Effect of HTF flow direction, mass flow rate and fins on melting and solidification in a latent-heat-based thermal energy storage device

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Abstract. Latent-heat-based thermal energy systems (LHTES) have commonly been used as a potential energy storage mode over any other mode of thermal energy storage. Many heat transfer enhancement techniques have been proposed over the past years. These techniques reduce the melting and solidification times. Most of these techniques focus on the phase change material (PCM). However, the flow direction of the heat transfer fluid (HTF) can affect the heat transfer performance and pumping power requirement of the system. In this paper, the effect of HTF-flow direction, HTF mass flow rate and addition of the fins on the melting and solidification of the PCM in a shell-and-tube type of energy storage is numerically studied. Two-dimensional transient simulations are performed with ANSYS-Fluent where the phase-change process is modelled using the enthalpy-porosity formulation. The model is verified and validated by comparing with the available experimental data. A reasonable match is observed. The validated model, is used to study the effects of various parameters, such as, mass flow rate of the HTF, and triangular fin (at a fixed fin pitch) for both charging and discharging of the PCM. Finally, an influence of flow direction on the melting and solidification time has been studied. It is found that the contribution of HTF mass flow rate, the addition of the fin and HTF flow directions respectively is 1.3-3.01%, 16.97-17.62%, and 1.3-1.77% of overall heat transfer performance. A major contribution to the enhancement of overall heat transfer of the system is from the addition of fins.

1. Introduction

Power and energy requirements are increasing day-by-day. To fulfil the growing need, non-traditional energy resources, for instance, wind, tidal, solar and geothermal energy are preferred over the conventional energy sources, such as, coal, petroleum and natural gas. However, the alternative energy for storage is available intermittently; the thermal-energy storage system plays a crucial role. The thermal-heat energy storage is explored in the form of sensible-heat, latent-heat and thermochemical energy. Out of these, the latent-heat type has an advantage of enthalpy of phase-change making it more efficient due to higher thermal storage density. The latent-heat-based thermal energy systems (LHTES) based on phase-change materials (PCMs), for instance, can store approximately 5-14 times higher energy for the same storage volume when compared to the sensible heat storage system [1]. Therefore, the LHTES are most widely used to take an advantage of a space constraint, compactness, and higher energy storage needs.
On the one hand, use of PCMs as a thermal energy storage medium are most attractive, but on the other hand, it suffers from low thermal conductivity leading to its poor thermal performance. This affects negatively on the energy storage. A remedy to overcome this is to enhance heat transfer rate by using some techniques. The heat transfer enhancement techniques employed in PCM based energy storage applications can be broadly categorized into two viz. fixed and free type. Fixed type uses extended surfaces like fins [2], heat pipes [3], honeycombs [4], graphite/ metal matrices [5, 6, 7] and free type uses dispersed particles or filaments like metallic nanoparticles [8], carbon nanofibre[9], and carbon nanotubes[10]. In many cases a combination of the above mentioned approaches is used to utilize their advantages to further improve the heat transfer.

In most of the numerical studies performed to enhance the heat transfer, critical parameters, linked to the melting and solidification behaviour of the PCM, are varied to study their effects. Akgun et al.[11] varied the properties associated with HTF, such as, the inlet mass flow rate and the inlet temperatures for both charging and discharging cases. Hosseinizadeh et al. [12] used fins as thermal conductivity enhancers and studied its effect on melting of PCM by varying fin height, fin spacing and fin thickness. Gopalan and Eswaran [13] studied the PCM-based storage device by using structured porous media. As thermal conductivity was enhanced, the heat transfer performance found to be improved. Sheikholeslami et al. [14] showed that the melting and solidification was enhanced by using longitudinal triangular fins in a triplex tube heat exchanger. One of the heat transfer enhancement methods is also employed by varying the properties associated with additive used in PCM. Arıcı et al. [15] enhanced the properties of PCM paraffin wax by adding nanoparticles and achieved faster melting.

