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Numerical Study of Latent Heat Storage Unit Thermal Performance Enhancement Using Natural Inspired Fins

Numerical Study of Latent Heat Storage Unit Thermal Performance Enhancement Using Natural Inspired Fins

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Abstract. Thermal energy storage plays an important role to control the intermittent nature of renewable energy. This paper presents a numerical study to the enhancement of the melting and solidification rates of phase change material (PCM) mounted in the annulus of a double pipe latent heat storage unit (LHSU). The enhancement is achieved by using the natural inspired fins (branch shape fins). One and two bifurcations branch fins were designed and their effect on the thermal performance of the LHSU was studied and compared with the longitudinal-finned. The result shows that the melting and solidification processes of the branch shape fins contributed to the improvement by about 44% and 46% respectively.

1. Introduction

The continual growth of human population (world population was 1 billion in 1800 and 7.8 billion in 2020 [1]) leads to increase the energy demand significantly. However, the fossil fuel obstacles (limitation, unfair distribution and their environmental issues) have caused many issues such as increase fuel price, energy crisis and environmental pollution. The renewable energy project shows a promising technology to overcome these issues. However, the intermittent nature of renewable energy such as solar and wind energy is another challenge to utilize the renewable energy [2-3]. Energy storage can play an important role to balance the energy supply and demand. Thermal energy storage (TES) is developed to store the thermal energy for many applications such as electricity generation (solar power planet) and for residence place heating and cooling. One of the most important application is to store the heat (from sun ray) during the day time and release it on the demand of night time. There are three main types of TES: thermo-chemical heat storage, sensible and latent heat energy storage. The latent heat energy storage shows an attractive method for thermal energy storage due to their high capacity of storage and can deliver the heat at almost constant temperature. The latent heat energy storage unit (LHSU) use phase change material (PCM) to store the heat in melting phase and release it during solidification process. Many materials such as paraffin wax can be used as PCM, depending on their melting temperature and the application requirement [4]. Paraffin wax is preferable material for its properties of: non-corrosive material, non-toxic, chemical stable, has high latent heat of fusion and negligible super cooling. Most PCM including the paraffin wax have a major drawback of

its low thermal conductivity which leads to reduce the heat transfer and thus the phase change rate leading to inefficient use of (LHSU) [5]. In the recent years, many researchers have carried out attempting to enhance the heat transfer in the PCM. Those researches can be classified to main two lines; the first line is by modifying in the construction of the heat exchanger (such as installing fins) [6-7] and the second line is by enhancing the thermal conductivity of the PCM by making composite material (such as nanoparticles-PCM and metal foam-PCM) [8-9].

[10] performed a numerical and experimental study on the thermal energy storage systems using PCM, the results showed that the melting time enhanced due to increase in natural convection when the storage enclosures have greater width and smaller height. [11] numerically compared the thermal behaviour at vertical and horizontal orientation of a double pipe LHSU. It was found that the horizontal orientation has a better thermal performance than the vertical orientation at the melting process, while no differences where showed between the two orientations at the solidification process. This result was supported by [12]. [13] study a three different annulus configuration of double pipe LHSU; one has circular pipe and the second has a circular finned pipe and the third has an elliptical pipe. It was found that the adding of fins enhance the melting and solidification rate significantly, also it was more efficient during solidification process. While the use of elliptical pipe showed an enhancement of the melting rate with no effect on solidification rate. [14] numerically investigated the effect of downward movement of the inner pipe during the melting rate of PCM of a double pipe LHSU. The results showed that the movement of the pipe downward increases the convection zone and thus enhance the melting rate significantly. [15] experimentally studied the enhancement of melting and solidification rate by adding three longitudinal fins to a vertically installed double pipe LHSU. It was showed that there was an enhancement of $\cong 43\%$ for both melting and solidification rate. [16] performed an experimental study for three different cases of a horizontal orientation double pipe LHSU; without fins, with circular fins and with longitudinal fins. It was showed that the LHSU with longitudinal fins have the best thermal performance during melting and solidification processes. [17] simulated the melting of PCM of a vertical double pipe LHSU under three different operational conditions: nanoparticle concentration, fin angle (α) and fin pitch. The results showed that the effect of adding nanoparticle at $\alpha = -45°$ didn't accelerate the melting process, while it did when $\alpha = +45°$. The fin pitch didn't show a significant effect on the melting process. [18] numerically studied the variation of fins angle (pitch) on the enhancement of melting rate of the PCM mounted in the annulus of a horizontal orientation double pipe LHSU. The numerical results showed that the increasing the fin angle from 60° to 120° enhance the natural convection heat transfer and thus reduce the total melting time. [19] numerically study the thermal performance of a horizontal double pipe LHSU with circular fins under the effect of many parameters. The main finding: showed that when the fins pitch was greater than 4 times of the inner pipe radius, the fin height and the fin thickness have little effect on the energy efficiency ratio and the heat storage rate. On the other hand, when the fins pitch was smaller than 4, the performance of LHSU becomes better with large fins height and width.

