Numerical and Experimental investigation of thermal energy storage in a conical finned tube in PCM storage unit

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ABSTRACT

In modern world, use of phase change materials (PCMs) in a thermal energy storage system is an efficient way to store the energy. There are many applications of thermal energy storage system in which PCMs is used, namely, heat pumps, solar systems, spacecraft thermal applications etc. The purpose of this paper is to identify effect of geometrical changes on the melting process of PCM. Computational fluid dynamics (CFD) is used to analyze phase change process. Thermal energy storage tank consists of a vertical tube in tube geometry where outer tube consists of phase change material and inner pipe carrying hot fluid. Paraffin is used as latent heat storage material. Further, the paper describes the effect of inlet temperature of heat transfer fluid on the phase change process. Two types of geometries are used, namely cylindrical and conical shaped. Result shows that charging time is 2.56% less for conical shaped storage system rather than the same for cylindrical shaped system. The results of CFD and experimental analysis considering the parameters like flow rate and inlet temperature of heat transfer fluid are compared. The results of the numerical analysis and the experimental readings shows a good agreement between them. It is observed that as the mass flow rate increases, the effectiveness of the PCM based heat exchanger decreases.

ISSN 1823- 5514, eISSN 2550-164X

Received for review: 2018-06-14
Accepted for publication: 2019-04-08
Published: 2019-12-31

Keywords: *Phase Change materials; Thermal energy storage; Paraffin; Melting and Solidification; Latent heat storage.*

Introduction

Inequality between energy required and energy supply affect different types of energy technologies. Typical examples of such problems are thermal power generation plant, solar systems, cooling and heating systems etc. This gap between available and needed energy can meet with the help of thermal energy storage systems. Sensible heat storage and latent heat storage are the common methods of thermal energy storage. Latent heat storage is most proficient than sensible heat storage because of its wide energy storage density and also latent heat is generated during the phase change at almost constant temperature.

Generally Phase change materials (PCMs) are used to store the thermal energy. The energy exchange takes place between PCM and working fluid, when it passes through melting and solidification processes. During melting process heat is transferred from hot fluid to PCM and in case of solidification process PCM rejects heat to the cold fluid. Energy storage systems not only deliver constant supply but also save the energy by improving the stability and performance of the system.

Farnarelli et al. [1] used Latent Heat Thermal Energy Storage (LHTES) system for concentrated solar power plant (CSP) which is analyzed numerically using CFD simulation. It was found that with convective model, time required to stored heat is reduced and it was about 30% less compared with pure conduction heat transfer model. Elisa Guela et al. [2] studied entropy generation analysis for the design improvement of finned tube thermal energy storage unit. It was observed that entropy generation was uniform with the increase in number of fins and reducing thickness of fin.

Abhay dinkar et al. [3] study shows experimental analysis of rectangular thermal energy storage unit, in which copper helical coil carrying hot fluid and phase change material is filled around it. They found that by increasing fluid flow rate through helical coil, time required for charging the system is reduced. Tay et al. [4] designed energy storage system with reference to effectiveness-NTU technique for the application in low energy buildings ventilation. The phase change storage unit was coupled to the cooling system during night and they determined the actual energy stored in the phase change material. They concluded that PCM based energy storage unit store 18 times more amount of energy as compared to sensible energy storage.

Meng and Zhang [5] investigated performance of tube in tank LTES unit using composite PCM. LTES unit using composite PCM and large temperature difference between the heat transfer fluid and PCM enhanced the heat transfer and required less time durations of the heat charging process and discharging process.

Sciacovelli et al. [6] performed CFD and experimental analysis of thermal storage unit filled with PCM. They used single tube in tube type LHTS device. Conduction is very important for lower part where melted PCM has not yet reached the outer shell. Larger Rayleigh number and Stefan number led to shorter melting time. El-Sawi et al. [7] studied the long-term performance of a centralized thermal energy storage system that is integrated with building mechanical ventilation. Paraffin RT20 was used as a PCM and fins were used to enhance its performance. Result indicated that when the unit length is increased from 50 cm to 65 cm then the cooling load reduces from 21% to 36% at a flow velocity of 1.5 m/s.

