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IC Value: 13.98

Volume 3 Issue III, March 2015
ISSN: 2321-9653

International Journal for Research in Applied Science & Engineering Technology (IJRASET)

Numerical investigation of the effects of natural convection on the melting process of phase change material in cylindrical annulus

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Abstract - A numerical simulation of the melting process of a phase change material in a horizontal cylindrical annulus has been studied in this paper. Numerical study has been carried out for melting of paraffin wax as phase change material, considering the natural convective flow of melt using finite volume code Fluent. Constant wall temperature is applied to heat transfer fluid pipe. Presented two-dimensional Numerical analysis shows the movement of melting front in the cylindrical annulus for analyzing the thermal behaviour of the system

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***
t	***Time (s)***
γ	***Liquid fraction***
ui ,u_j	***Velocity component in the i and j direction ,***
x_i ,x_j	***Cartesian coordinate.***

Keywords : Phase change materials, Cylindrical annulus, Melting, Natural Convection Effects

I. INTRODUCTION

In the recent years, most of the developing countries around the world, facing the problem of energy because of, large gap between demand and supply of energy. The mismatch between demand and supply can be minimize by increasing the reliability of Non convectional energy sources. Solar energy is one of the widely and acceptable form of renewable energy source. Solar based thermal systems have a high potential of diffusion in the domestic and industrial sector. The main hurdles in its popularity are non-reliability due the intermittent nature of sunshine, higher initial cost and space availability [1]. Integration of energy storage is, therefore, essential for a Solar based thermal systems. The energy storage system can minimize the gap between energy supply and energy demand. There are various techniques for storing solar 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 the phase change materials (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 latent heat storage 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] proposed simple methodology for the energetic simulation of buildings, including elements with PCMs using the program TRNSYS is presented and validated. This procedure does not aim a simulation of the real transfer processes inside the materials with PCM, but to evaluate the influence of walls/ceiling/floor with PCM in the whole energy balance of a building. The key parameter in the simulations is the equivalent heat transfer coefficient which has to be determined for each material. Hosseini et al. [6] reported combined experimental and numerical study aiming to understand the role of buoyancy-driven convection during constrained melting of phase change materials (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 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 presents previous studies on the numerical modeling of phase change materials (PCMs) through a commercial computational fluid dynamic (CFD) software and self-developed programming to study the heat transfer phenomena in PCMs. Avci et al. [8] reported experimental study on the melting and solidification of paraffin wax filled in shell-and-tube type horizontal heat exchanger. Paraffin was used as the phase change material (PCM) while the distilled water was used as the HTF. At first, the thermo-physical properties of the paraffin used are determined through the differential scanning calorimeter (DSC) analysis. Experiments are conducted to investigate not only the storage behavior (melting or charging) but also the removal one (solidification or discharging) of the PCM. The effect of the inlet temperature on the melting (for the charging) and solidification (for the discharging) time was 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 phase change material (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 melting of phase change material using N-eicosane inside a cylindrical container. Numerical simulations were performed for symmetric melting of phase change material between two cylinders in concentric and eccentric arrays using the FLUENT software which is sub-cooled initially to 1 °C. Inner cylindrical tube is considered hot wall while outer tube is insulated. Predicted result shows that melting rate is the same approximately for concentric and eccentric array before time of 15 min. After this time, melting rate decreases in concentric array. It is due to the pure conduction between hot tube and cold solid phase change material. 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 heat transfer fluid 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 heat transfer fluid 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 inner cylindrical tube is subjected to a constant heat flux, while the outer shell is thermally insulated. The phase change material (PCM) used is n-octadecane that is dispersed with CuO nanoparticles as thermal conductivity enhancer (TCE). The computational model is validated and the results showed a good agreement with previous related work. The effects of the nanoparticle concentration and the amount of applied heat flux (Rayleigh number) on the melting process are examined. The experimental and numerical results reveal that there is an improvement in melting characteristics with the emulsion of more nanoparticles in PCM (intensifying the effective thermal conductivity) and raising the wall heat flux and the corresponding Rayleigh number (augmenting the role of natural convection). This enhancement in the melting process can be indicated by increasing the melting rate which leads to acceleration of the melting time. Finally, the impact of eccentricity by lowering the center of the inside heated tube is also evaluated. The predicted results show that the eccentric mode has higher melt fraction in comparison with the concentric arrangement. Khillarkar et al. [13] presented a finite element computational study of the free convection-dominated melting of a pure phase change material 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 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 phase change material in the 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 contours.

