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Numerical investigation of the effect of the number of fins on the phase-change material melting inside a shell-and-tube cylindrical thermal energy storage

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ABSTRACT

A numerical analysis of the fin count that affects phase change material (PCM) melting within a cylindrical shell-and-tube thermal energy storage (TES) is provided. Using the ANSYS/FLUENT 16 tool, the enthalpy-porosity combination was quantitatively evaluated. PCMs made of paraffin wax were used in this experiment (RT42). The results of this investigation show that fins significantly affect melting, which reduces the time required to finish the operation. Since melting relies on natural convection, which has a sluggish rate of heat transfer, the process takes longer when there are no fins. The melting process takes 900 min to finish. The melting fraction grew monotonically with the number of fins, and the curve had an initial sharp trend followed by a gradual one. When more PCMs transitioned from a solid state to a liquid state over time, the pace at which they melted decreased, and the thermal resistance between the solid-liquid interface and the heat transfer surface increased. With the same heat storage effect, the maximum time difference was 236 min, and the biggest time difference was caused by the number of fins at 81.4 %. The total melting time was greatly affected by the number of fins in the design.

1. Introduction

Solar energy is strongly tied to human everyday life and has a substantial influence on the development of modern civilization, which is dependent on several key industries. Most people are aware that certain energy sources ultimately run out and that others have negative environmental consequences. As a result, researchers throughout the globe are working to develop substitute renewable energy sources. The fact that renewable energy is long-term affordable and ecologically good is only one of its many advantages. It has the potential to be utilized everywhere, but the lack of regular access to sources like wind and sunshine is its major constraint

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[1–3]. One method to deal with this is by storing thermal energy. PCMs are the primary materials used in the process of thermal energy storage [4–6].

Many experiments have been conducted on a wide variety of forms that are composed of PCMs, as well as the impact that shape has on the thermal energy storage capacity of a material. According to studies on methods to enhance heat transfer, using of fins seem to be the most successful [7]. Many studies demonstrated the benefit of using numerical projections in experimental experiments [8–10]. The melting of PCMs is sped up with every degree that the temperature of the air that is being introduced increases, and the energy charge for both sensible and latent PCM heat goes up considerably [11–13]. Experiments by Jesumathy et al. [14] and Harikrishnan and Kalaiselvam [15] testified the addition of nanofluid to PCMs to investigate how this would affect the material's capacity for thermal energy storage. In turn, an enhancement of thermal conductivity was concluded due to the addition of nanofluid to PCM, which decreases the required time to finish the melting process. Rizan et al. [16] analyzed the PCM melting process in a rectangular container. According to the study's findings, the melting process accelerates with every increase in heat flow. Ismail et al. [17] conducted a computational investigation on the possibility of PCM-filled cylindrical cells acting as thermal energy storage devices. Because of the PCMs' very high temperature in the center of the PCM cylinder, the cylinders in the first cell of the column melted more quickly than those in the cells that followed it in the column.

Esapour et al. [18] carried out extensive research into how PCMs melt in a shell and tube. It was demonstrated that the melting process has distinct effects on heat tubes. Increasing the inner heat transfer fluid tubes causes an acceleration in the melting process and enhanced heat transport with the addition of the nanoparticle. An experimental examination of shell and tube latent heat storage for solar dryers conducted by Agarwal and Sarviya [19] used paraffin wax as the heat storage medium. According to this study, the impact of natural convection is less significant in the bottom half of the spectrum than in the top.

Niyas et al. [20] numerically investigated the charging and discharging features of a lab-scale latent heat storage (LHS) prototype. To achieve this aim. The researchers developed a model to characterize the latent heat of the PCM and the buoyancy influence of the molten PCM layer. As the performance of the LHS prototype is affected by the number of embedded tubes and fins on the tubes, optimization was carried out to determine the number of tubes and fins on the tubes to ensure enhanced performance of the LHS system. In this regard, faster charging and discharging time can be achieved via increasing the number of tubes and fins with a penalty of increasing the cost and weight of the system. More importantly, the optimization found the necessity of having four embedded tubes and eight fins per tube to make a balance between performance and cost.

Natural convection is the primary mechanism for heat transfer, and melting occurs more quickly near the top owing to the buoyant effect [21]. Sattari et al. [22] presented experimental research on the PCM melting process in a spherical cell. The results indicate that the melting process slows down as cell lead width increases.

