Numerical study of PCM melting processes in trapezoidal channel

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Abstract. In this paper, a numerical investigation had been performed to improve the melting process of phase change materials (PCM) by utilizing a trapezoidal channel. Different geometrical parameters of the trapezoidal channel were investigated. These parameters included: the height and pitch of the trapezoidal channel. Two-dimensional numerical models were developed with ANSYS (FLUENT) software. The unit is a horizontal channel that the heat transfer fluid (HTF) (hot water) passes through the channel to melt the PCM which contained at the top and bottom sides of the channel. The results showed that the trapezoidal channel with a longitudinal pitch of 6 mm and a height of 4 mm is the most suitable parameters for increasing the PCM melting process compared to other geometrical parameters. It was also concluded that the melting time is decreased by 27% at a height of 4 mm, and by 8% at a pitch of 2 mm.

1. Introduction
"Latent heat thermal energy storage" (LHTES) systems that use phase change material (PCMs) are characterized by storage of thermal energy, because of their high energy density and almost constant temperature as the phase changes [1]. PCM is the material that releases or absorbs latent heat through phase transformation (solid to liquid and vice versa). The PCM absorbs latent heat through the melting process and release it through the solidification process. The PCM has been used in many important industries, including thermal energy storage, building cooling/heating, waste heat recovery, electronic cooling and medical purposes [3]. The drawback of PCM is their poor thermal conductivity which increases their charging and discharging time.

Much research has been done to improve heat transfer in LHTES systems through the use of advanced heat transfer mechanisms. Abed et al. [4] studied a 2D numerical model of turbulent flow across corrugated trapezoidal plate HE with different nanofluid. Different geometrical parameters such as longitudinal pitches and wavy amplitudes of the trapezoidal plate were studied. The results showed that, the optimum geometrical parameters were determined to trapezoidal channel longitudinal pitch of 6mm and height of 2.5mm. Also, their study showed that SiO2 had a higher Nusselt number value than another nanofluid. Abdulrahman et al. [5] studied the impact of Reynolds number on the PCM melting process of the HE numerically. A 3D model with triple inner walls of a rectangular HE was suggested. The Reynolds number simulated ranged between (500-2000). The results obtained that the melting process accelerated by increasing heat transfer fluid mass flow. Al-Mudhafer et al. [6]
introduced a webbed pipe HE to enhance the PCM melting process. The thermal performance of the webbed pipe HE is evaluated by comparing its heat performance with conventional heat exchangers. These exchangers involved: multi-tube HE, triple tube HE and shell and tube HE. The results displayed that, the melting process of PCM accelerated in case of employing the webbed pipe HE compared with other exchanges. Wang et al. [7] an experimentally and numerically studied the PCM solidification process of a zig-zag HE with various Reynolds number. Their results indicated that Reynolds number had a significant influence on the heat discharge process. Also, the zig-zag plate had a significant influence on the temperature in the discharge process with multiple PCM. Shahsavar et al. [8] studied the effect of different parameters on the PCM solidification process in double pipe HE numerically. These parameters included the Reynolds number and the fluid temperature. The results obtained that the channel with variable wavelength gave higher heat transfer compared to the channel with a fixed wavelength. Kousksou et al. [9] performed a numerical analysis of the PCM charging process of a vertical corrugated wall. A 2D model with constant wall temperature was used in the simulation. Their results appeared that the rate of melting increased with the amplitude value of the corrugated wall.

The present study focuses on examining the thermal performance of the PCM melting process under various geometrical parameters for a trapezoidal channel. The effect of different height (h) (2mm, 3mm and 4mm) and different pitch (w) (6mm, 9mm and 12mm) of the trapezoidal channel are analysed. A two-dimensional model and transient laminar flow are simulated to solve the governing equations.

2. Mathematical formulation

2.1. Model description

Figure 1 shows the physical configuration of the 2D model of the trapezoidal channel used in the numerical simulation. The model has the dimensions of height (H) = 8mm and length (L) = 45 mm. The trapezoidal plate was made from aluminium with a thickness of 0.5 mm. The solid PCM material was contained into the upper and lower sides of the channel. The thermo-physical properties of PCM were listed in Table 1.

| Property                  | Paraffin wax | Units           |
|---------------------------|--------------|-----------------|
| Density                   | 834.36       | (kg/m³)         |
| Viscosity                 | 0.008        | (kg/m. s)       |
| Specific heat             | 2890         | (J/kg. K)       |
| Latent heat of melting    | 70006        | (J/kg)          |
| Thermal conductivity      | 0.22         | (W/m. K)        |
| Solidification Temperature| 292          | (K)             |
| Melting Temperature       | 300          | (K)             |

Figure 1. The 2D physical model of the trapezoidal channel
2.2. Governing equations

The governing equations of the numerical model were solved with the following assumptions:

(1) 2D model was used and the PCM melting process was transient.
(2) Incompressible and Laminar flow.
(3) Physical and thermal properties of paraffin were constant.
(4) PCM was isotropic and homogeneous.
(5) PCM volumetric expansion was negligible.

