International Journal of Chemical, Materials and Biomolecular Sciences
ISSN: 2415-6620
Vol:10, No:6, 2016

Enhancement of Thermal Performance of Latent Heat Solar Storage System

Rishindra M. Sarviya, Ashish Agrawal

***Abstract*—**Solar energy is available abundantly in the world, but it is not continuous and its intensity also varies with time. Due to above reason the acceptability and reliability of solar based thermal system is lower than conventional systems. A properly designed heat storage system increases the reliability of solar thermal systems by bridging the gap between the energy demand and availability. In the present work, two dimensional numerical simulation of the melting of heat storage material is presented in the horizontal annulus of double pipe latent heat storage system. Longitudinal fins were used as a thermal conductivity enhancement. Paraffin wax was used as a heat-storage or phase change material (PCM). Constant wall temperature is applied to heat transfer tube. Presented two-dimensional numerical analysis shows the movement of melting front in the finned cylindrical annulus for analyzing the thermal behavior of the system during melting.

***Keywords*—**Latent heat, numerical study, phase change material, solar energy.

NOMENCLATURE

A_{mush}	Mushy zone constant (kg/m^{3}s)
$A(\gamma)$	Porosity function (-)
k	Thermal conductivity (W/m-K)
ρ	Density of PCM (kg/m^3)
μ	Dynamic viscosity (N s/m^2)
P	Pressure (Pa)
S_i	Source term (N/m^3)
t	Time (s)
γ	Liquid fraction (-)
u_i, u_j	Velocity components in the i and j directions respectively (m/sec)
x_i, x_j	Cartesian coordinates

List of Abbreviation

CFD	Computational fluid dynamics
DSC	Differential scanning calorimetry
HTF	Heat transfer fluid
LHS	Latent heat storage
PCM	Phase change material

I. INTRODUCTION

IN the recent years, population growth around the world and particularly in third world countries and improvement of living standards leads to increase in energy demand. This global energy demand is increasing faster than the population growth rate. The reliability and effectiveness of renewable energy systems such as solar energy can be improved by integrating energy storage system. The renewable energy sources are intermittent in nature and their energy intensity also varies with time, in such conditions, the energy storage system can store the energy when it is available and discharge when required [1]. The energy storage can be used for improving the efficiency of any thermal system by utilizing the waste energy of the system. Different industrial processes use different grade of heat. Waste heat from one process can be stored and this stored energy serves as heat source for another process, which requires heat at lower grade.

There are various techniques for storing energy in the form of sensible and latent heat. Latent heat storage (LHS) is based on the absorption or release of latent heat at a constant temperature when a storage material undergoes a change of phase from solid to liquid, liquid to gas or vice versa. Materials used in LHS are PCMs. A large number of organic, inorganic and artistic materials are identified as PCMs. These materials are available in temperature range from 0^{o}C to 150^{o}C.

Many researchers have reported the thermal and heat transfer characteristics of LHS systems with different geometrical configurations during charging and discharging. Khodadadi et al. [2] numerically studied melting process of PCM in the spherical container. Their results showed that the rate of melting is faster at top region of a sphere than at the bottom region. They investigated the effect of convection on melting rate. Zalba et al. [3] presented a review on heat storage material and their heat transfer characteristics and their applications. Heim et al. [4] modelled the behaviour of PCMs using ESP-r's special materials facility. The effect of phase transition is added to the energy balance equation as a latent heat generation term according to the so-called effective heat capacity method. Ibanez et al. [5] developed and validated the model in TRNSYS to simulate the energy balance in the building to evaluate the influence of walls/ceiling/floor with PCM. The key parameter in the study is equivalent heat transfer coefficient. Hosseini et al. [6] reported combined experimental and numerical study aiming to understand the role of buoyancy-driven convection during constrained melting of PCMs inside a shell and tube heat exchanger. The computations are based on an iterative, finite-volume numerical procedure that incorporates a single-domain enthalpy formulation for simulation of the phase change phenomenon. It was observed from experimental results that the melting front appeared at different times at positions close to the HTF tube and progressing at different rates outwards towards the shell. The computational results show that by

Rishindra M. Sarviya is with the Maulana Azad National Institute of Technology, Bhopal, India (phone: +91-755-4052210; e-mail: sarviyarm@ manit.ac.in).
Ashish. Agrawal, is with the Technocrats Institute of Technology-Excellence, Bhopal, MP, India (e-mail: er_ashishagarwal@yahoo.com).

increasing the inlet water temperature to 80°C, the total melting time is decreased to 37%.