From the above literature survey, it is found that very little attention is given to the effect of HTF flow direction with annular triangular fins. In this study, we study the effect of HTF flow direction on the melting and solidification of the PCM using a 2-D shell-and-tube model with triangular fins using ANSYS-Fluent. The paraffin wax and water is respectively used as the PCM and HTF. In the present work, to validate the code, dimensions of the LHTES used are same as those used by Akgun et al.[11] and comparison is done with their experimental data. Subsequently, the inlet mass flow rate of HTF along with the HTF flow direction is varied to study their effects on the melting (charging) and solidification (discharging) time and finally, the overall heat transfer performance of the LHTES is studied.

![Figure 1. 3-D model of the tube in shell-type energy storage: (a) without fin, (b) with fin.](image)

2. Problem definition

Figure 1 depicts the pictorial view of the shell-and-tube type (physical) model employed in the present numerical work. The storage unit is a shell-and-tube type arrangement of LHTES, consisting of an inner
tube through which the HTF circulates and an outer annulus space filled with PCM. The HTF flows through the inner tube in the vertically upward in the first case or downward direction in the second case. Due to the heat-exchange, the PCM in the annulus melts during charging and solidifies during discharging. The inner tube material and the fins material is copper and outer shell material is steel. The outer part of the annulus is thermally insulated. The dimensions of the physical models are: L=465mm, d_o=94.67mm and d_i=28mm. The fins used are triangular annular type with a fin height, h=24mm, fin pitch, p=30mm and thickness, w=6mm.

2.1. Governing equations

To study the inlet mass flow rate, fin and HTF flow direction effects on melting and solidification of PCM, assumptions are made: the PCM is homogeneous and isotropic; flow is laminar, Newtonian and incompressible; physical model used for the charging and discharging process of PCM is transient; volumetric expansion of the PCM is negligibly small; all the thermo-physical properties of the PCM are assumed to be not varying with temperature and pressure (i.e. constant). As there is no rotational flow in the circumferential-direction, the physical model is axisymmetric in nature. Therefore, we perform simulations in a 2-D domain (see, Figure 2) to save the computation time. The governing equations used in the PCM-region, HTF-region and fins are given in the following subsections.

![Figure 2. Schematic of numerical domain, locations and type of boundary conditions.](image)

2.1.1. PCM-region

The enthalpy–porosity model is used in this analysis to simulate the melting and solidification process of PCM. In this the melting or solidification interface is tracked explicitly. Liquid fraction is monitored and the liquid fraction represents cell volume present in the liquid phase. For every iteration the liquid fraction is computed by using the enthalpy balance [17]. Following are the governing equations for PCM:

Continuity equation: $\nabla \cdot \vec{V} = 0$; where, $\vec{V} = u\hat{i} + v\hat{j}$ (1)

Momentum equation:

i. x-momentum: $\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{\partial P}{\partial x} + \frac{\mu}{\rho} \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) + S_u$ (2)

ii. y-momentum: $\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{1}{\rho} \frac{\partial P}{\partial y} + \frac{\mu}{\rho} \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + \beta g(T - T_{ref}) + S_v$ (3)

The momentum source is represented by $S_u$ and $S_v$. They are represented in the following forms [18]:

$$S_u = -C(1 - \gamma)^2 \left( \frac{u}{\gamma^3 + \varepsilon} \right)$$
$$S_v = -C(1 - \gamma)^2 \left( \frac{v}{\gamma^3 + \varepsilon} \right)$$ (4)
where, \( \mathcal{C} \) is the mushy zone constant with value between 10^5 and 10^6.

Energy equation:
\[
\frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho \vec{V} H) = \nabla \cdot (k \nabla T) + \rho \beta \frac{\partial T}{\partial t}
\]
(5)

with \( H = h + \Delta H \), with \( h \) and \( \Delta H \) are respectively called as sensible enthalpy and latent heat. \( \rho \) is the material density, \( k \) is the thermal conductivity, \( \mu \) is the dynamic viscosity of HTF, \( \beta \) is the thermal expansion coefficient. The velocity components are represented by \( u \) and \( v \). \( P \) denotes the pressure and \( H \) denotes the enthalpy. A definition of sensible enthalpy is given by

\[
h = h_{\text{ref}} + \int_{T_{\text{ref}}}^{T} C_p dT
\]
(6)