In a comprehensive study, Bhagat et al. [23] evaluated the efficiency of a finned multi-tube latent heat thermal energy storage (LHTES) system for a medium-temperature (~200 °C) solar thermal power plant. In this regard, the influence of the number of fins, fin thickness, and fin height on the thermal performance of the LHTES was investigated. In turn, this enabled to study of the influence of different fin configurations on the thermal performance of the LHTES. Using a numerical model based on the enthalpy technique, the researchers optimized the LHTES to ensure a favorable configuration. The results indicated that an increase in the number of fins and fin thickness can significantly the thermal performance of the storage system due to enhancing the heat transfer rate in PCM. Specifically, the fin efficacy was enhanced by 16 % if the fin thickness is doubled. The optimization introduced the successfulness of using 24 fins. And fin thickness of 0.6 mm to have the best performance if compared to other configurations.

Ebrahimi et al. [24] demonstrated that adding nanoparticles to PCM can improve heat transport, shortening the time it takes for the melting process to complete. Yıldız et al. [25] investigated the natural convection heat transfer inside a PCM container that can be a representative model for PV/PCM systems by considering three aspect ratios (AR = 1, 2 and 4), three Rayleigh numbers (Ra = 10^4, 10^5 and 10^6), two types of fins as rectangular and tree-like branching fin, and three different length-to-height ratio of rectangular fin (w/H = 0.3, 0.4 and 0.5). The rates of increment and decrement are presented taking the finless enclosure as the reference case. The computed results revealed that the natural convection is promoted up to 20 %, depending on Ra and fin length by the inclusion of fins when the AR = 1, while it is degraded down by 5.5 % for AR = 4. Interestingly, at AR = 2, the percentage increase and decrease of mean Nu numbers are slighter compared to other aspect ratios.

Qin et al. [26] numerically studied the melting of phase change material (PCM) in a rectangular cavity with heat transfer fluids (HTFs) flowing at both sides from the bottom up (bilateral flow boundary conditions). A parametric study is performed by changing the Reynolds number (Re) of HTF in a range of 1 × 104, 3 × 104, 5 × 104, 7 × 104 and the Rayleigh number (Ra) in a range of 3×10^6, 4×10^6, 5×10^6, 6×10^6. The results showed that the formation of natural convection is due to the impacts of non-uniform heat transfer of HTF and cooling between the solid-liquid interface and liquid PCM. The asymmetric flow boundaries led to various skew forms of the PCM melting process and affect heat transfer and thermal energy storage. Hussein et al. [27] analyzed the PCM's multi-tube melting process. The researchers ascertained that the melting progress speeds up as temperature and tube count rise. The impact of T-shaped fins on PCM melting in a horizontal shell-and-tube storage unit was investigated by Liu et al. [28]. Eight horizontal plate fins with the same overall fin volume as four T-shaped fins were compared to the melting improvement performance of four T-shaped fins. The findings demonstrated that T-shaped fins, independent of the temperature of the heat transfer fluid, can greatly improve the melting process by reducing the total melting time and increasing melting homogeneity. T-shaped fins that are organized laterally, vertically, or at a 45-degree inclination to the horizontal plane reduce melting time by 34.5 % compared to lengthwise plate fins, but only by 8 %.

By incorporating twisted fins in a PCM enclosure with both vertical and horizontal orientations, Li et al. [29] evaluated the performance improvement of a shell and tube latent heat thermal energy storage system in terms of energy and exergy. The melting process was simulated using the Enthalpy-Porosity method. The fins have a continuous heat transfer area and come in single, double, triple, and quadruple fin shapes. A case study about the outcome of entering the fin inside the tube was also included, as PCM, paraffin wax was used. The triple fin in vertical orientation and the double fin in horizontal orientation were found to have the best effects on the melting enhancement of PCM, increasing melting time by 11.2 % and 10.7 %, respectively, in comparison to the worst finned case and 37.4 % and 30.5 %, respectively, in comparison to the base case.

Li et al. [30] discussed the creation of a lengthwise fin with a leaf-like structure for improving melting performance in a shell and tube thermal energy storage device. The phase transformation process in PCM is simulated using a two-dimensional algorithm that takes natural flow into account. The reliability of the model was confirmed by comparing the computational findings with published actual data. The leaf-shaped fin with improved performance's dynamic temperature development and reaction were first examined. By considering two distinct arrangements of rectangle and triangle sub-branches under the same working circumstances, the fin form impacts the PCM melting process. In comparison to a fin with a branch angle of 90°, one with a branch angle of 75° accelerates the entire melting process by 12 %. When compared to a fin with rectangle sub-branches, the overall melting time for the fin with triangle sub-branches can be shortened by 30.1 %.

