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# Compound usage of L shaped fin and Nano-particles for the acceleration of the solidification process inside a vertical enclosure (A comparison with ordinary double rectangular fin)

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## ABSTRACT

Performance enhancement of energy storing unite is a very important issue in renewable energy systems. In the present investigation, L shaped fins with two different orientations and various geometrical properties were considered to enhance the solidification performance inside a vertical enclosure. Furthermore, effect of two types of Nano-particles with different concentrations were evaluated. It was found that the application of downward L shaped fin is better than upward form in solidification process. Also, results revealed that case with same length in vertical and horizontal part of L shaped fin has best performance. Furthermore, results presented that there is no need to use high cost Nano-particles of Cu because low cost Nano-particles of  $Al_2O_3$  have better performance in considered issue. Best performance was related to case 3 which had 12.3% enhancement in the solidification time. Also, between the downward fins, the best case was related to case 8 which provided about 21.5% reduction in the solidification time. Furthermore, it was found that the application of  $Al_2O_3$  with concentration of 2% and case 8, provided about 27% improvement in the total melting time when compared to the Base case.

## 1. Introduction

Energy has become the most important issue in the lives of human beings [1] [–] [3]. The lack in sources of fossil fuels, economical constraints and the environmental effects of the fossil fuels have raised the importance of the investigation on the improvement of the

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utilization of renewable energy sources [4,5]. One of the most important energy utilization methods is the application of latent heat thermal energy storage (LHTES) systems [6]. However, the aforementioned systems have insufficient thermal conductivity which affects their charging and discharging process. To solve this issue, researchers have proposed to use fins, Nano-materials, porous media and different types of phase change materials [7,8]. Amongst all the mentioned techniques the application of fins due to their easy fabrication, low cost and high performance has gained attention. Numerous investigations have applied the fins to enhance melting and solidification process of the LHTESs. A summary of the investigations in this regard is provided in the following.

Gürtürk and Kok et al. [9] expressed a new orientation of the fins to improve the melting and solidification process of a thermal energy storage heat exchanger. They reported that the appropriate design of the fins could enhance the melting process up to 65%. Huang and Liu [10] evaluated the effect of fractural three type fin on the LHS unit. Their results presented that the utilization of fractural fins is more effective in the solidification process. Their results presented that by using fractural fins the solidification time could be reduced by up to 49.2%. In another investigation, Yu et al. [11] evaluated the effect of fractural fins on melting process of a LHS unit. They reported that by using optimal form of fractural fins, the melting time diminishes by 26.7% and the heat storage rate raises by 45.4%. Mahdi et al. [12] proposed a novel arrangement of fins inserted within a triples finned heat exchanger which as used as the thermal storage unit. They mentioned that the proposed arrangement of fins have better performance within the pure PCM rather than Nano-enriched PCMs. Meng et al. [13] probed the effect of copper made Foam fin on the melting performance a rectangular PCM enclosure. Zheng et al. [14] probed the application of three shaped fins to enhance the solidification process of a heat exchanger. They reported that the efficiency of the heat exchanger with three shaped fins in comparison with the traditional longitudinal fins could increase up to 53%. The influence of fins orientation and arrangement on the performance of a double tube LHS system with horizontal orientation was probed by Nie et al. [15]. Through their investigation the length and the number of fins were considered as the affecting parameters. They reported that in a constant volume of fins the application of longer fins could be more effective. Santos et al. [16] evaluated the solidification process around a fin tube and developed correlations to predict the thermal performance of the PCM material around the considered tubes. Their investigations presented that the developed correlations could predict the total melting time with a deviation of about 1.03%. Alizadeh et al. [17] probed the influence of using V shaped fins in the acceleration of the solidification process of the triplex-tube LHTES system. Also, they compared the effect of V shaped fins with the application of Nano-particles. They reported that by using V shaped fins more accelerated solidification process could be achieved. The effect of fins on the performance of a shell and tube heat exchanger used in an ice-storage system was probed by Zhang et al. [18]. They reported that the height of fins is the main factor which affects the performance of the ice storage system. Hosseinzadeh et al. [19] reported that the application of triplet fins could clearly influences the performance of the triplex thermal energy storage heat exchanger. They developed an accurate correlation for the prediction of the full time of solidification process. In another investigation, Hosseinzadeh et al. [20] evaluated the presence of three shaped fins in comparison with bare tubes. They reported that the usage of three like fins would diminish the solidification time by up to 78%. Nóbrega et al. [21] probed the solidification process of PCM around a vertical finned tube. They stated that augmentation in number and width of the fins leads to enhancement of the solidification process. They reported that there could be an optimized value in fin number and fin width after which no significant enhancement in the solidification process could be observed. The influence of longitudinal trapezoidal fins on the solidification process of a TES system was also evaluated by Huang and Yao [22]. They performed a 2D simulation and reported that using the considered form of the fins could lead to a 45% reduction in the total solidification time. Furthermore, in another study the effect of triangular longitudinal fins was evaluated by Yao and Huang [23]. They reported that by using the triangular fins, the solidification process of the TES system could be decreased up to 31% when compared to the ordinary rectangular fins. In another investigation, Ma et al. [24] proposed circular longitudinal fins and evaluated their effect on the solidification performance of a TES system within a shell and tube heat exchanger. They stated that by using the mentioned type of fins, the heat extraction exergy efficiency and heat release exergy efficiency of the thermal energy storage system could be up to 90% and 45%, respectively.

Through the recent decade the application of Nano-particles inside different thermal systems has gained the attention [25,26]. The simultaneous application of Nano-particles together with different type of fins was also considered as effective method to enhance the thermal performance of energy systems [27]. Ren et al. [28] probed the influence of optimized triangular fins together with Nano-particles. Their investigations presented that the augmentation of Nano-particles volume fraction increases the effective viscosity of the PCM material increases which weakens the buoyancy induced flows. Keshteli and Sheikholeslami [29]. probed the effect of Y shaped fins and nano-particles of  $Al_2O_3$  on the charging and discharging process of a triplex-tube system. They reported that the application of nano-material could enhance the melting and solidification process up to 6.4% and 12%, respectively. Furthermore, they reported that the application of Y shaped fins decreases the melting and solidification time up to 38% and 5%, respectively. Hajizadeh et al. [30] investigated the influence of nano-enhanced PCM with longitudinal Y shaped fin in the solidification of the TES system. They reported that the application of CuO Nano-particles and considered fins could reduce the solidification time up to 70%. In another investigation, Sheikholeslami et al. [31] stated that the utilization of triangular fins with nanoparticles of CuO could lead to performance enhancement of about 44.88% for a triplex heat exchanger within the solidification process of a thermal energy storage unit.

