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Numerical simulation of the melting of solid paraffin in a solar water heater and the effect of the number of fins and the height of the fins

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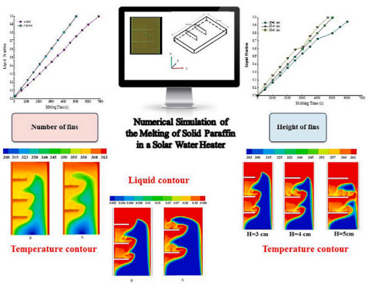
GRAPHICAL ABSTRACT



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ABSTRACT

Numerous theoretical and experimental studies were conducted on thermal energy storage utilizing phase change materials (PCMs). This study employs paraffin with particular properties as the PCM in a square solar water heater. Paraffin's melting point (MP) is 55 °C, the flow is transient, and natural convection is responsible for the heat transfer (HT). In this study, the effect of fin geometry, such as height (H) (3, 4, and 5 cm), and the number of fins (NoF) (double and triple), on the performance of the heat exchanger (HE) was investigated. For various parameters, temperature (T) and liquid fraction contours were produced. The results show that, the melting time (MT) for case A (without fins) about 3860 s. Based on the calculations, the reduction of MT for case B (with 3 fins) is 71%. The MT reduction at H=3, 4, and 5 cm equal to 48, 61, and 74% respectively.

1. Introduction

Heat transfer and increasing the thermal efficiency of systems has always been one of the most interesting topics for researchers, and researchers tried to find different methods to improve the efficiency of heating systems [1–4]; one of these methods is the use of PCMs. Materials containing chemical or mineral constituents that can retain and store tremendous amounts of heat energy are called PCMs. The research in the field of fluid mechanics and heat transfer is numerical and analytical. One of the most important fields in fluid analysis is numerical analysis using the computational fluid dynamics (CFD) tool, which is widely used in all fields today, and researchers have done a lot of research in this field [8,9]. Research has been carried out in the case of PCMs shows that these materials can be useful for improving and increasing the efficiency of heating systems [5–7,10]. If material changes its condition from one phase to another, it either absorbs or emits latent heat [11]. When phases with different compositions separate macroscopically, this is known as phase separation. The phase separation is one of the problems of renewable phase change. Sub-cooling occurs when the temperature falls significantly below the MP until the material starts to glaciate and discharge heat (Fig. 1). If this temperature is not reached, the PCM will not glaciate and will only store sensible heat [12]. The choice of PCM depends on the system's design temperature and the application. The operating temperature of the heating or cooling system must correspond to the phase change temperature of the PCM [13]. Ismail et al. [14] presented two classification techniques for PCMs. There are two categories of organic PCMs: paraffin and non-paraffin. Comparing paraffin and non-paraffin PCMs, it is possible to identify the following characteristics: high latent heat of melting, small volume change during melting, the low vapor pressure in the non-corrosive molten state, and relative affordability. Luo et al. [15] studied the enhancement of PCM melting HT by combined fractal fins. In a hybrid fractal fin HE, the total MT of PCMs is reduced by 68% compared to a conventional fractal fin HE. Zhou et al. [16] studied the effect of employing PCM for cooling in HEs. The findings indicate that PCMs may lower the cooling temperature by around 1 °C. Amanowicz et al. [17] created a numerical model on PCMs. According to their findings, the use of PCMs ameliorates thermal efficiency. Bisoniya et al. [18] examined the numerical analyses of PCM-containing HEs. Based on their findings, utilizing PCM as a passive cooling and heating solution is successful. Using a numerical method, Rodrigues et al. [19] examined the thermal recovery of the PCM-containing HE. Utilizing a multi-tube system instead of conventional systems was their proposed method for enhancing HE 's efficiency. According to their findings, the proposed method can increase the efficiency by more than 20%. In different geometries, Rosa et al. [20], Zhang et al. [21], and Ajdari et al. [22] investigated conventional PCMs containing nanoparticles. Yang et al. [23] examined experimental research on the utilization of PCM in HEs. According to their findings, this proposed system can reduce summertime temperature by approximately 4.5 °C. Harkrishnan et al. [24] studied the MT and freezing times of nanofluids. The result show that the created nanofluid might be one of the suitable PCMs for energy storage systems that operate at low temperatures. Ho et al. [25] determined the effect of employing Al_2O_3-water

