in which heat transfer in fluid module is set for heat transfer in the aluminum plate and the PCM. In this module, two special modules including the heat transfer in solid and the heat transfer with phase change are respectively defined for thermal analysis in the aluminum plate and the PCM, respectively. Total 1168 3-node linear triangular elements with 629 nodes are used to mesh the computing domain, as shown in Figure 3.

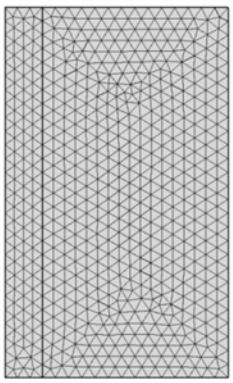
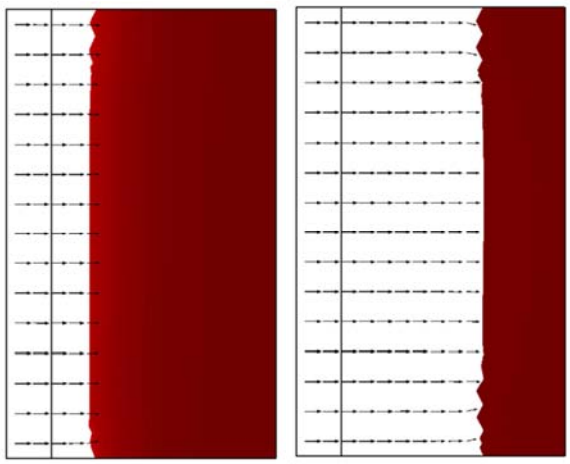


Figure 3. *Mesh configuration for the computing model.*

Firstly, with the specified materials properties in Table 1, Figure 4 shows the image of the melting front at two time instances, i.e. *t*=120s and 1800s. It's clearly seen that the liquid content (white region for liquid state and dark region for solid state in Figure 4) in the PCM increases with time. The melting front of the PCM moves right as the time increases, as expected. To show the temperature distribution in the computational domain at more times, the temperature variation along the bottom surface of the system is plotted in Figure 5, from which it is observed that the PCM is full solid state at *t*=0 because the temperature in the system is below the melting temperature of the PCM. Subsequently, as the time increases, the thermal energy transfers from the aluminum plate into the PCM rapidly, because the thermal conductivity of the aluminum material is more than one thousand times higher than that of the PCM. However, the temperature distributions all level out around the melting temperature point of the PCM because not all of the energy is going toward a temperature rise, and some is being absorbed to change the molecular structure and further the phase of the PCM. In addition, when the time reaches 4800s, the PCM almost entirely melts into liquid state. After this, the heat transfer fully occurs in the fluid phase. Moreover, the temperature variation at the right lower point of the system is displayed in Figure 6, from which it can be found that the temperature at this point keeps less than the melting temperature 26℃ over a long time interval, until the PCM is fully melted at *t*=4800s, due to the ability of energy absorption of the PCM during phase transition.



(a) *t*=120s (b) *t*=1800s

Figure 4. *Melting fronts at different time instances.*

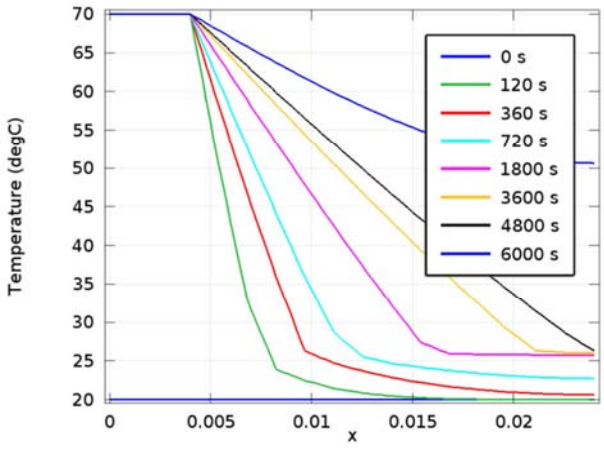


Figure 5. *Melting fronts at different time instances along the bottom surface of the system.*