where, \( h_{\text{ref}} \) is the enthalpy at \( T_{\text{ref}} = 273K \), with \( T_{\text{ref}} \) as reference temperature. The specific heat at constant pressure is denoted by \( C_p \) and the latent heat is defined as,

\[
\Delta H = \gamma L_m
\]
(7)

where, \( L_m \) is the latent heat of material and \( \gamma \) represents the liquid fraction the PCM during the charging process varying from 0 (solid) to 1 (liquid). It is defined by mathematical relation as: \( \gamma = 0, if \ T \leq T_s; \gamma = \frac{T-T_s}{T_l-T_s}, if \ T_s < T < T_l; \gamma = 1, if \ T \geq T_l \).

### 2.1.2. HTF-region

Continuity equation:
\[
\nabla \cdot \vec{V}_{HTF} = 0, \quad \text{where} \quad \vec{V} = u_{HTF} \hat{i} + v_{HTF} \hat{j}
\]
(8)

Momentum equation:

i. \( x \)-momentum:
\[
\frac{\partial \rho_{HTF} u_{HTF}}{\partial t} + \rho_{HTF} \frac{\partial u_{HTF}}{\partial x} + v_{HTF} \frac{\partial u_{HTF}}{\partial y} = \frac{1}{\rho_{HTF}} \frac{\partial P}{\partial x} + \frac{\mu_{HTF}}{\rho_{HTF}} \left[ \frac{\partial^2 u_{HTF}}{\partial x^2} + \frac{\partial^2 u_{HTF}}{\partial y^2} \right]
\]
(9)

ii. \( y \)-momentum:
\[
\frac{\partial \rho_{HTF} v_{HTF}}{\partial t} + \rho_{HTF} \frac{\partial v_{HTF}}{\partial x} + u_{HTF} \frac{\partial v_{HTF}}{\partial y} = \frac{1}{\rho_{HTF}} \frac{\partial P}{\partial y} + \frac{\mu_{HTF}}{\rho_{HTF}} \left[ \frac{\partial^2 v_{HTF}}{\partial x^2} + \frac{\partial^2 v_{HTF}}{\partial y^2} \right]
\]
(10)

Energy equation:
\[
\frac{\partial \rho_{HTF} C_{pHTF} T_{HTF}}{\partial t} + \rho_{HTF} C_{pHTF} \left[ u_{HTF} \frac{\partial T_{HTF}}{\partial x} + v_{HTF} \frac{\partial T_{HTF}}{\partial y} \right] = k_{HTF} \left[ \frac{\partial^2 T_{HTF}}{\partial x^2} + \frac{\partial^2 T_{HTF}}{\partial y^2} \right]
\]
(11)

### 2.1.3. Fins

Fin material considered is copper (Cu). As there is no phase change occurring in the fin, the energy equation representing the transient heat conduction is:

Energy equation:
\[
\frac{\partial (\rho_{Cu} C_{pcu} \partial T_{Cu})}{\partial t} = k_{Cu} \left[ \frac{\partial^2 T_{Cu}}{\partial x^2} + \frac{\partial^2 T_{Cu}}{\partial y^2} \right]
\]
(12)

### 2.2. Numerical conditions at the domain boundaries

Figure 2 depicts the numerical boundary conditions for the 2-D axisymmetric computational domain. The inlet mass flow rates are specified as 8kg/min, 6kg/min and 4kg/min. Inlet temperature for the charging (melting) process is 343K and for discharging (solidification) process it is 298K. The outer part of the annulus is thermally insulated wall and the axis is considered as symmetric-boundary. The inner wall of the tube and fins are given as a coupled-wall boundary condition. At the outlet an outflow boundary condition is specified. To start the numerical simulations, for a transient flow, an initial condition is needed. The initial temperature for the charging process considered is 300K and for discharging process it is 343K.
3. Numerical methodology