All aforementioned literatures are focused on the enhancement of heat transfer in the LHSUs by varying the storage geometry, orientation and/or the design parameters of the fins like fins pitch, height, thickness and numbers. Fins shape has found to be one of the most effective parameters can help to improve the heat transfer characteristics of general heat exchangers. In fact, there are several utilizations of the natural inspired fins can be found in heat transfer applications, more specifically in the surface type, liquid-liquid heat exchangers (for example, see [20]). These fins configurations, however, making the heat exchangers more efficient than the classical geometry. Based on the fact of that always nature inspires human to create successful designs, the present study is focused on usage of an innovative fins shape that can conduct heat better than classical fins shapes. By comparing the task of energy transportation in the fins with the transportation of sensation-impulses in the nerves and also when compare to the transporting of plant nutrients in the tree branches, it can be concluded that the branches shape are efficient way for transportation.

Accordingly, in the present study, as the first time, a new fins shape (branch shape) is designed to improve the heat transfer in the PCM during the melting and solidification process of the LHSU.

Practically, the branches shape fins can be manufactured using metal injection technique [21], which offers high quality parts along with high level of design freedom. The evaluation and comparison of the thermal performance of a branch-fins double-pipe LHSU with a longitudinal-finned double-pipe LHSU is the main aim of the study.

2. Physical model

The effect of adding branches fins on the thermal performance of shell and tube LHSU during both the PCM melting and solidification process was developed in this study. For the purpose of the model validation, the dimensions of the present LHSU were taken similar to that used by [11].

The inner tube was made of aluminum with 0.02 m and 0.022 m internal and external diameters respectively, while the shell diameter was 0.085 m. The annulus area which is formed between the inner and the outer pipes is filled with paraffin wax RT-50 as a PCM. The paraffin wax thermophysical properties are given in table (1) [11, 22]. Two different branch fins were designed to investigate their effect on the enhancement of the melting and solidification processes. The first fins design has two bifurcations (Fig. 1 Case (A)) and the second design has only one bifurcation (Fig. 1 Case (B)). The thickness of branch fin is divided to half at each bifurcation as shown in Figure 1. The thermal behaviour of branch finned LHSU is compared with the thermal behaviour of longitudinal fins LHSU (Fig.1 case (C)). To ensure the comparability among the three studied cases they were designed to have the same geometrical dimension, i.e. all the designs have the same: pipes diameters, fin height (0.03 m), fin surface area (0.00064 m²) and material (aluminum) as shown in Figure 1.
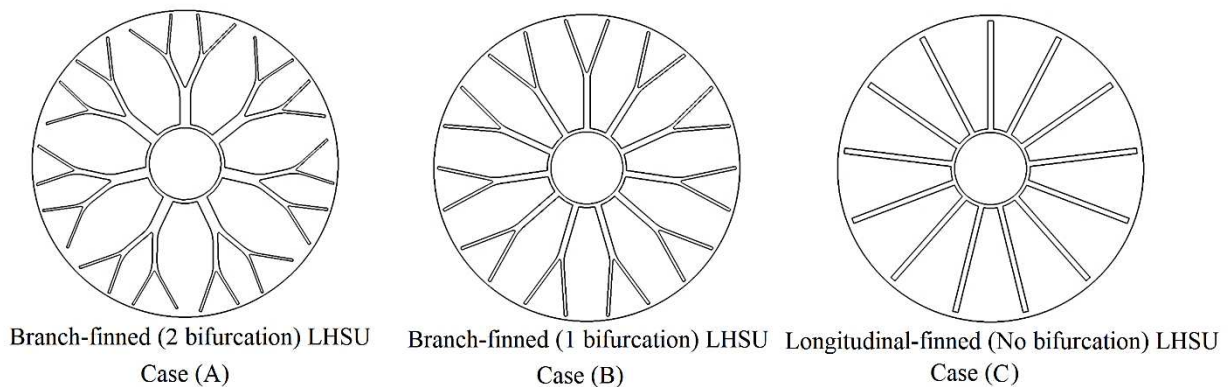

Branch-finned (2 bifurcation) LHSU   Branch-finned (1 bifurcation) LHSU   Longitudinal-finned (No bifurcation) LHSU

Case (A)   Case (B)   Case (C)

Figure 1. sketches of the computational domain: Case A, B and C.