Atal et al. [8] studied the thermal performance of shell and tube type thermal energy storage unit. The shell side contains paraffin as phase change material saturated in aluminium foam. They investigated the effect of the porosity of aluminium foam on the thermal performance of the system by comparing two foams with different porosity (95 and 77 percent). Both experimental and CFD analysis of shell and tube thermal energy device was performed in this study. Result shows that the utilization of conducting matrix with phase transition material considerably reduced the time required for an in operation cycle, and metal foam with less porosity additionally reduce the cycle time because of higher conductivity.

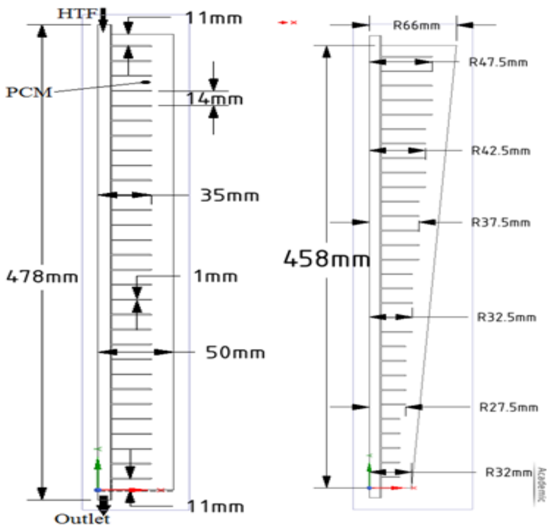
From the literature review it is clear that the drawback of PCM in thermal energy storage is that it has poor thermal conductivity. Due to its poor thermal conductivity, charging time (melting process) and discharging time (solidification process) is more and as result of this decrease the effectiveness of the thermal energy storage system. To overcome this problem number of heat transfer enhancement techniques are stated by different researchers. These techniques contains micro-encapsulation of the PCM, using finned tube system, using metal foam with PCM or using shell and tubes system.

Numerical Analysis

Modeling

In this study, the two cases of thermal energy storage units are analyzed numerically, namely finned tube in cylindrical tank (case I) and finned tube in conical shaped tank (case II) which are shown in figure 1.

Copper fin tube is used for performing the experiment. The number for fins used is 30 with thickness of 1 mm. The distance between two fins is 14 mm. These cases are designed for considering same amount of paraffin and same surface area of fins. All designed dimensions are shown in figure 1. Paraffin is filled in between the inner and the outer pipe and water is flowing through inner pipe. The required properties of paraffin are listed in Table 1. To reduce the computational time, the thermal energy storage units are modelled in a two dimensional domain.



(a) Cylindrical shaped (case I) (b) Conical shaped (case II)
Figure 1: Axisymmetric model of Thermal energy storage tanks.

Table 1: Properties of Paraffin Wax

Properties of Paraffin Wax	
Melting Temperature	58- 61 ˚C
Heat storage capacity	175±5 kJ/kg
Specific heat of paraffin	2.1 kJ/kg-K
Density (solid) at 35 ˚C	835 kg/m3
Density (liquid) at 80 ˚C	735 kg/m3
Thermal conductivity in both phases	0.2 W/m K

Governing Equations

The Equations for the unsteady analysis of the melting process of the PCMs involve Navier Stokes (NS) equation, continuity equation and energy equation. Boussinesq approximation is used for density change.

Continuity:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho V) = 0 \qquad (1)$$

Momentum:

$$\rho \frac{\partial V}{\partial t} + \rho(V.\nabla)V = -\nabla p + \mu \nabla^2 V + \rho g \beta (T - T_0) + S \tag{2}$$

Energy:

$$\frac{\partial}{\partial t}(\rho h) + \nabla.(\rho V h) = \nabla.(k \nabla T) \tag{3}$$