From the above literature, it could be understood that the form and orientation of the fins is a major factor having significant influence on the solidification process of the TES system. One of the most important TES systems is the vertical PCM enclosures which are widely used in building energy industries and also is applied in cooling of the electronic systems. Consequently, investigations on the improvement of the performance of these systems is worthy from the view point of thermal and electronic engineers and designers. The novelty of the present investigation consists of the following points. Through the present investigations, the effect of different form of "L" shaped fin were evaluated. Two different forms of downward and upward L shaped fin were considered. Also, for each form of the L shaped fin, the effect of length of horizontal part ( $L_H$ ) and vertical part ( $L_V$ ) were also assessed. Furthermore, for the best case obtained from the aforementioned evaluations, the effect of two different types of Nano-particles with different concentrations were

investigated. Up to author’s knowledge and based on the above mentioned literature, through the previous investigation the effect of geometrical properties of “L” shaped fin together with the effect of fin form and Nano-particles were not assessed before.

**2. Model definition and governing equations**

Through the present investigation, the effect of various types of L shaped fin together with the effect of Nano-particles were evaluated. The base model consisted of a vertical square shaped enclosure that included double rectangular horizontal fins. Whereas, the L shaped fins with two different upward and downward orientation were considered as the novel form of fin. Fig. 1 A and B present the schematic of the properties of considered geometrical model in the present investigation. The length of the vertical part ( $L_V$ ) and horizontal part ( $L_H$ ) of the L shaped fins were considered as the geometrical variants of the present investigation. Also, the Nano-particles of the Cu and  $Al_2O_3$  with the volume fractions of 1% and 2% were added to the base phase change material. The base phase change material was considered to be the Lauric Acid. Table 1, present the different cases considered in the present investigation. The thermo-physical properties of the considered Nano-particles as well as the Lauric Acid were represented in Table 2.

To simulate the solidification process of the considered model the Enthalpy porosity process was utilized [4,6]. The Phase change materials considered in the present investigation was considered to be an incompressible and Newtonian fluid. The effect of the thermal expansion coefficient was neglected. Due to the very low amounts of the buoyancy induced flows through the phase change process, the flow was considered to have a laminar regime. It is noteworthy that in the considered simulation method, the calculating domain was pondered as a porous medium where the volume fraction of each certain cell is the representative of the porosity of each cell. Indeed, the regions with the porosity of 1 represent the completely solid region and the areas with the porosity values of zero, show the completely melted parts. The above mentioned assumptions with respect to the presentation of the Nano-material has led to simulating the solidification process with the aim of the following governing equations. The governing equations for the conservation of mass, momentum and energy are formulated as below.

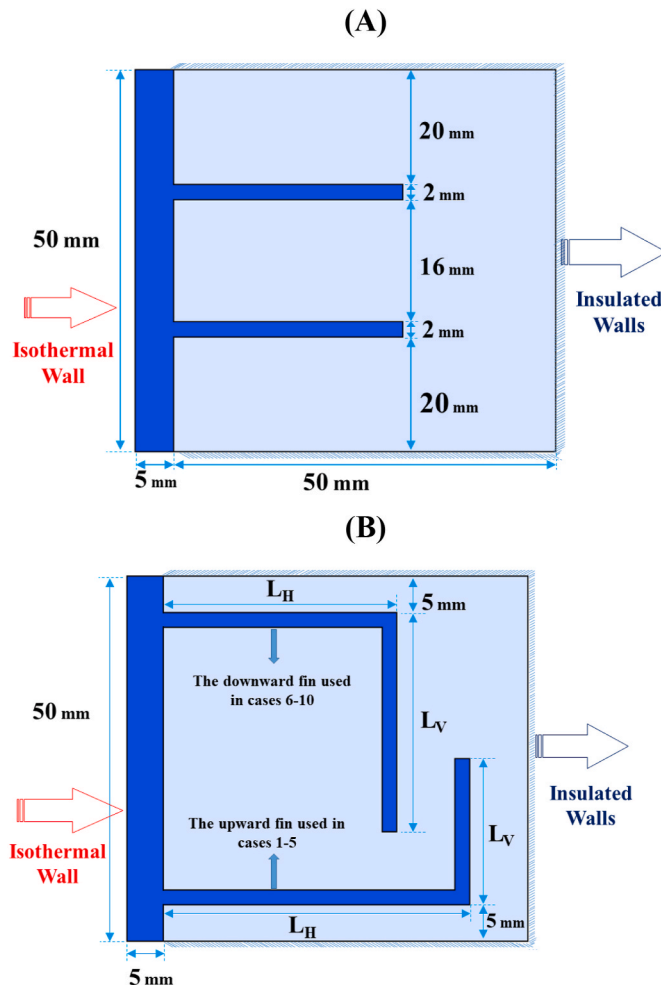


Fig. 1. Schematic of the base mode and L shaped fins.