II. COMPUTATIONAL DOMAIN AND BOUNDARY CONDITIONS

The computational domain under examination is shown in Fig. 1. The heat storage unit is considered as a 2D Model. Such a model is selected to reduce the computational time. The geometry used for this study is composed of an inner copper pipe having a radius 22 mm. The radius of outer pipe is of 120 mm. The PCM is filled between the outer and inner pipe. A constant wall temperature is applied at the wall of the inner pipe. The PCM is initially at the temperature of 303 K. The outer wall is considered adiabatic and temperature of the inner pipe wall is at 363K. The computational domain is discretized using quadrilateral mesh elements. The resulting system of non-linear partial differential equation is solved. A paraffin wax produced by the Indian oil Company was considered as PCM for the present study. DSC analysis of Paraffin wax sample was conducted for determining its specific heat, latent 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 1.

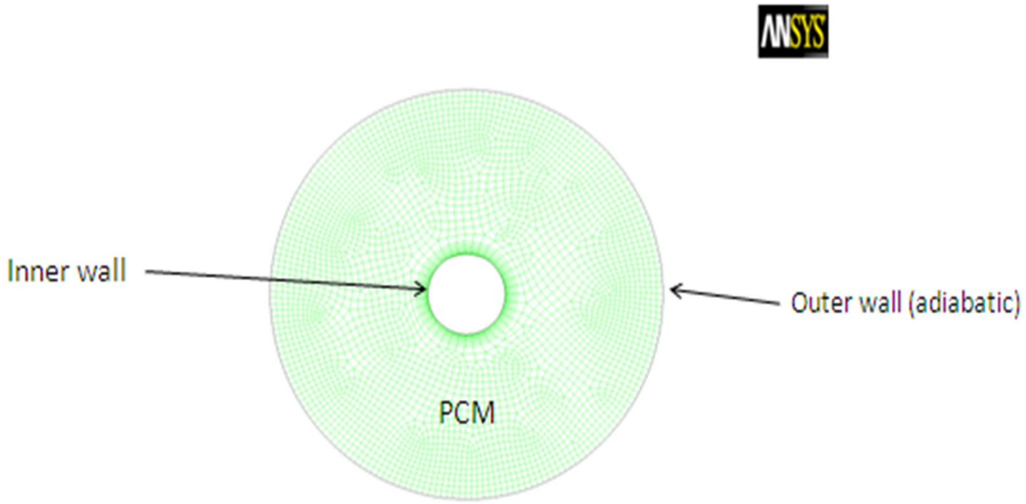

Fig. 1. Computational domain of plain cylindrical annulus

Table 1.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 SIMPLE algorithm [14] was utilized for solving the governing equations. The QUICK differencing scheme [15] was used for solving the momentum and energy equations, whereas the PRESTO scheme [15] was adopted for the pressure correction equation. By solving the governing equations at each time step, liquid mass fraction has been updated using Enthalpy-porosity equation. Different grid elements, such as square and triangular shapes were tried for this study. As geometry is not very complicated, square-element grid structure has been selected for present study. The results were obtained from different grid densities such as 50k, 80k and 100k. These results compared with each other and 80k grid distribution is chosen for this 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

In order to simulate phase change of PCM in cylindrical annulus, enthalpy-porosity method [16, 17] is used. The flow in the molten PCM is considered laminar, incompressible, 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. Ansys Fluent 12.0 has used to simulate the melting of Paraffin wax in proposed systems. 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 following equation

