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# Investigate the Natural Convection Heat Transfer in A PCM Thermal Storage System Using ANSYS/FLUENT

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**Abstract**

The present paper presents four dimensional models for simulation of a Latent Heat Thermal Energy Storage System (LHTESS). The LHTESS is in the form of a rectangular container with a central horizontal pipe surrounded by a Phase Change Material (PCM). Paraffin wax with melting temperature of 60 oC is used as a PCM whilst water is used as a Heat Transfer Fluid (HTF). Thermo physical properties of paraffin wax are assumed to be constant in the modelling process, whereas the density variation is handled by using Boussinesq model. ANSYS/FLUENT software was used in simulating four dimensional models of temperature distribution, melting fraction, and flow fields during the melting process. Simulations performed provide information on the instantaneous temperature distribution, solidification/melting dynamics and the velocities field in the storage unit during the melting process. The effects of the natural convection on the charging (melting) process were also investigated.



**Keywords:** *PCM; thermal storage system; paraffin; solar energy, natural convection, CFD, ANSYS/FLUENT.*

## 1. Introduction

Recently, solid-liquid phase change of PCM, for various geometric arrangements with natural convection in the liquid phase, has been investigated theoretically and experimentally. The thermal energy is stored in the PCM as latent heat and it is reutilized when it is needed. Therefore, understanding the natural convection inside the liquid PCM plays important rules in the design of thermal storage system. PCM is stored by different ways in LHTESS, for example, using cylinder enclosed with or without fins, cans, plates or sphere enclosure [1]. In the following study, the storage unit consists of a rectangular container with a horizontal pipe and PCM filled around the pipe. During the period of storage, a working fluid flows inside the horizontal pipe and the heat is transferred through the pipe walls to the PCM. Later, PCM reaches its fusion temperature and melting is started and then, natural convection motion appears. Consequently, the bouncy driven become strong enough to drive the melting process.

Many authors have tackled the natural convection during melting of PCM. Tan [2], experimentally investigated the buoyancy and natural convection phenomena during the melting process of PCM inside a spherical capsule. Indeed, validate these results with a numerical solution obtained with the CFD FLUENT. The most interesting finding was that the conduction heat transfer dominates during the early stage, whereas the buoyancy driven convection becomes more sufficient as the liquid fraction volume is increased. However, the molten PCM ascends upward to the upper regions of the sphere because of natural convection phenomena. Consequently, the upper region of the sphere melts first and then the other regions. Another interesting finding from the computational results was that some chaotic fluctuation of the temperature distribution in some points inside the sphere and this is due to the unstable fluid layer in these points. However, the findings of the this study support the previous researches by the author [1, 3].

Nsofor [4] also experimentally investigated the heat transfer and natural convection phenomena in packed bed thermal storage system for high temperature. However, positive correlations were found in terms of Nusselt number, Prandtl number as well as Reynolds number and comparisons were made with existing correlations developed with similar storage media. Wu and Lacroix [5] analysed numerically the natural convection of melting PCM in a vertical cylindrical capsule heated from below. The model was solved using finite-difference method and compared the numerical prediction results with the numerical and experimental results of other authors [6-8]. It was reported that the heat transfer rate at the top surface was dominated by conduction, while it was decreased to zero when melting progressed and natural convection was fully developed. It was also observed that the highest heat transfer was at the bottom surface of the capsule. Rieger and Beer [9] examined the effect of natural convection flow on heat transfer during melting process of ice inside an isothermal horizontal cylinder. They predicted numerically the overall and local heat transfer coefficients, temperature fields, interface positions and flow pattern and

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compared their numerical prediction results with the experimental results. It was reported that the heat transfer was enhanced at the lower part of the ice body when the wall temperature less than 8℃ because of the density effect, while the ice body move downward when the wall temperature exceed 8℃. The same procedures have been applied by Rieger et al. [10] to investigate the heat transfer during melting n-octadecane as a PCM inside horizontal tube. Saitoh and Hirose [11] numerically investigated the natural convection inside a horizontal circulator cylinder capsule packed with PCM during melting and solidification process in the case of high Rayleigh numbers. The model obtained the transient solid-liquid interface, solid-liquid temperature, streamlines, isotherms, and heat stored. The numerical results was validated through comparison with results of Pannu [12]. In general, there was quite different from theirs both quantitatively and qualitatively. It is interesting to note that the natural conviction controlled the melting heat transfer inside the capsule as well as the thermal instability happened at the bottom portion of the capsule.