**Table 1**  
Presentation of the different cases considered in this investigation.

Case number	L <sub>H</sub>	L <sub>V</sub>	PCM material	cooled wall temperature (K)	Fin orientation
1	20	40	Lauric Acid	298.15	Upward
2	25	35	Lauric Acid	298.15	Upward
3	30	30	Lauric Acid	298.15	Upward
4	35	25	Lauric Acid	298.15	Upward
5	40	20	Lauric Acid	298.15	Upward
6	20	40	Lauric Acid	298.15	Downward
7	25	35	Lauric Acid	298.15	Downward
8	30	30	Lauric Acid	298.15	Downward
9	35	35	Lauric Acid	298.15	Downward
10	40	20	Lauric Acid	298.15	Downward
11	30	30	Lauric Acid+ Al2O3 1%	298.15	Downward
12	30	30	Lauric Acid+ Al2O3 2%	298.15	Downward
13	30	30	Lauric Acid+ Cu 1%	298.15	Downward
14	30	30	Lauric Acid+ Cu 2%	298.15	Downward

**Table 2**  
Properties of lauric acid [32].

Parameter	Lauric acid	Cu	Al <sub>2</sub> O <sub>3</sub>
Specific thermal capacity solid/liquid (kJ/kg.K)	2.18–2.39	381	765
Melting temperature (C)	43.5–48.2	–	–
Latent heat of fusion (kJ/kg)	187.21	–	–
Thermal conductivity solid/liquid (W/m.K)	0.16/0.14	387.6	40
Density solid/liquid (kg/m <sup>3</sup> )	940/885	8978	3970

$$\frac{\partial \rho_{np}}{\partial t} + \Delta \cdot \rho_{np} \vec{V} = 0 \tag{1}$$

$$\rho_{np} \frac{\partial \vec{V}}{\partial t} + \rho_{np} (\vec{V} \cdot \Delta) \vec{V} = -\Delta P + \mu_{np} (\Delta^2 \vec{V}) - \rho_{np,ref} \beta_{np} \varepsilon (T - T_{ref}) \vec{g} - \vec{S} - \vec{F} \tag{2}$$

$$\frac{\varepsilon \partial \rho_{np} C_{p,np} T}{\partial t} + \Delta (\rho_{np} C_{p,np} \vec{V} T) = \Delta (K_{e-np} \Delta T) - S_L \tag{3}$$

At the above equations, the mean values of the thermal conductivity of the Nano-PCM were considered as the effective thermal conductivity of the phase change material through the solidification process [33,34] and is calculated as follows.

$$K_{e-np} = (1 - \varepsilon) K_{porous} + \varepsilon K_{np} \tag{4}$$

The variants of  $\rho$ ,  $t$ ,  $g$  and  $\vec{u}$  denote the values of density, time, gravitational acceleration and velocity, respectively. Furthermore, the term  $S$  was considered as a source term that is expressed as the below formulations.

$$\vec{S} = A_m \frac{(1 - \lambda)^2}{\lambda^3 + 0.001} \vec{V} \tag{5}$$

Through the above equation the term  $A_m$  was assumed to have the value of  $10^5$  [33,35]. Also,  $\lambda$  is defined by the following equation.

$$\lambda = \frac{\Delta H}{L_{np}} = \begin{cases} 0 & \text{if } T < T_{solidus} \\ 1 & \text{if } T > T_{liquidus} \\ \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} & \text{if } T_{solidus} < T < T_{liquidus} \end{cases} \tag{6}$$

In equation (6), the  $\Delta H$  is the energy that the phase change material achieves or loses through the phase change process. At the time that the phase change material is completely solid the  $\Delta H$  will occupy the value of Zero. However, for the completely liquid form the mentioned term will have the value of latent heat of blend of Nano-PCM ( $L_{np}$ ). It should be noted that through the mushy zone the term

$\Delta H$  was calculated according to the temperature of each certain cell. The formulation 7 to 8 were used to calculate the  $\Delta H$ :

$$H = h + \Delta H \quad (7)$$

Though which the  $h$  was defined as below:

$$h = h_{ref} + \int_{T_{ref}}^T C_{p,np} dT \quad (8)$$

Besides, the term  $\vec{F}$  in equation (2) was defined by equation (9):

$$\vec{F} = \left( \frac{\mu_{np}}{K} + \frac{\rho_{np} C |\vec{V}|}{\sqrt{K}} \right) \vec{V} \quad (9)$$

In equation (9), the variants of  $C$  and  $K$  defined by equations (10) and (11), respectively [33].

$$C = 0.00212(1 - \varepsilon)^{-0.132} \left( \frac{d_l}{d_p} \right)^{-1.63} \quad (10)$$

$$K = 0.00073 d_p^2 (1 - \varepsilon)^{-0.224} \left( \frac{d_l}{d_p} \right)^{-1.11} \quad (11)$$

In equations (10) and (11), the variants of  $d_l$  and  $d_p$  are named as pore size and Ligament diameter and are calculated by equations (12) and (13).

$$d_l = 1.18 d_p \sqrt{\frac{1 - \varepsilon}{3\pi} \left( \frac{1}{1 - e^{-(1-\varepsilon)/0.04}} \right)} \quad (12)$$

$$d_p = 0.0254 / \omega \quad (13)$$

Also, the term  $\vec{S}_L$  (as the source term) is expressed as below:

$$\vec{S}_L = \frac{\varepsilon \partial \rho_{np} \lambda L_{np}}{\partial t} + \Delta (\rho_{np} \vec{V} \lambda L_{np}) \quad (14)$$

As is known the addition of Nano-particles leads to variation in the properties of the phase change material. It is noteworthy to be mentioned that through the present investigation all the properties of the phase change material were considered to be constant except the thermal conductivity of the phase change material. The thermo-physical properties of the Nano-pcm are calculated as below.

$$\rho_{np} = \varnothing \rho_n + (1 - \varnothing) \rho_{pcm} \quad (15)$$

$$C_{p,np} = \frac{\varnothing (\rho C_p)_n + (1 - \varnothing) (\rho C_p)_{pcm}}{\rho_{npcm}} \quad (16)$$

$$L_{np} = \frac{(1 - \varnothing) (\rho L)_{pcm}}{\rho_{npcm}} \quad (17)$$

$$\mu_{np} = 0.983 e^{(12.959\varnothing)} \mu_{pcm} \quad (18)$$

$$\beta_{np} = \frac{\varnothing (\rho \beta)_n + (1 - \varnothing) (\rho \beta)_{pcm}}{\rho_{npcm}} \quad (19)$$

$$k_{np} = k_{pcm} \times \frac{k_n + 2k_{pcm} - 2(k_{pcm} - k_n)\varnothing}{k_n + 2k_{pcm} + (k_{pcm} - k_n)\varnothing} + 5 \times 10^4 \beta_k L_f \varnothing \rho_{pcm} k_{pcm} C_{p,np} \sqrt{\frac{BT}{\rho_n d_n}} f(T \cdot \varnothing) \quad (20)$$

$$f(T \cdot \varnothing) = (2.8217 \times 10^{-2} \varnothing + 3.917 \times 10^{-3}) / T_l - (3.0669 \times 10^{-2} \varnothing + 3.91123 \times 10^{-3}) \quad (21)$$

To solve the above equations, the numerical method based on the FVM method was used. To couple the pressure values to the velocity equations the SIMPLE algorithm was utilized. Besides, the PRESTO methods were utilized for the correction of the pressure equation. Also, the second order upwind method of discretization was used for the energy and momentum equations. The convergence criteria for each of the equations associated with continuity, momentum and energy were considered to be the residual values of  $10^{-4}$ ,  $10^{-5}$  and  $10^{-5}$ , respectively.

