Performance Analysis of Latent Heat Storage Systems

Hakeem Niyas and P.Muthukumar

Abstract— Storage of heat in the form of latent heat using phase change materials (PCMs) is an effective way of storing the thermal energy. PCMs have been used in many applications such as thermal energy storage in solar thermal power plants, thermal conditioning of buildings, thermal comfort in vehicles, cooling of electrical equipments, etc. In the present paper, numerical experiments carried out to analyse the performance of latent heat storage (LHS) systems using PCM have been presented. Effective heat capacity method is employed to account the latent heat of PCM. Boussinesq approximation has been included in the model to incorporate the buoyancy effect of the molten layer of PCM. For proper modelling of velocities in the mushy region, Darcy law's source term has been added. In the current study, Paraffin RT 50 has been selected as the PCM and water has been selected as the heat transfer fluid (HTF). Melting time of PCM packed in three different cylindrical configurations viz. pipe model, cylinder model and shell-and-tube model is compared. The mathematical model is validated with the data available in the literature. The thermal characteristics of the models have been analysed using isothermal contour plots and temperature time curves. The phase change in the shell-and-tube model was dominated by the effect of convective heat transfer. Numerical results shown that for the same mass of PCM and surface area of heat transfer, shell-and-tube model takes the minimum time for melting the PCM.

Index Terms— Heat transfer, latent heat storage, phase change material, thermal energy storage.

1 Introduction

THE intermittent availability of solar radiation limits the usage of solar energy in solar thermal power plants. To bridge the gap between demand and availability of heat, integration of thermal energy storage (TES) system is essential. Thermal energy can be stored in the form of sensible, latent and chemical reaction heat. Currently, phase change materials (PCMs) have got more attention as it allow large amounts of energy to be stored in a relatively small volume, resulting in lowest storage media cost. PCM is a substance with a high heat of fusion which can be melted and solidified at certain temperatures. It is also capable of storing or releasing large amount of heat at constant temperature. When solar radiation is available, the heat energy obtained from the solar receiver can be stored in the PCM by changing the phase of the PCM from solid to liquid, which is called charging process. Later on, when there is a higher electricity demand or during cloudy periods, the stored heat can be recovered by changing the phase of PCM from liquid to solid and the same can be used for steam generation, which is called discharging process.

Herrmann et al. [1] presented a comparative analysis of solar parabolic trough power plant with and without storage system. They showed that storage time of 12 hr can reduce the levelized electricity cost by 10 %. Tamme et al. [2] developed a simulation tool for analysing the transient performance of the heat storage systems. It was found that selection of geometry of the storage system is more important than the effects of storage material properties. Ho et al. [3] presented the numerical solutions for steady laminar two-dimensional natural convection in concentric and eccentric horizontal cylindrical annuli with constant heat flux on inner wall and a specified isothermal temperature on the outer wall. Zhang et al. [4] experimentally studied the melting of n-octadecane, which was heated at a constant rate from one side of a rectangular enclosure. It was found that during the melting process, temperature in the upper region of the liquid was higher than that in the lower region, consequently accelerating the melting process. It was due to the reason that natural convection of the liquid phase led to the ascending of hot liquid and the descending of cold liquid. Hence the natural convection effect has to be included while modelling the phase change problem to get the correct results.

From the previous reported works, it is seen that there is lack of information on comparison of the various proposed models of cylindrical configurations. Further it is observed that there is lack of studies on the optimization of the offset distance in the shell-and-tube model. Hence in this paper, a two dimensional thermal model is developed using the COMSOL Multi-physics to study the thermal storage behaviour of PCM packed in three different cylindrical configurations containing same volume of PCM and heat transfer area. The offset distance has been optimized based on the charging time in the shell-and-tube model.