Using flanged fins, Rawat et al. [31] provided a computational study on accelerating the melting of PCM in a rectangular container (T-shaped). The outcome of this research demonstrated that for low Lu/Ld ratios and strong thermal conductivities, a high PCM melting rate can result. The melting of RT42-PCM in a rectangle container was compared by Rawat et al. [32] using two fundamental fin geometries: a normal fin and a flanged fin (T-shape) with a constant fin area. Based on an upper (Lu) and lower fin (Ld) length relation, five instances of each fin variety, indicating ten double fin configurations, were investigated. The phase change mechanism was controlled by an enthalpy-porosity model. The results demonstrated that for the instances of the double fin configuration, a decline in the tm was seen as the Lu/Ld ratio was reduced. The PCM dissolves entirely in 3696 s in Case V, which has the highest melting rate and a uniform tail with a Lu/Ld ratio of 0.25. Wang et al. [33] investigated the stagewise melting heat transfer properties of lauric acid in a side-heated rectangular enclosure by using a numerical model. The conduction process is treated as stage I, the processes of mixed convection–conduction and convection are collectively treated as stage II, and the shrinking solid process is treated as stage III. The effects of the enclosure geometry and the thermal conditions encountered by the lauric acid on heat transfer are discussed, particularly the transition points between different adjacent stages and the heat transfer characteristics during each stage. Increasing the height delays the transition point between stages I and II, but advances it between stages II and III. Increasing the width does not affect the transition point between stages I and II, whereas it delays the transition point between stages II and III. Increasing the wall temperature and the initial temperature leads to an advancement of the two transition points.

Yan et al. [34] simulated the natural convection of phase change materials in a cavity, and the effect of adiabatic obstacle and fin is investigated by the lattice Boltzmann method. The obtained results are presented in different Rayleigh numbers ($Ra = 10^3$-10^5), and cavity angles ($\theta = -90$ to 90) in three scenarios (without an adiabatic fin and obstacle, with an adiabatic obstacle, and with adiabatic fin). The investigation across various cavity angles, with adiabatic obstacles and fins, demonstrates a consistent trend of effective melting process delay by up to 50 %, underscoring the significant impact of these adiabatic features on PCM behavior. Adiabatic obstacles induce localized melting delays due to un-melted zones around them. Streamlines highlight vortices formed by obstacles, and elevated Nusselt numbers correlate with accelerated melting facilitated by adiabatic fins. Jiang et al. [35] numerically studied melting thermal behaviors of lauric acid in the models with bifurcated fractal fins having different fin location ratios εd, fin length ratios εl, and fin numbers N. Increasing εd, εl, and N yields the enhancement of liquid fractions, and a maximum melting time reduction of 63.6 % is achieved by the case with $\varepsilon l = 0.75$ and $N = 3$. Raising εd is conducive to melting convection flows during the natural convection regime. Whereas, the effect of εl is primarily driven through heat conduction area enhancement. In addition, the results indicated that as εl increases, the impact of increasing N leads to a shift in flow intensity from enhancement to suppression.

Referring to the discussed above studies, the enhancement of heat transfer and consequently the melting of PCM in a rectangle container has been conducted via the utilization of different experimental, numerical, and optimization techniques. However, the effect of the fin number has not been yet addressed. Thus, this study comes to fill this gap in the open literature by comparing the robustness of three scenarios of fin number including, without fins, with four fins, and with eight fins. The container under investigation is a cylindrical thermal energy storage with shells and tubes. The inner tube is heated by hot water while the outside tube is filled with PCMs. To ensure an accurate comparison between various scenarios, this research intends to maintain the capacity of the fins and PCM consistent while changing the fin arrangement. Eight straight fins (A), eight opposing fins (B), and eight fan-shaped fins can all be compared to one another while keeping the volume of the fins and PCM consistent.

2. Phase change material (PCM)

In this research, PCMs (Rubitherm RT42) are used because they fill the outer tube while hot water (340 K) is employed as a heat source and travels into the inner tube. The thermophysical characteristics of the materials employed in this numerical analysis are shown in Table 1.

3. Numerical procedure

3.1. Physical modeling

Fig. 1 presents a shell-and-tube cylindrical thermal energy storage. The length of the fin is 3 cm, its thickness is 2 mm, and it is protected from the outside by a 10 cm diameter outer tube filled with phase change material and a 2.5 cm diameter inner tube through which hot water flows. Three cases—the first without fins, the second with four fins, and the third with eight fins—were investigated.

Table 1
Thermophysical proprieties of the material (Rubitherm RT42).