### 3. Independency analysis and validation of model

To check the credibility of outcomes of numerical simulations, the mesh independency and time independency analysis is urgent. Table 3, shows the results of total melting time for various cell numbers considered in this investigation. As could be seen, the deviation between the total melting time has reached the value of less than 1% in the cell numbers of 8900 and 1500. Consequently, the model has become independent to the cell numbers in the cell number of 8900.

Also, to check the time independence of the present model, four time steps of 0.1s, 0.2s, 0.3s and 0.4s were considered. Fig. 2, presents the melt fraction results versus time for different time steps considered in the present investigation. It could be seen that the melt fraction results associated with time steps of 0.4 and 0.8s were almost identical which presented the independence of the model to the time step size. Subsequently, the time step of 0.4 was chosen to conduct the rest of the investigation.

Another factor that is important in the reliability of the results is the comparability of the outcomes of present investigation with those published before. Fig. 3 A and B, expresses a comparison of melt fraction results and a certain point temperature results of the present investigation with results of Kamkari et al. [36]. The temperature results were related to the certain point denoted as the T1 point in the paper presented by Kamkari et al. [36]. Looking at Fig. 3 A and B, it could be realized that the maximum difference the outcomes of the present investigation and the results of Kamkari et al. [36] were about 5% for both melt fraction results and temperature results which presented a good reliability of the present paper.

### 4. Results and discussion

The present investigation deals with the influence of two different modes of L shaped fins and the effect of addition of Nanoparticles of CuO and Al<sub>2</sub>O<sub>3</sub> on solidification process of a vertical enclosure occupying the Lauric acid as the phase change material. In this part and at the first subsection the effect of L shaped fins are evaluated. Whereas, the influence of addition of mentioned Nanoparticles (with the best case of first subsection) are assessed in subsection 4.2.

#### 4.1. Effect of L shaped fin

##### 4.1.1. Solidification process

Fig. 4, shows the contours of melt fraction for Base case and cases 1 to 5. As mentioned before, the cases 1 to 5 were related to upward orientation of L shaped fins through which the vertical and horizontal part of each case has certain length. Through the enclosure with the Base fin, the solidification begins near the cooled wall and expand along with the horizontal direction of the enclosure. The presence of double fins helps to receive the thermal energy from right part of the enclosure and speeds up the solidification process in the regions near the right side of the enclosure. However, the presence of upward L shaped fins (based on the length of vertical and horizontal part) provides certain behavior to the solidification process. From the melt fraction counters of case 1, it could be observed that the solidification has been accelerated in the left-bottom side of the enclosure. Also, the vertical part of the L shaped fin speeds up the solidification process in the central area of the enclosure. Indeed, the presence of L shaped fin accelerates the heat extraction by means of heat conduction through L shaped fin. At the cases 2–5 the mentioned behavior for the case 1 is repeated. However, the variation in length of vertical and horizontal part has provided some important characteristics for the enclosure. For example, by the increment of length of horizontal part, the solidification process shifts to the right-bottom side. Also, in the central regions the solidification is accelerated. Whereas the solidification in the upper regions of the vertical enclosure were slowed down.

Fig. 5, depicts the evolution of melt fraction for the cases 1 to 5. It could be observed that evolution of melt fraction in the cases 1 and 2 are slower than the base case especially after the second of about 4000s. In the mentioned time step, the left side of the fin is completely solidified and the right part remains in fluid form. Indeed, in these conditions the heat transfer occurs almost in the horizontal direction. Considering, the point that the buoyancy induced motions occur in vertical direction, the buoyancy induced (gravity induced) motion will not be significant and the heat extraction due to convective heat transfer will be weak in the solidification process of the mentioned cases at the aforementioned time period. Consequently, the speed of the solidification process was reduced. On the other hand, the cases 3–5 have better solidification performance than the Base case. In these cases, the bottom sides of the enclosure were solidified sooner than the upper parts. consequently, in this region the temperature is lower than upper parts which increases the density of phase change material in this part. By the increment of the density in the lower parts, the buoyancy induced flows find more significant role in the heat extraction process. Indeed, as the gravity induced motions increase the heat extraction by means of convection increases. It is notified that case 3 has the most negative slope after the second of 5000s which means that after the second of 5000 the case 3 has the most accelerated solidification process. It could be mentioned, that through the case 3 because of the same length of horizontal and vertical part of the L shaped fin both the conduction and convective form of heat transfer has major role in solidification process which leads to faster solidification process.

Fig. 6, depicts the melt fraction contours for cases 6–10. Through case 6, it could be seen that the presence of downward L shaped

**Table 3**  
Mesh independency results.

Cell number	2750 cells	5600 cells	8900 cells	15000 cells
Total melting time (s)	5600	5800	6000	6080

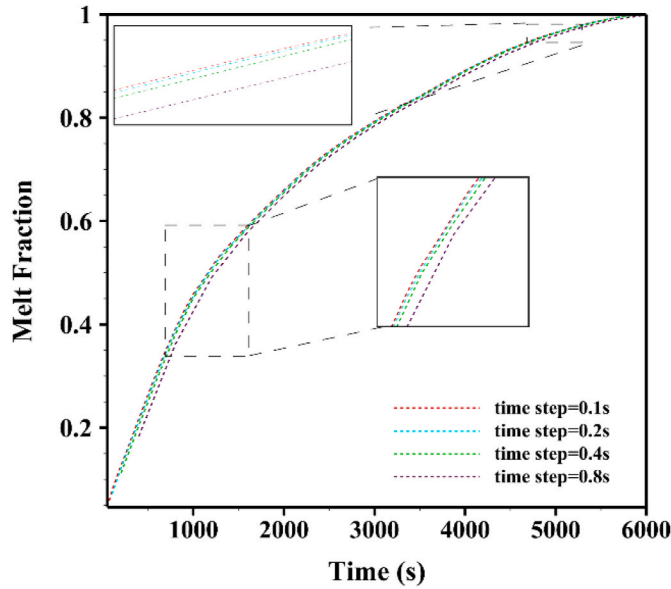


Fig. 2. Melt fraction results vs different considered time steps.