ANSYS FLUENT© is used for the analysis, wherein enthalpy-porosity method for modelling the solidification/melting process is employed. According to this method, expression for enthalpy h is given as:

$$h = h_{ref} + \int_{T_{ref}}^{T} C_p dT + \gamma L \tag{4}$$

Where, h_{ref} is the reference enthalpy at the reference temperature T_{ref}, L is the latent heat and liquid fraction γ is defined as

$$\begin{aligned} \gamma &= 0 && \text{if} \quad T < T_s \\ \gamma &= 1 && \text{if} \quad T > T_1 \\ \gamma &= \frac{\mathrm{T}-\mathrm{T_s}}{\mathrm{T_l}-\mathrm{T_s}} && \text{if} \quad T_s < T < T_1 \end{aligned} \tag{5}$$

Enthalpy porosity method treats distinct phases as porous media with the help of momentum source term S.

$$S = \frac{(1-\gamma)^2}{(\gamma^3 + \epsilon)} \times A_{mush} \times V \tag{6}$$

To prevent division by zero in the above momentum source term a small number ϵ ($\epsilon = 0.001$) is used. A_{mush} is the mushy zone constant.

Boundary conditions and problem setup

Initial temperature conditions for the HTF (heat transfer fluid) and PCM are constant at 27 ˚C. An initial velocity of PCM in all direction is zero. Hot water is flowing from top to bottom with a variable Stefan number (0.35, 0.30 and 0.25) and constant velocity throughout the simulation. Adiabatic wall condition is applied to external surfaces.

Solidification and melting model is used to analyze phase change process. Second order upwind scheme is used for approximating convective flux in the energy equation. SIMPLE algorithm is used for coupling between pressure and velocity. PRESTO is used for pressure correction. The time step is set as 0.1 sec. The number of iterations per time step is set as 20.

Grid Independency test

Three grid sizes, including 41249, 92323, and 146544 cells of quad element, were examined to check the independency of the grid size for the numerical solution. Table 2 shows result for the fine and very fine mesh which confirms the negligible variation in average temperature of PCM. The grid size of 146544 cells shows better results as compared to other two grid sizes. As this grid size shows better results this grid size has been considered for further analysis.

Table 2: Grid Independency Test

Mesh Size	Average temperature of PCM (in K) at 2500 sec	% variation in average temperature
Coarse (41,249)	345.395	-
Fine (92,323)	344.09	0.33
Very Fine (1,46,554)	344.239	0.043

Experimental Setup and Procedure

The experimental setup consists of two water tanks, water heater energy storage unit, circulating water pump and flow control valves. These components are connected via propylene tubes of half inch diameter as shown in figure 3. HTF (heat transfer fluid) as a hot water is used which flows from the tank 1 to storage unit to give energy to PCM. Then water is circulated with the help of water pump from tank 2.

The storage unit is a finned tube heat exchanger; the shell is a vertical conical shaped cylinder of minimum diameter 64 mm and maximum diameter 132 mm as shown in figure 2. Both fins and inner tube is made up of copper material. The finned tube is placed coaxially inside the shell. The entire region between shell and finned tube is filled with paraffin wax as a latent heat storage material. The electric heater (band heater) of 2 kW is provided in the tank 1 for heating water. The water temperature in the tank 1 is controlled and adjusted by using a thermal control system. A series of charging experiments are carried out under different working conditions. Experimental procedure is as follow

1. Turn on the electric supply for electric heater and adjust the thermostat to get desired water temperature in tank.
2. Temperature of the water in the tank 1 can be controlled by controlling electric heater with the help of dimmerstat.
3. When the temperature of water in container reaches the desired level, turn on valve V1.
4. Adjust the valve V1 to get proper volume flow rate through the energy storage unit.
5. Record the initial temperature of all location and then record all temperature readings for every 10 min interval in a period of 2 hours.

6. Plot the graph of effectiveness, Temperature difference and outlet temperature verses time.

Figure 2: Conical shaped finned tube.