3. Numerical model

To simulate the melting and solidification processes of the PCM, the enthalpy-porosity method [23] was considered. The natural convection was modeled by Boussinesq approximation, and the liquid PCM can move by natural convection, while the solid PCM can't move. The model is one plane (2d) of the cylindrical body. The governing equations of the model can be written in Cartesian form as follows:

Conservation of Mass

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

Conservation of Momentum in the x-direction

$$\rho \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - \frac{\partial P}{\partial x} + S_x \tag{2}$$

Conservation of Momentum in the y-direction

$$\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - \frac{\partial P}{\partial y} + S_y + \rho g\beta(T - T_o) \tag{3}$$

The enthalpy-porosity approach treats the mushy zone as porous medium. The porosity in each element is assumed to be equal to the liquid fraction of that element. The momentum sinks terms S_x and S_y due to reduced porosity in the mushy zone are [23]:

$$S_x = A_{mushy}\frac{(1-\lambda)^2}{\lambda^3 + 0.001}u \tag{4}$$

$$S_y = A_{mushy}\frac{(1-\lambda)^2}{\lambda^3 + 0.001}v \tag{5}$$

Where λ is the liquid fraction that is a value between 0 and 1, depend on PCM temperature:

$$\lambda = \begin{cases} 0 & T < T_{solid} \\ \frac{T - T_{solid}}{T_{liquid} - T_{solid}} & T_{solid} < T < T_{liquid} \\ 1 & T > T_{solid} \end{cases} \tag{6}$$

The coefficient A_{mushy} is the mushy zone constant which is fixed at $10^5\ kg/m^3.s$ in this study as it show good consistency when compare to experimental work [11].

Conservation of Energy:

$$\rho\left(\frac{\partial H}{\partial t} + \frac{\partial}{\partial x}(uH) + \frac{\partial}{\partial y}(vH)\right) = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) \tag{7}$$

In the equations above ρ, P, β, T_o, t, μ, g and k are density, pressure, thermal expansion coefficient, reference temperature, time, dynamic viscosity, acceleration due to gravity and thermal conductivity, respectively. Finally, H is the total enthalpy which a combination of sensible and latent heat effects:

$$H = h + \Delta H \tag{8}$$

where the specific enthalpy is:

$$h = h_o + \int_{T_o}^{T} C_p dT \tag{9}$$

And the enthalpy variation is due to the phase change in terms of the latent heat of the PCM:

$$\Delta H = \lambda L \tag{10}$$

where L is the latent heat of fusion of the PCM, which it varies between zero (for solid PCM) and L or (for liquid PCM).

The initial Temperature for the three cases is 25°C for melting process and 70°C for solidification process. To simulate the heat transfer fluid the inner wall of the inner pipe assumed at a constant temperature of 70°C at melting process and 25°C at solidification process and has no slip conditions. The outer surface of the outer pipe assumed to be well lagged therefore it has been set to be adiabatic.

A second-order up-winding scheme was applied to solve the energy and momentum equations and the PRESTO Scheme [24] was applied for the pressure. A Simplic algorithm [24] was applied to resolve the coupling between velocity and pressure. In order to enhance the convergence stability, the under-relaxation factors of 0.7, 0.3, 0.9 and 1 were considered for the momentum, pressure, liquid fraction and energy respectively as recommended by [22-23]. Convergence of the solution is checked at each time step, and the convergence criteria for the residual of continuity equation velocity components and

energy equation were 10^{-6}. Ansys fluent R.15 commercial CFD software used to simulate the model which utilize the finite volume numerical method [25-26].

The finite volume numerical method required to split the computational domain into small cells (mesh). In order to achieve an independent solution of both the mesh density and the time step. The effects of varying mesh density and time step on the average liquid fraction of the PCM was studied for all cases, but only case (A) for brevity shown in Figure 2 and Fig. 3, respectively. Figure. 2 shows the average liquid fraction curves during melting process of the PCM for meshes with 13300, 21200 and 40300 elements. It is clear from Fig. 2 that the curves for each mesh are qualitatively similar; however, there are insignificant differences when the number of elements in the mesh increased from 21200 to 40300. Figure. 3 shows the average liquid fraction curves during melting process of the PCM for simulation using a time step of 0.2, 0.1and 0.05 second. It is clear from Fig. 3 that the curves for time steps are qualitatively similar; however, there are insignificant differences when the time steps reduced from 0.1 to 0.05. Therefore, a mesh of 21200, 17400 and 6265 elements were chosen for case A, B and C respectively. And time step of 0.1 s was chosen for all cases.
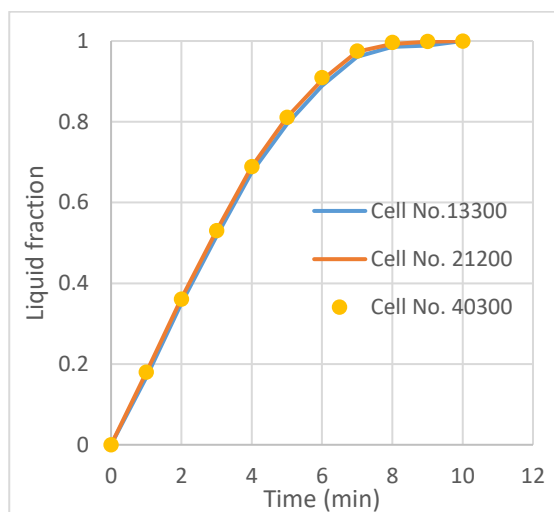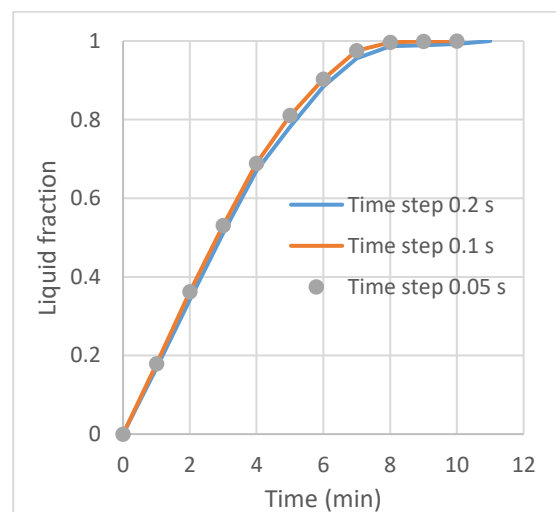