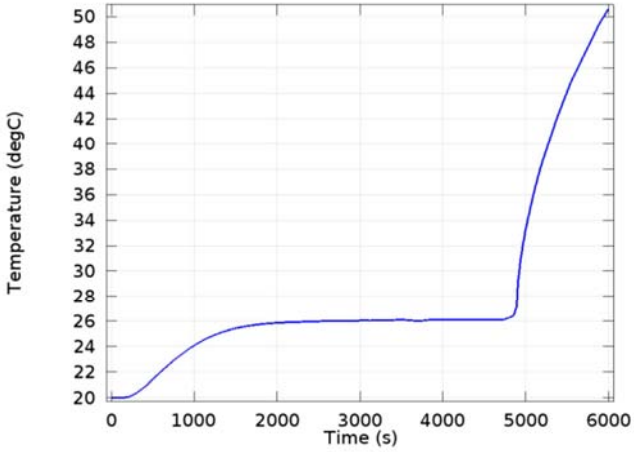


Figure 6. *Temperature variation at the right lower point of the system.*

It is known that the latent heat of fusion is a very important parameter for PCMs. Its value will affect the efficiency of thermal energy storage of PCMs. Secondly, in order to investigate the effect of the latent heat of fusion L_m of PCM, the temperature distributions along the bottom surface of the system are recorded and plotted in Figure 7 at t=3600s for three different values of L_m. It is found that the higher the latent heat is, the sharper the bend in the temperature profile in the PCM becomes. This means that more energy can be absorbed for phase change for higher latent heat of fusion. Besides, the temperature variation at the right lower point of the system is displayed in Figure 8 for three different values of L_m. It is observed from Figure 8 that the higher the latent heat is, the longer the horizontal segment in the temperature profile in the PCM is. It's reasonable that the PCM with higher value of the latent heat needs more energy for phase change, so that the thermal energy reaching the sampling point becomes less and the temperature at this point increases slowly.

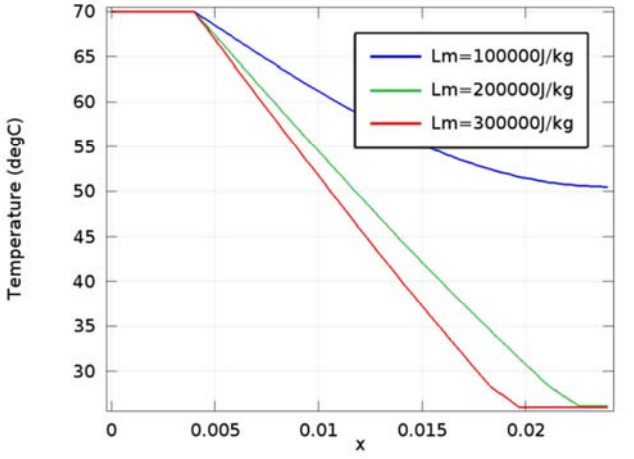


Figure 7. *Temperature variation along the bottom surface of the system for various latent heat of fusions at t=3600s.*

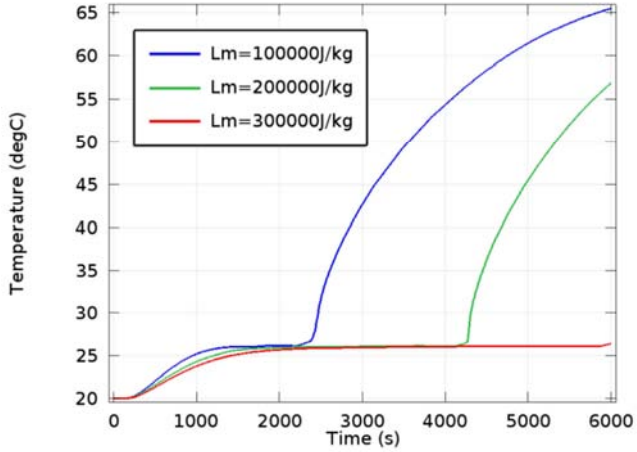


Figure 8. *Temperature variation at the right lower point of the system.*

4. Conclusions

In this work, the transient thermal behaviors of the system including the aluminum plate and the phase change material are studied by the finite element method implemented by COMSOL®. It is found from the simulation that the melting front in the PCM of the system almost keeps vertical during computation in the absence of natural convection. This phenomenon meets the symmetrical feature of the model. It is also observed that the PCM melts fully into liquid state at t=4800s, with the specific material properties. In addition, the results of sensitivity analysis of material parameter show that the latent heat of fusion of the PCM has strong effect on the position of melting front in the PCM. The higher the latent heat is, the more slowly the PCM melts. These results illustrate clearly the phase change process of the PCM during heating. However, the natural convection driven by buoyancy force is ignored in the present model, which may accelerate the melting of PCM. In the future, the effect of natural convection will be considered to improve the simulation.

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