Property	Value	Units
Density	760	kg m^{-3}
Specific heat	2000	C_p (J kg^{-1} K^{-1})
Thermal conductivity	0.2	W m^{-1} K^{-1}
Heat of fusion	165000	J kg^{-1}
Dynamic viscosity	0.0235	kg m^{-1} s^{-1}
Thermal expansion coefficient	0.0005	K^{-1}
Solidus temperature	311	K
Liquidus temperature	315	K

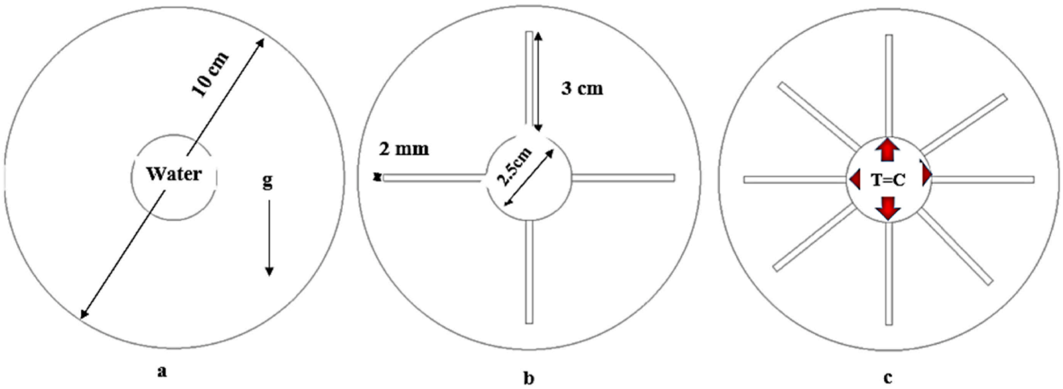

Fig. 1. Schematic diagram of the container with thermal insulation to the outside, a) without fin; b) with four fins; c) with eight fins.

3.2. Computational procedure

Numerical analysis carried out within the cylindrical container may be used to forecast the melting process. The model was built based on several assumptions. These include the following;

- PCM melting is a complicated process because it is not linear, it changes over time (unsteady), and the liquid-solid interface is always moving.
- The flow is incompressible, laminar, and only occurs in two dimensions.
- To show the melting process, the solid and liquid phases are isotropic, homogeneous, and keep the same temperature at the interface.
- The enthalpy-porosity technique is utilized to represent the phase-change zone contained within the PCM.
- There is no heat gain or loss from the environment.

The governing partial differential equations, continuity, momentum, and energy, are expressed as Eqs. (1)–(3) to model PCM melting [36–39]:

$$\frac{\partial \rho}{\partial t} + \nabla . \ (\rho V) = 0 \tag{1}$$

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

$$\frac{\partial}{\partial t} (\rho H) + \nabla . (\rho V H) = \nabla . (K \nabla T) \tag{3}$$

The sensible enthalpy (h) and latent heat (Δ H) make up the specific enthalpy (H):

$$H = h + \Delta H \tag{4}$$

Where,

$$h = h_{ref} + \int_{T_{ref}}^{T} C_p \, dT \tag{5}$$

$$\Delta H = \beta \, L_f \tag{6}$$

The fraction of liquid (β) may be stated as follows:

$$\beta = \begin{cases} 0 \ solidus \text{ if } T < T_s \\ 1 \ liquidus \text{ if } T > T_l \\ \dfrac{T - T_s}{T_l - T_s} \text{ if } T_s \le T \le T_l \end{cases} \tag{7}$$

The damping term for Darcy's law is the source term S in the momentum equation. The influence of the phase change on the convection led to the introduction of this factor, which is included in the momentum equation. It may be inferred from the fact that the momentum equation's source term can be determined from the following:

$$S = \frac{C(1-\beta)^2}{\beta^3} V \tag{8}$$

Where the shape of the melting front is shown by the coefficient C, which is a constant for a mushy zone that can reflect the morphology of the melting. This constant is substantial, often between 10^4 and 10^7 [40]. C is set at 10^5 in the present study and is considered to be constant.

3.3. Grid independency test

The grid independency study can be done by comparing the average liquid percentage over time for the different grid sizes shown in Table 2. Fig. 2 shows a computational grid. To account for the movement of the melting interface at each time step, the mesh needs to be precisely calibrated all over the domain. Fig. 2 depicts how changing the mesh size during melting affects the liquid fraction. The Grid 2 mesh is used for all of the numerical simulations in this study. This mesh was chosen based on the results of the mesh independence analysis.

3.4. Validation

This section intends to interpret the consistency between the obtained numerical results from ANSYS/FLUENT 16 simulations and the available experimental data of Ahmed et al. [8] for the melting of PCMs. Precisely, Ahmed et al. [8] conducted a set of experiments for the melting enhancement of PCM in a finned tube latent heat thermal energy storage. To conduct this validation study, the liquid fraction of PCM against operational time was solved using the computational technique described in this study. In this regard, the comparison includes the assessment of the melting liquid fraction of PCM against the operational time for both the simulation re-

Table 2
Grid independency test for numerical results.

