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Numerical Study of the Effect of Fins on the Natural Convection Driven Melting of Phase Change Material

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Abstract: In this study, a simplified two-dimensional model was created in COMSOL Multiphysics 4.1 in order to simulate melting in a latent heat energy storage system (LHESS) with internal fins. PCM (octadecane) was stored in a rectangular container and different configuration (number and length) of copper fins were added to the system. Properties of the PCM were inputted manually, piecewise functions were used for the specific heat and viscosity and natural convection was accounted for by adding a volume force and using the Boussinesq approach. Results showed that natural convection played a noticeable role in determining position and behavior of the solid-liquid interface. Moreover, it was found that the fin length and positioning played a major role in increasing heat transfer when dealing with natural convection driven melting of a PCM.

Keywords: Phase Change Heat Transfer, Natural Convection, Melting, Fins Addition.

1. Introduction

Thermal energy storage (TES) has attracted more and more attention in recent years due to the rising cost of fossil fuels and increasing importance of environmental protection. TES could convert available energy and improve its utilization which provides a promising solution for smoothing the discrepancy between energy supply and demand. Current TES systems can be categorized by the method they use to store energy such as sensible heat storage, latent heat storage and thermochemical heat storage. Among all these energy storage methods, latent heat energy storage system (LHESS) shows more potential due to its advantages of high energy storage density and nearly constant temperature during phase change.

LHESS uses phase change material (PCM) as energy storage medium: energy is stored during melting and released during solidification. Numerical study of PCM phase change is complicated due to the transient characteristics of the process. It was observed that ignoring natural convection in mathematical modeling results in the PCM taking longer to reach its maximum temperature [1]; for that reason, natural convection has to be accounted and simulated for in order to properly describe the physics encounter in the phase change process, especially during melting [2].

As a promising medium for energy storage, PCM suffers from low thermal conductivity which limits its wide application in industry. Various heat transfer enhancement methods have been explored by researchers such as inserting metal matrix into PCM [3], PCM encapsulation [4], adding fins to PCM container [5], combination with another material which has a higher thermal conductivity [6].

In this paper, a simplified two-dimensional model was created in COMSOL Multiphysics 4.1 in order to simulate melting in a LHESS with internal fins. Also, in order to study the effect of fins on thermal performance, different configuration (number and length) of copper fins were added to the system. The effect of natural convection during PCM melting was also studied.

2. Materials and Geometry

The selection of proper PCM for a certain system should be analyzed carefully, and the compromise between PCM melting temperature and practical temperature range of designed system should be taken into account. Most of the research on PCM problems has been carried out within the temperature range 0-65°C which is suitable for domestic heating and cooling [7].

In this study, octadecane was used as PCM. Octadecane starts melting at a temperature of 303 K and a melting temperature range of 1 K was selected, defining a mushy region from 303 to 304 K. The thermophysical properties used for octadecane are shown in Table 1.

The geometry used for this study is a simple 2D rectangular enclosure, 0.1 m wide by 0.15m high as shown in Fig. 1. The enclosure is filled with octadecane.

Table 1. Thermophysical properties of octadecane

Thermal Conductivity	0.2W/m·K
Heat Capacity	1.25kJ/kg·K
Density	800kg/m^3
Latent Heat of Fusion	125kJ/kg

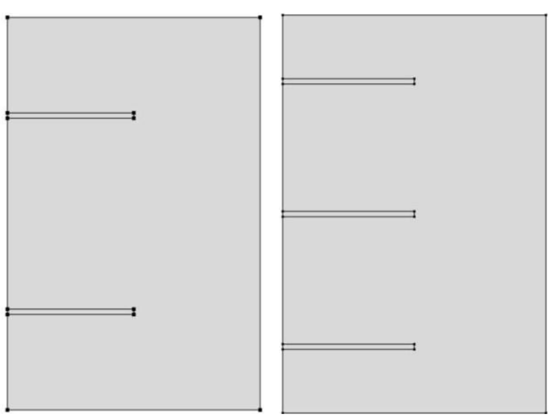
Table 2. Thermophysical properties of copper (fin)

Thermal Conductivity	400W/m·K
Heat Capacity	0.385kJ/kg·K
Density	8700kg/m3

For the study, the PCM is initially solid at its melting temperature, T_m = 303K. At t = 0, the temperature on the left side of the container is fixed at T_w = 313K, maintaining the temperature on the right side at 303K. The top and bottom walls are insulated. The following assumptions are made:

(a) Heat transfer modes are heat conduction and natural convection;
(b) The flow in the liquid PCM is laminar.

