Numerical Study of Improved Heat Transfer with Phase Change Material Inside Rectangular Cells using Copper Rods

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Abstract. This work presents a numerical study of improving heat transfer to PCM (paraffin wax) inside a rectangular cell using copper rods. The numerical study is conducted using an enthalpy–porosity formulation in (ANSYS/FLUENT software16). The phase replacement material used in this study is paraffin wax (RT58). This study aims at improving heat transfer and absorption within phase-changing materials. The work demonstrates the effect of the presence and number of copper rods in the cell on heat transfer and the effect of this on time required to finish the melting process, thus improving the heat storage or absorption process. It is found that using copper rods inside cell filled of PCM increases the feasibility process and decreases the time to complete the melting process in the rate of 50%. It is also found that increasing the number of rods from three to five increases the melting process in the rate of 10%. In contrast, increasing number of rods decreased the time to complete the melting process.

Keywords. Paraffin wax, Cell, Rectangular, Copper, Rod, PCM, Melting.

1. Introduction

The energy usage in the development of modern civilization is increasing largely. As some energy sources are about to run out and others have a major impact on the environment, researchers around the world are trying to find alternatives, and the most important of which is renewable energy. The renewable energy has many economic advantages in the long run and has no impact on the environment. However, the main disadvantage is the lack of availability at all times such as solar energy and wind energy [1].

To address this problem, heat energy storage has been used, and the most important material used in conserving energy storage is the phase replacement materials [2]. Many researchers have been studying containers that contain phase replacement materials and their effects on storing heat while improving heat transfer. The most important of which is the use of copper rod. Some numerically investigated the design optimization of solar passive barriers including PCMs using rectangular cell [3]. Others studied experimentally the fusion process for the PCM in the rectangular cell and showed that any increase of the temperature has led to the increase of the melting process [4]. Sun et al. conducted a study of the heat transfer of PCM at rectangular cell [5]. The study showed that any temperature rise of the air inside increased the fusion rate of PCM and improved the energy charging of the agreeable and potential heat for PCM. Yadav et al. published numerical research on fusion process of PCM in a rectangular container, and they observed that any increase for heat flux resulted in increasing the melting process [6]. Alshara et al. studied theoretically the thermal energy storage
using cylindrical cell filled with PCM and the results showed that any of the initial cylinders in the pillar is melting quickly than the final rollers in the pillar and the temperature of PCM is hotter in the center of PCM rollers and colder in the outer surface [7]. Numerical Investigation of the melting process inside a horizontal cylindrical capsule discovered that the melting process of PCM is controlled by conduction at first stages, and natural convection controlled the melting process and affected the duration required to finish the melting process [8]. Bechiri et al. conducted numerical study on the fusion of PCM not fully filled in a vertical cylindrical tube [9]. They concluded that the tube diameter, final barrier surface temperature and the layers and thermophysical characters of tube cortex significantly influenced the melting mechanisms. Rizan et al. performed experimental study on PCM melting in the middle of a rounded cell, and the study found that any increase the power of the heater led to increase the melting process [10].

Ismail et al. studied the melting process of the fusion mechanisms PCM in a globular geometry showing that any increase the cell diameter decrease the melting process [11]. Further numerical simulations of melting process of PCMs in a globular capsule showed this melting is at the end half of the engine is quicker than the bottom due to the effect of natural convection [12]. Agarwal et al. investigated experimentally the cortex and pipe potential heat storage for solar dryer for take advantage PCMs [13]. The study showed that heat transfer is significantly affected by usual convection and melting average is earlier at the upper part because of buoyant effect. Esapour et al. found that any increase in the number of tubes and temperature resulted in increasing the melting process [14]. Ebrahimi et al. investigated the melting process of PCMs in a cortex and tube showing that heat pipe affects the melting process noticeably while increasing the HTF tubes has led to an increase in the melting process [15]. Jesumathy et al. carried out an experimental study to improve heat transfer by addition of nanoparticle [16].