Meshing	Grid 1	Grid 2	Grid 3
Elements number	36,507	41,883	69,773

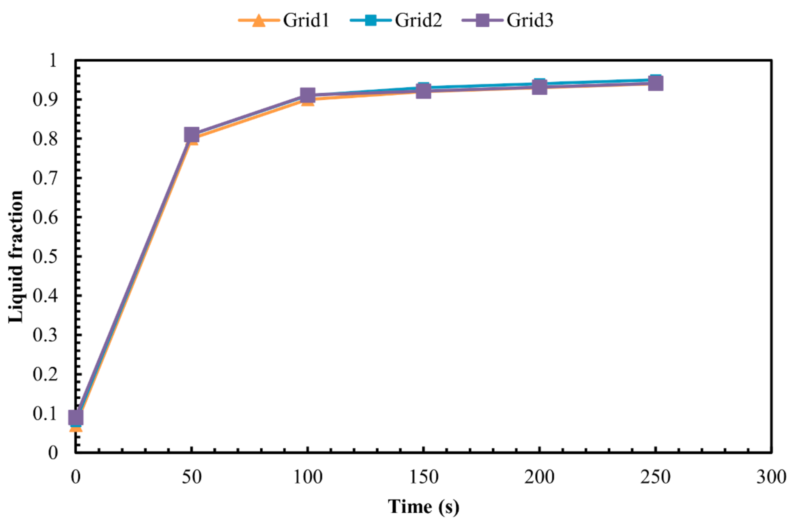

Fig. 2. Grid independency test.

sults and experimental data. Fig. 3 introduces the high consistency and strong agreement between the simulation outcomes and experimental data of Ahmed et al. [8]. In other words, this section assures the precision and reliability of the code used in this investigation.

4. Results and discussion

The numerical simulation program utilized in this work was ANSYS-Fluent 16.0. Two-dimensional simulations were performed using an algorithm called SIMPLEC with velocity-pressure coupling and the equation of pressure correction in the PRESTO scheme on the foundation of the finite volume method (FVM). The momentum and energy equations were discretized using the second-order UPWIND methodology, whereas Gradient's discretization method used the Least Squares Cell-Based approach.

4.1. Case one (without fins)

As heat is transported from the heat source to the PCM through conduction, the melting process begins, and we can observe that it happens swiftly. The sluggish process of natural convection after that, which involves the transfer of heat, affects the process of melting. Since melting in Fig. 4 relies on natural convection, where heat transfer is sluggish, the process of melting takes longer to finish. The melting process is finished in 900 min. Fig. 5 shows the heat transfer to the PCM, where it is easy to see that it is sluggish since it relies on natural convection. Fig. 6 reveals the speed of the process of melting as it moves from the portion that is in touch with the heat source to the higher part and then accelerates as a consequence of the liquid component moving to the top. This figure also shows the shape of the melting process.

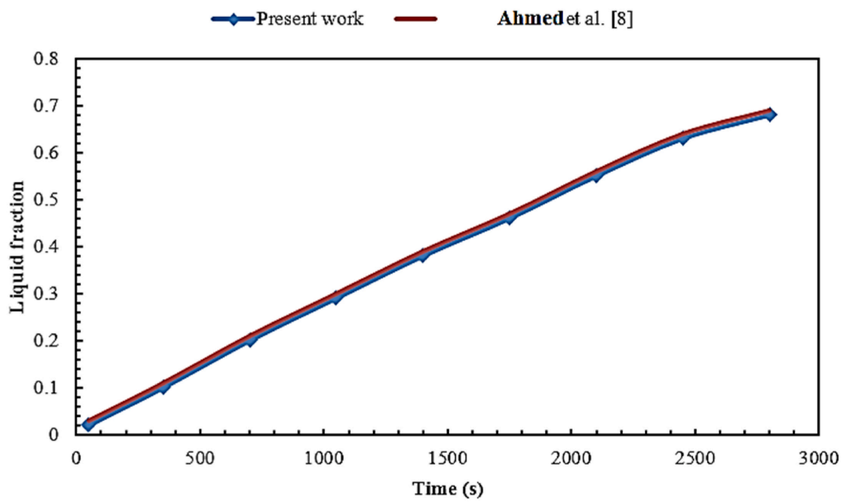

Fig. 3. Comparison of simulation results and the findings of Ahmed et al. [8].