Geometries having various fin configurations (one, two and three fins of various lengths) are also built. Copper was selected as the material for the fin given its high thermal conductivity; Table 2 provides the thermophysical properties of copper. Figure 1 shows the geometries with 2 and 3 fins.



a) b)

Figure 1. Model geometry with a) two fins, and b) three fins.

3. Use of COMSOL Multiphysics

COMSOL Multiphysics 4.1 was used to simulate the melting of octadecane in those systems. Simulations were run for a total simulated time of 5,000 seconds. Longer simulations will be conducted in future studies. The heat transfer and laminar flow physics were used in COMSOL to simulate the thermo fluid and phase change processes.

There are three heat transfer mechanisms that must be considered in such system: conduction, natural convection and phase change heat transfer.

3.1 Conduction

At the onset of PCM melting, heat is transferred from the hot surface (left vertical wall and fins) to the PCM in its solid phase by heat conduction. Heat conduction is also present in the metallic fin. The energy equation for this process is:

$$\rho C_p \frac{DT}{Dt} = k\nabla^2 T \quad (1)$$

where ρ is the density of the material, C_P is the specific heat, k is the thermal conductivity and T is the temperature. A time derivative is found in that equation since this problem is transient in nature.

3.2 Natural Convection

When enough PCM material has melted, liquid PCM will start circulating between the hot walls and the liquid-solid interface, giving rise to natural convection heat transfer. From this point on, the shape of the liquid-solid interface will be determine by the effect and magnitude of natural convection in the liquid melt.

In order to model convection only in the liquid PCM, the dynamic viscosity μ was inputted as a piecewise, continuous second derivative function centered on T_m. This accounted for the viscosity of the liquid PCM in the melted region and forced the solid PCM to remain fixed by having a solid viscosity 10^8 times larger than the liquid one. See the paper from Murray and Groulx [8] for more detail.

A volume force was also added to the model to provide the driving force for natural convection in the liquid PCM using the following equation:

$$F = g\rho\alpha(T - T_0) \quad (2)$$

where g is gravity, α is the thermal expansion coefficient for octadecane, T_0 is the reference temperature at which the density is selected in the Boussinesq approximation and T is the local temperature in the liquid PCM.

3.3 Phase Change Heat Transfer

A large amount of energy must be provided to melt a PCM. In order to account for this latent heat present over the melting temperature range of the PCM, the specific heat of the PCM is modified using a piecewise function, following the method presented by Ogoh and Groulx [9].

In this numerical model, octadecane is taken to melt between the temperature of 303 and 304K and it has a latent heat of fusion of 125kJ/kg. The octadecane specific heat is then modified over this 1 K melting temperature range to account for the total amount of latent heat required to melt the material. To do so, the following equation is manually inputted into the model for the specific heat of octadecane:

$$C_p = \begin{cases} 1.25\text{kJ/kg} & \text{for } T < 303\text{ K} \\ 125\text{kJ/kg} & \text{for } 303\text{K} < T < 304\text{K} \\ 1.25\text{kJ/kg} & \text{for } T > 304\text{ K} \end{cases} \quad (3)$$

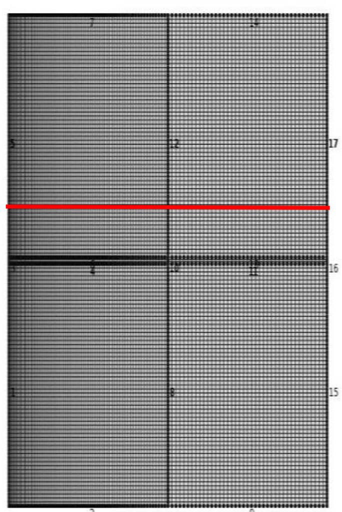


Figure 2. Schematics of the mesh used in this study. The red cutting line indicates where the temperature distribution presented in Fig. 3 was taken,

3.4 Mesh Generation

A mapped mesh was used for better control of the element shape and size. Also, since most of melting happened on the left half of the enclosure, the geometry was split into 2 boxes along the x axis (Fig. 2). A convergence study was performed in order to determine the optimum number of elements needed to minimize simulation time and maintain the highest level of accuracy.