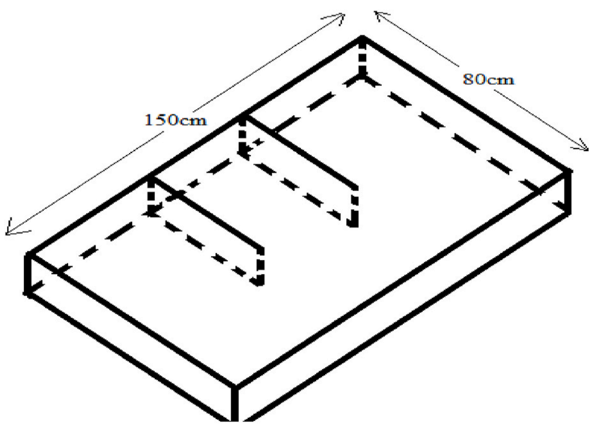

Fig. 1. The 3D geometry of fin.

nanofluid in the HE. Due to the combination of proper thermal conductivity and absorption of latent heat by PCM, their findings demonstrate that the efficiency of the HE is enhanced. Minaei and Safikhani [26] simulated the transient HE in three dimensions. They examined the effect of fluid flow velocity on the system's efficiency and concluded that increasing the velocity increases the HT rate. Mashayekhi et al. [27] investigated the thermal manner of nanofluid in the HE-containing PCMs. They discovered that the nanofluid flow could decrease battery T by 8.5%. Moreno et al. [28] discussed HT in a PCM-containing chamber. The HT and flow fields were analyzed. Using PCM in the chamber improves thermal efficiency and hydraulic efficiency, as demonstrated by the results. Aljehani et al. [29] investigated the flow field and HT in an energy storage system with PCMs (ethylene glycol-paraffin-graphite). Also, in recent years, other interesting studies were conducted in the field of PCMs [30–32].

The utilization of PCMs increases the HT rate. In this study, the effect of fin geometry, such as height (3, 4, and 5 cm), and the NoF (double and triple), on the performance of the HE in Fluent software was investigated. For various parameters, temperature and liquid fraction contours were produced.

2. Equations

The governing equations are as follows [30–32]:

Continuity equation:

$$\nabla.\left(\rho.\vec{V}\right) = 0 \tag{1}$$

Momentum equation:

$$\rho\left(\frac{\partial\vec{V}}{\partial t} + \vec{V}.\nabla\vec{V}\right) = -\nabla P + \mu\nabla^2\vec{V} + \rho\vec{g} + S \tag{2}$$

where S is the momentum source term due to the reduced porosity in the mushy zone and can be expressed as:

$$S = \frac{(1-\beta)^2}{(\beta^3+\varepsilon)} C_{mush}\vec{V} \tag{3}$$

where ε is a small number (0.001) to prevent division by zero, C_{mush} is the mushy zone morphology constant. This constant measures the amplitude of the damping and describes how steeply the velocity is reduced to zero when the material solidifies. This constant should be in the range of 10^4–10^7 [33]. such that10^5 are chosen in this study.

Energy equation:

$$\frac{\partial}{\partial t}(\rho H) + \nabla.\left(\rho\vec{V}H\right) = \nabla.(k\Delta T) \tag{4}$$

In Eqs. (1), (2) and (4), $\vec{V}$ is the fluid velocity, ρ is the density, μ is the dynamic viscosity, P is the pressure, $\vec{g}$ is the gravitational

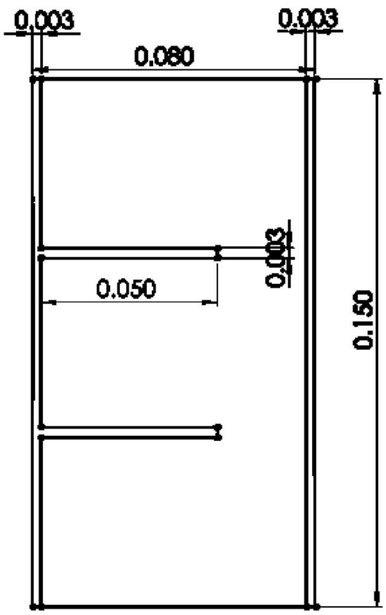

Fig. 2. The two-dimensional geometry.