Trp [13, 14] studied the transient heat transfer in the shell-and-tube thermal storage system in an experimental and numerical study. He developed a mathematical model based on non-isothermal phase transition and it has been implemented with a FORTRAN computer code. The numerical results were validated through a comparison with experiment data. He concluded that heat transferred from HTF to the PCM was slow; this is because of the large Prandtl numbers of the HTF. Therefore, a large amount of heat was carried out downstream with the HTF, whiles a small amount of heat was transferred to the PCM upstream. The same author [15] numerically investigated the effect of several geometric parameters and different HTF operation conditions on the heat transfer during both melting and solidification processes. They measured the transient temperature distribution of the HTF, PCM and tube wall.

The objective of this study is to investigate numerically the natural convection dominated melting of PCM filled around horizontal pipe within a rectangular container. Four different models are investigated (Fig. 1). First, the centre of the horizontal pipe is located at the centre of the rectangular container (Fig. 1.A). Second, the centre of the horizontal pipe is located by 5mm down from the centre of the rectangular container (Fig.1.B). Third, the centre of the horizontal pipe is located by 10mm down from the centre of the rectangular container (Fig.1.C). Last, the centre of the horizontal pipe is located by 15mm down from the centre of the rectangular container (Fig.1.D). The CFD findings are presented and discussed in the present study.

## 2. Simulation Model

Fig. 1 shows the cross section of the four different rectangular thermal storage configurations with horizontal pipe. The test unit has dimensions 75mm (width) × 50mm (height) × 500mm (depth). The rectangular container is filled with Paraffin wax which has a melting point of 60℃, latent heat storage capacity of 200 kJ/kg, density of 800 kg/m3, specific heat of 2050J/kg K, dynamic viscosity of 0.035 kg/m-s, and thermal conductivity of 0.25 W/m K. The horizontal pipe was 10mm of inner diameter with a thickness of 1mm. The HTF is circulated inside the pipe with inlet temperature of 353 K in order to charge the PCM storage unit. The mass flow rate of water is 0.0037 Kg/s. The computational grid of the system was built using ICEM CFD 13.0 software by ANSYS. Meshing of the model was generated by using hexahedral elements and boundary layers were created around the pipe. Upon several trials it was found that the hexahedral computational grid with 636768 elements would be sufficient for accurate 3D modelling of the heat transfer in the PCM system.

