Numerical Studies For Charging And Discharging Characteristics Of Composite Phase Change Material In A Deep And Shallow Rectangular Enclosure

Santosh Chavan¹, Arumuga Perumal D², Veershetty Gumtapure²
¹ Research Scholar, Department of Mechanical Engineering, National Institute of Technology Karnataka, Surathkal, Mangalore 575025, India
² Assistant Professor, Department of Mechanical Engineering, National Institute of Technology Karnataka, Surathkal, Mangalore 575025, India
E-mail - santosh.chavan083@gmail.com¹, perumal@nitk.edu.in², veersg@yahoo.co.in².
* Corresponding Author- veersg@yahoo.co.in

ABSTRACT
In this study, a numerical analysis of the melting process with natural convection in a rectangular enclosure has been performed using enthalpy porosity model. A Composite phase change material (Paraffin wax (98%) is used as base material and copper nanoparticles (2%) as additives) is used. The enclosure is heated from one side and opposite side is isothermal at 300 K, and remaining walls are thermally insulated. Melting heat transfer in a rectangular enclosure with different orientations are investigated numerically. The flow field results in nonuniform melting of the composite phase change material (CPCM). The interface morphology is used to infer flow structure and the extent of two-dimensional energy transport. These flow patterns are found to be dependent on the orientation and the initial CPCM subcooling. The results reveal that the enclosure orientation has a significant effect on the formation of natural convection currents and consequently on the heat transfer rate and melting time of the CPCM. As the orientation changed from deep to shallow, the convection currents in the enclosure, increases and chaotic flow structure appear. Hence, it can be concluded that the heat transfer enhancement ratio for the deep enclosure is more than that of the shallow enclosure.

Keywords: - Composite phase change material, heat transfer enhancement, nanoparticles paraffin wax, rectangular enclosure.

1. Introduction
Phase change materials (PCMs) are recognized as good applicant material for thermal energy storage (TES) systems to wipe out misalliance between the demand and supply. Thermal energy can be conserved with different practices and techniques, for example, latent, sensible, and chemical methods. The promising TES approach is thought to be better in latent heat storage (LHS), because of lower volume necessity and higher storage capacity (volume necessity for melting and solidification is same) and gives improved stability. Contingent upon the phase change temperature suitable PCM can be considered for appropriate TES applications. Melting of PCMs in the rectangular enclosure has attracted immense attention because of its simplicity in design and applications. Fields, for example, metallurgical process, casting, and TES are more concerted. An accountable number of numerical, analytical and experimental examinations consider the phenomena related to melting through constant temperature heating from one side of the rectangular enclosure. The solid to fluid phase change amid the melting
process can store a lot of energy by using the appropriated material. LHS materials likewise called PCMs because of conserving and reutilizing vast amounts of energy inside miniature volumes. It is known that the isothermal nature gives the capacity to keep their temperature steady during the melting and solidification process have discovered various designing applications, for example, energy preservation in buildings, solar powered energy conservation, human body and greenhouses Dhaidan et al. [1].

The PCM, which can improve the part of conduction heat transfer, it was seen that the laminar buoyancy driven natural convection significantly influences the solid-liquid interface patterns and the melting rate. Reducing the slant edge from the deep to the shallow orientation produces unpredictable interface patterns and expands the quality of the vertical streamline patterns in the fluid PCM. The solid-liquid interface evidently showed the regions of the covered in which convection currents play the substantial role of heat transfer between the liquid PCM and solid interface Ebrahimi et al. [2]. Decreasing the orientation from 90° to 0° produces unpredictable solid-liquid interface and builds the quality of the vertical streamline structures in the fluid region. The states of the fluid-solid interfaces amid the melting in the closed cavity demonstrate the effect of natural convection in the fluid region Kamkari et al. [3].

2. Physical Model
Thermal storage model was assumed to the enclosed domain with two different orientations, deep and shallow enclosure as shown in figure 1. Geometrical model of the enclosure with different aspect ratio was modeled to study the effect of changing the orientation of the enclosure with respect to the horizontal base. The thermal storage medium used for the investigation is composite phase change material (CPCM) (a mixture of 98% of Paraffin and 2% Copper nanoparticles) with enhanced thermophysical properties. The boundary conditions imposed are (i) Base wall is maintained isothermal at atmospheric temperature, (ii) Both the vertical walls are insulated and (iii) Heat flux applied from the top face of the enclosure, for both the cases.