The study showed that the use of nanoparticle to PCM helped improving heat transfer and therefore decreasing the time required to finish the melting process. Harikrishnan et al. investigated adding nanofluids to PCMs as a new stage replacement material for the heat energy storage which improved the thermal conductivity and therefore decrease time to complete of the melting process [17]. Through studying the literature above, it can be noted that researchers have studied nearly all the shapes, and some researchers have studied possible ways for improving the heat transfer process inside the phase variable materials. This research, however, studies the effect of adding copper rods from the wall to the PCM to improve heat transfer to PCM and thus reduce the time required to complete the melting process which improves thermal energy storage process.

2. Numerical procedure

2.1. Physical model

The physics model of the rectangular cell in figure 1-a shows the two-dimensional cell is 30 cm long and 20 cm wide, isolated on three sides and the last side is the heat source by passing hot water on it without a rod copper. In figure 1-b, a three copper rods of 10 cm in length and 2 cm in diameter are added to the cell itself. The copper rods are fixed to the heat source wall at distance of 7.5 cm. In figure 1-c, a five copper rods of 10 cm in length and 2 cm in diameter are added to the cell itself. They are fixed to the heat source wall a distance of 0.5 cm. The rods are used to investigate their effects on the melting process.
2.2. Computational procedure

A numerical study through which the characteristics of melting that occurs in a rectangular basin can be known. The flow instability for the purpose of incompressible, layers, and two dimensional. For the purpose of simulating the fusion processes, the solid and liquid stages must be heterogeneous and homogeneous at thermal stability in the interface. Depending on the porosity of the material the phase is transformed into a PCM. The melting of the PCM is a complex phenomenon due to its nonlinearity, time-behaviour and continuously movement of solid and liquid interface. The melting of phase change material is modelled by considering the Concurrent continuity, momentum and energy governing differential equations are modelled as equations (1), (2) and (3), respectively:

\[ \frac{\partial p}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \]  
\[ \frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla P + \nabla (\vec{F}) + \rho \vec{g} + \vec{S} \]  
\[ \frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho \vec{v} H) = \nabla (K \nabla T) \]  

The specific enthalpy \( H \) is the sum of the sensible enthalpy \( (h) \) and the latent heat \( (\Delta H) \),

\[ H = h + \Delta H \]  

Where;

\[ h = h_{ref} + \int_{T_{ref}}^{T} C_p dT \]  
\[ \Delta H = \beta L_f \]

The content of the internal heat can alter between zero (for a solid and one for a liquid) and the liquid fraction (\( \beta \)) can be written as:

\[ \beta = \begin{cases} 
0 \text{ solids} & \text{if } T < T_s \\
1 \text{ liquids} & \text{if } T > T_l \\
\frac{T - T_s}{T_l - T_s} & \text{if } T_s \leq T \leq T_l 
\end{cases} \]  

The origin of the symbol \( S \) in the momentum equation is the Darcy’s law damping symbol that is added to the momentum equation. Because of the effect of stage alteration on convection, it is known by: the origin of the symbol in the momentum equation is shown by:
\[ S = \frac{C(1-\beta)^2}{\beta^3} \]  

(8)

Where; the coefficient C is soft region constant which reflects the morphology of the melting front. This constant is a big number, generally 10^4 to 10^7. In the present study C is assumed fixed and is set to 10^5.

2.3. Boundary conditions

For the purpose of providing a heat source, hot water is passed to the wall with a flux average of 50 L/min. and a temperature of 95 °C. The cell is isolated on three sides to prevent heat transfer and the hypothesis that thermal is transferred from the barrier to the entire PCM without losses. The melting process in rectangular cell is assumed two-dimensional problem. The vertical wall of the cell is assumed isothermally heated by flowing HTF,

\[ T_{wall} = T_{HTF} \]  

(9)

The wall of the cell is thermally insulated,

\[ \frac{\partial T}{\partial x} = 0, \quad \frac{\partial T}{\partial y} = 0 \]  

(10)

The initial temperature of the PCM can be defined as,

\[ T|_{t=0}=T_{ini} \]  

(11)

In Figure 2, the boundary conditions for the cell are shown without the use of rods, which are the same conditions in the cell using three or five rods.

A paraffin wax (RT58) is used as a stage change material. The thermophysical features of PCM are included in Table 1 [18].