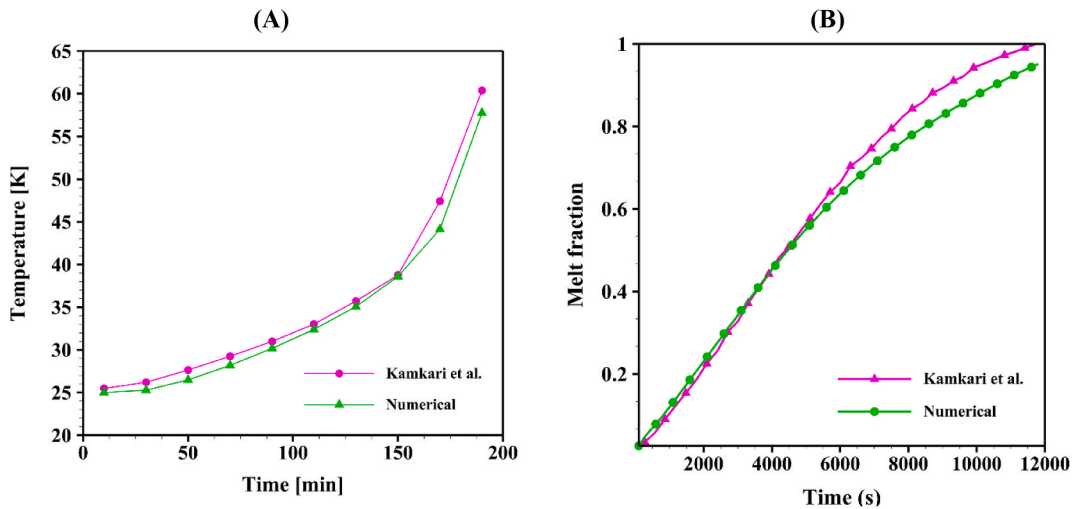
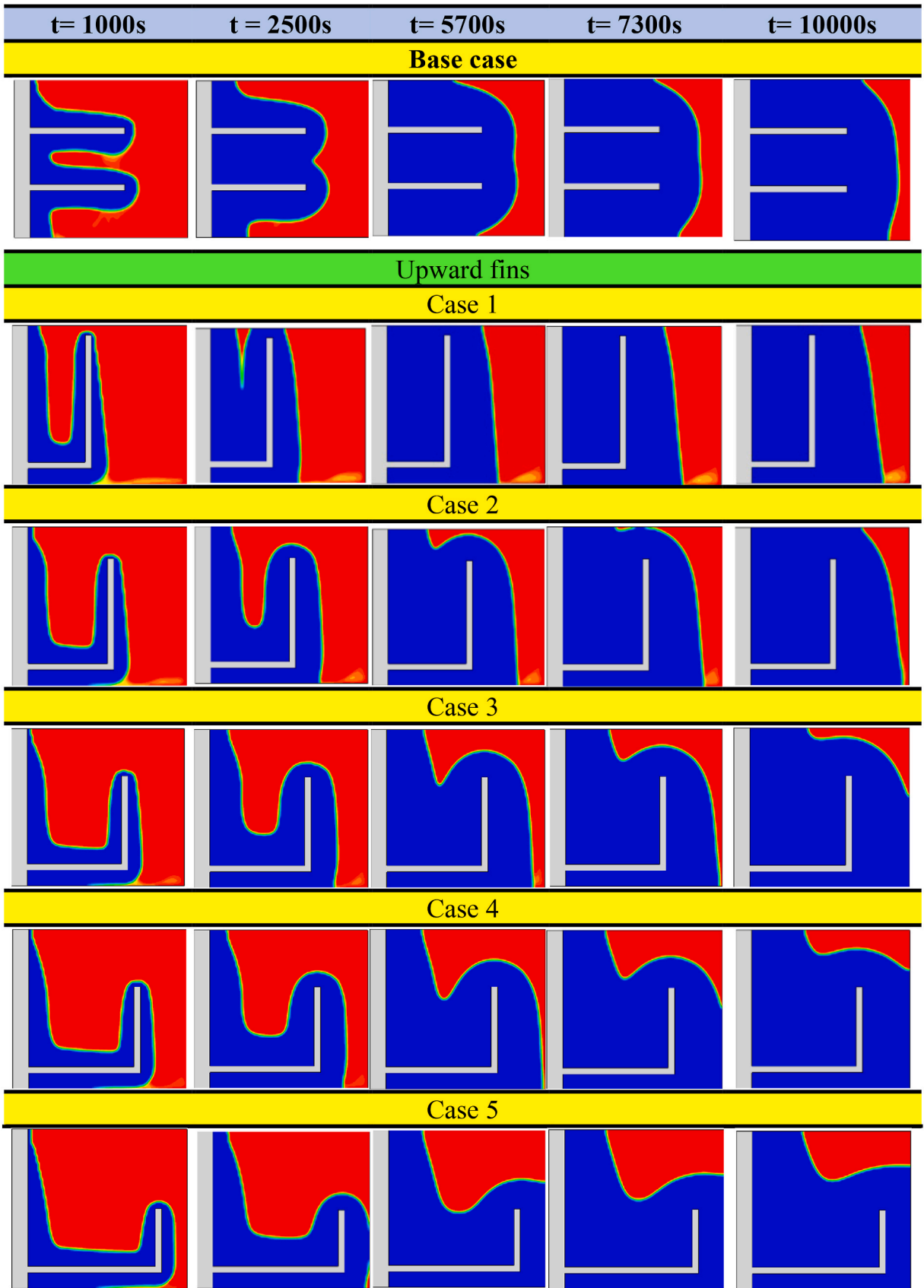