Figure 2. Mesh study of case (A)

Figure 3. Time step study of case (A)

4. Result and discussion

4.1. Model validation

To confidently use the present numerical model for simulating the real case studies, the PCM liquid fraction calculated results were compared against the result of [11], as shown by Fig. (4). It is clear that a good agreement is achieved between the present study results and the result of [11]. Thus, the present numerical model can be dependably used to simulate the melting and solidification process of the PCM in the LHSU.
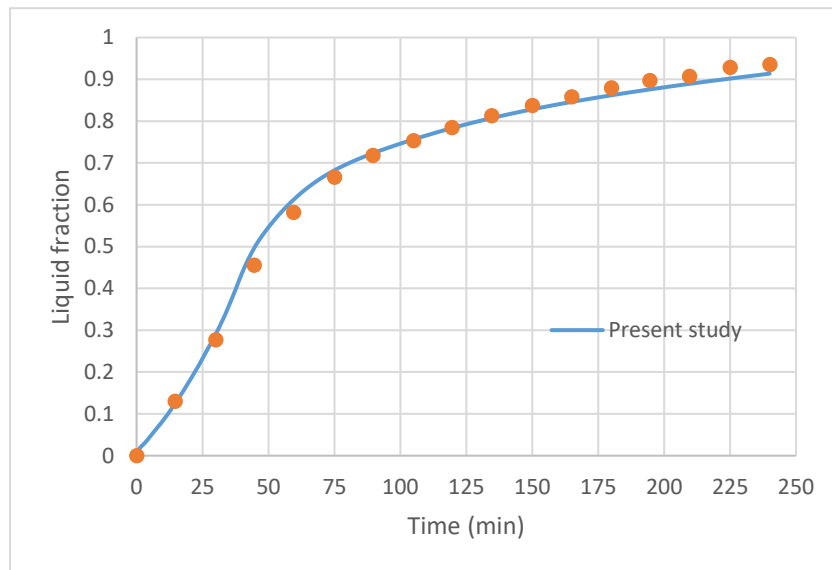
Figure 4. validation of the numerical model with the results of [11] for the liquid fraction of PCM.

4.2. Melting process

The variation of the liquid fraction contour of RT-50 (PCM) with the melting time is shown in Figure 5 for case A (2 bifurcations-branch-fins), case B (1 bifurcations-branch-fins) and case C (non-branch-fins or longitudinal finned tube). The solid and liquid phases were presented by black and white colors respectively, the Figure also shows the temperature contour of the fins. It can be seen that for three cases under study, at the earlier time of melting process a thin layer of the PCM which is adjacent to the fins wall is melted.

This could be due to the conduction of heat from the fins wall to the solid PCM. After a while, (about 6 min) of the melting process the convection effect is clear especially for case C since the melted PCM in the upper part of the shell and tube annulus is more than that at the lower part. As a result the light hot liquid PCM is lifted up by the effect of buoyancy force which increases the hot liquid PCM mass in the upper part and thus increases the melting rate. However, during this period, about 90% of the PCM of case A is melted. This could be attributed to the fast heat transfer rate in the PCM zone due to the efficient distribution of heat transfer surfaces (branches) in the PCM.