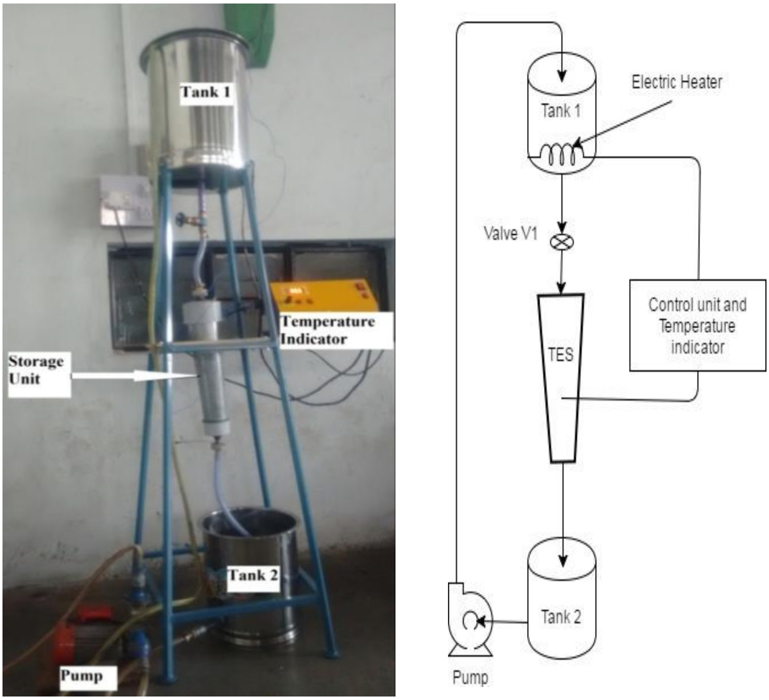
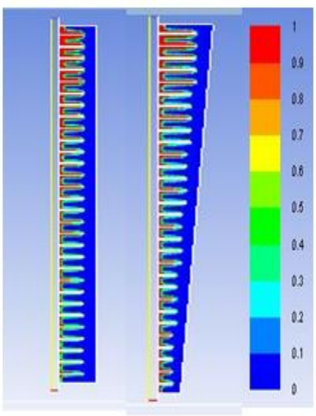


Figure 3: Experimental setup.

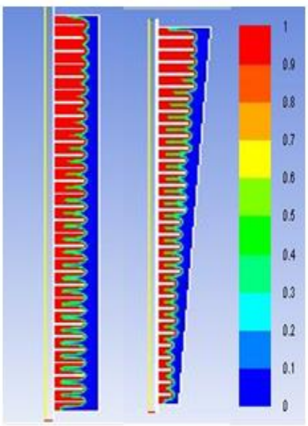
Results and Discussions

In this analysis, thermal performances of latent heat storage system with two different shapes of storage tank are compared. These cases are compared by varying the Stefan number (Ste). Stefan number is given by eqn. (7).

$$\text{Ste} = \frac{\text{Cp}(\text{T}_{\text{in}} - \text{T}_{\text{m}})}{\text{L}} \tag{7}$$



(a)



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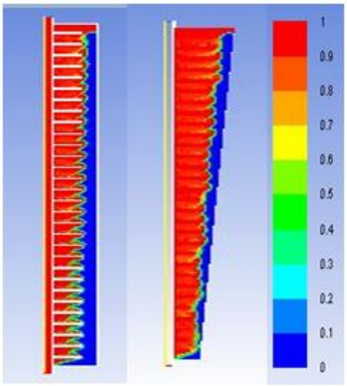
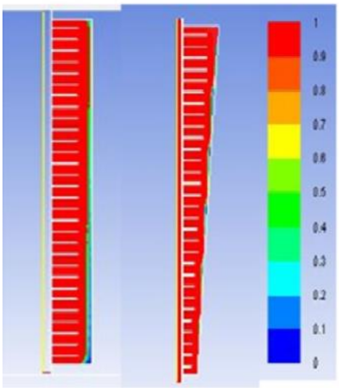


(c)



(d)

Figure 4: (a) Contour of liquid fraction for Stefan number 0.35 (a) at time 1000sec (b) at time 2000sec (c) at time 3500sec (d) at time 6000sec.

Where C_p is specific heat (J/kg-K), T_{in} is water inlet temperature (K), T_m is melting temperature of paraffin (K) and L is specific latent heat (J/kg).

Liquid fraction

Figure 4 shows the contours of a liquid fraction with respect to time for the case 1st and 2nd. At the starting stage, heat is carried out by only conduction in the solid state and heat flows in outward direction according to the temperature distribution. Initially liquidification takes place around the fins and pipe wall because of heat transfer is setup between PCM and HTF. Amount of liquid PCM slowly increases with time until the storage tank is completely filled with the liquid PCM. The liquid fraction is increasing faster in up to 2000 sec to 2300 sec, after that it requires more time as seen in figure 4 (a) and (b). This is due to paraffin around fins melt fast and the same which is away from fins needs more time because of the temperature gradient.