2 Design of Storage Models

Once the PCM has been selected based on the temperature range of application, the next most important factors to consider are the geometry of the PCM container, heat transfer fluid (HTF) to be used, thermal and geometric parameters of the container. Each of these factors has a direct influence on the heat transfer characteristics in the PCM and ultimately affects the melting time and the performance of the PCM storage unit. Three cylindrical models namely the pipe model (HTF flows through the pipe and PCM kept outside the pipe),

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cylinder model (HTF flows outside the pipe and PCM kept inside the pipe) and shell-and-tube model (HTF flows through the pipe and PCM kept in the shell) are analysed. Paraffin RT 50 has been selected as the PCM and water has been selected as the HTF. The thermo physical properties of Paraffin RT 50 is given in Table.1. The diameter (d) of the copper tube for the pipe and cylinder models is chosen as 60 mm with a thickness of 1.8 mm. To ensure equal volume of PCM in both these models, the outer diameter (D) was found to be 87.4 mm. The shell-and-tube model selected consists of six copper tubes of diameter 10 mm with a wall thickness of 0.3 mm. Similarly the outer diameter (Ds) of the shell was found to be 65.4 mm. The length (L) of all the three models is chosen as 200 mm. The configuration of different thermal storage models are shown in Fig.1.

3 Thermal Modelling

The thermal model of latent heat storage (LHS) bed is developed based on the assumption that the outer surface of the cylinder is adiabatic and PCM is isotropic.

Table 1.Thermophysical properties of Paraffin [8]

Solidus temperature (T_S, K)	318
Liquidus temperature (T_L, K)	324
Phase transition temperature (T_m, K)	321
Density (ρ, kg/m³)	780
Specific heat (C_P, kJ/kgK)	2
Latent heat (ΔH_f, kJ/kg)	168
Thermal conductivity (k, W/mK)	0.2
Coefficient of thermal expansion (β, 1/K)	0.0006
Dynamic viscosity (μ, Ns/m²)	0.0039

The flow is considered to be incompressible, laminar and Newtonian. The major problem associated with the numerical analysis of the phase change process is the inclusion of latent heat required to melt the PCM. This problem is dealt by using the effective heat capacity method which defines a modified heat capacity over the melting range of the PCM that accounts the specific heat capacity as well as latent heat of the material. The heat capacity of the PCM is modified as Eq. (1) and the effective heat capacity $C_{p,eff}$ is calculated using Eq. (2)

$$C_p = \begin{cases} C_{ps} & for\ T < T_S \\ C_{p,eff} & for\ T_S \le T \le T_L \\ C_{pl} & for\ T > T_L \end{cases} \quad (1)$$

$$C_{p,eff} = \frac{C_{ps} + C_{pl}}{2} + \frac{\Delta H_f}{2\Delta T_m} \quad (2)$$

where C_{ps} and C_{pl} are the specific heat (J/kgK) of solid and liquid PCM, respectively. ΔH_f is the latent heat of fusion of PCM. T_S is the solidus temperature and T_L is the liquidus temperature. $T_L - T_S$ is the range of phase transition and ΔT_m is the semi phase transition range. This approximation is necessary since melting at an exact temperature cannot be modelled numerically. Problems of this type are often referred to as mushy region problems. The discontinuous modified heat capacity is implemented in the commercial CFD software COMSOL Multiphysics using a smoothed Heaviside function with a continuous second derivative.

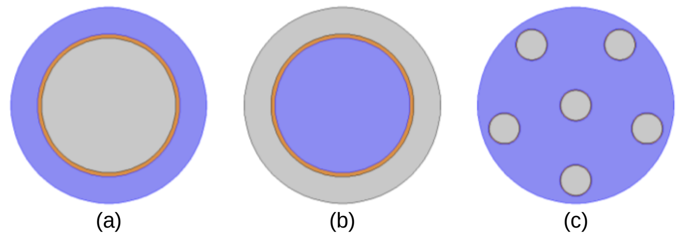

Fig. 1. (a) Pipe model, (b) Cylinder model and (c) Shell-and-tube model

Accordingly the continuity, momentum and energy equations has been given below.

$$\nabla . \vec{V} = 0 \quad (3)$$

$$\frac{\partial \vec{V}}{\partial t} + (\vec{V}.\nabla)\vec{V} = \frac{1}{\rho}\left(-\nabla P + \mu \nabla^2 \vec{V} + \rho \vec{g} \beta (T - T_m) + \vec{S}\right) \quad (4)$$

$$\rho C_p \frac{DT}{Dt} = k \nabla^2 T \quad (5)$$

where ρ, μ, k and β are density (kg/m³), dynamic viscosity (Ns/m²), thermal conductivity (W/mK) and coefficient of thermal expansion (1/K) of PCM. $\vec{S}$ is the Darcy law's source term which is defined in Eq. (6).