Abidi et al. [7] reported a review study on CFD applications for latent heat thermal energy storage. This review study presents the different modeling techniques for modeling the melting and solidification of PCM. Avci et al. [8] evaluated the performance of horizontal shell and tube LHS using paraffin wax as heat storage material, during melting and solidification of paraffin wax. The DSC analysis of paraffin wax was performed to determine its thermo-physical properties. The effect of inlet temperature of distilled water (Heat transfer fluid) has been determined and discussed.

Hosseini et al. [9] reported combined experimental and numerical study to analyze the thermal behavior and heat transfer characteristics of Paraffin RT50 as a PCM during constrained melting and solidification processes inside a shell and tube heat exchanger. A series of experiments were conducted to investigate the effects of increasing the inlet temperature of the heat transfer fluid (HTF) on the charging and discharging processes of the PCM. The computations are based on an iterative, finite-volume numerical procedure that incorporates a single-domain enthalpy formulation for simulation of the phase change phenomenon. The molten front at various times of process has been studied through a numerical simulation. The experimental results show that by increasing the inlet HTF temperature from TH = 70 °C to 75 and 80 °C, theoretical efficiency in charging and discharging processes rises from 81.1% to 88.4% and from 79.7% to 81.4% respectively.

Darzi et al. [10] reported numerical investigations on symmetric melting of PCM (N-eicosane) using the FLUENT software inside a double pipe container. The thermal performance of container was study for two arrangements of pipes: concentric and eccentric. Results of the study shows that the melting rate is similar for two arrangements of pipes during the beginning of melting but after some time the melting rate decreases in concentric pipes due to conductive dominated heat transfer between hot heat transfer tube and cold solid PCM. Başal et al. [11] designed a new type thermal energy storage system consisting of a triple concentric-tube arrangement, for the storage performance enhancement. The motivation for the present proposal is that an annulus shaped PCM layer, that is in contact with the HTF from both inner and outer surfaces provides a larger heat transfer area. For the present purpose, a numerical investigation was conducted by using enthalpy method. Based on the numerical calculations, the effects of system parameters such as mass flow rate and the inlet temperature of the HTF and the variation of the tube radii on the system performance were investigated parametrically. The results indicate that, a significant enhancement in the system performance can be achieved by replacing classical hollow cylinder type storage with the presently proposed triple concentric-tube storage system. Another outcome of the study was that the most important design parameters for a triple concentric-tube storage system are the radial location and the thickness of the PCM filled annulus.

Dhaidan et al. [12] reported experimental and numerical investigation of melting of nano-enhanced phase change materials (NePCM) inside an annular cavity formed between two circular cylinders. The effect of applied heat flux and nanoparticle concentration on the melting rate has been determined and discussed. The considerable improvement in melting rate has been observed with the emulsion of more nanoparticles in PCM. Khillarkar et al. [13] presented a finite element computational study of the free convection-dominated melting of a pure PCM contained in concentric horizontal annuli of the following configurations: (a) square external tube with a circular tube inside — annulus type A and (b) circular external tube with a square tube inside — annulus type B. In this study the effects of the Rayleigh number as well as heating of the inside, outside or both walls at a temperature above the melting point of the material were studied. In this study flow and temperature patterns within the melt, local heat flux distributions at the heating surface and the cumulative energy charged as a function of time was presented and discussed.

Based upon the literature review it is found that, the very less works have been carried on melting of paraffin wax in the finned cylindrical annulus considering the effects of natural convection. The primary objective of the present study is to investigate the effects of natural convection on the heat transfer during melting of PCM in the finned cylindrical annulus of a heat exchanger. In the present research work, the transient thermal behavior of the heat storage system is analyzed and presented at different instants of time in terms of melt fraction contours.