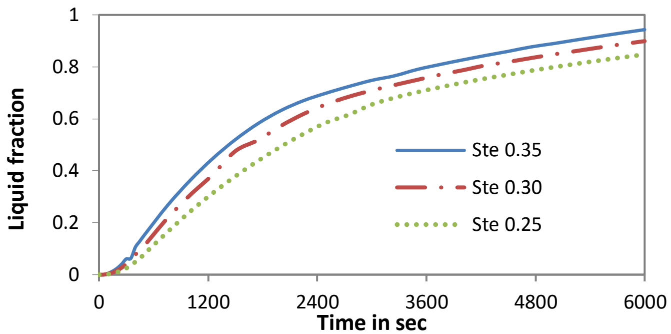


Figure 5(a): Effect of Stefan number on melting process for case I.

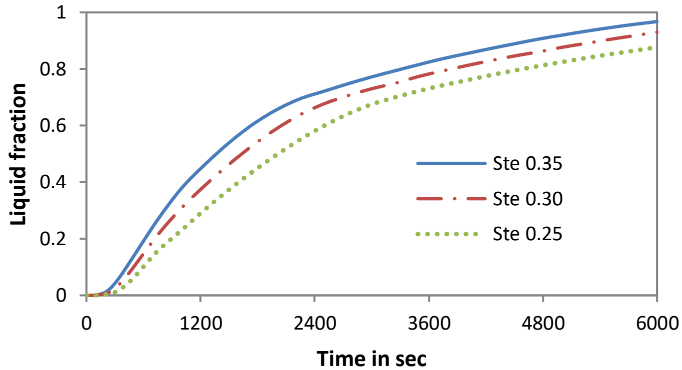


Figure 5(b): Effect of Stefan number on melting process for case II.

Effect of Stefan number on the melting behaviour of paraffin has been investigated for both the cases as shown in figure 5 (a) and (b). When the Stefan number increases from 0.25 to 0.35, results in reduction in the time required to melt paraffin which ensure better performance of the system. This is due to the increased temperature difference between the water and the paraffin. During the charging process (melting process), it is seen that temperature in the upper part of thermal energy storage tank is higher than that of the bottom side. Therefore, paraffin melts faster in upper part rather than bottom side as shown in figure 4. This effect is due to change in paraffin density, the hot PCM (melted PCM) moves upward by a natural process which results in the increase in temperature in the upper side of a tank. Due to above reason, in conical shaped storage tank, melting occurs 2.56% faster due to more amount of paraffin in the top side as compared to the bottom side. Liquid fraction for both the cases are same up to 2000 seconds and then the time required for conical shaped storage tank is less as compared to cylindrical shape as shown in figure 6.

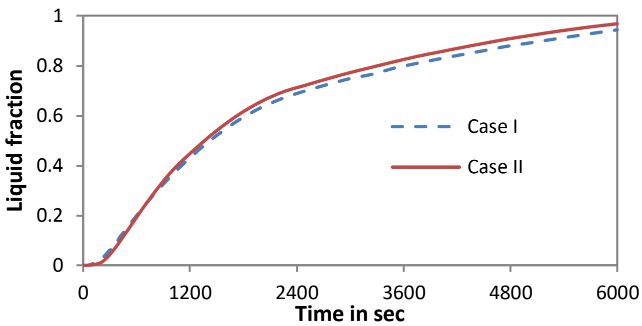


Figure 6: Comparison of liquid fraction (at Stefan number 0.35) between finned tube in cylindrical and conical shaped shell.