Computational analysis is performed to solve the governing equations (eqns. (1) to (12)) for a transient laminar flow using ANSYS Fluent 16.0 software. The enthalpy-porosity method (eqns. (1) to (7)) is employed to model the charging and discharging process of the PCM and to monitor the temporal evolution of the liquid–solid interface. Convection terms in the x- and y-momentum and energy-conservation equations are interpolated using a second-order upwind (SOU) interpolation discretization-scheme and the second-order diffusion terms are discretized using the central difference (CD). PRESTO! is employed for the pressure interpolation. The flow field is obtained using a SIMPLE algorithm. The thermo-physical properties of HTF and PCM are considered to be constants; they are mentioned in the Table 1. The under-relaxation factor used for pressure is 0.3, momentum is 0.7, energy is 1 and liquid fraction is 0.9. Solution convergence criteria used is $10^{-6}$ for continuity and x- and y-momentum and $10^{-9}$ for energy equation. The maximum numbers of iterations per time-step considered are 10.

Table 1. Thermo-physical properties of paraffin wax and water [11].

| Property                        | Unit       | Paraffin-Wax | Water    |
|---------------------------------|------------|--------------|----------|
| Density of material             | kg m$^{-3}$| 794          | 998.2    |
| Specific heat at constant pressure | J kg$^{-1}$K$^{-1}$ | 2100        | 4182     |
| Material thermal conductivity   | W m$^{-1}$K$^{-1}$ | 0.43        | 0.6      |
| Dynamic viscosity               | kg m$^{-1}$s$^{-1}$ | 0.0269      | 0.001003 |
| Latent heat storage capacity    | J kg$^{-1}$ | 249000       | -        |
| “Solidus” temperature           | K          | 317          | -        |
| “Liquidus” temperature          | K          | 324          | -        |

3.1. Grid-size ($\Delta x$ and $\Delta y$) and time-step ($\Delta t$) independence

For the determination of an optimum grid-size and time-step, a process of time-step and grid-size independence is carried out for both the no fin and fin cases. For the no fin condition, 900 cells, 1800 cells, 3600 cells and 7200 cells and for the fin condition, 2569 cells, 5138 cells and 10276 cells are considered. In the study of time-step independence, time-step sizes used are 1s, 0.5s and 0.1s, for both the no-fin and fin situations.

Figure 3. Grid-size ($\Delta x$ and $\Delta y$) independence and time-step ($\Delta t$) independence study for no-fin and fin condition.
The grid-size and time-step independence study is performed with the maximum inlet mass flow rate i.e., 8kg/min and total duration of 600 seconds. The Figure 3 depicts the variation of average temperature along the radial direction (x-direction) at a fixed axis (y-direction) location. It can be observed from the Figure 3, that the optimum grid-size for no-fin case is 3600 cells and 5138 cells in fin case. The optimum time-step was found to be 0.5s for both the no-fin and fin cases. Hence, the numerical simulations are performed on the optimal grids (in no-fin case is 3600 cells and 5138 cells for fin case) and time-step (0.5s).

3.2. Validation of the numerical procedure

A validation of the current model is performed by comparing the results with the data from the experiment [11] available for a charging process. A radial average temperature along the radial direction is compared with the experimental data [11] (refer Figure 5 in the reference paper) as shown in Figure 4. From the figure, a relative error of 0.073% is observed, which is negligible. Therefore, with a reasonably good agreement between the present computational study and available experimental data, the present model is used for further study.

4. Results and Discussion

In the present work, the thermal-energy performance of the shell-and-tube type LHTES is carried out by analysing the influence of flow-direction of HTF on the melting (charging) and solidification (discharging) of PCM. The system parameters, for instance, flow direction and inlet rate of mass flow rate are varied and the fin pitch is kept fixed.

4.1. Effect of mass flow rate of HTF

In the present section we compare the HTF flow directions effect on melting and solidification in the absence of the fin. Figure 5 depicts the comparison of the maximum temperature observed in the whole PCM domain with the flow-time at various inlet conditions, viz., 4kg/min, 6kg/min, and 8kg/min, for both charging and discharging mode additionally with the directional effect of HTF direction in the upward (Case-1) and downward (Case-2) direction. It shows that the fastest melting time is 357.33 minutes and 363.67 minutes, respectively, for HTF mass flow rate direction in the upward (Case-1) and downward (Case-2) direction, at 8kg/min mass flow rate. Similarly, the fastest solidification time is 407.67 minutes and 420 minutes, respectively, for HTF mass flow rate direction in upward and downward direction.