II. Computational Domain and Boundary Conditions

The computational domain selected for the present study is shown in Fig. 1. The two dimensional computational model is selected to reduce the computational time. The finned cylindrical annulus consists of inner and outer tube of radius 22 mm and 120 mm, respectively. The paraffin wax which is used as PCM, is filled in the annulus and four longitudinal fins were attached to inner tube to increase the heat transfer from inner tube to paraffin wax. The temperature of heat transfer tube is assumed to be constant at 363 K and the PCM is initially at the temperature of 303 K. The outer pipe is considered adiabatic, so heat loss from the pipe is assumed to be zero. The quadrilateral mesh elements were used to discretized the computational domain. The resulting system of non-linear partial differential equation is solved. A commercial grade paraffin wax manufactured by the Indian oil Company was selected as PCM for the present study. DSC (differential scanning calorimetry) analysis of paraffin wax sample was conducted for determining its latent heat, specific heat and melting range. DSC analysis was performed on a Thermal Analyzer Pyris DSC 6000, TA Instruments in heating and cooling cycle. The calculated thermo-physical properties of PCM are listed in Table I.

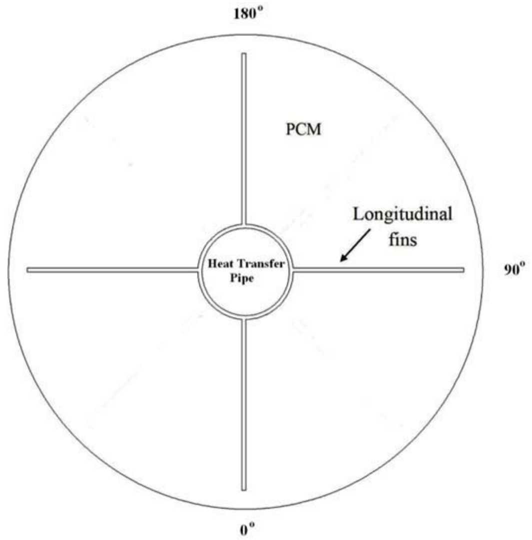

Fig. 1 Computational domain of cylindrical annulus with longitudinal fins

TABLE I
THERMO-PHYSICAL PROPERTIES OF PARAFFIN WAX

Property	Value
Melting temperature range (K)	314 - 328
Latent heat capacity (kJ/kg)	176
Specific heat (kJ/kg-K)	2.8
Density (kg/m^3)	835
Thermal Conductivity (W/m-K)	0.21

III. NUMERICAL PROCEDURE

The governing equations for the phase change simulation was solved by selecting the SIMPLE algorithm [14]. Momentum and energy equations were solved by selecting QUICK differencing scheme [15], whereas the PRESTO scheme [15] was adopted for the pressure correction equation. Liquid mass fraction at each cell is updated by solving the governing equations at each time step using Enthalpy-porosity equation. As geometry of computational domain is not complicated, square-element grid structure has been selected for the present study.

The grid independency test has been carried to obtain accurate results. The simulations were performed for different grid densities i.e. 50k, 80k and 100k. The results were compared with each other and 80k grid distribution was selected for the study. The time step in the calculations was as small as 0.05 s and the number of iterations for each time step was 25. The grid size and the time step were chosen after careful examination of the independency of the results. The convergence was checked at each time step, with the convergence criterion of 10^{-7} for all variables. The numerical approach makes it possible to calculate the processes that occur inside the solid PCM (conduction), liquid PCM (convection) and to account for the phase-change, moving boundary due to the variation of the PCM volume, and solid phase motion in the melt.

IV. MATHEMATICAL FORMULATION

Enthalpy-porosity method [16], [17] is used to simulate the melting of PCM in the finned cylindrical annulus. The flow of molten PCM is considered incompressible, laminar and two-dimensional. The viscous dissipation term is considered negligible, so that the viscous incompressible flow and the temperature distribution in annulus space are described by the Navier-Stokes and thermal energy equations, respectively. In the present study Ansys Fluent 12.0 software code is used to simulate the melting of paraffin wax in proposed system.