Simulations were performed changing the amount of nodes used in the mapped distribution along the x axis for the left half of the enclosure; the amount of nodes was changed from 55 to 85 as shown in Fig. 3. The temperature plotted in Fig. 3 shows the results obtained along the red cutting line presented in Fig. 2. It can be seen from this temperature plotting that a good convergence is obtained when a distribution of 70 to 85 nodes are used. For the purpose of this study, 80 nodes will be used for the x axis distribution in the left half of the enclosure. After similar convergence study in the other sections of the geometry, 60 nodes are used in the distribution on the right side and 120 nodes are used in the distribution along the y axis. The final mesh shown in Fig. 2 has 14,670 elements in total.

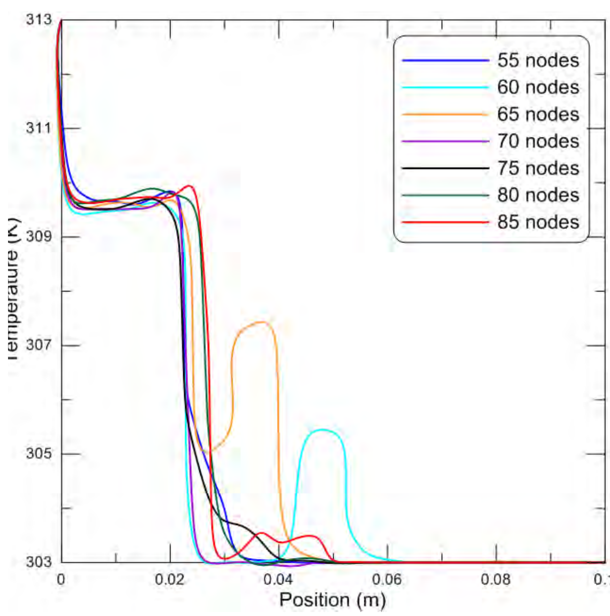
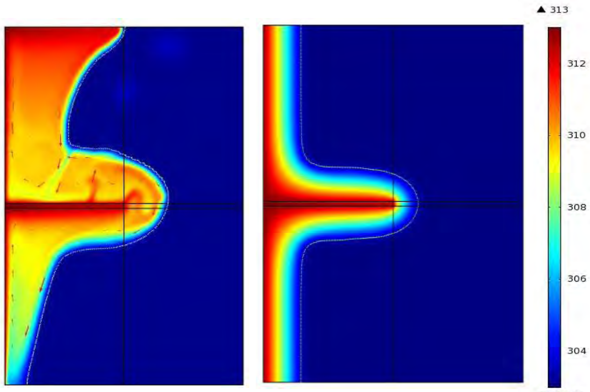


Figure 3. Temperature along the highlighted cut line from Fig. 2 as a function of the amount of distributed nodes in the left half of the enclosure.



a) b)

Figure 4. Temperature distribution after 5,000 s for the one fin system: a) accounting for heat conduction and natural convection, and (b) accounting for heat conduction only

4. Results and Discussion

4.1 Effect of Natural Convection

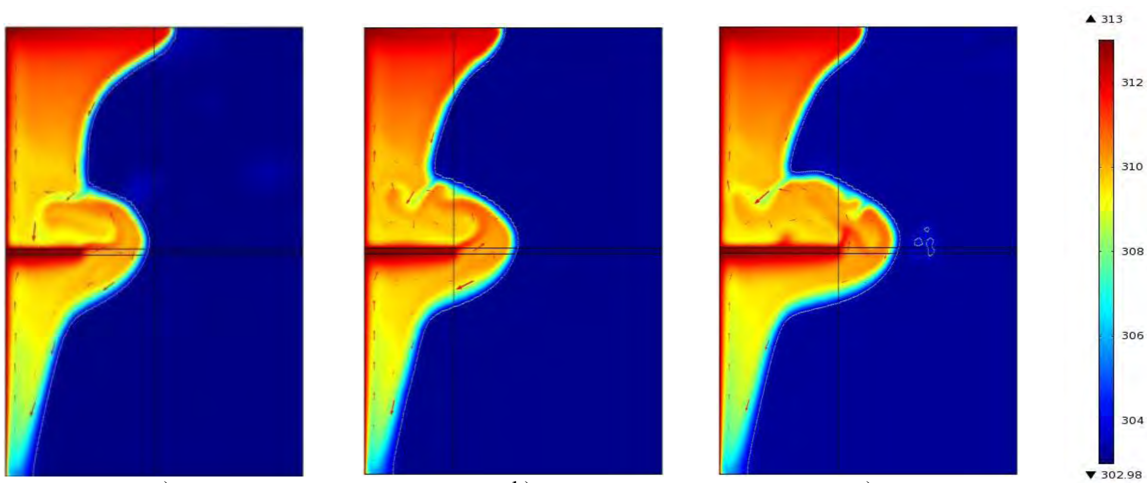
In order to determine the true effect of natural convection on the overall melting process, a simulation accounting only for pure conduction was carried out for a one fin system (fin length of 0.05 m) with identical initial and boundary conditions as all the other convection driven simulations. This was achieved by disabling the volume force acting on the PCM.