 In fact, the shape of the branch fins also offers a low heat transfer resistance in comparison with the non-branch fins shape (longitudinal fins shape) could be another important reason leading to the fast PCM melted in case A, that its thick at the HTF pipe wall (maximum heat flow required) then its thickness reduce accordingly at each bifurcations i.e. this shape has lower resistance to the flow of heat than the non-branch shape. The low thermal resistance contributed by heating up the fins' material which turns in to increase the temperature driving force (ΔT) between the the fins and the PCM. This is of course led to enhance the heat transfer rate to the PCM consequently led to a fast melting of the PCM. See the temperature contours of fins in Figure 5

More interestingly, the Figure (Figure 5) also shows that at the same time period the melting process of case B is faster than of case C although it is slower than case A. This could give an evidence that the heat transfer rate in the LHSU strongly depends on the shape of the fins. Accordingly, the melting process with branch fins is more efficient than of non-branch fins (longitudinal fins) and so by increasing the number of fins' bifurcations the heat transfer rate increases significantly. Unfortunately, due to some mechanical and manufacturing reasons the number of bifurcations in the branch fins is constrained by only two [21].
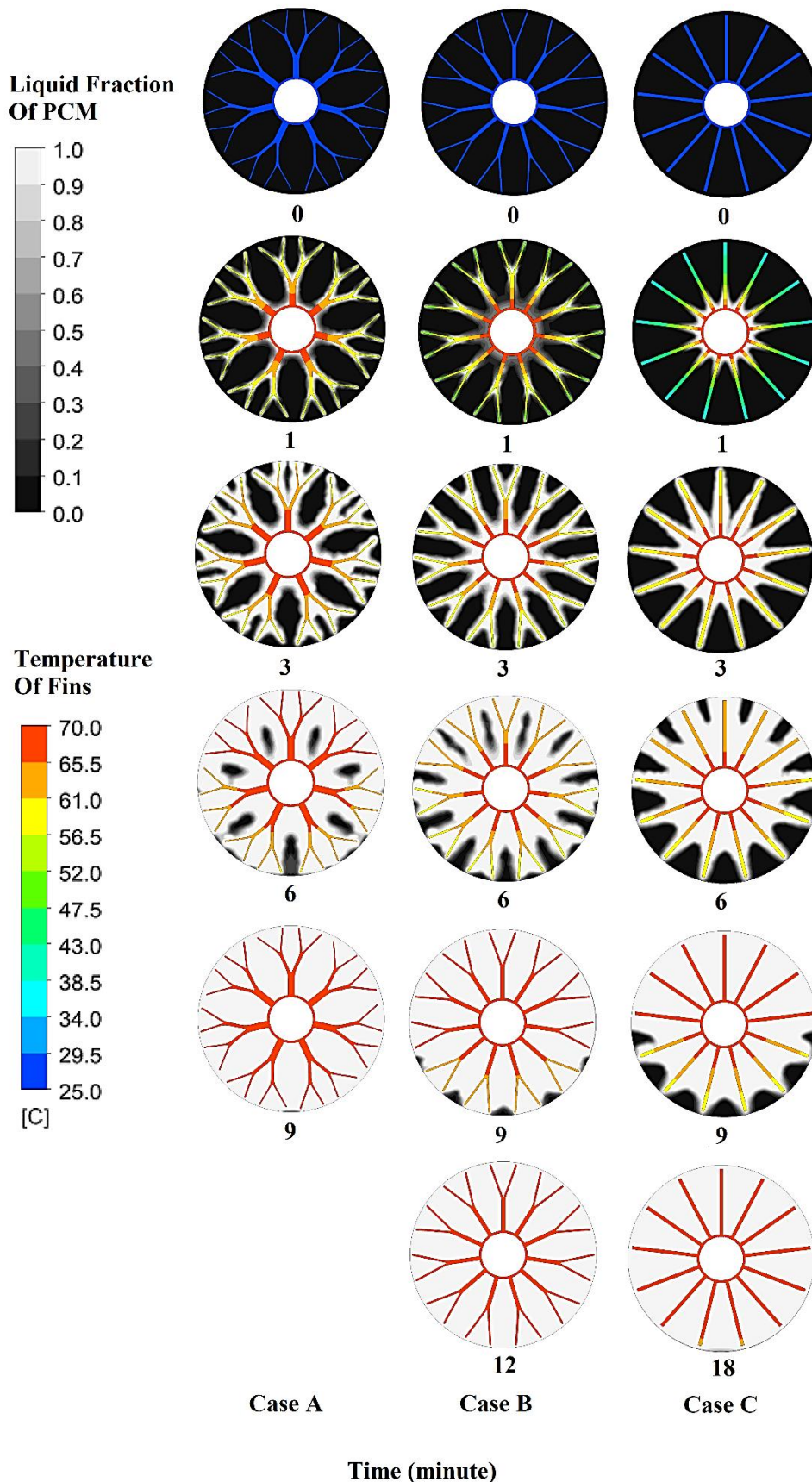
Figure 5. Liquid fraction contours of Case A, B and C during melting process.