![Figure 1: Physical model of (a) Deep Enclosure and (b) Shallow Enclosure.](image)

There are some assumptions made for evaluation such as, (a) the molten fluid acts like Newtonian fluid and the flow is incompressible, (b) The phase transition phenomenon takes place in laminar form with trivial viscous dissipation rate, (c) The thermophysical properties of working substance varies with temperature, (d) Conduction and convection heat transfer rates can be monitored,(e) Volume does not change during phase transition and (f) the working substance always remains in contact with the boundary walls of the domain.
3. Computational Methodology

The geometrical model was developed by using ICEMCFD15.0 pre-processing software of ANSYS 15.0 version, in order to interpret the superior results good quality mesh was generated all over the computational domain. At the boundaries, the mesh size was reduced and made a uniform to retort imposition of inputs and resolve the boundary layer conflicts. In order to reduce the computational time, the center part of the domain, the mesh is maintained relatively larger. To investigate the problem Fluent 15.0 was utilized and concerned parameters were defined, boundary conditions were imposed and temperature dependent user-defined functions (UDF) were interpreted. The thermophysical material properties were defined using UDFs. First order UPWIND differential scheme was adopted to solve the momentum and energy equations, and PRESTO scheme was used for pressure correction equation. The under-relaxation factors were 0.5, 0.3 and 1.0 for velocity components, pressure correction, and thermal energy respectively. The convergence criteria for continuity and momentum equations were $10^{-6}$ and for thermal energy $10^{-9}$, FLUENT adopted enthalpy porosity model for evaluating melting process. To get the optimum values of cells used grid independent test was conducted and the maximum temperature difference was approximately 0.03%. The number of cells and nodes used was 6215 and 6576 respectively and time step used was 0.1 sec.

3.1 Numerical study of composite phase change materials

The continuity, momentum and energy governing equations are considered in the resent work. The thermophysical properties of base PCM (Paraffin wax) and nano additives (Cu Nanoparticles) are listed in Table 1. The density, specific heat capacity, latent heat, Dynamic viscosity and thermal conductivity of the CPCM is defined as follows Zennouhi et al. [4]:

$$\rho_{cpcm} = \varphi \rho_{np} + (1-\varphi) \rho_{pcm}$$

$$C_{p_{cpcm}} = \frac{\varphi (\rho C_{p})_{np} + (1-\varphi)(\rho C_{p})_{pcm}}{\rho_{cpcm}}$$

$$L_{cpcm} = \frac{1-\varphi}{\rho_{pcm}} \rho_{pcm} (12.959\varphi)$$

$$\mu_{cpcm} = 0.983 e^{(12.959\varphi)} \mu_{pcm}$$

$$k_{cpcm} = \frac{K_{np} + 2 K_{pcm} - 2 (K_{pcm} - K_{np}) \varphi}{K_{np} + 2 K_{pcm} + (8 K_{pcm} - K_{np}) \varphi} k_{pcm} + 5 \times 10^4 \beta k \varphi \rho_{pcm} C_{p_{cpcm}} \frac{BT}{\rho_{npd} \rho_{np}}$$

Where $B$ is Boltzmann constant, $1.381 \times 10^{-23} \text{ J/K}$ and $\beta_k = 8.4407(100\varphi) - 1.07304$

$$f(T, \varphi) = (2.8217 \times 10^{-2} \varphi + 3.197 \times 10^{-3}) \frac{T}{T_{ref}} + (-3.0669 \times 10^{-2} \varphi - 3.91123 \times 10^{-3})$$

Where $T_{ref}$ is the reference temperature =273 K, and $\zeta$ is the correction factor and its value is same as the value for liquid fraction $\beta$.

**Table 1:** Properties of copper nanoparticles [2] and Paraffin Wax [3].

| Sl.No. | Properties | Nano additives | Base phase change material |
|--------|------------|----------------|---------------------------|
|        |            | Copper | Paraffin Wax |            |
| 1      | Density ($kg/m^3$) | 8954 | 750 | 0.001$(T - 319.15) + 1$ |
| 2      | Specific heat ($J/kg K$) | 383 | 2890 |
| 3      | Thermal conductivity ($W/mK$) | 400 | 0.21 if $T < T_{solids}$ | 0.12 if $T > T_{liquids}$ |
| 4      | Viscosity ($Ns/m^2$) | - | 0.001 x exp ($-4.25 + \frac{1790}{T}$) |
| 5      | Thermal expansion | $1.67 \times 10^{-5}$ | 5 $\times 10^4$ |
| co-efficient β (1/K) | Latent heat (J/kg) | Solidus temperature (K) | Liquidus temperature (K) |
|----------------------|--------------------|-------------------------|--------------------------|
| 6                    | 173400             | 319                     | 321                      |

3.2 Validation of numerical model

To ensure the accuracy of the current results, initially simulation has been carried out and the results were compared for two different cases with existing results of Khodadadi and Hosseinizadeh[5] and Arasu et al.[6]. However, the results are not presented here, obtained results for streamlines and melting interface patterns were compared with existing results, and both the results were reasonably matching and good.