The results of both the conduction only and the convection driven heat transfer are presented in Fig. 4. For this one fin case, the melted fraction (*MF*) of PCM after 5,000 s is 34.23% when natural convection is taken into account. When natural convection is ignored, for the same 5,000 s of simulated time, only 20.8% of the PCM is melted. Moreover, it took twice as long (10,000s) to melt the same amount of the PCM when natural convection was ignored, owing to the increase thermal resistance in the ever growing liquid PCM in the absence of convection. The same conclusion was made by Lamberg [1]. The melted fraction *MF* is calculated by taking the surface integral of the 2D system for every element having a temperature above the average mushy region temperature, in this case 303.5 K, and dividing by the total area of all the elements as follow:

$$MF = \iint \frac{Area\ with\ (T>303.5\ K)}{A_{tot}} dxdy \tag{4}$$

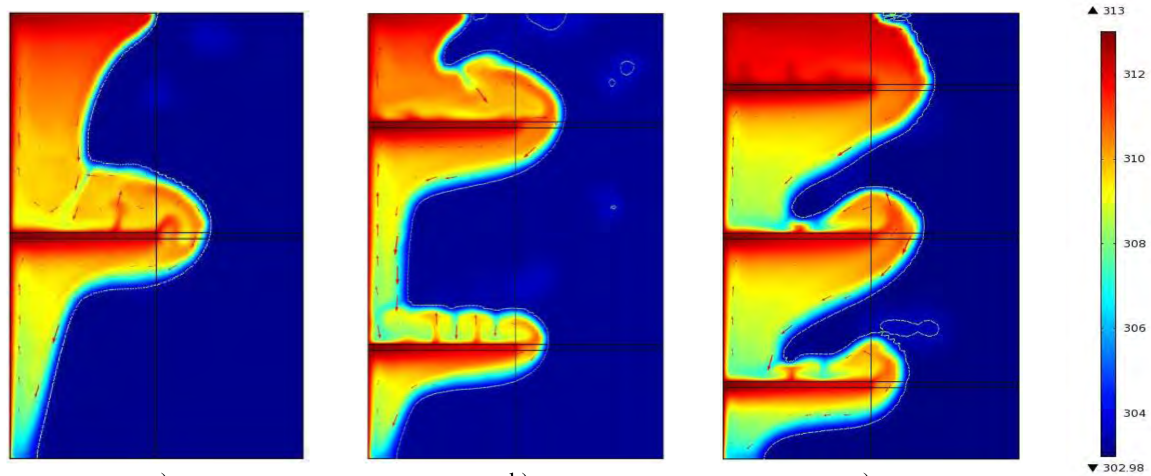
From Fig. 4, one can easily see the drastic difference in the shape of the melting front (the liquid-solid interface is shown on the temperature plot with a white contour line). This clearly shows that ignoring natural convection effect in the case of PCM melting leads to large inaccuracies. However, some researchers did not take into account natural convection when the volumes studied were small [11]. In these cases, the effect of natural convection decreases as the volume decreases, making heat conduction the dominant heat transfer mode [12].

The distance between the heating surface and the solid-liquid interface also plays an important role in dictating the strength of natural convection. In general, a greater distance, encountered when a greater volume of PCM as melted, will lead to increased natural convection



a) b) c)

Figure 5. Temperature distribution and melting front for a one fin system with fin length of a) 0.025 m, b) 0.03 m and c) 0.04 m.



a) b) c)

Figure 6. Temperature distribution and melting front for fined systems with fin length of 0.05 m having a) 1 fin, b) 2 fins and c) 3 fins.