The governing equations used in this study are given by-

Continuity:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

Momentum:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_i}(\rho u_i u_j) = \mu \frac{\partial^2 u_i}{\partial x_i x_j} - \frac{\partial P}{\partial x_i} + \rho g_i + S_i \tag{2}$$

Energy:

$$\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x_i}(\rho u_i h) = \frac{\partial}{\partial x_i}\left(K \frac{\partial T}{\partial x_i}\right) \tag{3}$$

where h is the specific enthalpy of PCM, ρ is the density, T is the temperature, k is the thermal conductivity, S_i is the source term, u_i and u_j are the velocity component in the i and j direction, x_i and x_j are the Cartesian coordinates.

The source term in the momentum equation is given by

$$S_i = -A(\gamma)u_i = \frac{A_{mush}\,(1-\gamma^2)}{\gamma^3+\varepsilon} u_i$$

In the above equation ε is small number to avoid division by zero and its value equal to 0.001 has been taken for this study. A_{mush} is the mushy zone constant, this constant reflects the morphology of the melting front. The value of A_{mush} is ranging between 10^4 to 10^8 kg/m^{3}s. Value of $A_{mush} = 10^6$ kg/m^{3}s was taken in this study which had been suggested by [18]. $A(\gamma)$ is defined as the "porosity function" which governs the source term in the momentum equation.

V. VALIDATION OF NUMERICAL RESULTS

In order to validate the modeling of phase change process of heat storage material in the presented work the average temperature profile in the PCM is compared with the experimental results. The experiments were conducted in the double pipe heat exchanger of same configuration as used in the numerical simulation. The comparison of numerical and experimental results is shown in Fig. 1. The temperature of inner wall is maintained at 363 K.

Good agreement between numerical and experimental results is observed.

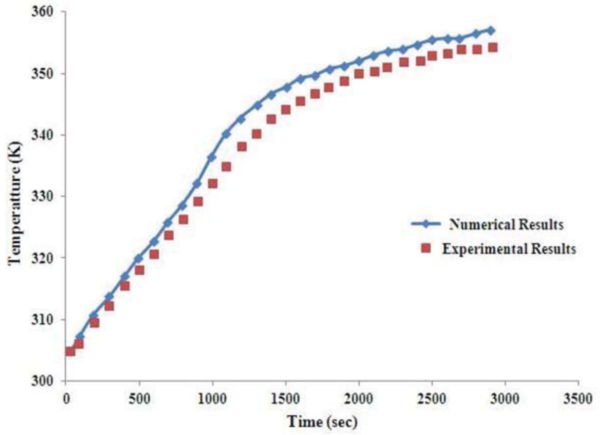

Fig. 2 The average temperature profiles obtained by experimental and numerical study for melting of PCM in finned cylindrical annulus

VI. Results and Discussion

In the present CFD analysis the numerical simulation results have been presented for the buoyancy driven melting of a paraffin wax, encapsulated between two concentric horizontal cylindrical annuli. The developed numerical model and the associated CFD model are able to track the transient progression of the melting process for any PCM. The model is particularly able to handle the irregular movements of mushy zone due to natural convection and the interaction between the solid and liquid phases under different flow conditions. The mushy region is the region between the liquidus and solidus isotherms, where solid and liquid coexist in thermal equilibrium [19]. The instantaneous contours of the melt fraction in the annulus of heat storage system have been obtained by computational analysis at different instant of time during melting of the PCM in cylindrical annulus.

A. Melt Fraction Contours at Different Instants of Time

The melt fraction contours show the position of the melt front at different instant of time during melting. Fig. 3 shows melt fraction contours for inner wall temperature of 90°C for a plain cylindrical annulus.