**Table 1. Thermophysical proprieties of the materials.**

| Heat properties                  | Paraffin RT58 |
|----------------------------------|---------------|
| Density [kg/m³]                  | 840           |
| Specific Heat [J/kg K]           | 2100          |
| Thermal Conductivity [W / m K]   | 0.21          |
| Dynamic viscosity [kg/m s]       | 0.0269        |
| Thermal expansion coefficient [1/K]| 0.00011      |
| Heat of fusion [J / kg]          | 180000        |
| Solidus Temperature [°C]         | 48            |
| Liquidus Temperature [°C]        | 62            |
2.4. Assumptions
Is resolved a mathematical formulation of the melting process inside a rectangular cell, the following assumptions are considered:

1. The melting is modelled as a 2-D.
2. Initially, the cell is filled completely with a solid PCM.
3. The flow is deemed unstable, Thin layers, and not be able compress.
4. Thermo-physical properties of the PCM are assumed to be constant in both solid and liquid phases.
5. The viscous dissipation term is negligible.
6. The effect of volume ends while changing the solid and liquid phase.
7. Do not generate an increase or decrease in convection in surrounding sides.

2.5. Enthalpy–porosity method
The simulation of the solid-liquid process of PCM is obtained by adopting the enthalpy-porosity method. The enthalpy-porosity method depends on the liquid fraction which denotes the ratio of mass of liquid to the total mass in each cell. A quantity called the liquid fraction which indicates the fraction of the cell volume that is in liquid form is associated with each cell in the domain. As the temperature distribution is determined, the liquid fraction is not evaluated explicitly but it is evaluated implicitly by using enthalpy balance in each iteration. The porosity of solid and liquid phases are considered to have a value of 0 and 1 respectively while the porosity of the mushy zone is between these values.

2.6. Computational procedure
The computational study relies on ANSYS/FLUENT 16 software package to simulate the governing equations and associated boundary and initial conditions of transient, nonlinear and moving boundary of the melting process. A computational domain was defined to consider the forced convection in HTF, conduction heat transfer in copper wall and conduction/natural convection associated with the melting process of PCM.

2.7. Meshing of the domains
The domains are divided into numerous numbers of meshes. This number depends on the mesh quality. Low quality Mesh produces poor simulated result and even divergence. Two-dimensional quadrilateral grids are used to discretize the domain. Figure 3 shows the division of the grid for a numerical models. Figure 3a shows the meshes distribution of the cells without rods and the number of nodes was 20585. Figure 3b shows the mesh distribution of the cells with three rods and the number of nodes was 23350. Finally, figure 3c shows the meshes distribution of the cells with five rods where the number of nodes was 27989.

![Figure 3. Mesh size of model.](image)
2.8. Setup the problem

The melting of PCM inside a rectangular cell is a transient and two-dimensional problem with gravity effect. The simulation of the melting process of PCM requires the selection of solidification and melting model. The energy and viscous (laminar) models are activated automatically. Pressure-velocity coupling is achieved to derive an additional condition for the pressure by reformatting the continuity equation. The pressure-based solver allows to solve the flow problem in either a segregated or coupled manner. The melting problem in this study uses SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm. The SIMPLE scheme uses a relationship between velocity and pressure corrections to enforce the mass conservation and to obtain the pressure field. There are many setting steps to control the spatial discretization of the convection terms in the solution equations. The spatial discretization contains the gradient setting for computing the gradients in governing equations (Least Squares Cell Based method is used), the pressure settings (Second Order technique is applied) and momentum settings (Second Order Upwind scheme is used). The iteration procedures are used to solve the hydrodynamic-thermal behaviour of the melting process numerically. The convergence of the solution can be accelerated by applying over-relaxation technique, whereas, under-relaxation is used to stabilize the numerical results. In this study, the under-relaxation factors for pressure, density, body force, momentum, and Liquid fraction are 0.3, 1, 1, 0.7, and 0.9, respectively.

3. Results and discussion

3.1. Case one (the cell without rod)

In this case, the melting needed a time of 1090 minutes to complete the process, and the reason for this is that PCM have little thermal conductivity and the heat transfer was mostly dependent on natural convection. Figure 4 shows the melting process, where we notice that at the first of the fusion process, the heat transfer based on the conduction, and we note the speed of the heat transfer and the melting of PCM along the wall. After that, the heat transfer depends on the natural convection, where it can be noticed that the dissolving process takes a longer time as we move away from the wall. Figure 5 depicts the temperature, as it shows that the thermal transfer at the first of the fusion process is along the wall and after that the heat transfer is related on the natural convection load becomes slow and needs a longer time whenever away from the wall.