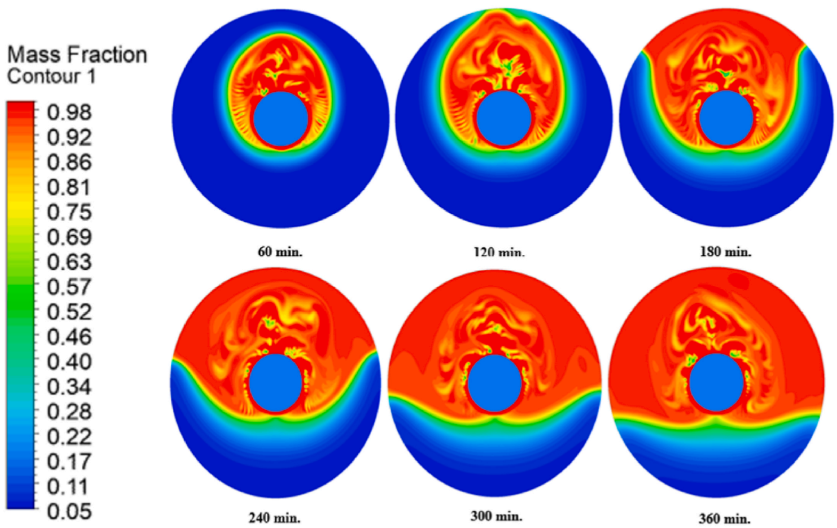

Fig. 4. Predicted evolution of the melting process without fins.

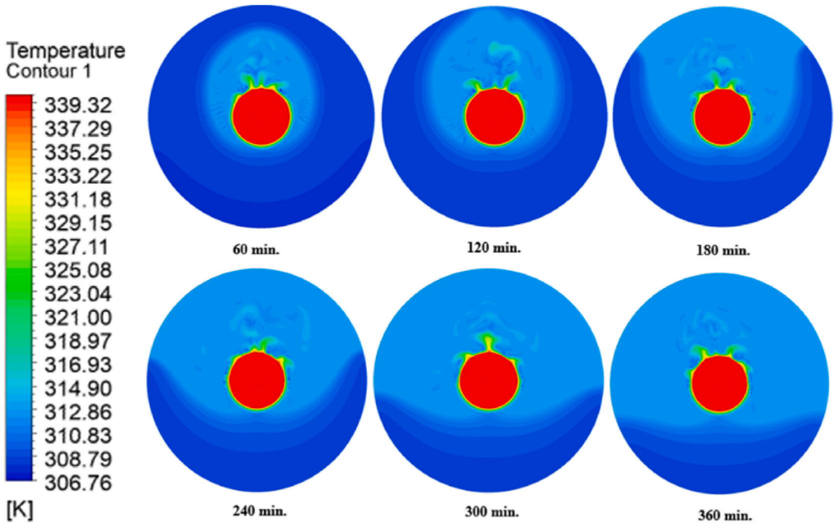

Fig. 5. Temperature distributions without fins.

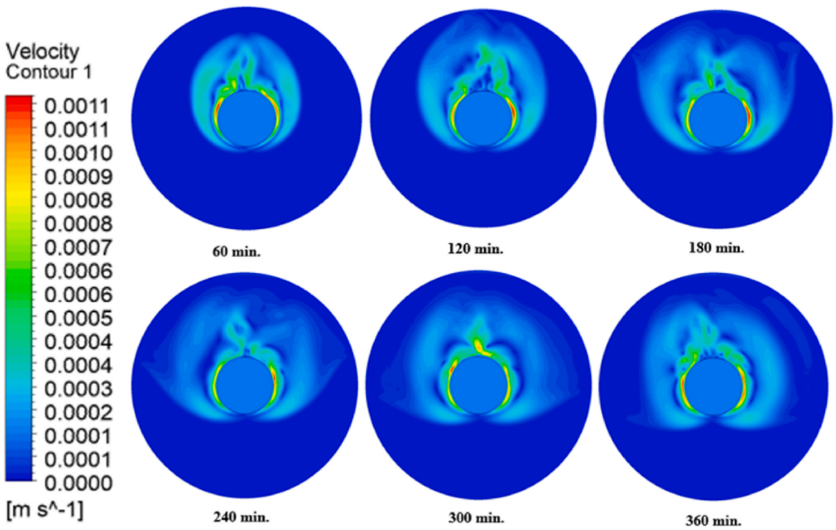

Fig. 6. Velocity distributions without fins.

4.2. Case two (with four fins)

Through conduction, heat moves from the source of heat to the PCM. This starts the melting process, which happens quickly. As a consequence of the existence of fins, the melting process is accelerated because heat is transferred to a greater area via conduction rather than by natural convection, which has an impact on the melting process after that. Because of the existence of fins, where the heat transfer is quicker, the melting process in Fig. 7 is shown to occur more quickly. This is because the melting process is dependent on the conduction load. It takes 120 min to melt. Fig. 8 illustrates the heat transfer to PCMs, and it is easy to see how the dependency on convection-conduction results in a fast heat transfer. Fig. 9 depicts the speed of the melting process as it begins at the section closest to the heat source and subsequently advances to the higher part as a result of the liquid's motion. Due to the acceleration, the top portion and the resulting form of the melting process are visible.