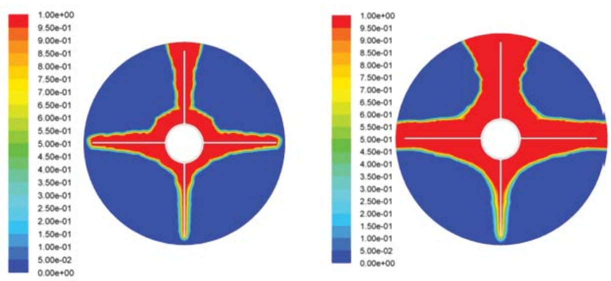

Fig. 3 (a) Melt Contour at 200 sec Fig. 3 (b) Melt Contour at 400 sec

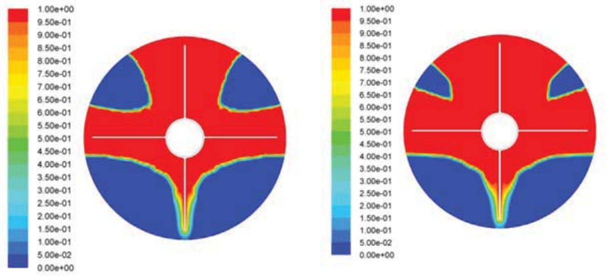

Fig. 3 (c) Melt Contour at 600 sec Fig. 3 (d) Melt Contour at 800 sec

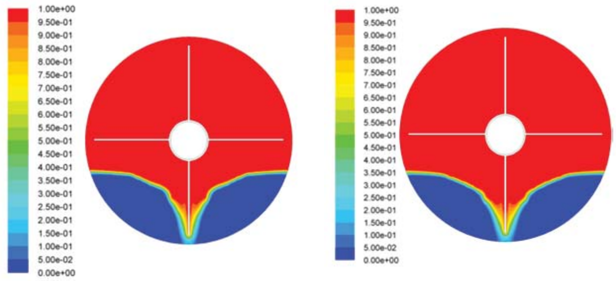

Fig. 3 (e) Melt Contour at 1000 sec Fig. 3 (f) Melt Contour at 1200 sec

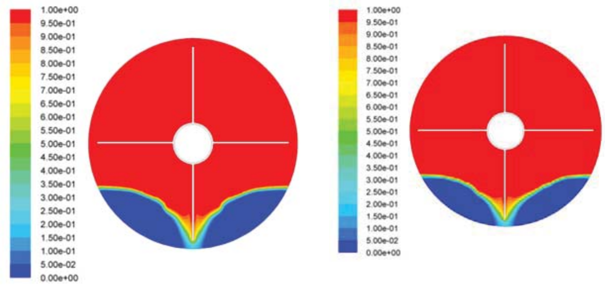

Fig. 3 (g) Melt Contour at 1400 sec Fig. 3 (h) Melt Contour at 1600 sec

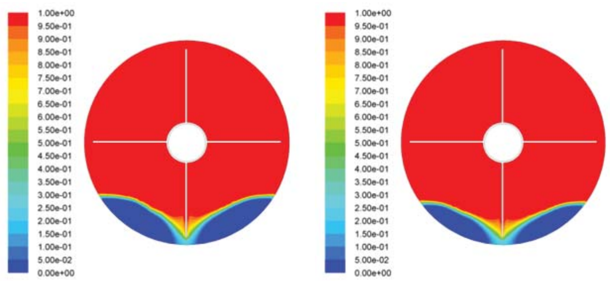

Fig. 3 (i) Melt Contour at 1800 sec Fig. 3 (j) Melt Contour at 2000 sec

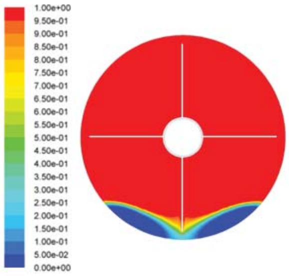

Fig. 3 (k) Melt Contour at 2200 sec

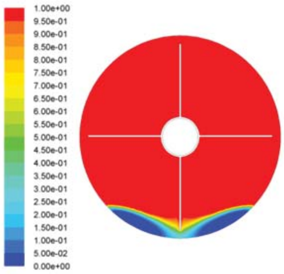

Fig. 3(l) Melt Contour at 2400 sec

Fig. 3 shows the melt fraction contours in the PCM for a finned cylindrical annulus for different instants of time. Due to low thermal conductivity of PCM the heat transfer rate in PCM is very low. Four fins are attached to the outer surface of the inner cylinder at equal angular spacing to increase the heat transfer area. The aim of considering this study is to analyze the effect of fins on the melting rate and natural convective flow of molten PCM. Initially the PCM melts near the surface of the inner cylinder and fins, due to conduction mode of heat transfer. As the time advances, the more melting is observed near the fins and the wall of inner pipe and convection mode of heat transfer comes into the effect. At time instant of 200 sec the more melting is observed around the inner pipe and at the end of fin located at 180^0. It is due to the high rate of heat transfer due to mixed conduction-convection heat transfer. Buoyant forces developed along the surface of fin located at 180^0 and as a result less dense molten PCM move from the bottom to top end of the fins and trapped at the top end of the fin, thus more melting is observed at this location. As the time advances melting area becomes wider at the end of fin compared to other area near to fin, as shown in Fig. 3 (b), at time instant of 400 sec. Melting is uniform along the fin located at 90^0. More melting is observed at the top region compared to the bottom. It is evident from the Fig. 3 (c) that the melting rate is higher in the upper region compared to lower region at 600 sec. The melting front takes the shape of parabola due to the blockage effect produced between the fins at 90^0 and 180^0 at the top region of the annulus. Intense buoyant forces at the top portion lead to higher melting rate. At this time instant two recirculation regions are found in the upper region. One smaller recirculation region located at the end of the fin and the larger recirculation region is located near the pipe