Fig. 3. (A) comparison of temperature results; (B) comparison of melt fraction results.

fin's geometry has a major influence on solidification of the top side of the PCM enclosure. By the increment of the horizontal part of the fin, the solidification process initially starts from the top side and the solidification in the bottom side starts later. Indeed, the solidification in the bottom side is slower than the upper part. Also, the increment of the horizontal part (which is equal to decrement of vertical part) shifts the beginning of the solidification to the central points of the enclosure. Consequently, the regions between the cooled wall and the vertical part of the fin remain unsolidified up to the second of about 5000. These regions are more significant for the cases 9 and 10 at which the bottom side and right-bottom side are the last parts that the PCM changes to solid form. Indeed, as the top side becomes solid the temperature of these parts goes down. This causes the liquid material to be trapped in the lower part. Subsequently, the only mechanism for the heat extraction will be the conduction which is slower inside the liquid part. Consequently, the overall process of the solidification slows down too.

Fig. 7, presents the solid fraction evolution versus time for the cases 6–10. It could be seen that up to the second of about 4000s, the solid fraction evolution is almost the same for all cases. However, after the second of 4000s, the cases 6 and 10 have slower evolution than the base case. It could be explained from the solid fraction contours of Fig. 6 that through the case 6 and 10, after the second of 4000s, the regions between the vertical part of fin and the cooled wall are completely solidified. In this condition the solidification process (heat transfer) happens in the horizontal direction and since there is negligible temperature difference between the top side and bottom side of the enclosure, there are no significant buoyancy induced flows occur and consequently the heat extraction process only





← Fig. 4. Melt fraction contours for base fin and Upward L shaped fins.

occurs based on the conduction mechanism which is weaker than the convection inside the liquid part. Indeed, through the cases 6 and 10, the heat is extracted from certain regions (by means of conduction and through the L shaped fins) that after the solidification of these regions the buoyancy induced flows are weakened which causes to reduction of the role of convection at the solidification of phase change material. For the case 10, since the liquid part was trapped in right-bottom side the heat conduction reduces. For the cases 7, 8 and 9 the solidification performance of the enclosure was better than the Base case. For the cases 8 and 9, the reduction slope of the melt fraction curves was very significant after the second of about 6000s. For the cases 8 and 9, the presence of the fin was in a form that the buoyancy induced motions could participate in the heat extraction system. Consequently, the heat extraction occurs faster than other cases and leads to a better solidification performance.

Fig. 8 A and B, present the total solidification time vs time for cases 1–10. It could be seen that among cases 1–5 the least solidification time was related to case 3 which had the total solidification time of 17900s. It should be mentioned that case 3 provided up to 12.2% enhancement in the solidification time. For the downward L shaped fins (cases 6–8) the least solidification time was related to the case 8 which had the total solidification time of 16000s. It is noteworthy that the case 8, provided an improvement of 21.5% in the total solidification time. From the above statements, it could be seen that case 8, had the best performance among all the cases considered in this investigation. The case 8 was related to a downward L shaped fin and had dimensions of 30 mm and 30 mm associated with the vertical part and horizontal part of the fin, respectively.

#### 4.2. Effect of addition of nano particles

In the present section, the simultaneous effect of addition of L shaped fin and the usage of Nano-particles are evaluated. In this section the case 8 is used as the base mode which had the best performance amongst the 10 cases investigated in the previous section. The effect of Cu Nano-particles with the concentration of 1% and 2% as well as the effect of Nano-particles of  $Al_2O_3$  with the same concentrations were evaluated. Fig. 9 A presents the evolution of melt fraction values versus time (s) for the various cases considered in the present section. It could be observed that at the beginning of the solidification process the evolution of melt fraction curves is almost the same for all cases. However, after the second of the 2000s the differences were noticed. It is observed that the cases with Nano-particles of Cu have worse performance than case 8. However, the cases with Nano-particles of  $Al_2O_3$  are better than case 8. However, the effect of Nano-particles of Cu was completely different. Not only the addition of Cu particles worsens the solidification performance, but also the increment of the mentioned Nano-particles percentage has negative effect on the solidification. It should be noted that inside a vertical enclosure both the conductivity of the PCM and the buoyancy (gravity) induced flows have certain influence. Besides, it should be considered that addition of Nano-particles has influence on both the thermal conductivity and the flow resistance. Consequently, from the above mentioned statements it could be concluded that the addition of Cu has more effect on the flow resistance than the thermal conductivity of the PCM. Consequently, the cases with Nano-particles of Cu have worse solidification performance than other cases. Indeed, the addition of Nano-particles of  $Al_2O_3$  not only provides better conductivity for the phase change material, but also, due to the reasonable increment in the viscosity of the PCM, the buoyancy (gravity) induced motions could provide their role in the augmentation of heat transfer inside the phase change material and leads to better solidification process.

Fig. 9 B, presents the total solidification time for the cases with Nano-particles as the additives. From the mentioned figure, it could be observed that the case with Nano-particles of  $Al_2O_3$  and concentration of 2% has the least solidification time which had the total solidification time of 14800. Comparing the case with  $Al_2O_3$  2% and case 8, it is observed that the utilization of  $Al_2O_3$  has provided up to 8% reduction in the total solidification time. Furthermore, if the case with  $Al_2O_3$  2% is compared to the Base case, it will be concluded that the simultaneous usage of downward L shaped fin and Nano-particles of  $Al_2O_3$  with concentration of 2% would provide a 27% reduction in the solidification time. However, the addition of Cu with concentration of 2%.

## 5. Conclusions

In this study the simultaneous influence of using L shaped fin and Nano particles of Cu and  $Al_2O_3$  were numerically examined. Two types of L shaped fin, fins, namely downward and upward were evaluated. For each mode of L shaped fins, the effect of variation in the vertical part and horizontal part were examined. The best case of effect of L shaped fin was chosen to investigate the effect of Nano-particles. For each of the mentioned Nano-particles two different concentrations of 1% and 2% were examined too. The below findings were the most important findings of the present investigation.