4.3. Case three (with eight fins)

We observe that heat transfer via conduction from the heat source to the PCMs causes the melting process to begin quickly. Heat transfer by natural convection then affects the melting process. However, due to the fins, conduction spreads heat more quickly and over a larger area. We can observe in Fig. 10 that the melting process occurs more rapidly due to the presence of fins, where heat transport is faster. This is so because the conduction process is necessary for the melting process. The thawing process takes an hour. Fig. 11 depicts how rapidly heat transfers to the PCMs due to its dependence on thermal conductivity. Fig. 12 illustrates how the flow of the liquid causes the melting process to proceed swiftly from the region in direct contact with the heat source to the higher region. The top section, which shows the shape of the fusion process, was created via acceleration.

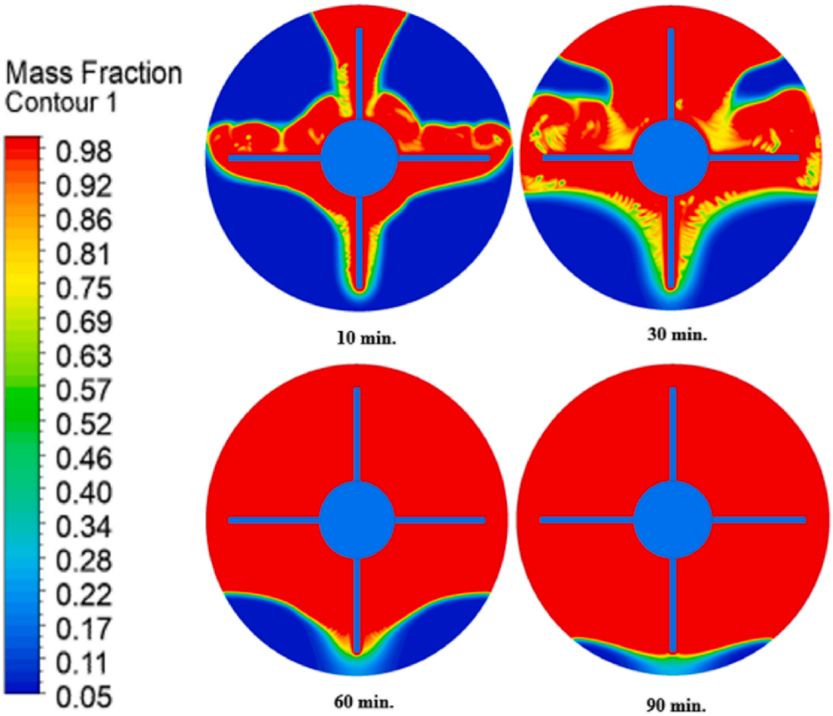

Fig. 7. Predicted evolution of the melting process with four fins.

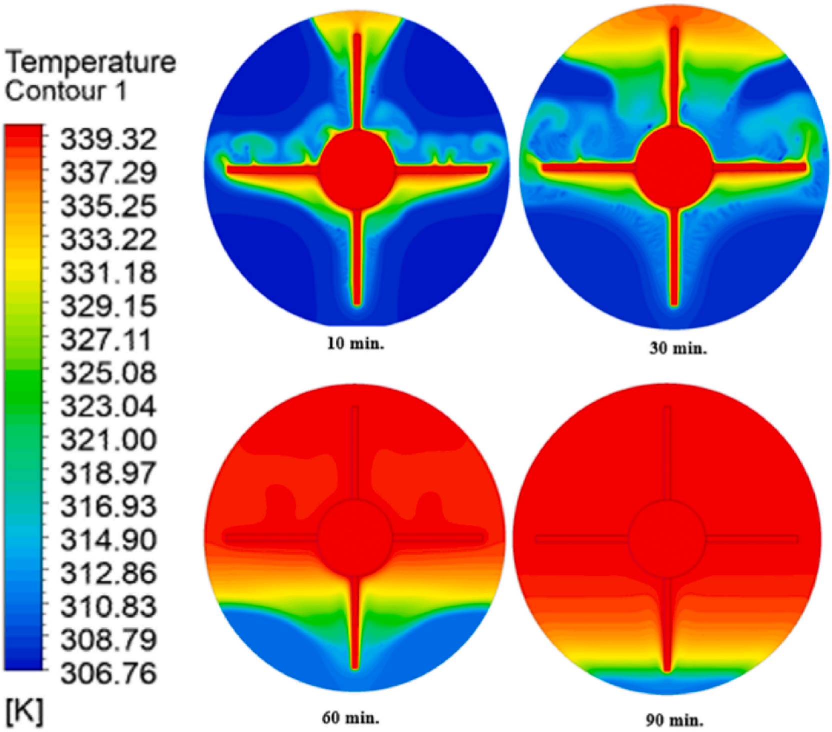

Fig. 8. Temperature distributions with four fins.