$$\vec{S} = \frac{(1-\theta)^2}{(\theta^3 + \varepsilon)} A_{mush} \vec{V} \quad (6)$$

where θ is the melt fraction of PCM which can be calculated using Eq. (7)

$$\theta = \frac{T - T_m + \Delta T_m}{2\Delta T_m} = \begin{cases} 0 & for\ T < T_S \\ 0-1 & for\ T_S \le T \le T_L \\ 1 & for\ T > T_L \end{cases} \quad (7)$$

Here $\vec{V}$ is the velocity field and A_{mush} is the mushy zone constant which defines the transition of velocity in the mushy region. Here it is assumed to be 10^6 for having a steeper change in the velocities. ε is a small value (0.001) to avoid division by zero. T_m is the phase transition temperature of the PCM. The dynamic viscosity variation of PCM during melting has been added in the form of a step function which is

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smoothened throughout the phase transition range. Boussinesq approximation has been included in the momentum equations to incorporate the effect of natural convection and to reduce the complexity in solving the Navier-Stokes equations. Initially all the domains are at constant temperature of 298 K (T_{ini}). At any time ($t > 0$), the inner tube is specified a constant temperature of 343 K (T_{inlet}) which is higher than the phase transition temperature of PCM. Before melting of PCM, the Darcy law's source term dominates all other terms in momentum equations and force the predicted velocities near to zero. During melting, once a molten layer of PCM is formed, the source term decreases and approximates the Darcy law in the mushy region. As the local melt fraction reaches a value of 1, the source term becomes zero and the momentum equations are in terms of actual fluid velocities.

4 Optimization of Offset Distance

The distance between the inner tube and the adjacent layer of tubes in the shell-and-tube model can be termed as offset distance (ϕ). Increasing the offset distance in the shell-and-tube model decreases the charging time due to the proper distribution of heat to the maximum volume of the storage model. But for the maximum offset distance case, the heat transfer surface area becomes lesser which increases the charging time. Therefore, optimization of offset distance is important to achieve a lesser charging time. The charging time of shell-and-tube model for different offset distances is presented in Fig.2. It is observed that the charging time decreases steadily from 2095 s (ϕ = 2.15 cm) to 1858 s (ϕ = 2.45 cm) and then increased to 1912 s (ϕ = 2.55 cm). Hence offset distance of 2.45 cm gives the least charging time for the corresponding model.

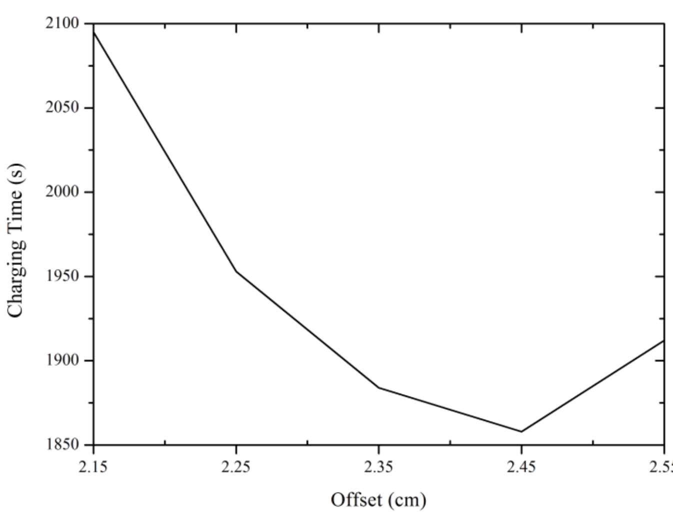

Fig. 2. Optimization of offset distance.

5 Results and Discussions

5.1 Temperature distribution

PCM kept in the containment is initially in the solid state. When the high temperature HTF passed through the tubes, heat is transferred from the HTF to the tubes by convection and then from the tubes to the PCM by conduction. As the molten liquid layer is getting formed around the circumference of the HTF tubes, due to the lesser thermal conductivity of PCM the dominant heat transfer mode has been shifted from conduction to convection which can be seen in Fig. 3. It is observed that at t = 5 min, the heat transfer in both pipe and cylinder models is only due to conduction, which is characterised by the concentric variation of temperature. But at the same time, the heat transfer shift has started in the shell-and-tube model. The effect of natural convection can be clearly seen from the oval shaped temperature contour around the HTF tube of pipe model (t = 20 min), cylinder model (t = 15 min) and shell-and-tube model (t = 10 min). This shows that the provision of multiple tubes increases the heat transfer thereby reducing the melting time of PCM.