acceleration, k is the thermal conductivity and H is the specific enthalpy, which is defined as the sum of the sensible enthalpy (h) and the latent heat (ΔH):

$$H = h + \Delta H \tag{5}$$

$$h = h_{ref} + \int_{T_{ref}}^{T} C_p dT \tag{6}$$

The content of the latent heat can vary between zero (for a solid) and L (for a liquid):

$$\Delta H = \beta L \tag{7}$$

The liquid fraction (β) can be written as:

$$\Delta H = \beta L$$

$$\begin{bmatrix} \beta = 0 \quad \text{if} \quad T \le T_{solidus} \\ \beta = 1 \quad \text{if} \quad T \ge T_{liquidus} \\ \beta = \dfrac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} \quad \text{if} \quad T_{solidus} \le T \le T_{liquidus} \end{bmatrix} \tag{8}$$

3. Specifications of the investigated geometry

Figs. 1 and 2 show three-dimensional and two-dimensional geometries:

According to the type of analysis, the sensitivity of modeling increases. In this project, Gambit software was used to generate geometry since geometry is a two-dimensional. Gambit software is one of the most powerful software in mesh generation. The output of this software is the input of Ansys-Fluent software. In every numerical problem, the definition of geometry, the computational domain's formation, and the domain's division into smaller areas or grids are discussed. Meshing work was done on the generated model in Gambit software. Figs. 3 and 4 show a view of generated geometries in Gambit.

In this section, as mentioned, using meshing techniques, the type and size of the elements around the fin are selected to be smaller for a better solution to fluid equations. It was tried to select and generate the best possible mesh for this analysis. For this purpose, first, the normal grid was implemented on the body, and then, according to the obtained results (contours of density, pressure, and position of the free surface, the meshes on the body are of the rectangular type with the side length of 0.1 mm). Due to the organized geometry of the square, grids with the organization of quadrilateral elements were used. One of the important things that should be paid attention to in numerical analysis is the size of generated meshes. The size of the mesh is very influential in the results of the analysis. The bigness of the grid causes errors in the analysis. Therefore, the size of the meshes should be as small as possible. But with the increase in the number of meshes, the number of calculations increases. The investigated problem is transient with natural convection.

4. Boundary conditions

In addition to the mathematical discussion of solving the equations, the type and physics of the flow must be known. There are

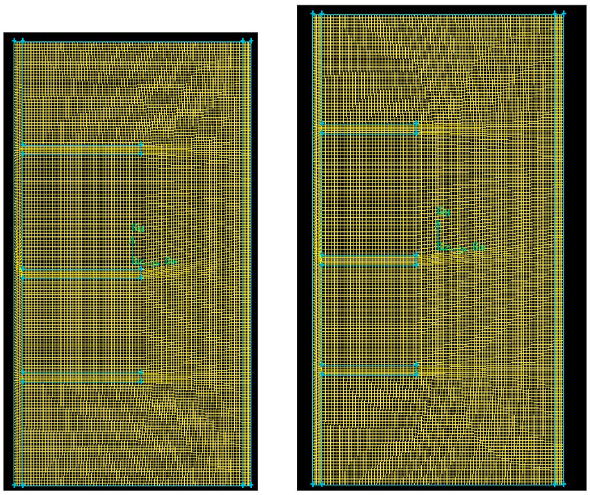

Fig. 3. Geometry in Gambit software.

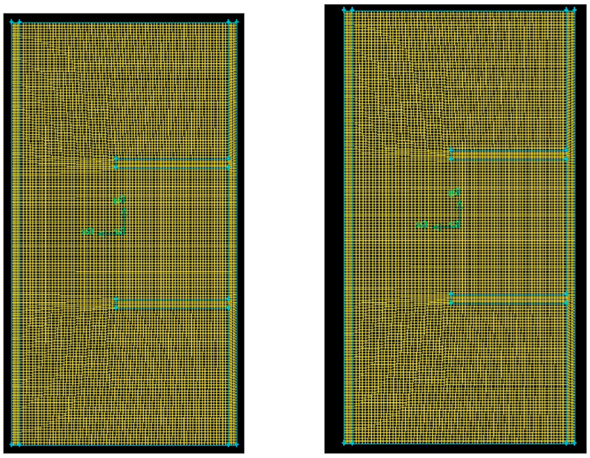

Fig. 4. Geometry in Gambit software.

several forms of boundary conditions for flow simulation. Determining the boundary conditions is an important part of numerical analysis [36,37]. According to the conditions of the problem in question, there is no inlet and outlet boundaries in the problem. The left and right walls and the fin have a constant T. The upper and lower walls are insulated, and the area where the paraffin PCM is located is defined as the area containing the fluid. Table 1 shows the physical properties of solid paraffin as the PCM [34].