- The application of L shaped fins instead of double rectangular fins could have both positive and negatives effect on the solidification performance of a vertical enclosure.
- The negative and positive effect on the solidification performance could be observed in both the upward and downward fins.
- Amongst the upward fins, case 3 has the best performance which provided 12.3% improvement in the solidification time.

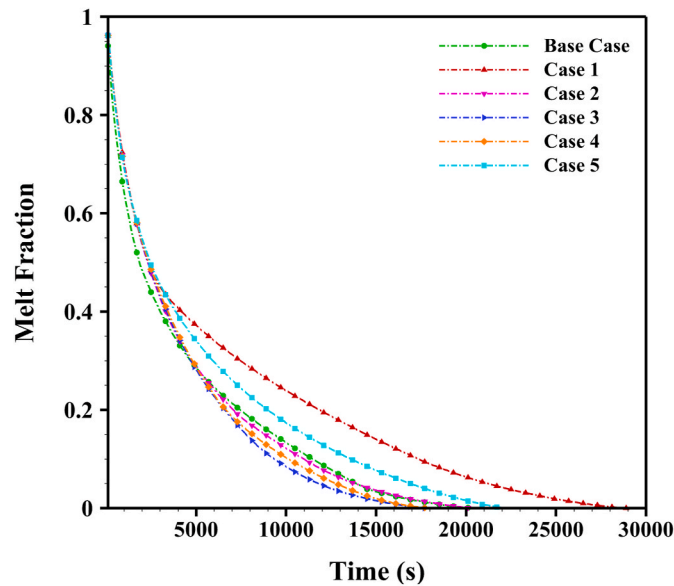


Fig. 5. Evolution of melt fraction vs time for cases 1-5.

- Amongst the downward fins, case 8 was the best one which provided up to 21.5% improvement in the solidification time.
- For the individual effect of L shaped fins, case 8 was the best case which had the length of 30 mm in both vertical and horizontal parts.
- The application of Cu Nano-particles has not a very significant effect on the total solidification time. However, the application of  $Al_2O_3$  has a major effect on the solidification performance.
- The application of  $Al_2O_3$  2% with the fin of case 8, provided about 27% improvement in the total melting time when was compared with Base case (vertical enclosure with double rectangular fins).
- The increment of the concentration of Cu Nano-Particles worsens the solidification process, whereas the increment in the concentration of  $Al_2O_3$  Nano-particles enhances the solidification performance.
- As the overall outcome, the present study revealed that the application of downward L shaped fin is better than the upward form in the solidification process inside a vertical enclosure. Besides, it was observed that the case with the same length in vertical and horizontal part of L shaped fin has the best performance. This point denotes that when it comes to real applications, the downward L shaped fin with the vertical and horizontal parts having the same length would have the best performance in the solidification process. Also, it presented that there is no need to use high cost Nano-particles of Cu because the low cost Nano-particles of  $Al_2O_3$  have better performance.

#### CRedit authorship contribution statement

**Yuning Chen:** Resources, Formal analysis, Investigation. **Li Feng:** Resources, Writing – review & editing, Writing – original draft, Writing and editing-revised draft, Investigation. **Sajjad Shaukat Jamal:** Resources, Formal analysis. **Kamal Sharma:** Writing – review & editing, Conceptualization. **Ibrahim Mahariq:** Software, Post processing, Mesh generation. **Fahd Jarad:** Writing – review & editing, Methodology, Formal analysis. **Akbar Arsalanloo:** Methodology, Formal analysis.