Based on these assumptions, the continuity, momentum, and energy equations can be written as below [11]:

(i). Continuity equation:

\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \]  

(ii). Momentum equation:

\[ \frac{\partial (\rho V)}{\partial t} + \nabla \cdot (\rho V) = -\nabla P + \mu \nabla^2 V + S. \]

(iii). Energy equation:

\[ \frac{\partial}{\partial t} (\rho H) + \nabla \cdot (\rho VH) = \nabla \cdot (-kVT) \]

Where: \( V, P \) and \( \mu \) refer to velocity vector, pressure and dynamic viscosity respectively. \( H \) is the specific enthalpy, \( \rho \) is the density and \( T \) is the temperature. \( k \) and \( S \) stand for thermal conductivity and source term, respectively. The PCM total enthalpy \( 'H' \) was calculated by summation the latent heat \( '\Delta H' \) and sensible enthalpy \( 'h' \). In terms of latent heat content, the latent heat for PCM \( 'L' \) was defined as follows:

\[ \Delta H = \beta L \]

Where \( \beta \) refer to liquid fraction and was given as:

\[ \beta = \begin{cases} 0, & \text{if } T < T_{solidus} \\ 1, & \text{if } T > T_{liquidus} \\ \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}}, & \text{if } T_{solidus} < T < T_{liquidus} \end{cases} \]

Solving the temperature is basically the iteration between (3) and (5). Porosity technology treats the porous region as a porous medium. In each cell, the porosity is determined on an equal basis with the liquid fraction in that cell and the liquid fraction is in a mushy zone between 0 to 1.

2.3. Boundary conditions

In the numerical simulation, the inlet boundary conditions were set at a constant velocity and a constant temperature of 0.01 m/s and 310K respectively, while the pressure boundary condition at the outlet was used. Insulated boundary conditions were assumed in the upper and lower walls. Non-slip and conjugated heat transfer boundary conditions were applied to interior trapezoidal wall surfaces. The initial temperature for PCM is 291K. The boundary conditions for the computational field were specified in figure 1 as below:

1. Inlet 
\[ u = u_{in}, v = 0 \text{ and } T = T_{in} \]

2. Outlet
3. Walls

(i). External walls: Upper and lower walls were insulated.

\[
\frac{\partial u}{\partial x} = \frac{\partial v}{\partial y} = 0, \quad \frac{\partial T}{\partial x} \quad \text{and} \quad P_{\text{out}} = 0
\]

(ii). Internal walls

Fluid-solid interfaces:

\[
u = v = 0 \quad \text{and} \quad \frac{\partial T}{\partial y} = 0
\]

Fluid-solid interfaces:

\[
u = v = 0, \quad -k_f \frac{\partial \tau_f}{\partial y} = -k_s \frac{\partial \tau_s}{\partial y}
\]

PCM-solid interfaces:

\[
-k_s \frac{\partial T_s}{\partial y} = -k_p \frac{\partial T_p}{\partial y},
\]

Where, \(p = \text{PCM}\) and \(s = \text{solid (Aluminum wall)}\)

2.4. Computational procedure

The ANSYS Fluent software was used to solve governing equations built on the finite volume method. The SIMPLEC algorithm was chosen to link the velocity and pressure, and for pressure correction equations the PRESTO scheme was adopted. Relaxation factors for liquid fraction, pressure, velocity and energy were determined at 0.9, 0.3, 0.7 and 1, respectively. The time step was set to 0.1s and the iterations maximum number per time step was 20. The convergence criterion is \(10^{-4}\) for all variables. The meshes of all configurations were generated using triangular cells as shown in Figure 2.

![Figure 2. 2D Geometrical meshing.](image)

3. Results and discussion

3.1. Grid independence

As the first step for all simulations, grid independence test has been performed. Three grid sizes of 10258, 12337, and 15904 were tested and shown in Figure 3. Through comparisons, the grid with
10258 cells was selected in this study to produce a similar variation in the water temperature outlet and reduce run time.