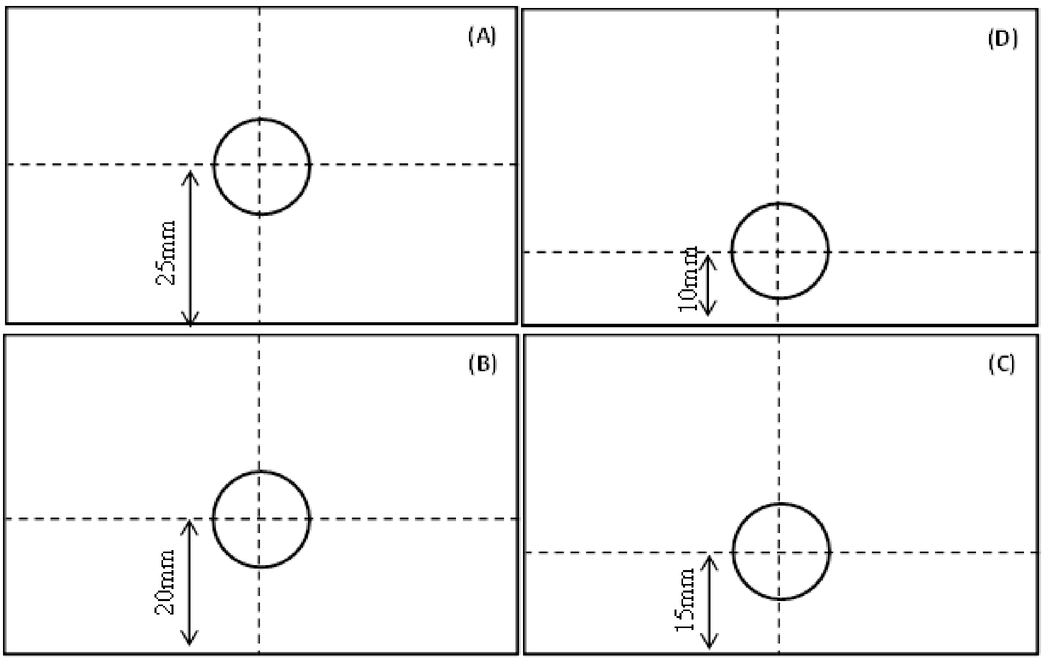


**Figure 1:** Schematic view of the four different models, (A) case 1, (B) case2, (C) case3, and (D) case4

The flow inside the pipe was described using transient simulations with *k-epsilon* turbulence model deployed. The solidification/melting model was used in order to examine the phase change phenomena in paraffin wax. The time step used in calculations was set to 0.1 second. To obtain numerical results the first-order upwind spatial discretization and the pressure solver with PRESTO algorithm for pressure-velocity coupling were used. Convergence criteria were defined by setting the absolute residual value at 10-6 for energy and at 10-3 for all other variables. The mathematical formulations for solving PCM related problems have been categorized [16] as fixed grid, variable grid, front-fixing, adaptive grid generation, and enthalpy methods. Two methods are used to analyse the heat transfer in solid-liquid PCMs. These are the temperature-based and enthalpy-based methods. In the former, temperature is considered to be a single dependent variable. The energy equations for both solid and liquid are formulated separately; and thus the solid-liquid interface positions can be tracked easily to achieve an accurate solution for the problem [17]:

$$\frac{\partial T_s}{\partial n} k_s = \frac{\partial T_l}{\partial n} k_l + \rho L v_n \quad (1)$$

where $T_s$ denotes the temperature in the solid phase; $T_l$ is the temperature in the liquid phase. $k_s$ , and $k_l$ are the thermal conductivity of the solid phase and liquid phase, respectively; *n* is the unit normal vector to the interface; *L* is the latent heat of the freezing; and $v_n$ is the normal component of the velocity of the interface.

However, an enthalpy-porosity method is used for modelling the solidification/melting process [18]. This technique is described in detail by Voller and Prakash [19].

The energy conservation equation for this case is written as:

$$\frac{\partial}{\partial t}(\rho H) + \nabla.(\rho \vec{v} H) = \nabla .(k \nabla T) + S \quad (2)$$

where *H*, is the enthalpy, *ρ* is the density, $\vec{v}$ is fluid velocity and *S* is the source term.

The enthalpy of the material is calculated as the sum of the sensible heat, *h*, and latent heat, *ΔH*:

$$H = h + \Delta H \quad (3)$$

The sensible heat is calculated as:

$$h = h_{ref} + \int_{T_{ref}}^{T} c_p dT \quad (4)$$

where, $h_{ref}$ is the reference enthalpy, $T_{ref}$ is the reference temperature and $c_p$ is the specific heat at constant temperature.

The latent heat is also calculated as:

$$\Delta H = \beta_l L \quad (5)$$

The liquid fraction, $\beta_l$ , can be calculated as:

$$\beta_l = 0, when T < T_{solid}$$
$$\beta_l = 1, when T > T_{solid} \quad (6)$$
$$\beta_l = \frac{T - T_{solid}}{T_{liquid} - T_{solid}} \; if \; T_{solid} < T < T_{liquid}$$

The solid and liquid temperatures are also calculated as:

$$T_{solid} = T_{melt} + \sum_{solutes} K_i m_i Y_i \quad (7)$$

$$T_{liquid} = T_{melt} + \sum_{solutes} m_i Y_i \quad (8)$$

where, $K_i$ is the partition coefficient of solute *i*, which is the ratio of the concentration solid to that in the liquid at the interface; $Y_i$ is the mass fraction of solute *i*, and $m_i$ is the slope of the liquid surface with respect to $Y_i$ [18].

The source term in the momentum equation can be written as [18]:

$$S = \frac{(1-\beta)}{(\beta_l^3 + \epsilon)} A_{mush} (\vec{v} - \vec{v}_p) \quad (9)$$

## 3. Result and Discussion

Numerical simulation is carried out for cyclic melting process of Paraffin wax filled in rectangular thermal storage unit involving horizontal pipe and the results are presented and evaluated in this section. Numerical simulations investigate the natural convection dominated melting of PCM for different model geometries (Fig.1). At the start of the melting cycle, the inlet temperature of HTF inside the pipe is maintained at fixed temperature of 353 K and the initial temperate of PCM is 300 K. Further, mass flow rate of HTF is maintained at 0.0037 Kg/s. Figs. 2-3 distinctly show temperature distribution and melting/solidification fields along the four different geometries after 10000sec.