![Figure 4](image4.jpg)

**Figure 4.** Predicted evolution of the melting process at the rectangular cell without rod.

![Figure 5](image5.jpg)

**Figure 5.** Temperature distributions at the rectangular cell without rod.
3.2. Case two (the cell with three rods)
In this case, three rods were added that are fixed to the wall, where we notice that the melting process took 720 minutes. Figure 6 shows that the melting process is faster with rods. Inserting rods helped to transfer heat to PCM by conduction. Figure 7 depicts the heat transfer and the importance of the presence of bars which increases the melting process and thus affects the thermal energy storing process and even in the discharge increases the speed of heat transfer.

![Figure 6](image1.png)
**Figure 6.** Predicted evolution of the melting process at the rectangular cell with three rod.

![Figure 7](image2.png)
**Figure 7.** Temperature distributions at the rectangular cell with three rod.

3.3. Case three (the cell with five rods)
In this case, five rods have been added, where 690 minutes needed to complete the melting process; it is a noticeable difference compared to the two previous cases. The melting process is faster with five rods as shown in Figure 8. The additional rods helped to transfer heat to PCM by conduction, thus the speed of melting was significantly increased. The heat transfer and the importance of the presence of bars can also be clearly seen in Figure 9.

![Figure 8](image3.png)
**Figure 8.** Predicted evolution of the melting process at the rectangular cell with five rod.

![Figure 9](image4.png)
**Figure 9.** Temperature distributions at the rectangular cell with five rod.
3.4. A comparison of the three cases

By comparing the three cases, it was found that the use of rods raises the heat transfer and thus it reduces the period that required to finish melting process. It is shown in Figure 10 that the melting process of the cell without rods requires a longer duration because the heat transfer process at the first of the fusion process slightly depended on the conduction and then mostly on the natural convection, and this required more time since the heat transfer was slower. The figure also shows that adding three rods can have significant impact on the melting duration. However, by increasing the number of bars from three to five, only slight difference is observed.

![Figure 10. Variation melt fraction with time at flow rate= 50L/min. at $T_{in}$= 95 °C.](image)

Similar observation can be seen by depicting the melting process and the temperature contours in figure 11 and figure 12 respectively.

![Figure 11. Comparison of the melting process between the cell without rods and cell with three and five rods.](image)

![Figure 12. Comparison of the temperatures between the cell without rods and cell with three and five rods.](image)
4. Conclusions
In this work, a numerical study was conducted to clarify the effect of using copper rods inside a rectangular cell on the melting process. The study was conducted using an enthalpy–porosity formulation in ANSYS/FLUENT and the PCMs used paraffin wax (RT 58). The use of copper rods inside PCMs increased the melting process by transferring heat and thus improving the process of storing or discharge thermal energy. It is noted that the use of three rods decreased the duration to finish the melting process by 50%, and the use of five rods reduced the time needed to complete the melting process by 63% when compared to a cell without rods. However, when comparing a cell with three rods with a cell with five rods, slight difference of 10% was seen. The use of rods inside the PCMs influenced the heat transfer process and thus improved the melting process and the conductivity inside the PCMs.

Nomenclature

| Symbol | Description                      |
|--------|----------------------------------|
| c      | specific heat (J/kg K⁻¹)         |
| β      | melt fraction                    |
| H      | rate heat transfer coefficient (W m⁻² K⁻¹) |
| K      | heat conductivity (W m⁻¹ K⁻¹)    |
| L      | latent heat of fusion (kJ/kg)    |
| tₑ     | elapsed time for each test run (s) |
| T      | temperature (K)                  |
| Α      | heat diffusivity (m² s⁻¹)        |
| βᵣ     | liquid thermal expansion coefficient (K⁻¹) |
| P      | density, (kg m⁻³)               |
| Ν      | kinematic viscosity (m² s⁻¹)     |

Subscripts

| Symbol | Description |
|--------|-------------|
| H      | hot water   |
| L      | liquid PCM  |
| M      | melting     |
| PCM    | phase change material |
| s      | solid PCM   |

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