![Grid independence test for different grids for the outlet water temperature with time.](image1)

**Figure 3.** Grid independence test for different grids for the outlet water temperature with time.

### 3.2. Effect of geometrical parameters

The geometrical parameters effects (height (h) and longitudinal pitch (w)) see figure 1 on the PCM melting process of the trapezoidal channel were tested and discussed in this section:

Figure 4 shows the effect of changing the longitudinal pitch size of PCM temperature. It is observed from the results that, by reducing the pitch sizes the temperature of PCM is increased. Figure 5 illustrates the longitudinal pitch sizes effect on PCM melting process. From this figure, it is clear that the PCM melting process accelerated by reducing the pitch size. The PCM temperature and liquid fraction reach its maximum value at the trapezoidal pitch = 6mm followed by 9mm and 12mm. This happens because by decreasing longitudinal pitch increase the number of the corrugated trapezoid and this increase heat transfer surface area and accelerate the melting process.

![Longitudinal pitch sizes effect on the temperature of PCM during the melting process](image2)

**Figure 4.** Longitudinal pitch sizes effect on the temperature of PCM during the melting process
Figure 5. Effect of longitudinal pitch on the liquid fraction during the melting process

Figure 6 shows the influence of trapezoidal height on PCM temperature during melting process. It is observed from the results that as the trapezoidal height increases, the temperature of PCM increases. Figure 7 shows the effect of trapezoidal height on PCM liquid fraction. It can be noticed from these figures that, the trapezoidal height of 4mm have the largest PCM temperature and liquid fraction, followed by 3mm and 2mm. This happens because by increasing the trapezoidal height, the surface area of heat transfer increase and this accelerate the PCM melting process.

Figure 6. Effect of trapezoidal height on the temperature of PCM during the melting process.
Figure 7. Effect of trapezoidal height on the liquid fraction of PCM during the melting process

Figure 8 illustrates the variance of the outlet water temperature verse the time for different trapezoidal height values. It can be seen from this figure that the outlet water temperature increases during the melting process. This takes place because as time passes the more percentage of PCM becomes, so the heat released from the water decreases. This agreement with [8]. Meanwhile, the trapezoidal height of 4mm has the lowest water temperature outlet than the channels with the lowest height.

Figure 8. Effect of trapezoidal height on the outlet water temperature during the melting process.

Figure 9 and figure10 show the contours of PCM liquid fraction at various time stages for different pitch and height of the trapezoidal channel respectively. It is observed that the melting of paraffin begins at the time (10s) and increases with time for all cases. It is also noted that the PCM has melted near the walls of the corrugated channel due to the flow of the hot water. It can be seen from these figures that the melting of PCM accelerated by increasing the height and decreasing the pitch. Additionally, the melting of paraffin is faster for the trapezoidal channel with a pitch of 6mm and a height of 4mm, due to the increase in trapezoidal ripples that increases the surface area.
Figure 9. Contours of the PCM liquid fraction for different trapezoidal pitch.

Figure 10. Contours of the PCM Liquid fraction for different trapezoidal heights.
Figure 11. Contours of PCM temperature distribution for different trapezoidal pitch.

Figure 12. Contours of PCM temperature distribution for various trapezoidal heights.
Figure 11 and figure 12 display the contours of PCM temperature distribution with different pitch and height configurations respectively at various time stages. From these figures, it is clear that the temperature of the paraffin begins to increase gradually until the paraffin is melted. The reason is that the rate of heat transfer at the beginning of the melting process is high due to the high-temperature difference between the PCM and fluid. Also, it is observed that the highest temperature of PCM reached 305K for height = 4mm at the time (135s) and reached to 306K at pitch = 6mm at the time (185s). It is also noticed that the outlet temperature of the water reduces at the time (10s) for all cases, and then begins to increase because the heat absorbed by the paraffin decreases when it completely melted. In this case, the lowest temperatures at a height of 4 mm and a pitch of 6 mm, reached 307K and 308K, respectively.

4. Conclusion
The present study included a numerical investigation of the PCM melting process in a trapezoidal channel. Influence of different geometrical parameters of the trapezoidal channel (height and pitch) was analyzed. A 2D model was used to solve governing equations using the FLUENT program. Numerical simulation results showed that the lowest longitudinal pitch and highest height show the best performance for increasing the PCM melting process compared to other geometrical parameters.

5. References
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