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Research paper

Numerical investigation on the phase change process of different shaped macro encapsulated PCM

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Abstract

Latent heat energy storage using macro encapsulated phase change material is an emerging technique for thermal energy storage applications. The main aim of the present investigation is to investigate the melting process of phase change material filled in different shaped configurations. The selected different cavities are square, circular and triangular. A mathematical model based on convection dominated melting is required to be developed, especially in view of the complex flow geometries encountered in such problems. Thus, an attempt has been made to develop a model using ANSYS Fluent 16.2 to investigate the heat transfer rate and solid-liquid interface visualization of PCM filled in different shapes of cavity. It is found that triangular shaped macro encapsulated PCM melts faster than square and circular shaped encapsulated PCM.

Keywords: *Latent Heat Storage Unit; Macro Encapsulation; Melting; Natural Convection; Phase Change Material (PCM).*

1. Introduction

Thermal energy storage (TES) is of great importance to many fields of engineering since it offers numerous benefits for various areas of the industry. Thermal energy storage is inevitable for effective utilization of renewable energy sources due to their intermittent nature, especially solar energy, which is the most prospective energy source. For instance, one of the most common problems that solar power generation systems face is the gap that exists between the availability of the solar resource and energy demand, causing the need for an effective method by which excess heat collected during periods of high solar irradiation can be stored and retrieved later for use at night or during periods of darkness.

Thermal energy storage can be classified as Sensible Heat Storage (SHS), Latent Heat Storage (LHS) and thermochemical storage. In Sensible Heat Storage (SHS), the thermal energy is stored by raising the temperature of the storage material without undergoing phase transformation. On the other hand, LHS involves phase transformation of the storage material from one state to another, such as solid-liquid, solid-solid or liquid-gas and vice-versa when heated to the transformation temperature. The third method of energy storage is the thermochemical storage, which involves a reversible physio-chemical phenomena to store the thermal energy chemically and recovers the energy upon supplying heat. [1]

Among the various methods of energy storage, the latent heat thermal energy storage system using Phase Change Material (PCM) is most promising, mainly due to their high thermal energy storage density and their ability to provide heat at a constant temperature. The amount of heat stored in a latent heat storage system is given by following equation:

$$Q_{Latent} = \int_{T_1}^{T_2} mC_p\,dT + mL + \int_{T_2}^{T_3} mC_p\,dT \qquad (1)$$

Q is the amount of thermal energy stored or released (kJ), m is the mass of the material used to store thermal energy (kg) and L is the latent heat of fusion or vaporization (kJ/kg). First term of equation is energy stored in form of sensible heat, when temperature is raised from initial temperature T1 to melting point T2. Second term indicates energy stored in form of latent heat at constant temperature T2, and third term is again sensible heat storage, when temperature is raised from melting temperature T2 to final temp. T3.

The latent heat energy storage is the most promising means of thermal energy storage. Most of researchers have carried out study of phase change materials in shell and tube heat exchanger [2]–[4] .However, due to low thermal conductivity of PCM and thermal stability over extended thermal cycles the use of latent heat storage unit (LHSU) is not as per expected. This requires the heat transfer enhancement in such systems. The various enhancement techniques used are: Extended surfaces, Employing multiple PCM method, Thermal conductivity enhancement and Encapsulation of PCM. Out of these heat transfer enhancement techniques, macro-encapsulation of PCM is a new and immersing technique. Macro-encapsulation is in some form of self-assembled structure or a package such as tubes, pouches, spheres, panels or other receptacle. These containers usually are larger than 1 cm in diameter and can be incorporated in building products as well. The main advantage of the macro-encapsulation is its applicability to both liquid and air as heat transfer fluids and easier to ship and handle. Macro-encapsulation of the PCM helps to overcome the barrier of low thermal conductivity by increasing heat transfer rate. It is also helpful in forming a barrier and protecting the PCM from the outside environment and controlling the volume changes of the PCM. It has developed an interest in several researchers, especially because it can be cost effective compared to other techniques. Spherical and square shape for encapsulation of PCM is mostly used. Since the heat transfer is dependent on surface area, there is a need to investigate optimized shape for containers. Many researchers have studied different shaped macro capsules and few of them have been described below.