After 9 minutes the melting process of case A still the most enhancing case among the three cases under study (case A, B and C). In this context, the PCM was completely melted at nearly 9 min, while the melting time period was longer for case B which the PCM was completely melted at about 12 min. This is entirely different for case C since delay melting is really evident (about 18 min) as shown by Fig. 5. As mentioned above, the well distribution of the branch fins through the PCM could be the reason for the different in the completion of the PCM melting.

Figure 6 shows the variation of the liquid fraction with melting time for the three cases (A, B and C). Obviously, for three cases the liquid fraction increases steeply with time during the first few minute of the PCM melting process. Again, among the three cases the melting process seems superior at case A. Thereafter, liquid fraction of case B being the second while the melting process of case C still at the lowest value. This is completely agreed with our finding above (see Fig. 5) and hence the same justification could be applying here. The Figure also presents a quantitative evidence that the melting rate is enhanced by 44% and 11% for case A and B respectively, when compared to case C.
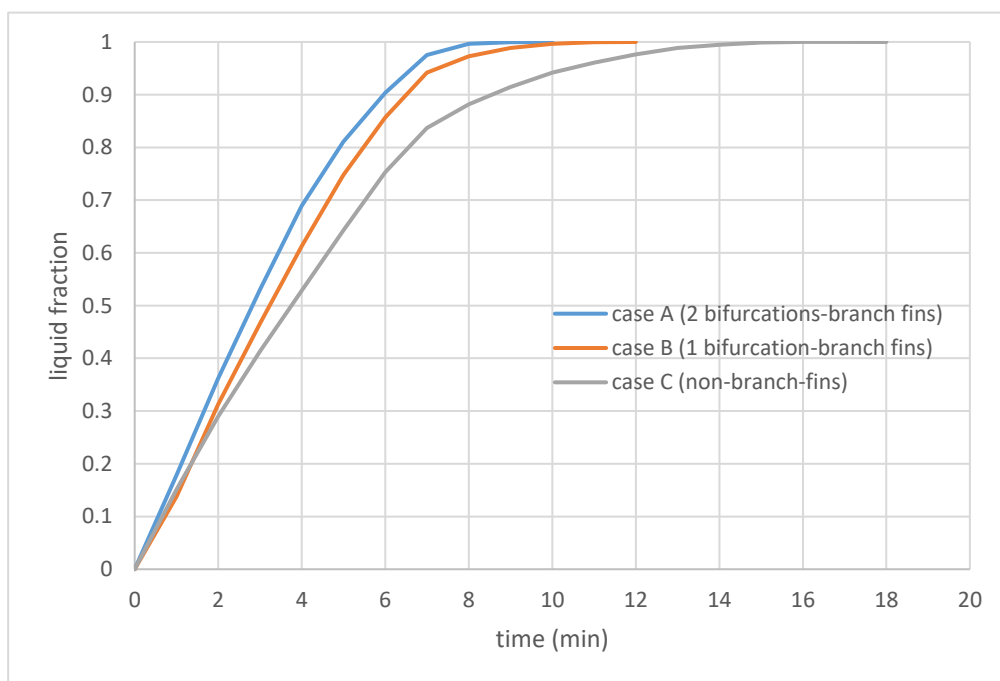

Figure 6. Liquid fraction curves of the PCM during melting process for case A, B and C.

The average temperature of fins of three cases A, B and C during the PCM melting process can be shown by Fig. 7. At the earlier stage of the PCM melting process the temperature of the fins of all cases under study seem increased with same value. This could be resulted from that at this stage (about 1 min) the heat transfer was almost all by conduction. The behavior, however, of the temperature curves is divergence to three different temperature values when convection becomes dominant. Hence the heat exchange rate between the fins and the PCM is intensified, the slop of the temperature curves is reduced which indicates to a high cooling rate of the fins. Nevertheless, because of the different ability of different fins configuration to transfer heat, the temperature of the fins represented by case A still the maximum then case B and finally case C.
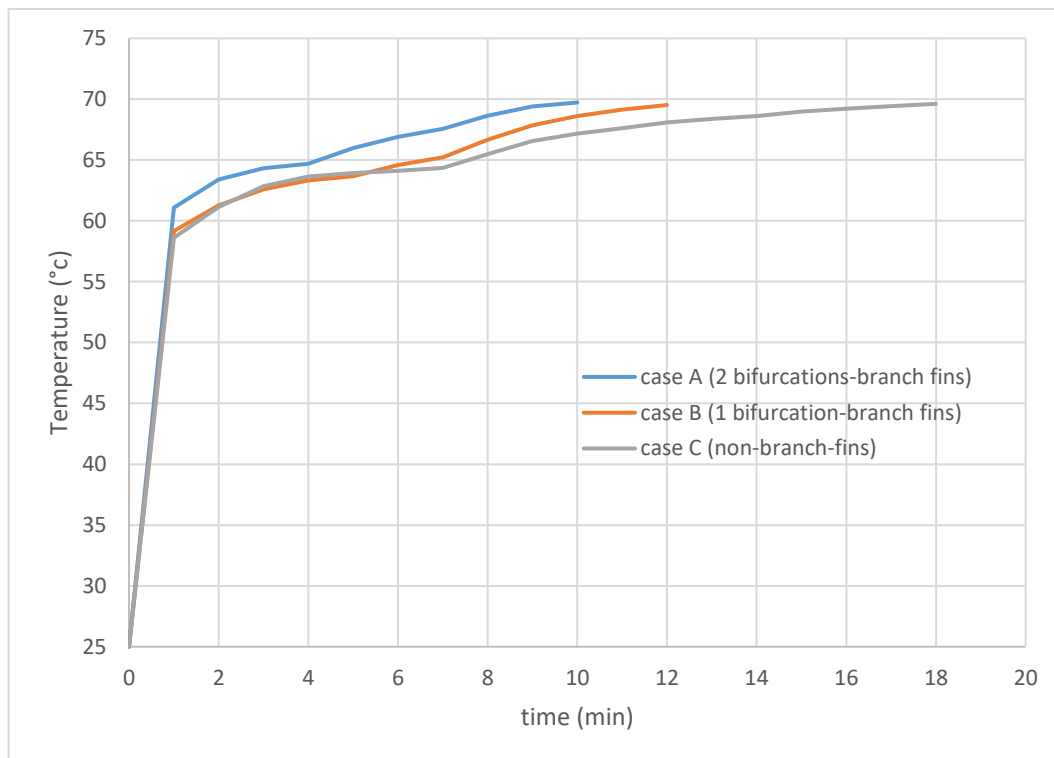
Figure7. Temperature curves of the HTS surfaces (fins) during melting process for case A, B and C.