The other area that acts as a fin is the solid area with solid copper material, in which HF will be happened.

5. Numerical method

FORTRAN programming language and finite volume method (FVM) were used for numerical simulation in this study. By integrating in each control volume, the governing equations are transformed into a set of algebraic equations that are solved by iteration methods. The central difference method is used to separate the second-order sentences in the governing equations, and the UPWIND method is used for the first-order sentences. The total number of elements used in this problem is 12843. The problem was investigated in four grid modes to check the process of grid independency. By comparing the MT, it was observed that 3.06% of the error between the answers. But the important point here was the high calculation time for the number of meshes due to the low error between these two meshes. A low number of meshes were used. Table 2 shows the changes of MT vs. increase in the number of nodes. As seen in Table 2, the error between steps 3 and 4 is very small; taking into account the computing time factor, step 3 gridding can be used.

6. Results and discussion

After gridding and validating the solutions, the effect of adding an extended surface will be investigated. For this purpose, the NoF, blade height, and thickness were investigated. The present work was compared with the experimental work done by Kamkari et al. [35] in Fig. 5. To validate the data, and according to Fig. 5, a good match was achieved. They investigated the melting process of PCMs in a rectangular closed environment with and without the presence of fins.

The boundary conditions in their work are similar to the present work; so, the upper and lower walls are insulation, and the left and right walls are considered constant temperature. It is also placed on the left wall of the fin. The test was performed at three different wall temperatures of 55, 60, and 70 °C for the case with/and without fins. In their work, the visual study of the melting process and the quantitative and qualitative information on the melting phenomenon were obtained directly by using digital photos and simultaneously examining the evolution of the melting process and recording the temperature in the middle plate of the water heater. They concluded that with the increments in the NoF, the unheated area becomes smaller. In the end, they extracted the empirical relationship between Nusselt number and liquid fraction in dimensionless parameters. The current study is entirely different from the previous works regarding the investigated parameters, the numerical solution method, the obtained results, and the boundary conditions. In the following, we will investigate the effect of various factors on the temperature field and liquid fraction.

Table 1
The physical properties of solid paraffin as a PCM [34].

Properties	Solid phase
MT	55 (°C)
Latent heat	142.7 (kJ/kg)
Thermal conductivity	0.24 (W/m.K)
Density	670 (kg/m^3)
Specific heat (C_p)	2.0 (kJ/kg.K)

Table 2
Changes of MT vs. increase in the number of nodes

MT (s)	Number of nodes	The number of grid elements
3820	7820	7788
3841	11728	11260
3862	14780	14322
3869	17642	17244
3871	21438	21008