Bedecarrats et al. [5] experimentally investigated the performance of phase change energy storage encapsulated in spherical capsules during the charging and the discharging processes. The influence of super-cooling phenomenon during charging was studied. They concluded that both mass flow rate and HTF temperature were influencing parameters on charging and discharging, but both must be selected in combined (coupled) manner. Lacroix [6] numerically investigated melting of octadecane in rectangular cavity. He also studied the effect of degree of sub-cooling on melting time. He determined analytical expression for the duration of close contact melting of a PCM block at the melting temperature resting on a heated plate. Murray et al. [7] Numerically investigated melting process of two PCMs, octadecane and sodium nitrate in the rectangular shaped cavity. The effects of parameters like thermal conductivity, fluid viscosity and addition of fins were investigated. Maheswari and Reddy [8] investigated experimentally and numerically packed bed of spherical macro-encapsulated PCM .They also compared results for paraffin wax and stearic acid with different sizes of the spheres. It was observed that, the time taken to complete the phase change in the sphere changes as the size changes and paraffin takes less time compared to stearic acid in this cases. Khodadadi and Zhang [9] also considered the effects of natural convection on the constrained melting of phase change materials within spherical containers. They also state that during the initial melting process, the conduction mode of the heat transfer is dominant. As the buoyancy-driven convection is strengthened due to the increase in the melting zone, the process at top region of the sphere is much faster than at the bottom due to the increment of the conduction mode of heat transfer. Assis et al.

[10] investigated both numerically and experimentally on the melting of partially filled PCM in a spherical shell. They performed their numerical studies using the commercial software Fluent 6.0. Computational results had good agreement with the experimental results for different wall temperatures and different shell diameters. They presented a correlation for the melting fraction based on the non-dimensional Grashoff, Stefan and Fourier numbers. Their correlation had good agreement with the obtained data for Stefan number less than 0.1 which corresponds to temperature difference less than 10°C.

Literature shows that many researchers had focused their work in the field of macro-encapsulated PCM. Few of them have worked in area of innovative techniques of macro encapsulation, while many have investigated thermal performance of PCM. But very few researchers have worked for visualization of phase change process in different shaped macro capsules. Rare literatures are found in which other than spherical shape is considered for the analysis. The performance of the macro encapsulated PCM is established by the key parameters like aspect ratio, boundary conditions, geometries for encapsulation. However, there is need to compare/optimise different shapes for application in thermal energy storage systems for enhancement purpose. Thus, the main objective of the present work is to establish the thermal performance of the PCM filled in different shaped cavities using numerical analysis.

2. Mathematical modelling

Phase change process of PCM with convection-diffusion controlled phenomenon are very complicated. PCM changes one medium to another that has different liquid fraction values with time, nature of temperature distribution is non-linear. The finite volume method has been widely applied to solve conduction-controlled phase change problems. And it is now making inroads in problems involving convection-dominated melting of PCMs, especially in view of the complex flow geometries encountered in such problems.

An enthalpy-porosity method is employed for tracking the moving boundary of PCM. For transient 2-D heat transfer problem in latent thermal energy storage unit, the governing conservation equations are continuity, momentum and energy equation.

2.1. Governing equations

For mathematical modelling of melting process assumptions are [11]:

- PCM is homogeneous and isotropic.
- Initially PCM is in the solid phase for melting with uniform temperature.
- Thermo-physical properties of the PCM are constant.
- Boundary condition is constant wall temperature.
- The flow in the molten PCM is considered laminar, incompressible.
- The viscous dissipation term is considered negligible.
- Boussinesq approximation is valid only for free convection.

The continuity, momentum, and thermal energy equations can be expressed as follows:

$$\nabla \cdot \vec{V} = 0 \tag{2}$$

Momentum

$$\frac{\partial V}{\partial t} + V \cdot \nabla V = \frac{1}{\rho}\{-\nabla P + \mu \nabla^2 V + \rho \beta g (T - T)\} + S \tag{3}$$

Thermal energy

$$\frac{\partial H}{\partial t} + \nabla \cdot (Vh) = \nabla \cdot \left(\frac{k}{\rho c_p} \nabla h \right) \tag{4}$$

The enthalpy of the material is computed as the sum of the sensible enthalpy, h, and the latent heat, ΔH:

$$H = h + \Delta H \tag{5}$$

Where

$$H = h_{ref} + \int c_p dT \tag{6}$$

The latent heat content can be written in terms of the latent heat of the material, L:

$$\Delta H = \lambda L \tag{7}$$

$$\lambda = \begin{cases} \frac{\Delta H}{T} = 0, \ if T < T_{solidus} \\ \frac{\Delta H}{T} = 1, \ if T > T_{liquids} \\ \frac{\Delta H}{T} = \frac{T - T_{solidus}}{T_{liquids} - T_{liquids}}, \ if T_{solidus} < T < T_{liquids} \end{cases} \tag{8}$$

In momentum equation, is the Darcy's law damping terms (as source term) that are added to the momentum equation due to phase change effect on convection. It is defined as

$$\vec{S} = \frac{(1 - \lambda)^2}{\lambda^3} A_{mush} \vec{V} \tag{9}$$

The coefficient A_{mush} is a mushy zone constant. This constant is a large number, usually 10^4–10^7 [12]. In present study A_{mush} is asummed constant and is set to 10^5.