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

In the above equation 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 Shmueli et al. [18]. ε is small number to avoid division by zero and its value equal to 0.001 has been taken for this study. $A(\gamma)$ 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 computational modeling of melting in our finite volume CFD code, we compare the average temperature profile in the PCM between experimental and computational work. For validation of CFD results experimental study is also conducted by maintaining the temperature of the inner pipe wall at a constant level by resistance heating element. The outer and inner radius of pipe of shell and tube heat storage used for experimental study is same as used for the present numerical analysis. The temperature of the inner wall is maintained at 90^{o}C . Comparisons of experimental and numerical result during melting of PCM in plain cylindrical annulus are presented in Fig. 1. Good agreement between numerical and experimental results is observed.

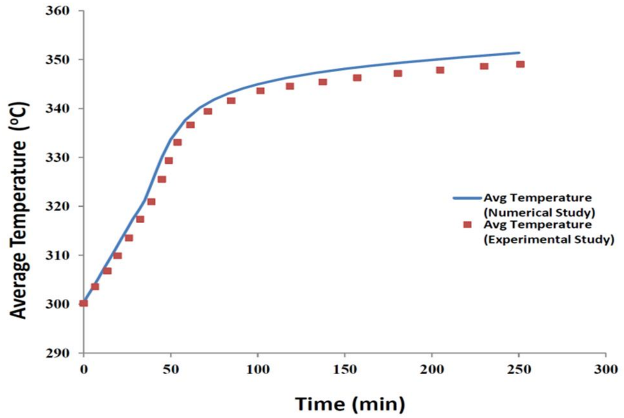

Fig. 2 Comparison of average temperature profile obtained by numerical and experimental study for complete melting of the PCM in cylindrical annulus.

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 annulus. 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. The Fig. 3 shows melt fraction contours for inner wall temperature of 90 ^{o}C for a plain cylindrical annulus.