The results show that the temperature starts to rise gradually in the region of the storage container close to the pipe wall and then ascends upward to the upper region at the centre of the container. In this stage, sensible heat was transferred from the pipe wall to the PCM solid by pure conduction, and then a thin liquid layer was created between the pipe and the solid PCM. The solid-liquid interface expanded gradually over the axial and radial directions with respect to time. Thereafter, the melting fronts were dominated by natural convection heat transfer in the melted regions of PCM. Consequently, the convection heat transfer drives circulation in the melted PCM due to the buoyancy force. The molten PCM ascends upward from the bottom to the upper regions at the center of the container and returns downward to complete the natural convection circle, since the molten PCM has the lower density and viscosity. The convection circle became more sufficient as the liquid fraction volume is increased.

 

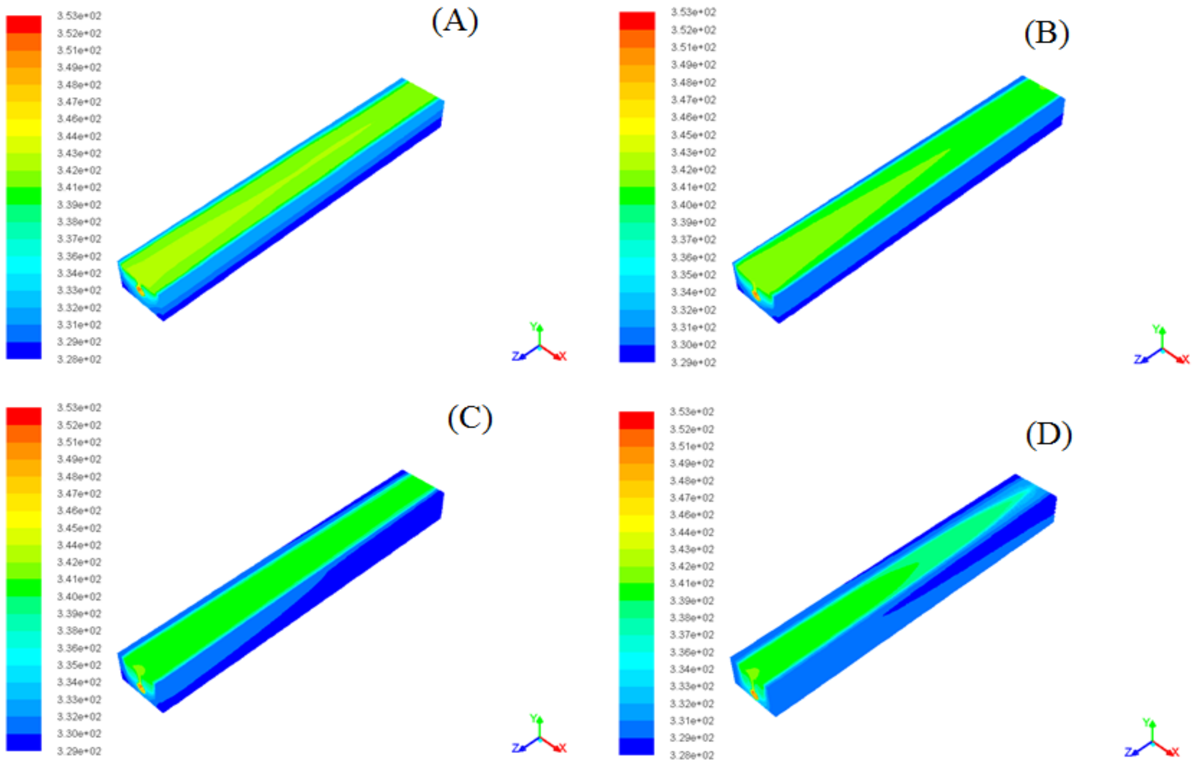


**Figure 2:** Temperature distribution process in the domain, (A) case 1, (B) case2, (C) case3, and (D) case4. Elapsed time is 10000 s.

Two factors affected the natural convection in the melted PCM; these are the temperature difference as well as the distance between the pipe wall and solid-liquid interface. This is clearly explained in Figs. 4-5. It can be also deduced that the molten regions of PCM is remarkably bigger in case 4, and then in cases 3 &2 with respect to that of case 1.