5.2 Phase change diagram

In order to show the phase transition process of PCM, the PCM temperature at a point (2, 1) inside the PCM domain of shell-and-tube model is presented in Fig.4. It can be seen that for the selected point, the temperature increases steadily from 298 K to 318 K due to sensible heating (0 – 500 s). After that, increase in temperature is slow (500 – 1000 s) due to melting of PCM in the phase transition zone of 318 K to 324 K. Once the phase change process is completed, the temperature of PCM again increases steadily from 324 K to 340 K (1000 – 1250 s). As the driving potential i.e. the temperature difference between the PCM at the point and HTF inlet temperature is less (ΔT = 3 K), the temperature increases very slowly (1250 – 3000 s).

5.3 Charging time

Charging time of LHS model is defined with respect to the temperature rise of PCM and thus the melt fraction. The storage bed is said to be fully charged when the entire PCM has melted. For complete charging of PCM, pipe, cylinder and shell-and-tube models have taken 4425 s, 2319 s and 1860 s. The reduction in charging time for the shell-and-tube model is about 22.38 % and 59.32 % when compared with cylinder and pipe model for the present case.

The variation of average temperature and melt fraction are presented in Figs.5 and 6. It can be seen from Figs. 5 and 6 that, the shell-and-tube model and cylinder model have a steady increase in average temperature and melt fraction when compared to the pipe model. The high thermal resistance offered by the PCM in the outer periphery of the pipe model and delayed heat transfer shift from conduction to convection leads to the increase in its charging time. Shell-and-tube model offers the least charging time due to the even distribution of heat through the multiple convective zones in the HTF tubes. Also it is observed that after a melt fraction of 0.9, as the driving potential for heat transfer is less in all the models, it has taken more time to completely melt the PCM.