4. Results and Discussion

Case (A): Deep Enclosure

4.1 Streamlines patterns

The Streamline patterns variation for a time interval of 500 and 2000 sec shown in figure 2. In deep enclosure top wall heating streamline patterns were uniform at adjacent to the hot wall and at left top corner it forms eyeball like structure. As time progresses, structure starts expanding and covers complete cavity with a small elliptical pattern flows to the right side. In charging process, the streamline patterns flow towards occupation of entire bounded domain forms an elliptical shape in the right side of the domain. In discharging process streamline patterns breaks at a time interval of 500 sec and spreads the whole domain, which indicates the complete solidification of the CPCM and completion of the discharging cycle.

![Figure 2: Streamline variation during charging (a) at t= 500 & (b) at t= 2000 sec and discharging process (c) at t= 500 & (d) at t= 2000 sec for deep enclosure.](image)

4.2 Temperature profile

The temperature distribution over the surface of the deep enclosure shown figure 3. The temperature over the entire domain was uniform, a drop-in temperature occurs in the melting region. The reason behind is the heat energy coming from the melting front is absorbed by the sub-cooled solid CPCM and allows only a small portion to penetrate slightly. At the culmination of the melting process, the temperature profile was uniform other than the isothermal wall.

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4.3 Melting Fraction
The melting process starts due to the supply of heat energy from the top surface of the deep enclosure, as time progresses the melting front moves forward direction and convection comes dominates at 500 sec of time duration. The constant heat flux intensifies the melting front to travel in the downward direction and starts to develop a convex shape in the domain, as shown in figure 4. At the commencement of the melting process, the melt forms a straight line at 2000 sec on the surface of the sub-cooled CPCM, maintained below its phase transition temperature. The solidification process follows the reverse process, now the instead of supplying constant heat flux heat is removed at a constant rate. After 500 secs of duration, the solidifying front forms a bulged rectangular shape, shrunken from both the ends, as time succeeds size of the bulged rectangle gets reduce and towards the center. During the solidification mechanism moves towards termination, it forms a tiny circle near the center towards the isothermal wall.

Figure 4: Mass fraction variation during charging (a) at t= 500 & (b) at t= 2000 sec and discharging process (c) at t= 500 & (d) at t= 2000 sec for the deep enclosure.

Case (B): Shallow enclosure
4.4 Streamline patterns
In the beginning, periods of melting streamline patterns change abruptly as the temperature varies the convection fronts travel and start to form the patterns. As the volume of the liquid portion in the enclosure increments with time, the impact of viscous forces against the enclosure walls diminish, along these lines permitting the liquid to rise. The smooth movement keeps on strengthening until the point that it levels off after around 2000 sec shown in Figure 5. Until the natural convection currents in the enclosure is completely developed. The streamline patterns were completely different from deep enclosure.
4.5 Temperature profiles
The variation in temperature distribution towards the center of the enclosure shown in figure 6. The temperature currents started from the hot top wall due to enhanced heat transfer rate by conduction mechanism (up to 500 secs for heating). At accomplishment of the complete melting process, the temperature currents were distributed uniformly all over the surface. For the discharging process (at 500 secs for cooling), the temperature currents formed a bulged rectangular shape same as deep domain. As time succeeds, the shape gets reduce gradually and finally at 2000 sec, only a tiny circle remained adjacent to the center of the enclosure.

4.6 Melting Fraction
The position and morphology of the melt front in melting of the CPCM inside a shallow enclosure shown in figure 7. The melting progress identically to deep enclosure but with dome-shaped structure at a time step of 500 sec as time leads the melting front travels along the insulated vertical walls up to the vicinity of the isothermal base wall. Observed 5-8 percent sub-cooled material remained in contact with the wall and remained sub-cooled for the whole process.
Figure 7: Mass fraction variation during charging (a) at t= 500 & (b) at t= 2000 sec and discharging process (c) at t= 500 & (d) at t= 2000 sec for the shallow enclosure.

The difference in the charging and discharging process shown in figure 8 & figure 9. For deep and shallow enclosure respectively. Shallow enclosure indicates the time saving for the thermal storage applications as mass fraction is higher during charging and lesser during discharging for the case of shallow enclosure as compare to deep enclosure. Hence, the shallow geometry can be selected to achieve the faster charging and discharging rates for the same working conditions.

Figure 8: Variation of mass fraction with time for charging and discharging process inside the deep enclosure.
Figure 9: Variation of mass fraction with time for charging and discharging process inside the shallow enclosure.

5. Conclusion
Numerical study of a rectangular domain with two different geometries with aspect ratio 1.5 with the application of constant heat flux and analyzed the variation in patterns of melting and solidification. Observed the streamline patterns, temperature and melting/ solidification contours with time evaluation. The shallow enclosure shown faster charging/discharging rate compared to the deep enclosure (up to 10% less time). The shallow enclosure can be preferred for better charging/ discharging rates, which could be essential in thermal storage applications.

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