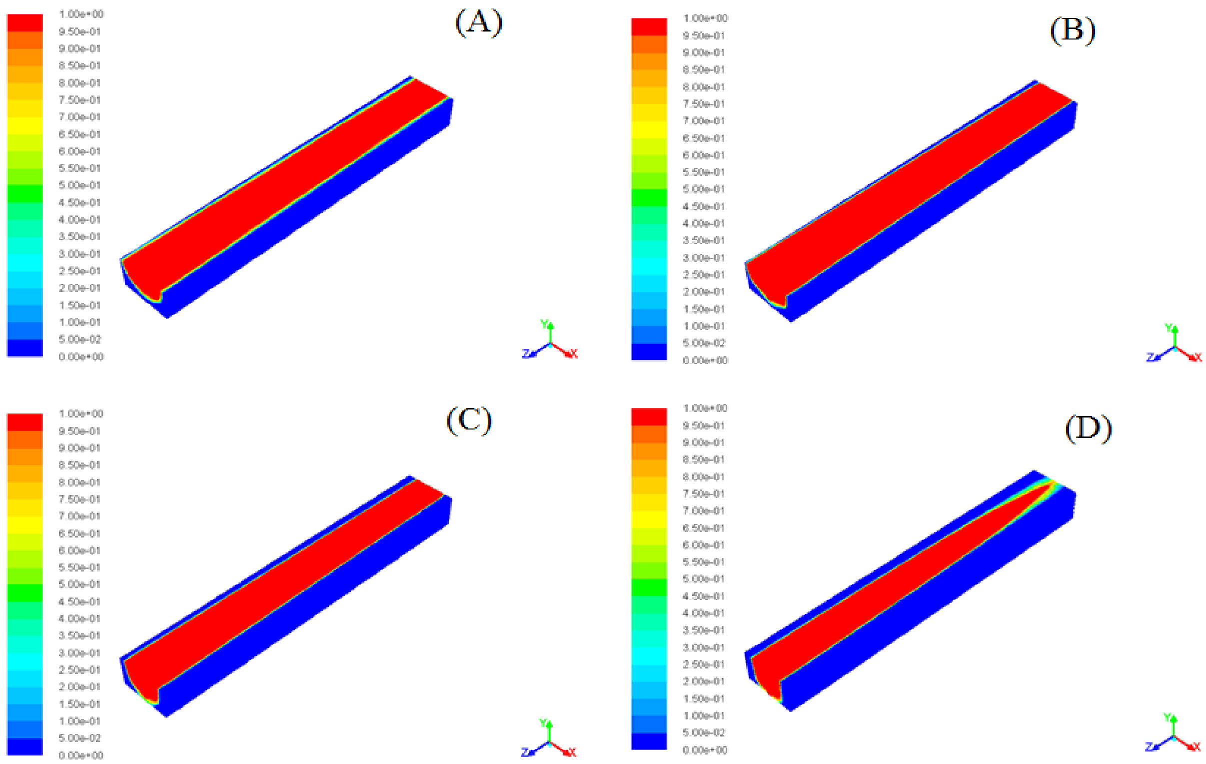


**Figure 3:** Solidification/Melting process in the domain, (A) case 1, (B) case2, (C) case3, and (D) case4. Elapsed time is 10000 s

This is because the natural convection in the PCM is affected by the temperature difference as well as the distance between the pipe wall and the solid PCM. This therefore increases the amount of PCM, resulting of increase the distance between the pipe wall and solid PCM, and so increases the natural convection mechanism.

In order to evaluate the performance of the thermal storage unit 132 monitoring points were set inside the domain with PCM to record the variation of the temperature as a function of time. These points are located in 11 measurement planes perpendicular to the axis of the domain (see Fig. 6). Each plane contains 12 monitoring points, as shown in Fig. 7. All monitoring points are divided into three groups. The first group of 44 points was set in the upper part of the computational domain (u1-u44).