4.3. Solidification process

The energy stored in the PCM during the melting process would be used for later demand. Hence, study of the thermal behaviour of proposed LHSUs during the solidification process is important. Figure 8 shows the variation of the liquid fraction contours of RT-50 with the solidification time for case A, B and C.

The initial temperature was 70°C for all cases. It can be seen that a thin layer of PCM is solidified at the cold fins wall at the beginning of solidification process. Due to the low thermal conductivity of the PCM the layer produces a high thermal resistance to the flow of heat from the hot PCM to the cold fin walls. This results in decreasing the temperature differences at the PCM zone, which turns in constraining the convection current and making the conduction to become dominated. As the conduction heat transfer mechanism dominates during the solidification process, the time required for completing the solidification process is larger in comparison with the melting process. It is clear from Figure 8 that case A has a superior solidification rate. As mentioned in the melting section, the branch shape fins involve a better heat transfer surface distribution hence the branches of the fins are well cover the hottest PCM area collecting the heat and conduct it to the HTF pipe. Figure 9 shows the average liquid fraction curves of the PCM with the solidification time for case A, B and C. The Figure presents a quantitative evidence that the solidification rate is enhanced by 46% and 37% for case A and B respectively, when compared to case C.
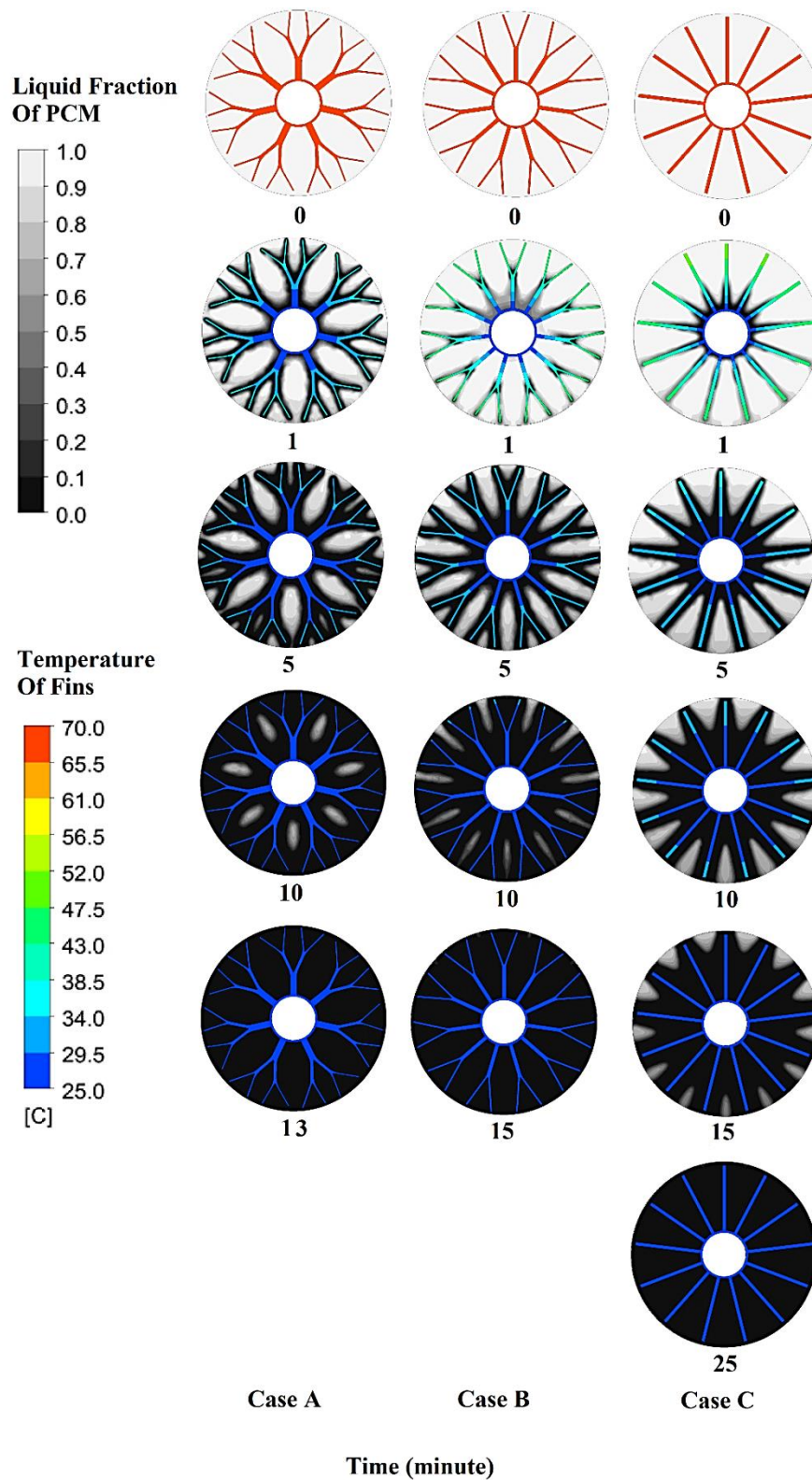
Figure 8. Liquid fraction contours of Case A, B and C during solidification process
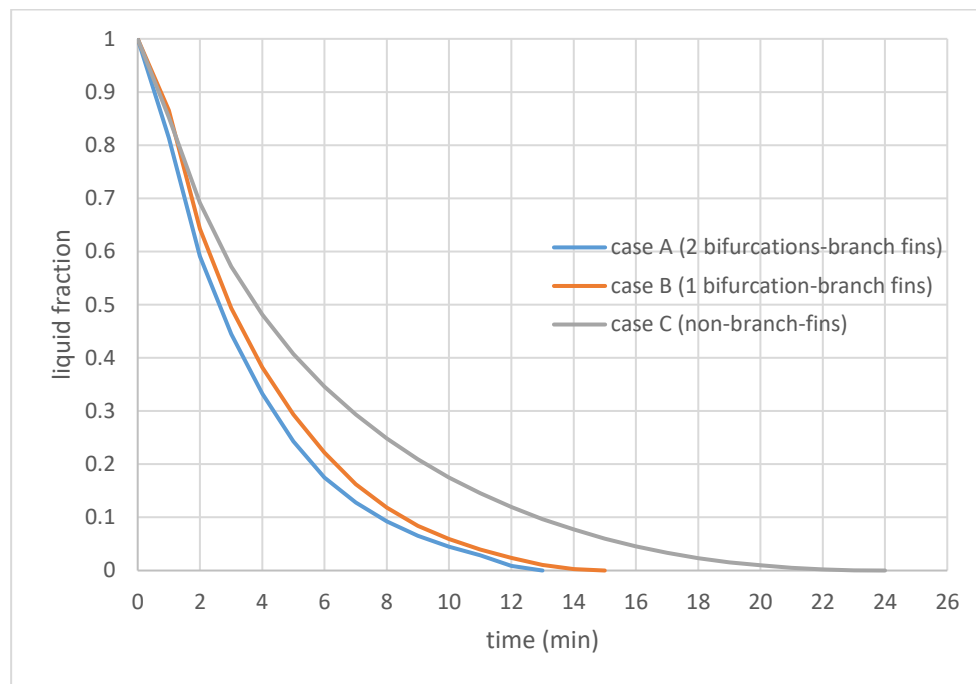
Figure 9. Liquid fraction curves of the PCM during solidification process for case A, B and C.

5. Conclusion

The paper deals with a numerical study of the thermal behaviour of the PCM melting and solidification processes of a double pipe LHSU integrated by natural inspired fins (branch shape fins). Two branch fins were designed; the first one has two bifurcations (case A) while the second has only one bifurcation (case B). The thermal performance of the two cases were compared to longitudinal fins installed in the same size LHSU (case C). The results showed that the melting and solidification rate was enhanced by increasing the number of bifurcations of the branch fins. The average enhancement was found about 45% and 24% for case A and B respectively in comparison with case C.

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