wall. The distorted melting front is observed at time 800 sec in the upper region and the smaller solid region is left in the upper region. By comparison of melt contours at time 600 sec and 800 sec, it is found that the melting front moves at a very slow rate in the lower region of the annulus and shape of melting front is remain parabolic. The stagnant time for the present study is 900 sec, after stagnant time the heat transfer to PCM becomes slower and heat transfer is purely governed by conduction. It is evident from the melt contours (1000 to 2400 sec) that the velocity of melting front is progressively reduces with time and melting front remains stagnant at the bottom region of the annulus.

Due to the addition of fins on the outer wall of inner pipe, the heat transfer rate is enhanced. During the initial period of melting high heat transfer is observed due to the large difference of temperature between PCM and inner pipe. The melting is dominated by conduction at early stages and occurs along the wall and fins surface and melting front is symmetrical in all directions. As more melting takes place with time, buoyancy-driven convective flow of melt is observed and the melt moves from bottom to top end of vertical fins in both upper and lower portions of the annulus. Due to the blockage effect of the fins the melting front takes the shape of a parabola in the upper and lower portion of the annulus. The melting rate at the lower section is significantly lower than any other part of the annulus.

VII. Conclusions

Based on the findings of the present numerical study of the melting of PCM inside the horizontal finned cylindrical annulus, the following conclusions have been drawn:

1. During initial stage of melting, conductive mode is dominated over convective mode of heat transfer so that the symmetrical melt front is observed in the upper and lower part of annulus. As the time advances and more melting takes place near to inner pipe wall and fins surface, the heat transfer is then dominated by convective flow of melt.
2. Due to the blockage effect of the fins the melting front takes the shape of a parabola in the upper and lower portion of the annulus.
3. Natural convective flow of melt is suppressed by longitudinal fins, still due to mixed conductive-convective mode of heat transfer the melting take place at faster rate in the upper and lower part of annulus.
4. The large temperature difference exists between upper and lower portion of annulus. The overheating of PCM is observed at the upper portion of the annulus due to convective flow of melt. More melting is observed at the upper portion of annulus due to high heat transfer rate compared to bottom portion.