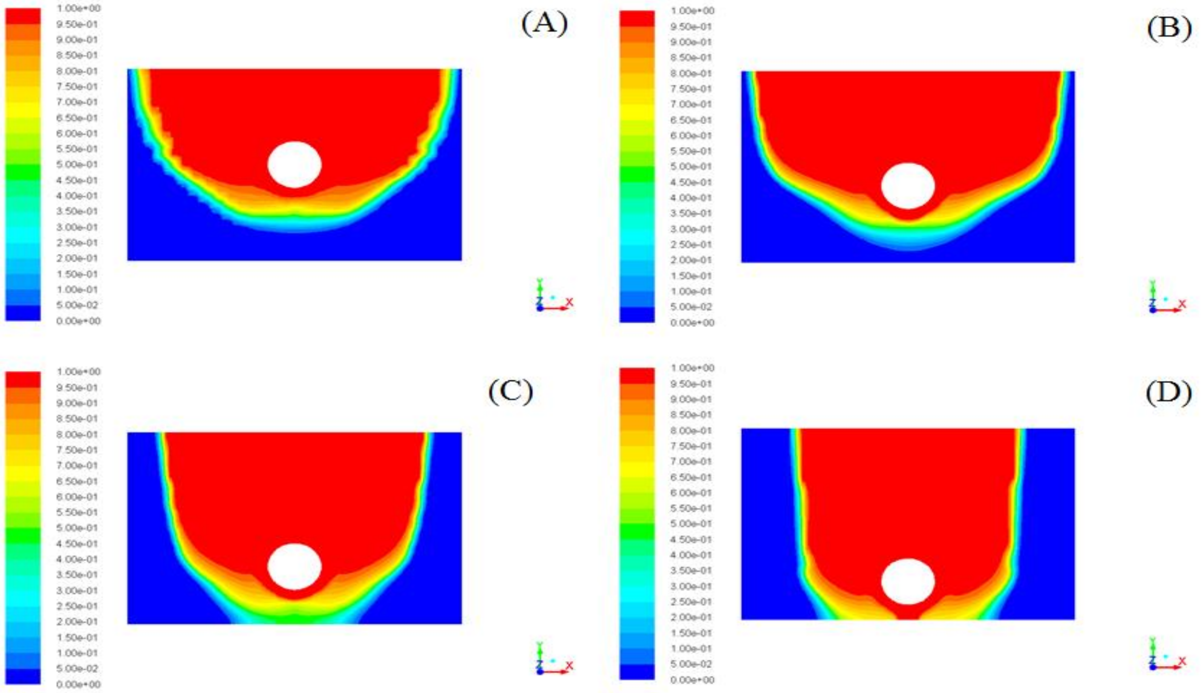


**Figure 4:** Melting process in the front section of the domain, (A) case 1, (B) case2, (C) case3, and (D) case4. Elapsed time is 10000 s.