Table 3. Octadecane Melted Fraction in a one fin system.

Fin Length	*MF*
0.025 m	28.67%
0.03 m	29.53%
0.04 m	32.21%
0.05 m	34.23%

and melting rate as demonstrated by Sari and Kaygusuz [13]. The reason being that buoyancy effect increases as the distance between the heating surface and the solid-liquid interface increases.

4.2 Fin Length

Simulation were performed on systems having a single fin of length of 0.025, 0.03, 0.04 and 0.05 m in order to compare the effect fin length has on the melting profile, the natural convection strength and the overall temperature distribution in those systems. Figure 5 shows the resulting temperature plots for the fin length of 0.025, 0.03 and 0.04 m, the results for the fin length of 0.05 m are presented in Fig. 6a).

It can be observed from those figures that the effect of the fin is mainly confined to its immediate entourage, where it increases the local temperature and the melting fraction in the system. This can be explained by the larger heat transfer area provided by the longer fins. Also of interest, regardless of the fin length, the heat transfer near the bottom wall of the enclosure remains relatively poor. Table 3 presents the total melting fraction obtained as a function of the fin length used.

4.3 Fin Numbers

Simulations were also performed with systems having set fin length of 0.05 m but with a variable number of fins: 1, 2 or 3 fins. The rectangular PCM container being relatively small, more than three fins would have made provide too small volumes of PCM between each fin to clearly observed the effect of natural convection. Figure 6 shows the temperature distribution plots and melting front position after 5,000 s of simulated time for the three cases studied.

It was observed that fins have strong effect on the total amount of melted PCM. Adding fins resulted in increased melting in the immediate entourage of the fin. From Fig. 6c), it can be observed that using 3 fins, resulted in a large increase in melting near the top of the enclosure, since a fin in the near proximity promoted increased heat transfer and stronger upward natural convection flow. Also of interest, thermal plumes can be seen forming over the fins.

Table 4. Octadecane Melted Fraction using fin length of 0.05 m.

Number of fin	*MF*
1	28.67%
2	42.57%
3	51.70%

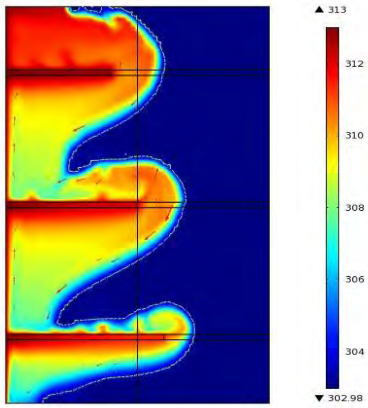


Figure 7. Temperature distribution and melting front for a 3-different length fin system.

Also, from the same figure, increase melting is also observed at the bottom of the enclosure. Again, the fin in the near proximity promoted increased heat transfer by increasing the total surface area available for heat transfer mainly by conduction to the bottom of the enclosure.

Still, for fins position higher in the enclosure, more melting occurs. In order to achieve complete melt of the PCM, extra heat transfer enhancement must be used at the bottom. Another simulation was carried out using three fins as presented in Fig. 7. In that case, different fin lengths were used for each fin conserving the same total heat transfer area as in the situation presented in Fig. 6c): the upper fin had a length of 0.04m, middle fin, 0.05m, and lower fin, 0.06m. In that case, it can be observed that more PCM melted, especially near the bottom of the enclosure, resulting in a total *MF* of 53.06%.

5. Conclusion

In this paper, a simplified two-dimensional rectangular enclosure was created to simulate melting in a LHESS with internal fins. Also, the effect of fins on thermal performance and the effect of natural convection during PCM melting were studied. It was found that for a relatively small (0.1 m by 0.15 m) rectangular enclosure, natural convection should not be ignored. For one fin model with a fin length of 0.05 m, total melting PCM will be reduced by 9.23% if no natural convection is taken into account. Four fin lengths were tested in this study and the best thermal enhancement performance was obtained with the longest fin.

Moreover, it was observed that fins have strong effect on the total amount of melted PCM. Adding fins resulted in increased melting in the immediate entourage of the fin. Heat transfer in the bottom of the container was poor and an optimized design was proposed. By keeping the same heat transfer area, the new design increased melting fraction by 2%.

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