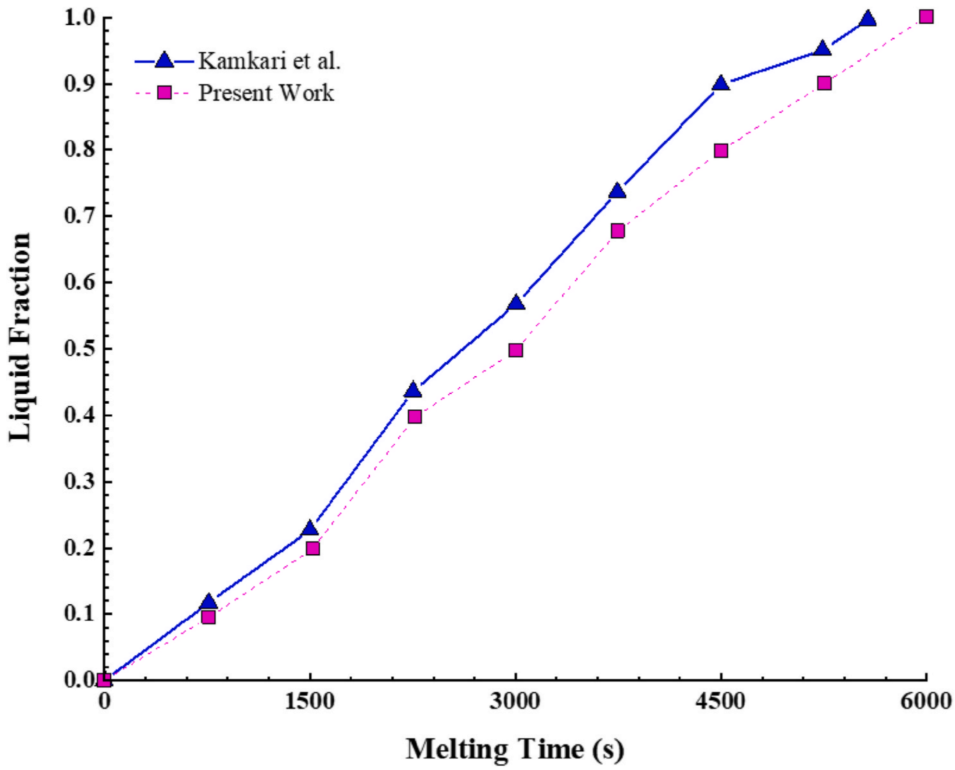

Fig. 5. Comparison of the present work with the experimental work of Kamkari et al. [35].

6.1. *Investigation of the effect of the NoF*

Fig. 6 shows the effect of adding the NoF on the MT. The MT diminishes with the increments in the NoF.

According to Fig. 6, the complete MT for case A (without fins) is about 3860 s. Based on the calculations, the reduction of complete MT for case B (with 3 fins) is 71%. It can also be seen from this figure that increasing the NoF has a significant effect on the MT of the PCM, especially for more fins. This effect is because by increasing the NoF, the HT contact surface is added, and more heat is transferred to the material. Fig. 7 shows the T contour according to the NoF for samples A and B after 1000 s.

Fig. 8 shows the contour of the liquid fraction over changes in the NoF for samples A and B. With the increase in the fins, a larger amount of the PCMs becomes liquid. According to Fig. 8, the average T increments with increasing the NoF, which reduces the MT of the PCM. The HT between the converter's hot surface and the PCM's surface occurs by the displacement HT method. A thin layer is formed in the fins' upper part, expanding over time and increasing the liquid fraction. The heated liquid is directed upwards owing to the density difference, representing natural convection HT.

6.2. *Investigating the effect of fin height*

Fig. 9 shows the effect of H on reducing the MT, as it can be seen that the MT diminishes with the increment of H. The MT reduction at H of 3, 4, and 5 cm equal to 48, 61, and 74%, respectively. Increasing the H of the fins has a significant effect on the MT of the PCM. This effect is because of the increments of the contact surface between the hot surfaces and the PCM.

Fig. 10 shows the temperature contour in terms of H changes for Case B at heights of 3, 4, and 5 cm for 1000s.

7. Conclusion

This research discusses the effect of height (3, 4, and 5 cm) and NoF on the performance of the HE in Fluent software. The contours