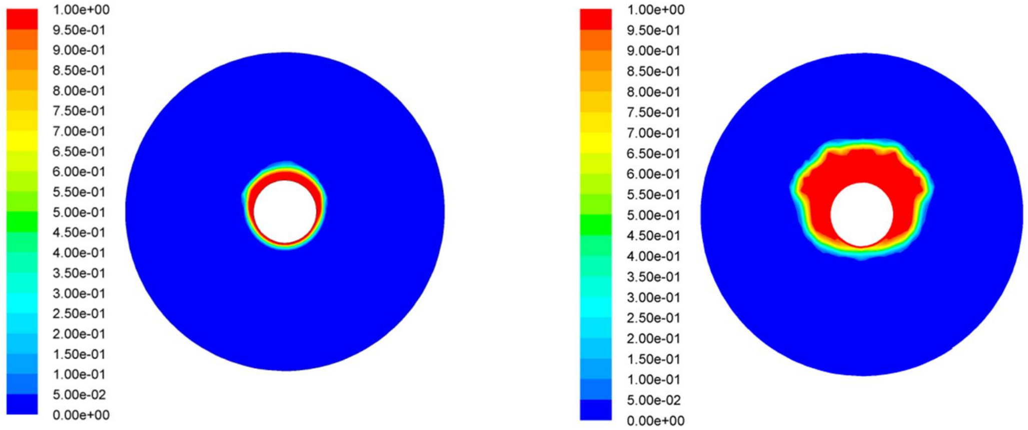

Fig. (a) Melt Contour at 100 sec

Fig. (b) Melt Contour at 500 sec

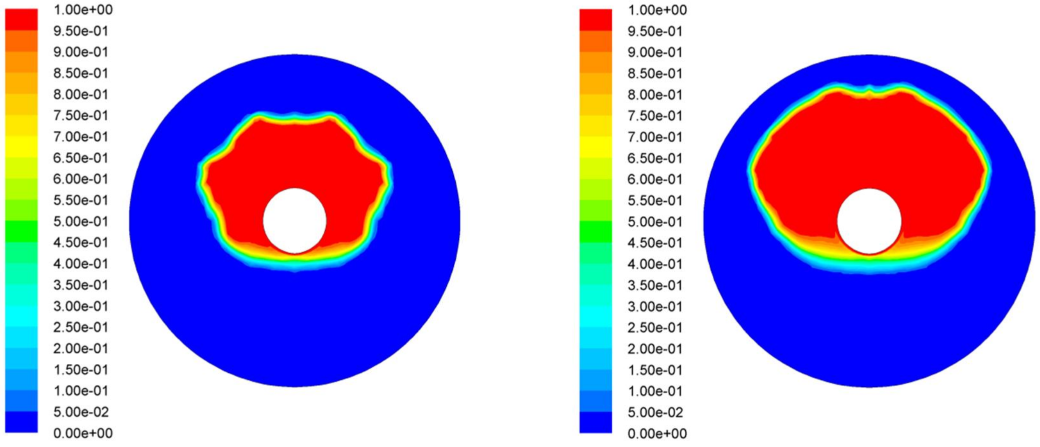

Fig. (c) Melt Contour at 1000 sec

Fig. (d) Melt Contour at 1500 sec

Fig. 3 The melt fraction contours in PCM at different instants of time

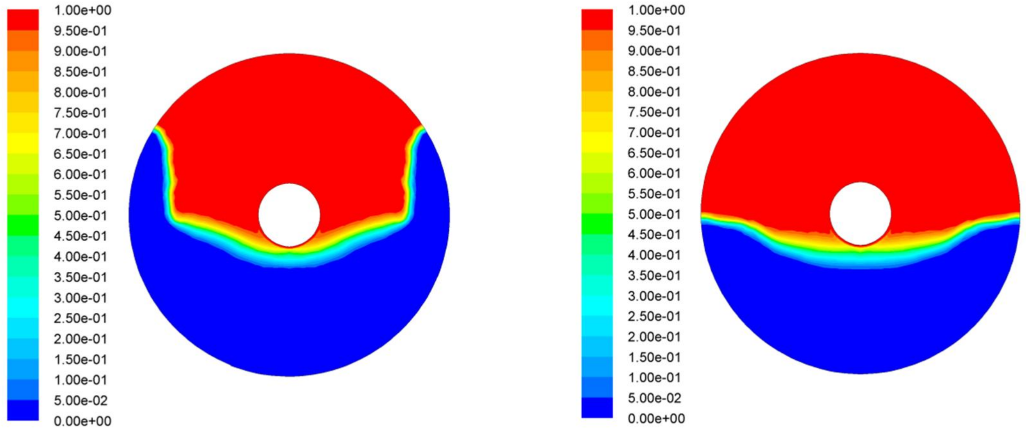

Fig. (e) Melt Contour at 2000 sec

Fig. (f) Melt Contour at 2500 sec

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IC Value: 13.98 *ISSN: 2321-9653*
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