#### 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.

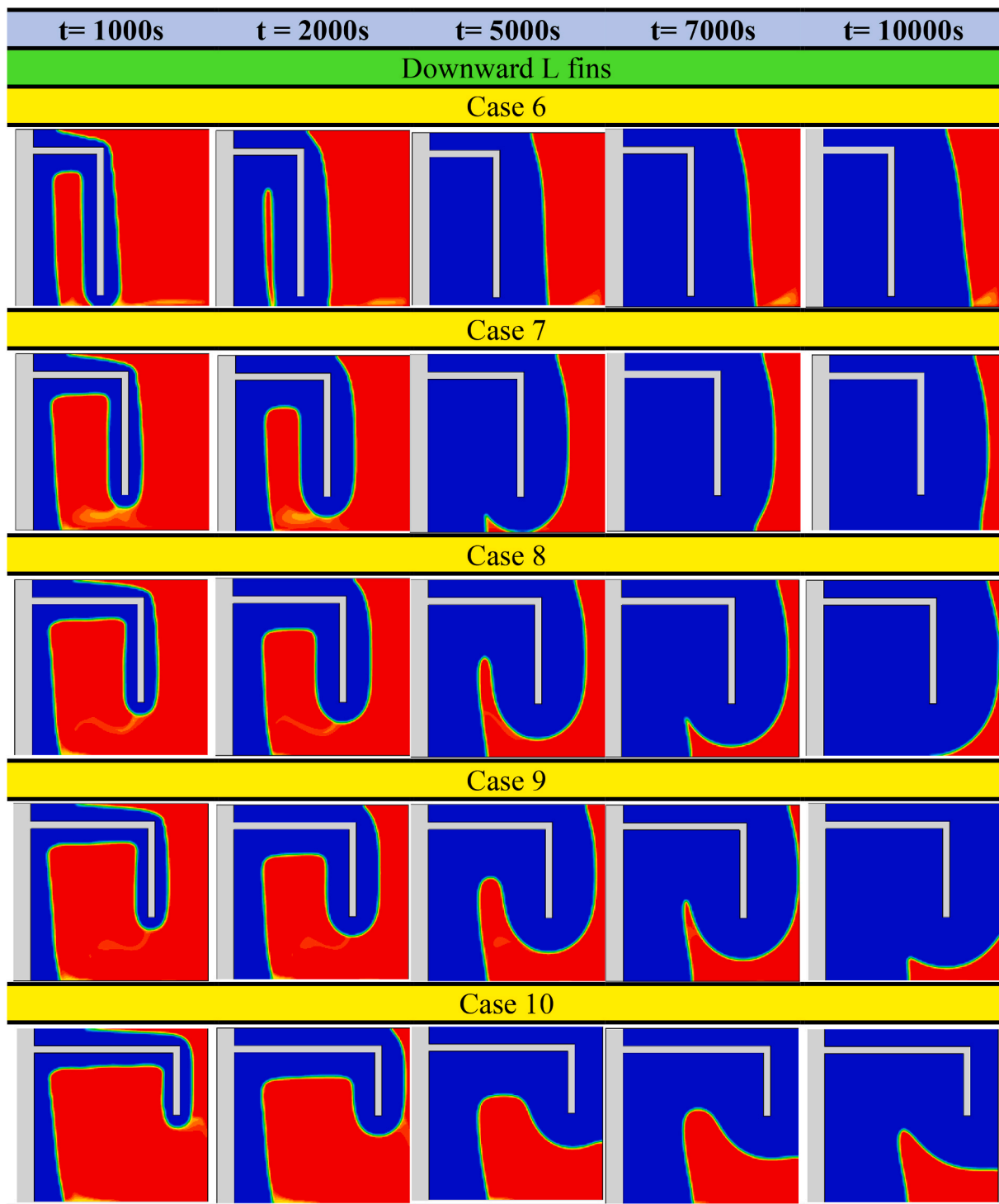


Fig. 6. Melt fraction contours for Downward L shaped fins.

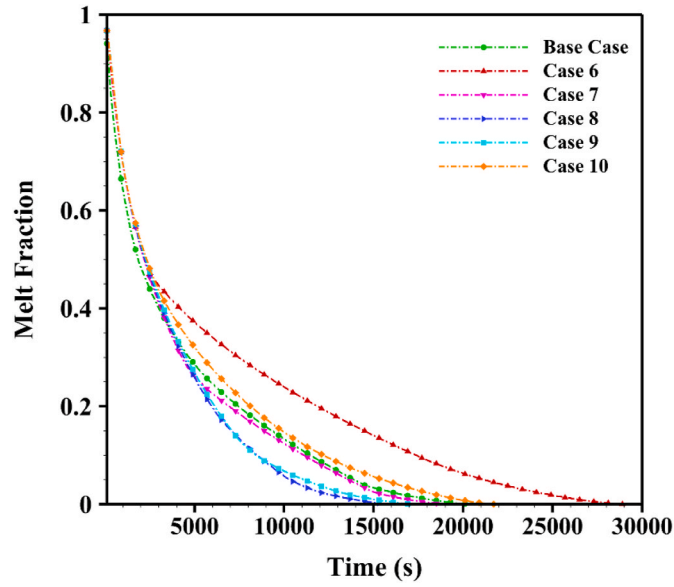


Fig. 7. Evolution of melt fraction vs time for cases 6-10.

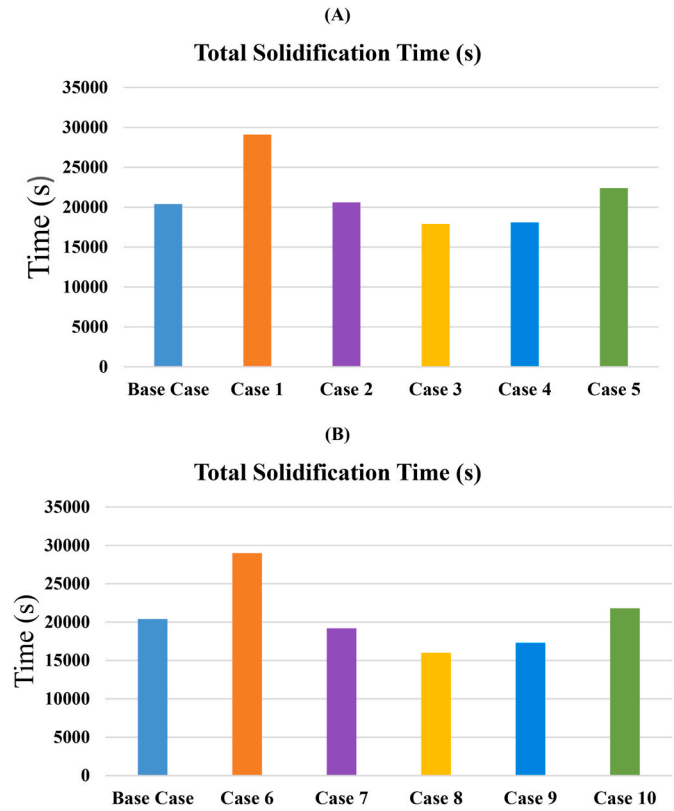


Fig. 8. Total solidification time for: A) cases 1-5; B) cases 6-10.

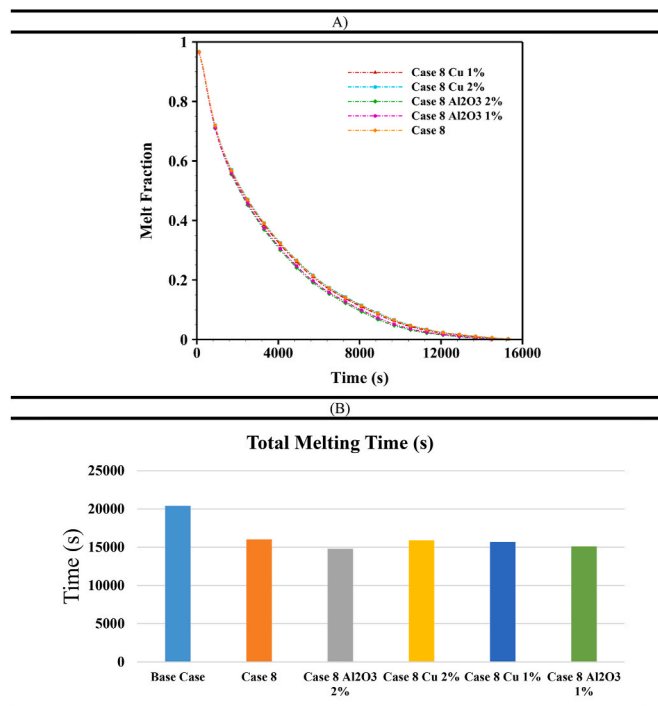


Fig. 9. A) Evolution of melt fraction values for the cases with Nano-particles; B) total melting time for the cases with Nano-particles.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.csite.2021.101415>.

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