At higher HTF mass flow rate (8kg/min), the melting
process is faster by 1.2% and 2.35% respectively for Case-1 and Case-2. Similar trend is observed during the solidification; it is faster by 3.01% and 2.06% respectively for Case-1 and Case-2.

Figure 5. Temperature variation with respect to flow time for no-fin case at different inlet mass flow rates of HTF.

4.2. Effect of fin

As we observed from the previous section that heat transfer is improved at 8 kg/min, effect of fin additions, for a fixed fin pitch p=30 mm, is studied at an inlet HTF mass flow rate of 8kg/min. A standard procedure is followed in the selection of the length and thickness of an annular triangular fin. A maximum temperature distribution versus flow time is plotted for no-fin and fin condition as shown in Figure 6. A drastic reduction in the melting (charging) and solidification (discharging) times (about 16 - 17%) of the PCM is observed with the addition of the fin.

Figure 6. Maximum temperature versus flow time for no-fin and fin cases when flow direction is upward (Case-1) and downward (Case-2).
Figure 7 shows a qualitative field data of the mass fraction (solid or liquid) for melting (liquid) and solidification (solid) processes at 167 minutes (at this time, temperature difference between fin and no-fin case is small, see Figure 6). Although the temperature difference between no-fin and fin case quantitatively small, a drastic change in the qualitative picture are observed with the addition of fin. Therefore, it can be said that, with the addition of the triangular annular fins, the performance of the system significantly improves.

![Figure 7. Mass fraction contours at various cases showing melting and solidification of PCM.](image)

4.3. Effect of HTF flow reversal of directions

An effect of flow reversal of directions of HTF may help in reducing pumping power for gravity-assisted downward flow as against that of the upward flow. Therefore, we intended to study the impact of HTF flow direction on the melting and solidification in this section. The maximum temperature versus flow time data is shown in Figure 8 for both the flow directions. From Figure 8(a) and 8(b), when no-fin is used, it can be seen that the HTF flow against the direction of gravity shows respectively faster melting and solidification of 1.77% and 1.3%. Similarly, from Figure 8(c) and 8(d), when fin is used, it can be seen that the HTF flow against the direction of gravity shows respectively faster melting and solidification of 1.4% and 1.67%. Therefore, in all the cases, the HTF flow against the direction of gravity showed faster melting and solidification. A possible reason can be that when the HTF flow is in an upward direction (Case-1) the convection heat currents seem to be additive in nature to PCM. Whereas, for the Case-2, the convective heat currents are not additive in nature to the PCM, as the fluid particles at higher temperature regions will try to occupy the low temperature regions.
Figure 8. Maximum temperature versus flow time: no fin (a) and (b) and fin (c) and (d) at an inlet mass flow rate of 8kg/min [Case-1: HTF flow against the direction of gravity; Case-2: HTF flow along the direction of gravity].

5. Conclusion

An effect on HTF (water) flow direction and the addition of annular triangular fin on the charging (melting) and discharging (solidification) of the phase-change material (PCM) is numerically studied using 2-D shell-and-tube axisymmetric model at the inlet mass flow rates of 4kg/min, 6kg/min and 8kg/min for both fin and no-fin case. The following conclusions are made:

1. With the increase in HTF mass flow rate solidification and melting time is found to reduce. For inlet mass flow rate of 8kg/min, the melting process is faster by 1.2% and 2.35% respectively for HTF mass flow rate direction in upward and downward direction. Similarly, the solidification process is faster by 3.01% and 2.06% respectively for HTF mass flow rate direction in upward and downward direction.

2. Addition of fins found effective, thereby, reducing the melting (charging) and solidification (discharging) time by 16.97% and 17.62% respectively for HTF flow against the direction of gravity with an inlet mass flow rate is 8kg/min. Similarly, the melting and solidification time was reduced by 17.27% and 17.47% respectively for HTF flow along the direction of gravity for the same inlet mass flow rate.