References

[1] Reddy Sudhakar and Jyoti P. Painuly. "Diffusion of renewable energy technologies—barriers and stakeholders' perspectives." Renewable Energy 29(9) (2004): 1431-1447.
[2] Khodadadi J.M. and Y. Zhang, "Effects of buoyancy-driven convection on melting within spherical containers", Heat and Mass transfer. 44 (2001) :1605-1618.
[3] Zalba B.N., "Review on thermal energy storage with phase change: materials, heat transfer analysis and applications". Applied Thermal Engineering, 23(3) (2003): 251-283.
[4] Heim D., and Clarke, J. A. "Numerical modelling and thermal simulation of PCM–gypsum composites with ESP-r". Energy and buildings, 36(8) (2004) : 795-805.
[5] Ibáñez Manuel, Ana Lázaro, Belén Zalba, Luisa F. Cabeza. "An approach to the simulation of PCMs in building applications using TRNSYS." Applied Thermal Engineering 25(11) (2005): 1796-1807.
[6] Hosseini, M. J., A. A. Ranjbar, K. Sedighi, and M. Rahimi. "A combined experimental and computational study on the melting behavior of a medium temperature phase change storage material inside shell and tube heat exchanger." International Communications in Heat and Mass Transfer 39(9) (2012): 1416-1424.
[7] Al-abidi, Abduljalil A., Sohif Bin Mat, K. Sopian, M. Y. Sulaiman, and Abdulrahman Th Mohammed. "CFD applications for latent heat thermal

energy storage: a review." Renewable and sustainable energy reviews 20 (2013): 353-363.
[8] Avci Mete, and M. Yusuf Yazici. "Experimental study of thermal energy storage characteristics of a paraffin in a horizontal tube-in-shell storage unit". Energy conversion and management, 73 (2013): 271-277.
[9] Hosseini M. J., M. Rahimi, and R. Bahrampoury. "Experimental and computational evolution of a shell and tube heat exchanger as a PCM thermal storage system." International Communications in Heat and Mass Transfer, 50 (2014): 128-136
[10] Darzi, AhmadAli Rabienataj, Mousa Farhadi, and Kurosh Sedighi. "Numerical study of melting inside concentric and eccentric horizontal annulus." Applied Mathematical Modelling, 36(9) (2012): 4080-4086.
[11] Baal Birol, and Ahmet Ünal. "Numerical evaluation of a triple concentric-tube latent heat thermal energy storage." Solar Energy, 92 (2013): 196-205.
[12] Dhaidan, Nabeel S., J. M. Khodadadi, Tahseen A. Al-Hattab, and Saad M. Al-Mashat. "Experimental and numerical investigation of melting of NePCM inside an annular container under a constant heat flux including the effect of eccentricity." International Journal of Heat and Mass Transfer 67 (2013): 455-468.
[13] Khillarkar, D. B., Z. X. Gong, and A. S. Mujumdar. "Melting of a phase change material in concentric horizontal annuli of arbitrary cross-section." Applied Thermal Engineering 20(10) (2000): 893-912.
[14] Patankar S.V., Numerical methods in heat transfer and fluid flow, Hemisphere Publishing Corporation, Washington, DC, 1980.
[15] Ferziger J. H. and M. Peric, Computational Methods for Fluid Dynamics, Springer, 2002.
[16] Brent A. D., V. R. Voller, and K. J. Reid, "Enthalpy-porosity technique for modeling convection-diffusion phase change: application to the melting of a pure metal," Numerical Heat Transfer, 13(3) (1988):297–318.
[17] Z.X. Gong, S. Devahastin, and A. S. Mujumdar, "Enhanced heat transfer in free convection-dominated melting in a rectangular cavity with an isothermal vertical wall," Applied Thermal Engineering, 19(12) (1999):1237–1251.
[18] Shmueli, H., Ziskind, G., Letan, R., Melting in a vertical cylindrical tube: numerical investigation and comparison with experiments, International Journal of Heat and Mass Transfer, 53 (2010): 4082-4091.
[19] Adine, Hamid Ait, and Hamid El Qarnia. "Numerical analysis of the thermal behaviour of a shell-and-tube heat storage unit using phase change materials."Applied mathematical modeling, 33(4) (2009): 2132-2144.