2.2. Validation

Numerical code developed using Ansys Fluent 16.2 for melting process is validated with results obtained by Hosseini et al. [12]. Shell and tube heat exchanger of 22mm tube diameter and 85mm shell diameter is considered. Water is flowing from shell side and PCM RT50 is stored in inner tube. The values of density, 780 kg/m^3; thermal conductivity, 0.2 W/m-K; latent heat, 168000 J/kg; specific Heat, 2000 J/kg-K; dynamic viscosity, 0.00025 kg/m-s; solidus temperature, 318 K; liquidus temperature 324 K, coefficient of thermal expansion, 0.0006 $/^{0}$C; for RT50 are considered. The initial temperature of PCM is taken as 25°C and HTF is flowing at 70°C.

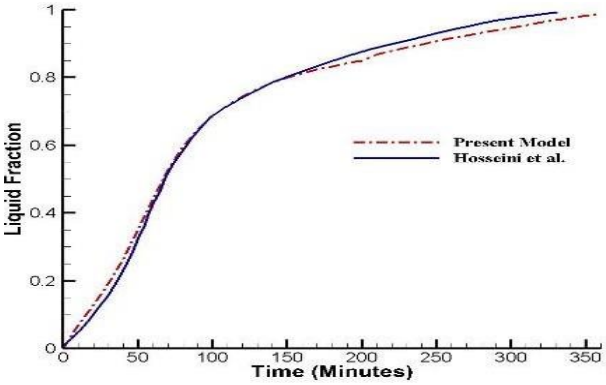

Fig. 1: Liquid Fraction Comparison of Present Numerical Results with Numerical Results by Hosseini Et Al. [12].

Figure 1 shows comparison of temporal liquid fraction variation using numerical code with results of Hosseini et al. [12]. The results of the present model showed an acceptable agreement with the results of Hosseini et al. [12]. Thus, methodology used for solution is correct and further study can be carried out with the same model for melting process.

3. Numerical study

The main objective of the present study is to develop the numerical models for different shaped cavity filled with the PCM and compare the performance of the same in the form of melting rate and heat transfer characteristics. For that a case study is considered in which paraffin wax as a PCM is filled in square, circular and triangular cavity. The physical configurations of all cavities are shown in fig. 2. The dimensions are chosen in such a way that area of the configurations remain same. Table 1 shows the thermo-physical properties of paraffin-wax.

Table 1: Thermo-Physical Properties of Paraffin Wax

Property	Value
Density	778 kg/m^3
Thermal conductivity	0.25 W/m-K
Specific Heat	2600 J/kg-K
Viscosity	0.003 kg/m-s
Thermal expansion coefficient	0.000012 1/K
Melting Heat	220000 J/kg
Solidus temperature	326 K
Liquidus temperature	333 K

4. Results and discussion

Melting process of paraffin wax as PCM has been studied using ANSYS Fluent 16.2. Here, melting behavior of PCM in different cavities and comparative analysis between square, circular and triangular cavities has been studied. During melting process, PCM is initially kept at 30°C and boundary of encapsulated PCM is subjected to constant temperature 85°C.

Figure 3 shows temperature variation at different locations of square, circular and triangular cavities respectively. Point A is located at centre of cavity, while point B and point D are located at 20mm above and 20mm below the centre respectively. Point C and point E are located at 20mm right side and 20mm left side of the centre respectively. From fig. 3 it is observed that for all cavities, rate of temperature increment for point A is slowest, because it is located farthest from the hot boundary. Temperature distribution for point B, C, D and E are almost same upto 15 minutes, which indicates uniform heat transfer and dominance of conduction. After that temperature increment of point B becomes faster than others. This is because of buoyancy driven natural convection. Once liquid formation starts temperature gradient occurs in liquid and due to density difference hot PCM moves upwards and cold PCM goes downwards, thus temperature of upper portion (point B) increases faster than all other points. Here, sharp rise in temperature of PCM at locations A and B is mainly because of replacement of solid PCM with liquid