3. The upward HTF flow direction, i.e. against the direction of gravity, for no-fin situation, the melting time is faster by 1.77% and solidification time by 1.3%. However, for fin situation, a melting time is faster by 1.4% and solidification time by 1.67% for the upward HTF flow direction i.e. against the direction of gravity. It seems that the HTF flow against the direction of gravity adds convection heat current to PCM as compared to the gravity assisting flow.
4. Among the parameters viz. mass flow rate of HTF, addition of the fin and direction of HTF flow, a major contribution to the betterment of overall heat transfer in the system comes from the addition of fins.

References

[1] Farid M M, Khudhair A M, Razack S A K, Al-Hallaj S, 2004 “A review on phase change energy storage: materials and applications”, Energy Convers. Manage. 45: 1597–1615.

[2] Yang X, Lu Z, Bai Q, Zhang Q, Jin L, Yan J, 2017 “Thermal performance of a shell-and-tube latent heat energy storage unit: role of annular fins”, Appl. Energy; 202:558–70.

[3] Nithyanandam K, Pitchumani R, 2013 “Computational studies on a latent thermal energy storage system with integral heat pipes for concentrating solar power”, Applied Energy (2013); 103: 400–15.

[4] Pal D, Joshi Y K, 1998 “Thermal management of an avionics module using solid-liquid phase-change materials”, J. Thermophysics Heat Transfer; 12:256–62.

[5] Zhao C Y, Lu W, Tian Y, 2010 “Heat transfer enhancement for thermal energy storage using metal foams embedded within phase change materials (PCMs)”, Solar Energy; 84: 1402–12.

[6] Mahdi J M, Nsofor E C, 2017 “Melting enhancement in triplex-tube latent heat energy storage system using nanoparticles-metal foam combination”, Applied Energy; 191:22–34.

[7] Mahdi J M, Nsofor E C, 2017 “Solidification enhancement in a triplex-tube latent heat energy storage system using nanoparticles-metal foam combination”, Energy; 126:501–12.

[8] Khodadadi J, Hosseinizadeh S, 2007 “Nanoparticle-enhanced phase change materials (NEPCM) with great potential for improved thermal energy storage”, Int. Commun. Heat Mass Transfer; 34: 534–43.

[9] Elgafy A, Lafdi K, 2005 “Effect of carbon nanofibre additives on thermal behavior of phase-change materials”, Carbon; 43: 3067–74.

[10] Zeng J, Liu Y, Cao Z, Zhang J, Zhang Z, Sun L, 2007 “Thermal conductivity enhancement of MWNTs on the PANI/tetradecanol form-stable PCM”, J. Therm. Analysis Calorimetry; 91: 443–6.

[11] Akgun M, Aydin O, Kaygusuz K, 2007 “Thermal energy storage behaviour of a paraffin during melting and solidification”, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 29:14: 1315-1326.

[12] Hosseinizadeh S F, Tan F L, Moosania S M, 2011 “Experimental and numerical studies on performance of PCM-based heat sink with different configurations of internal fins”, Applied Thermal Engineering 31: 3827e3838.

[13] Gopalanand K S, Eswaran V, 2016 “Numerical investigation of thermal performance of PCM based heat sink using structured porous media as thermal conductivity enhancers”, Int. J. of Thermal Sciences 104: 266e280.

[14] Sheikholeslami M, Kesh teli A N, Shaf ee A, 2020 “Melting and solidification within an energy storage unit with triangular fin and CuO nano particles”, J. of Energy Storage 32; 101716.

[15] Arici M, Tütüncü E, Kan M, Karabay, 2017 “Melting of nanoparticle-enhanced paraffin wax in a rectangular enclosure with partially active walls”, Int. J. of Heat and Mass Transfer 104: 7–17.

[16] Padmanabhan S, Thigagaran S, Kumar D R, Prabhakaran D, Raju M, 2020 “Investigation of temperature distribution of fin profiles using analytical and CFD analysis”, Materials Today: Proceedings.

[17] FLUENT 16.0 user’s guide.

[18] Voll er V R, Prakash C, 1987 “A fixed grid numerical modelling methodology for convection-diffusion mushy region phase-change problems”, Int. J. Heat Mass Transfer 30: 1709-1719.