Effectiveness

The energy storage systems can be examined as a heat exchanger where heat is exchanged between PCM and the HTF. In this case, the effectiveness (ε) of this process is defined as the ratio between actual heat transfers to the maximum possible heat transfer [9].

$$\varepsilon = \frac{T_{in}-T_{out}}{T_{in}-T_m} \tag{8}$$

Where, T_{in} and T_{out} are the inlet and outlet temperatures of the HTF and T_m are the phase change temperature of the PCM. Figure 7 shows the effectiveness of the PCM storage system during melting process for different geometry. At the starting stage, the effectiveness is maximum and the effectiveness decreases slowly during the melting process. It is observed that, effectiveness is more for the conical shaped energy storage tank as compared to cylindrical shaped one for the same values of the mass of the PCM, the storage tank volume, the heat transfer surface area, the heat transfer coefficient of the HTF, mass flow rate and the inlet temperature of the HTF.

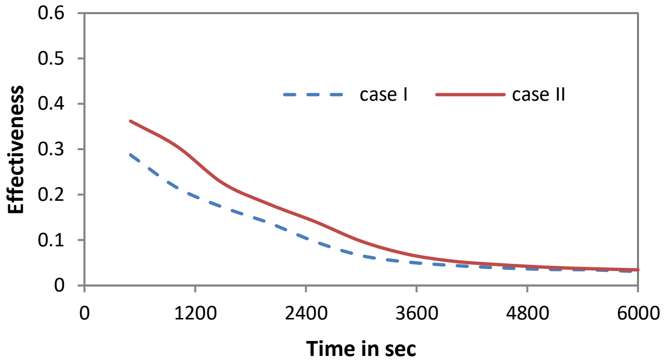


Figure 7: Effectiveness of the PCM during melting process for two cases.

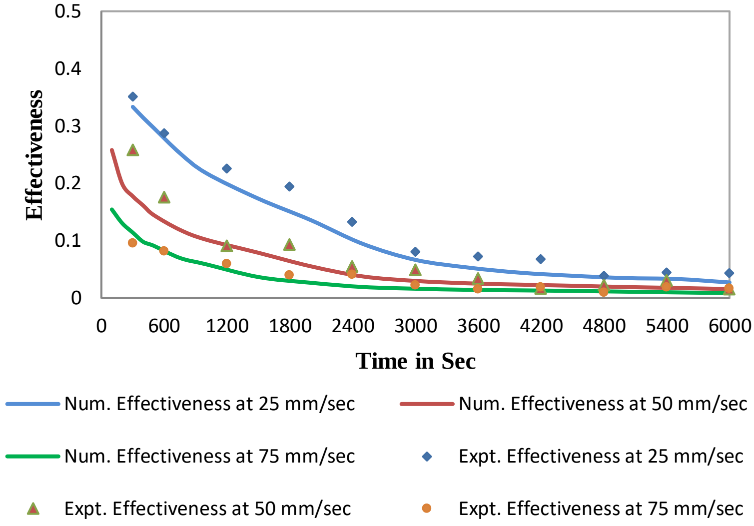


Figure 8: Effectiveness of conical shaped thermal energy unit for different inlet velocities of water.

Figure 8 shows the effectiveness of the energy storage system during melting process for different inlet velocities of water and at constant inlet temperature of water. As seen from the figure 8, it observed that the effectiveness of PCM storage heat exchanger increases with decreasing velocity of inlet fluid. Decreasing the velocity of water results in the enhancement of temperature difference between inlet and outlet which results in further increase in the effectiveness.

From the numerical results, in the starting stage, the effectiveness is maximum and attains 0.38, 0.25 and 0.15 for the flow rate of 25, 50 and 75 mm/sec respectively. During transition period of melting process, effectiveness remains constant and decreases slowly. After, the effectiveness decreases quickly and reaches (at 3000 sec) 0.064, 0.030 and 0.016 for the flow rate of 25, 50 and 75 mm/sec respectively. The numerical and experimental effectiveness evaluation during the melting (charging) process is performed at the inlet temperature of 90˚C and different flow velocities of water as shown in figure 8. It shows that, the experimental results quite agree with the numerical results under various operating conditions.

The variations in effectiveness between the numerical and experimental values are due to constant inlet temperature of water in a case of numerical analysis but it is not stable during the experiment. Another reason for the variations between the numerical and experimental values is that, there may be slight deviation in properties of paraffin used in numerical investigation from the actual values of paraffin.