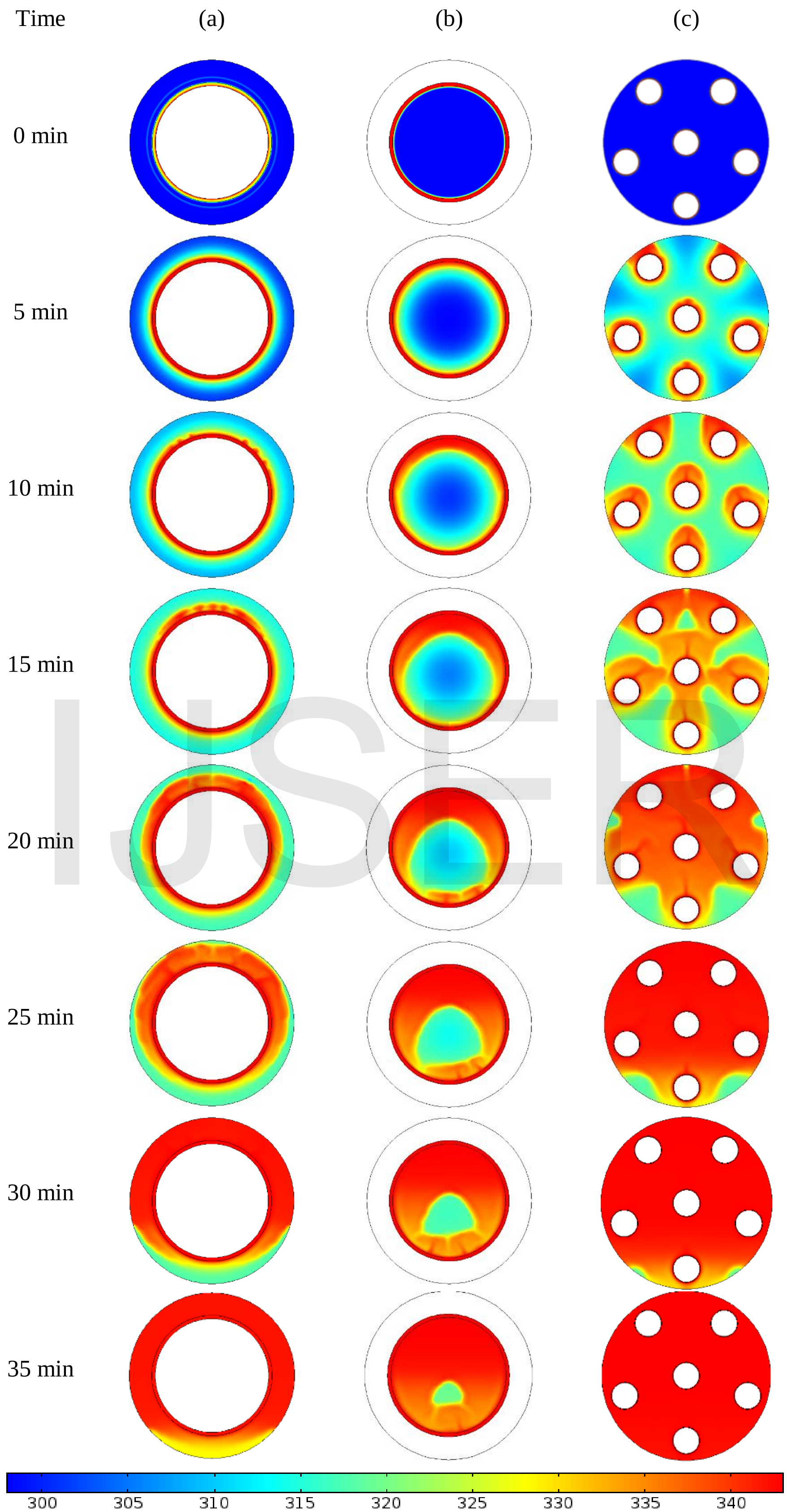

Fig. 3. Temperature contours of (a) pipe, (b) cylinder and (c) shell-and-tube models.

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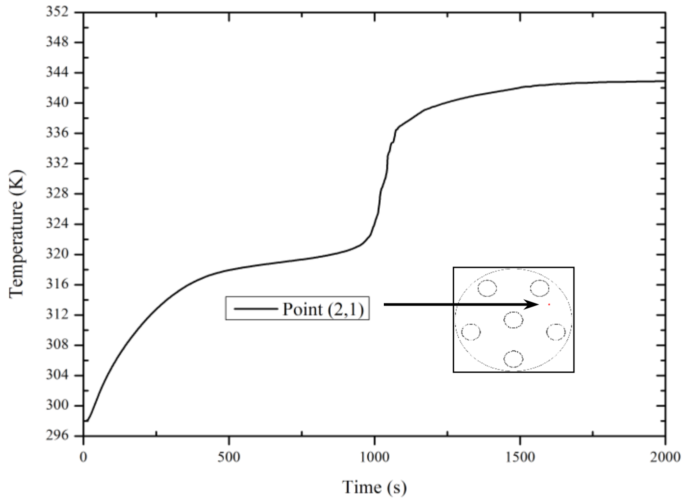

Fig.4. Phase change diagram of PCM at a point.

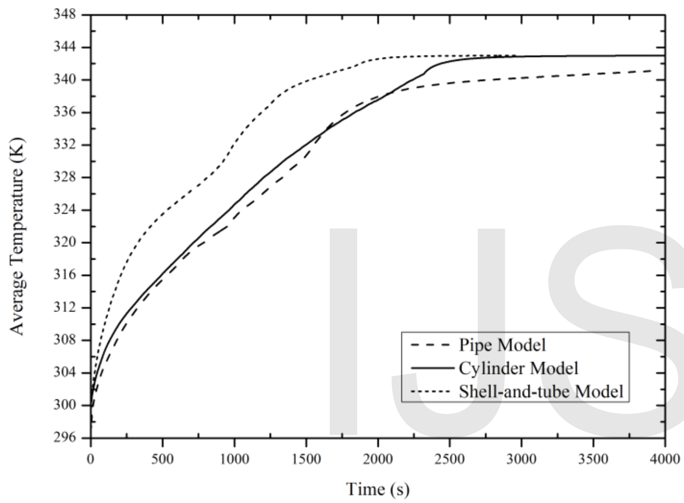

Fig.5. Average temperature variation.