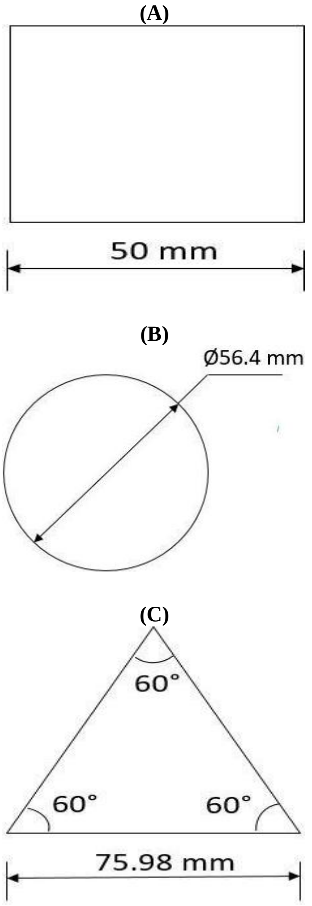

Fig. 2: Physical Configurations of Different Shaped Cavity A)Square, B)Circular and C)Triangular.

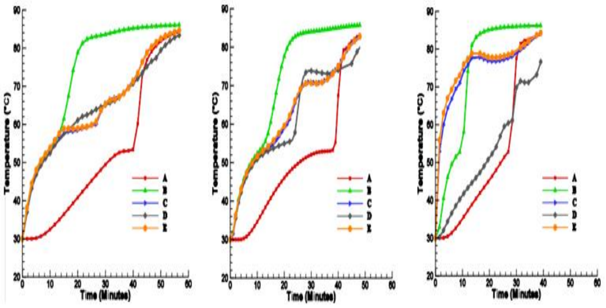

Fig. 3: Temperature Variation at Different Locations of Cavities during Melting Process.

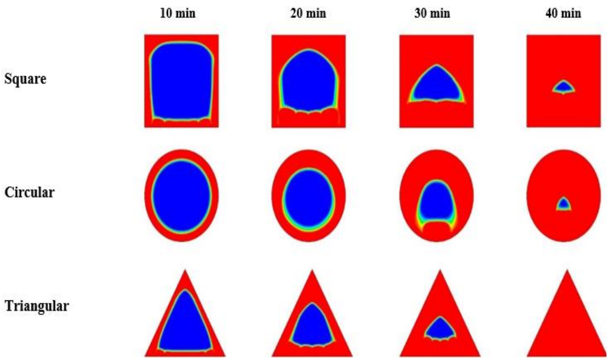

Fig. 4: Liquid Fraction Contours for Square, Circular and Triangular Cavity during Melting Process.

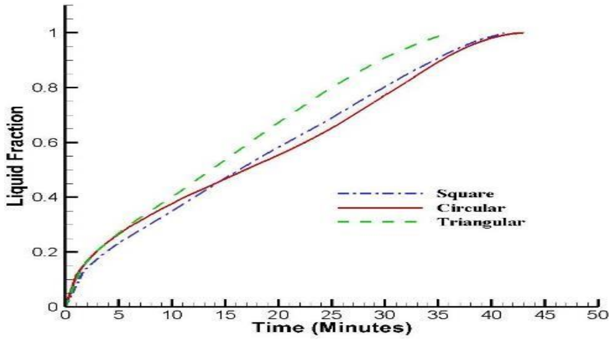

Fig. 5: Comparison of Numerical Liquid Fraction for Square, Circular and Triangular Cavity during Melting Process.

The instantaneous contours of the liquid fraction of PCM after 10, 20, 30 and 40 mins have been shown in fig. 4. It is observed that upto 10 min. liquid fraction contours are parallel to the boundary of all cavities. This shows heat transfer domi- nates by conduction mode of heat transfer. Thus, PCM melts uniformly. After that upper portion of PCM melts faster than the lower one because the hot molten PCM rises to top of the cavity. This phenomenon is due to density difference induced by buoyancy driven natural convection. Fig. 5 shows the transi- ent variation of numerical liquid fraction for all cavities. It can be seen that melting rate is faster initially, but with time it be- comes constant. The complete melting time for square, circular and triangular shaped cavities are 42, 43 and 36 minutes respectively. Melting rate in square and circular cavities are al- most same, while it is maximum for triangular cavity. Here reduction of melting time for square and triangular cavities are 2.32% and 16.27% compared to circular cavity.

5. Conclusion

Melting of encapsulated PCM mainly depends on the ge- ometry of encapsulation, thus there is need to optimize the shape and propose new geometries for enhanced characteris- tics. During charging process, heat transfer is dominated by conduction mode initially. As PCM starts to melt, both conduc- tion and buoyancy driven natural convection effects heat trans- fer, and natural convection has more influence on heat transfer. It is also observed that melting time required in case of macro- encapsulated PCM having square and circular shape is almost same, while for triangular it is minimum. Thus, for energy stor- age applications using macro encapsulated PCM triangular shaped cavity gives better performance than square and circular shaped cavities.

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