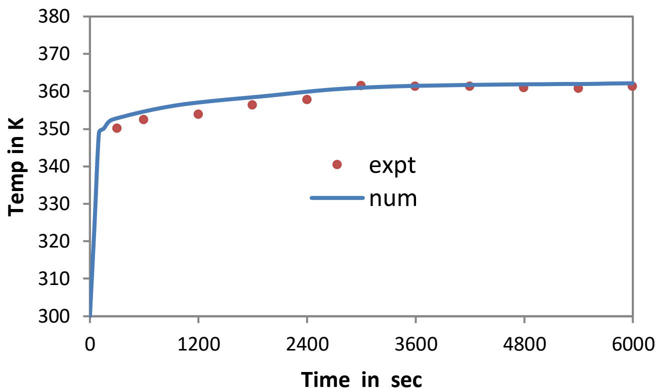


Figure 9: Comparison between numerical and experimental outlet temperature of water.

Outlet temperature

Figure 9 shows the comparison between numerical and experimental outlet temperature of water with respect to time. There is a better agreement between the numerical and experimental results for 90 ˚C inlet temperature of water. The outlet temperature (numerical) reaches 349 K (76 ˚C) in just 100 sec then increase slowly reaching at 360.17 K (87.17 ˚C) in 2500 sec, then the outlet temperature remains almost constant reaching 362.18 K (89.18 ˚C) at the end.

Temperature difference

The temperature difference between inlet and outlet temperatures of the water (HTF) are evaluated both numerically and experimentally for the conical shaped thermal energy tank and is shown in figure 10. There is a deviation observed between the experimental and numerical results which is due to unstable inlet temperature during the experiment. It is determined that the temperature difference value is decreasing more and more throughout the entire charging process, which shows that the heat transfer rate decreases in the thermal energy storage tank. At the starting stage, the temperature difference value is more due to the paraffin temperature is lower than that of the water. As the paraffin (PCM) enters the phase transition stage, the PCM temperature keeps almost constant. It's slow down the deviation trend of the temperature difference. In comparison of these two cases, the temperature difference curve is almost same except at initial stage and the variation of the temperature a difference is slightly more in the case of conical shell.

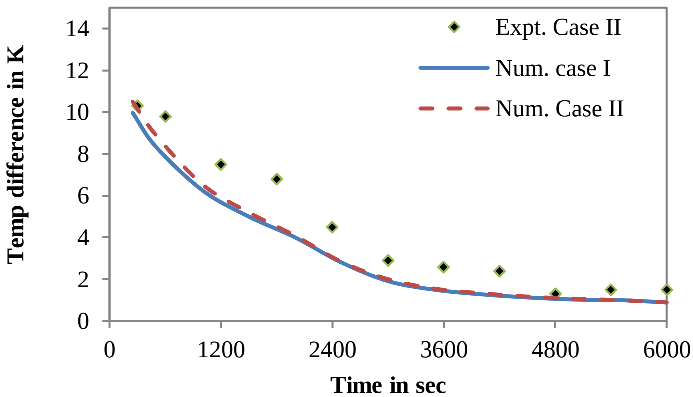


Figure 10: The temperature difference between inlet and outlet temperatures of the water.

Conclusions

In this paper, a CFD analysis of melting process in thermal energy storage system has been performed. The CFD analysis used enthalpy porosity method yielding quantitative data about the heat transfer rates and melt fraction.

1. Early stage of melting process is dominated by conduction mode of heat transfer, after that melting is affected by natural convection.
2. Paraffin at the topside of the unit attains the melting temperature in the less time than paraffin at the bottom side.
3. Inlet condition of hot water is strongly affected the melting rate, larger Stefan number, that is higher inlet temperature, can induce a reduction in melting time up to 11% with reference to original condition.
4. The Time required for melting process for cylindrical shaped storage tank is 2.56% more than time required for conical shaped storage tank.
5. Effectiveness is 27.32% (average) more for the conical shaped energy storage tank as compared to cylindrical shaped one.
6. The effectiveness of the thermal energy storage unit decreases with increasing flow rate. Increasing flow rate involves the deduction of water temperature difference between outlet and inlet.
7. From the above results, we can see better agreement between the experimental and numerical results.

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