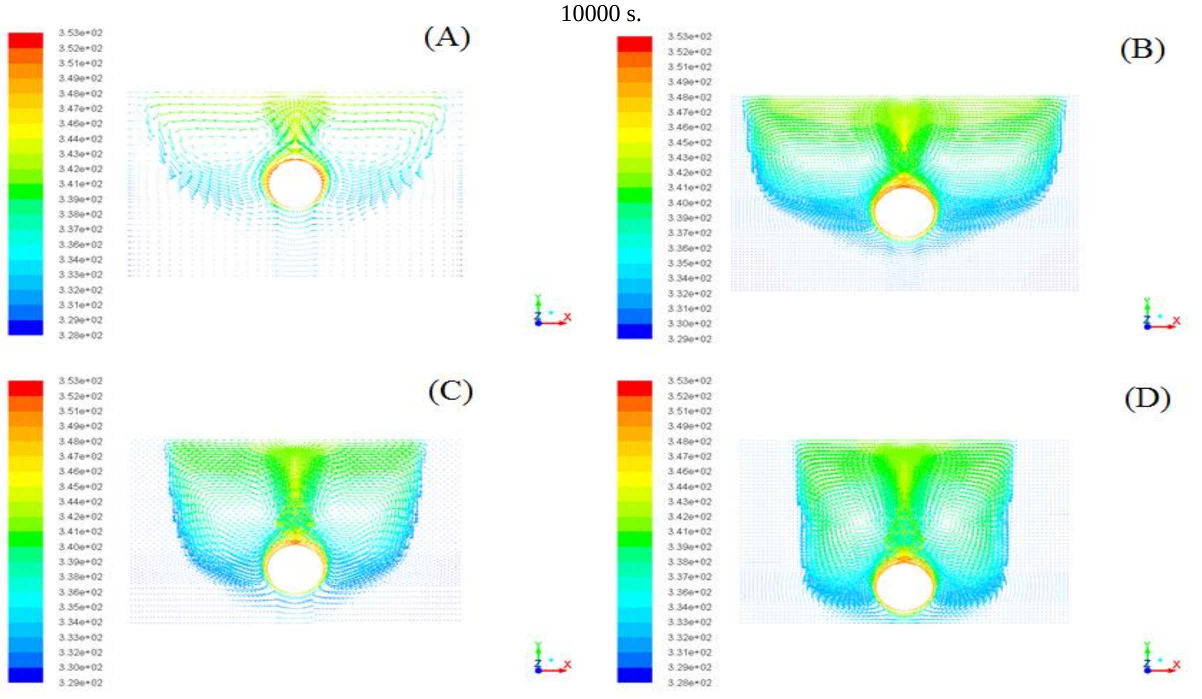


**Figure 5:** Velocity profile in the front section of the domain, (A) case 1, (B) case2, (C) case3, and (D) case4. Elapsed time is 10000 s.

The second groups of 44 points are located in the bottom part of the domain (b1-b44), and the last groups of 44 points are located at the side of the domain (e1-e44). Figs. 4-6 show the temperature variations monitoring points in the first section of the computational domain (the measurement plane 1). Fig. 3 shows the temperature variation at u4, which located at the upper part of the domain. It can be seen that the temperature in case1 is the highest compared to that in cases 2, 3 and 4. The reason behind this is that the distance between the point u4 at the upper part (Fig. 8) and the outer surface of the pipe is less than those in cases 2, 3 and 4.

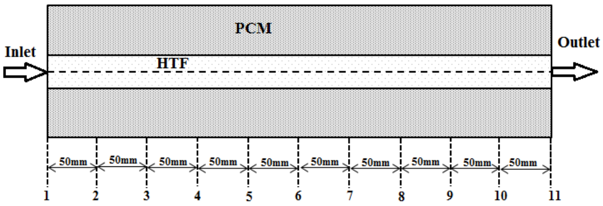


**Figure 6:** Measurement planes along the tube.

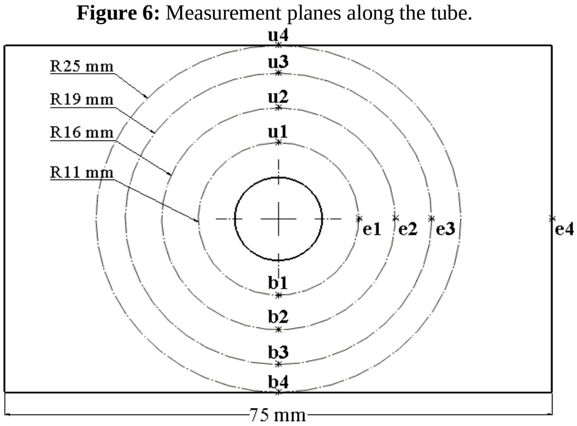


**Figure 7:** The location of 12 monitoring points in the measurement plane 1.

It can be contributed to the conduction heat transfer from the pipe wall to the PCM is maintained constant due to the same inlet parameters and boundary conditions in all cases. However, the temperature distribution in case1 is more significant on the points at the upper part of the storage unit due to the effect of natural convection. On the contrary, the temperature at the points at the bottom parts in is significantly increased as the distance between the PCM and the HTF decreased. It can be seen in Fig. 9 that the temperature variation at the bottom parts in case 4 is higher with respect to that of other cases.

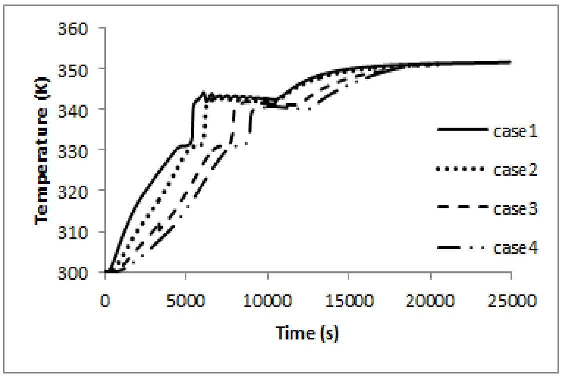


**Figure 8:** The temperature variation at point u4 (the top of the domain, first measurement plane).

Figs. 11 and 12 show the liquid fraction on PCM against time variation and total melting time. It can be deduced from this figures that the total melting time was reduced by approximately by 16.57% with case2, 31.83% with case3 and 41.3% with case 4, compared to that of case1. As mentioned above, the average heat is transferred to the PCM by conduction heat transfer from the pipe wall to solid PCM and convection heat transfer in the melted PCM. Indeed, conduction heat transfer was maintained by using the same operation and boundary conditions on the pipe and HTF in all cases. Thus, total melting time was significantly reduced in cases 3&4 due to the natural convection in melted PCM. The analysis further indicated that the appropriate configuration and height for the tube as in case 4 which provides the shorter melting time of the PCM.