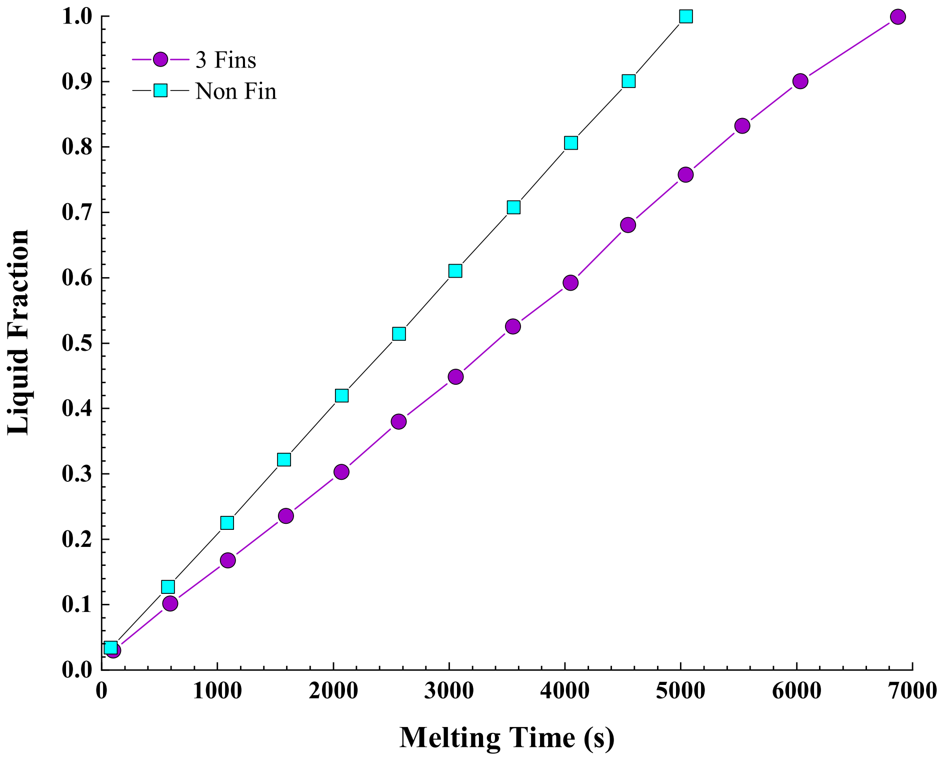

Fig. 6. The effect of the NoF on reducing the MT.

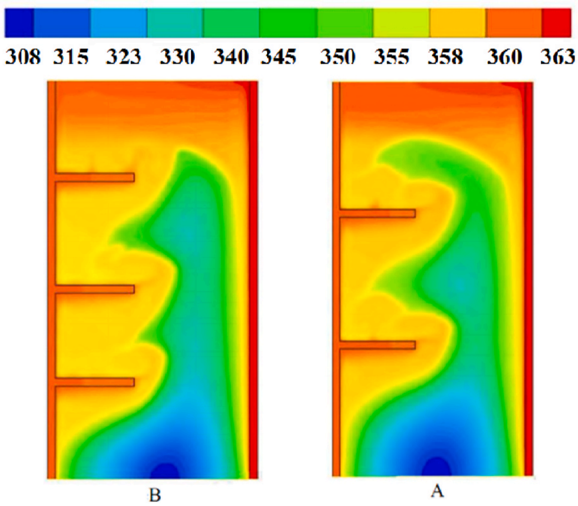

Fig. 7. The T contour with the time of 1000 s according to the increase in the NoF.

of temperature and liquid fraction were obtained for different parameters. The summary of the results is as follows:

- The MT for case A (without fins) is about 3860 s. Based on the calculations, the reduction of MT for case B (with 3 fins) is 71%.
- The heated liquid is directed upwards owing to the density difference, representing natural convection HT.
- With the increments in the NoF, the unheated area becomes smaller.
- Increasing the NoF significantly affects the MT of the PCM, especially for more fins. This effect is because by increasing the NoF, the HT contact surface is added, and more heat is transferred to the material.
- The MT reduction at H of 3, 4, and 5 cm equal to 48, 61, and 74% respectively. Increasing the H of the fins has a significant effect on the MT of the PCM.

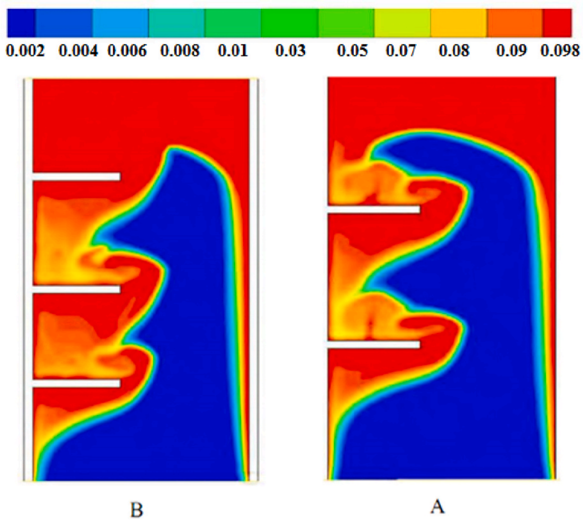

Fig. 8. The contour of the liquid fraction with the time of 1000 s over the increase in the NoF.