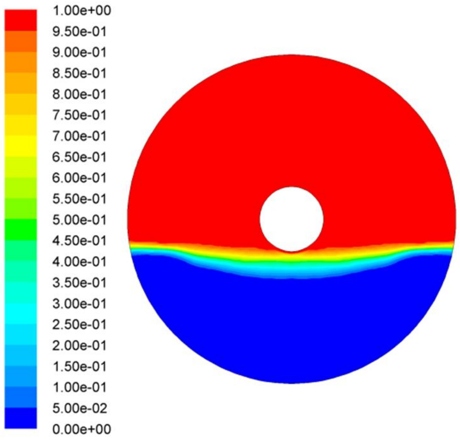

Fig. (g) Melt Contour at 3000 sec

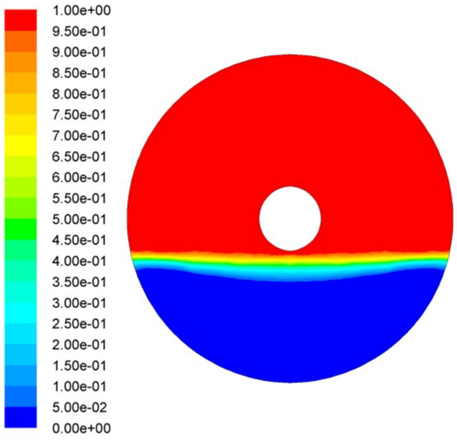

Fig. (h) Melt Contour at 3500 sec

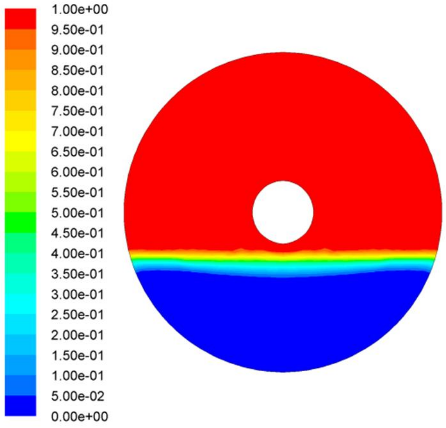

Fig. (i) Melt Contour at 4000 sec

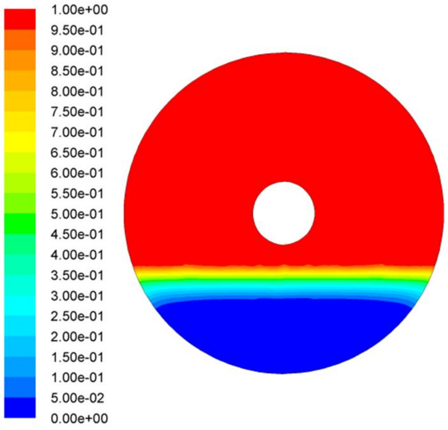

Fig. (j) Melt Contour at 6500 sec

Fig. 3 continued…

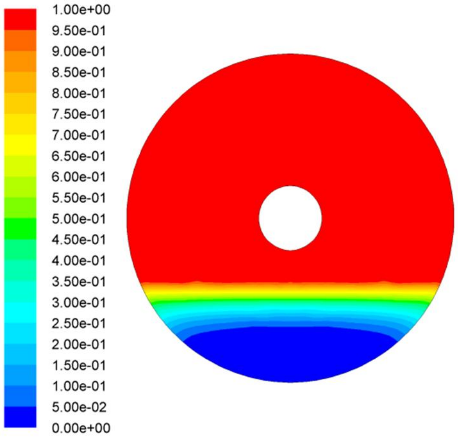

Fig. (k) Melt Contour at 9000 sec

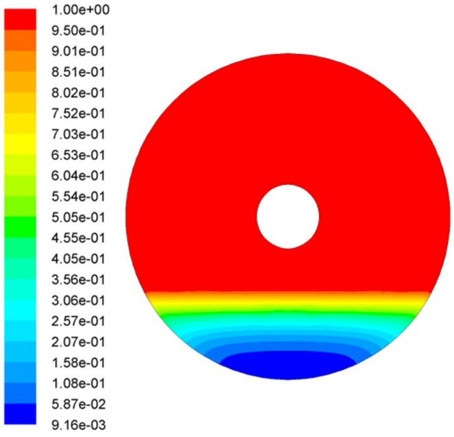

Fig. (l) Melt Contour at 12000 sec

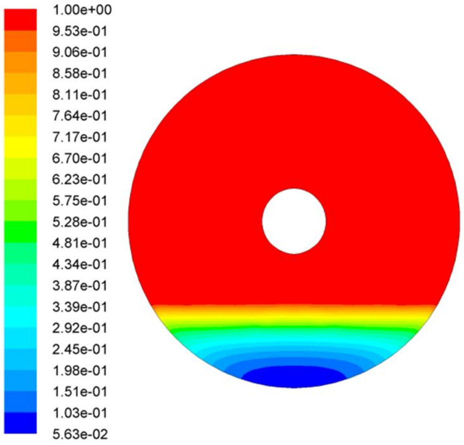

Fig. (k) Melt Contour at 14000 sec

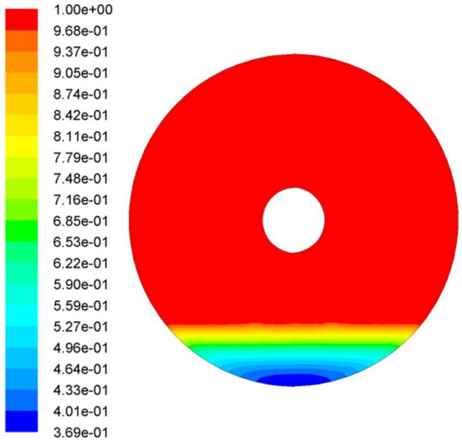

Fig. (l) Melt Contour at 20000 sec

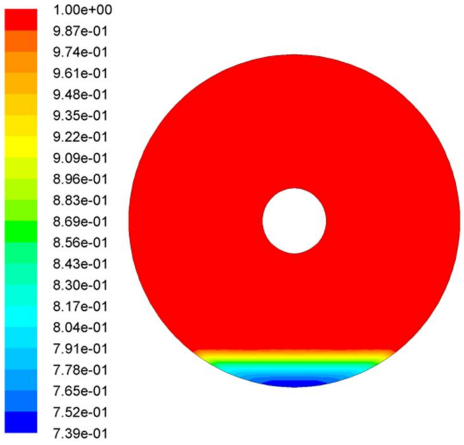

Fig. (k) Melt Contour at 25000 sec

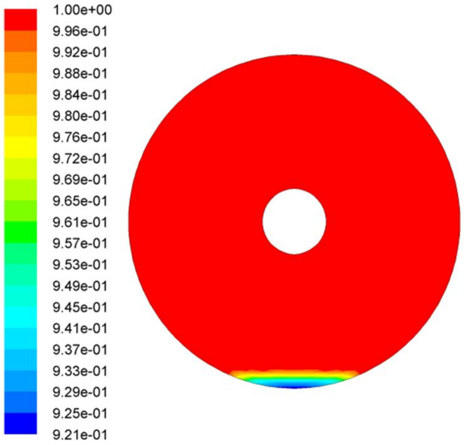

Fig. (l) Melt Contour at 27000 sec

Fig. 3 continued…

The temperature of inner wall for this case is 90^0C, which is 36 ^{0}C higher than the melting temperature of the PCM. The melt contour is concentric to inner cylinder wall at the beginning due to conduction mode of heat transfer. At the initial period of melting the solid starts to melt initially due to conduction and melting front is symmetrical in all directions. On further melting natural convection comes into play and shape of melting front become irregular, this thing clearly visible in figure at the time instant of 500 sec. Melt contour at time 1000 sec shows that the melting front become wider in the uppermost section compared with a lower section. As melting time progresses, the natural convection is intensifying and the wider melting region is formed at the upper region of the annulus and the molten PCM occupies the major part. Melting in uppermost section is completed at time instant of 2500 sec, after this time period the melting rate becomes very slow. It can be seen that as time advances from 2500 sec to 27000 sec, the melting front remains stagnant at the lower section. The melting front moves in downward direction at a very slow rate. The melting rate at the lower section is significantly lower than any other part of the annulus. A similar trend was observed by other researchers in the literature during melting of PCM within horizontal shell and tube heat storage.

VII. CONCLUSIONS

Based on the findings of the present computational study of the melting inside the horizontal cylindrical annulus, the following conclusions are drawn:

A. High heat transfer is occurred at the upper portion of annulus due to buoyancy driven convective flow of melt.

B. Large difference is observed between upper and lower portion of annulus, overheating of liquid PCM is observed at the upper portion while the lower portion still in the solid phase.

C. Some heat transfer enhancement technique such as highly porous metal matrix of high thermal conductivity should be adopted for improving the heat transfer in the lower section.

D. Conduction is dominated during initial stage of melting and as more melting takes place near to inner pipe wall, convection mode of heat transfer dominate over conduction mode.

E. Melting of PCM in upper portion of annulus is largely influenced by convection while the melting of PCM in the lower portion is dominated by conduction.

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