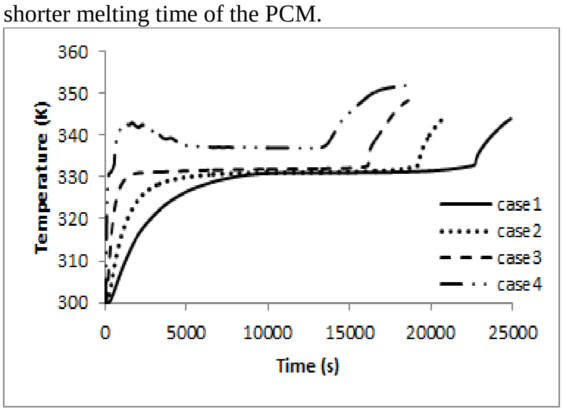


**Figure 9:** The temperature variation at point b4 (the bottom of the domain, first measurement plane).

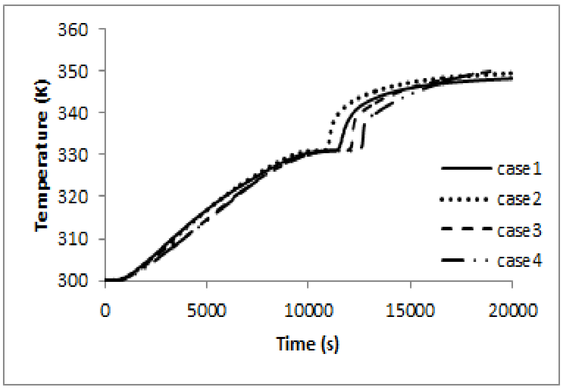


**Figure 10:** The temperature variation at point e4 (the side of the domain, first measurement plane).

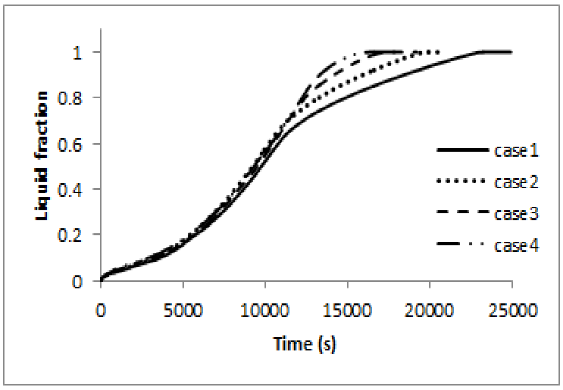


**Figure 11:** Melting fraction on PCM.

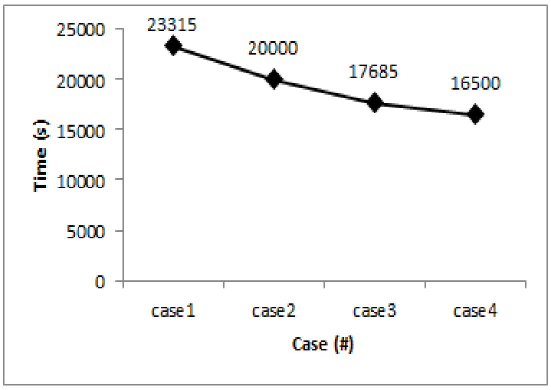


**Figure 12:** Total melting time of PCM.

## 4. Conclusion

In the present study, a numerical simulation has been carried out to determine the effect of natural convection dominated melting of PCM filled around horizontal pipe within a rectangular thermal storage unit. The most obvious finding to emerge from this study is that the natural convection heat transfer has a considerable effect on both axial and radial temperature distribution along the storage unit, and so reducing the temperature difference between the pipe walls and solid-liquid interface, therefore, reducing the total melting time of PCM. The tests for investigating four different thermal storage configurations were carried out. The results indicate that the total melting time was approximately reduced 16.57% with case2, 31.83% with case3 and 41.3% with case 4, compared to that of case1. Indeed, heat transfer rate enhanced is significantly more pronounced in natural convection in melted PCM, while the conduction heat transfer was maintained constant in all cases by using the same operation and boundary conditions on the pipe and HTF.

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