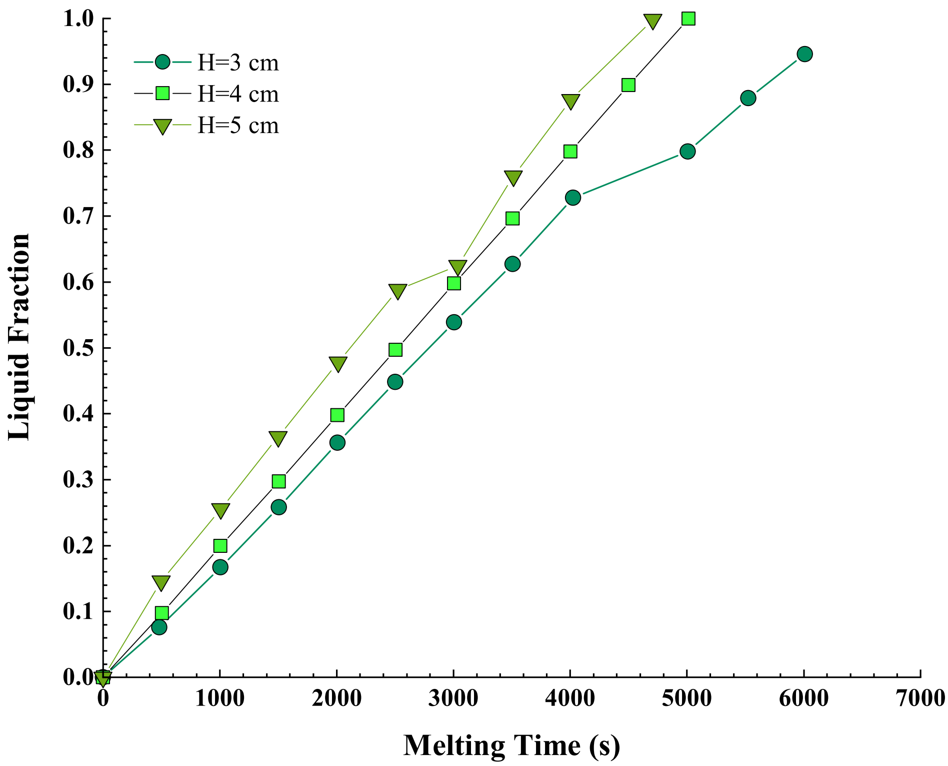

Fig. 9. The effect of H on reducing the MT.

Author statement

Methodology, Software and Validation: Yinling Wang *[1], Navid Nasajpour-Esfahani[2], As'ad Alizadeh[3]*, Ghassan Fadhil Smaisim[4,5], Azher M. Abed[6]*, **Writing - Original Draft**: Yinling Wang *[1], Navid Nasajpour-Esfahani[2], Ali Hashemi[9], Maboud Hekmatifar[2]*, ***Investigation:** Ghassan Fadhil Smaisim[4,5], Azher M. Abed[6]*, Salema K. Hadrawi[7,8], Ali Hashemi[9], Maboud Hekmatifar[2]*, Revision: Yinling Wang *[1], Navid Nasajpour-Esfahani[2], As'ad Alizadeh[3]*, Ghassan Fadhil Smaisim[4,5], Azher M. Abed[6]*, Salema K. Hadrawi[7,8], Ali Hashemi[9], Maboud Hekmatifar[2]*

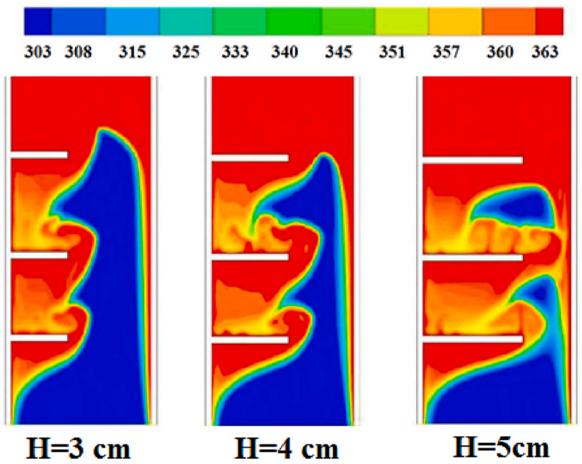

Fig. 10. The T contour with the passage of 1000 s based on the increase in H.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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