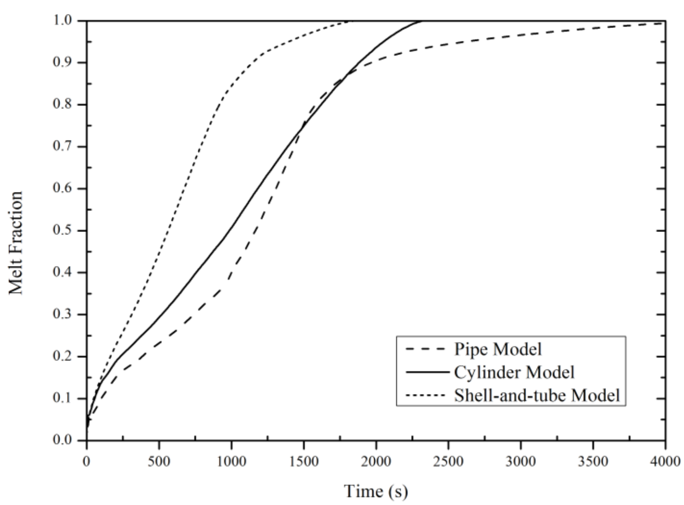

Fig.6. Melt fraction of PCM.

6 Results and Discussions

In order to validate the thermal model of the LHS unit, the results obtained for the melt fraction of storage bed have been compared with the melt fraction reported in literature [8]. The physical model chosen for the numerical validation, thermo physical properties of the PCM and initial and boundary conditions of the model are taken from literature [8]. It is evident from Fig.7 that the current numerical results showed good agreement with the results reported in literature [8].

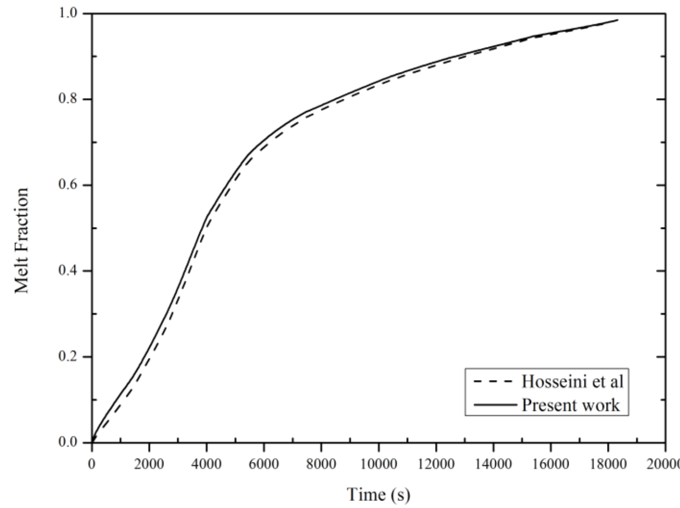

Fig.7. Validation of the numerical model.

7 Conclusions

Thermal models for comparing the charging characteristics of LHS units of three cylindrical configurations viz. pipe model, cylinder model and shell-and-tube model have been developed. Boussinesq approximation has been included in the model to incorporate the buoyancy effect of the molten layer of the PCM. Darcy law's source term has been added for proper modelling of velocities in the mushy region. The offset distance has been optimized based on the charging time in the shell-and-tube model. The temperature contours of pipe model, cylinder model and shell-and-tube models have been presented at certain time intervals. Variation of average temperature and melt fraction for the models have been presented. The numerical model of LHS unit has been validated and a close match was found with the data reported in the literature. It has been observed that the provision of multiple tubes increases the heat transfer to the PCM, thereby reducing the melting time of PCM. The phase change in the shell-and-tube model was dominated by the effect of convective heat transfer. Numerical results shown that for the same mass of PCM and surface area of heat transfer, shell-and-tube model takes the minimum time for melting the PCM. For complete charging, pipe model, cylinder model and shell-and-tube model have taken 4425 s, 2319 s and 1860 s. The reduction in charging time for the shell-and-tube model is about 22.38 % and 59.32 % when compared with cylinder and pipe model for the present case.

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