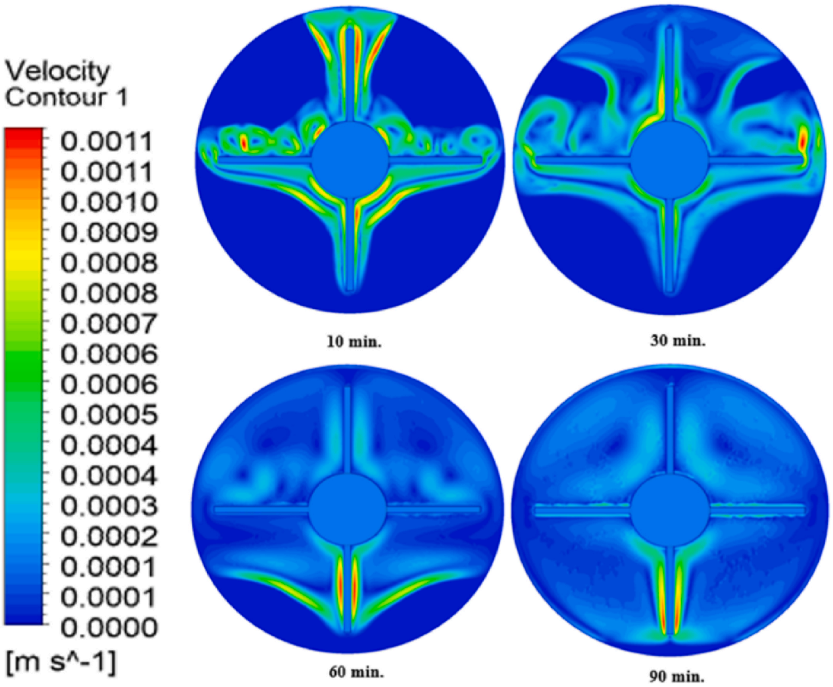

Fig. 9. Velocity distributions with four fins.

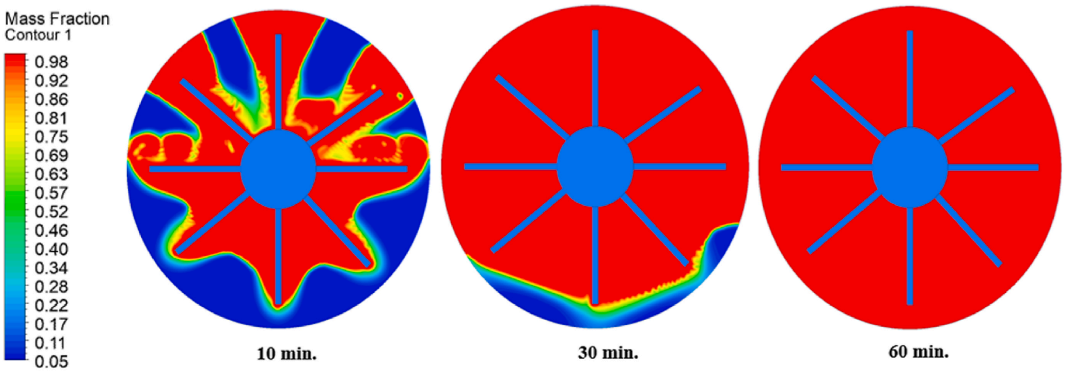

Fig. 10. Predicted evolution of the melting process with eight fins.

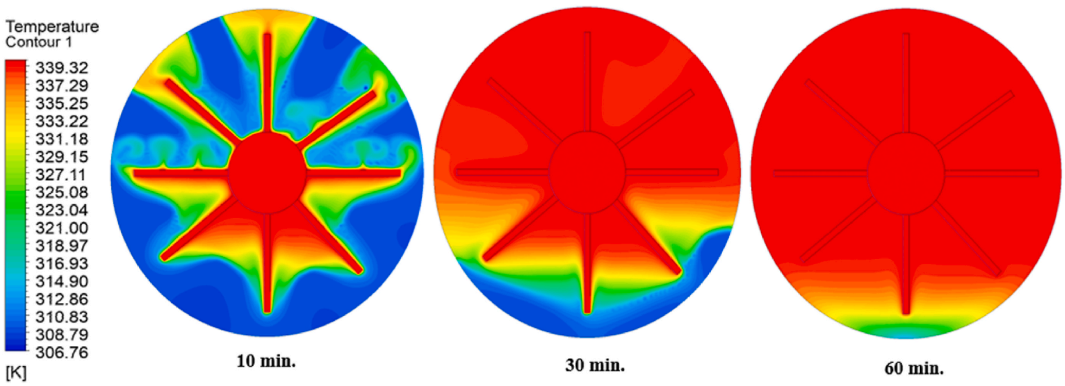

Fig. 11. Temperature distributions with eight fins.

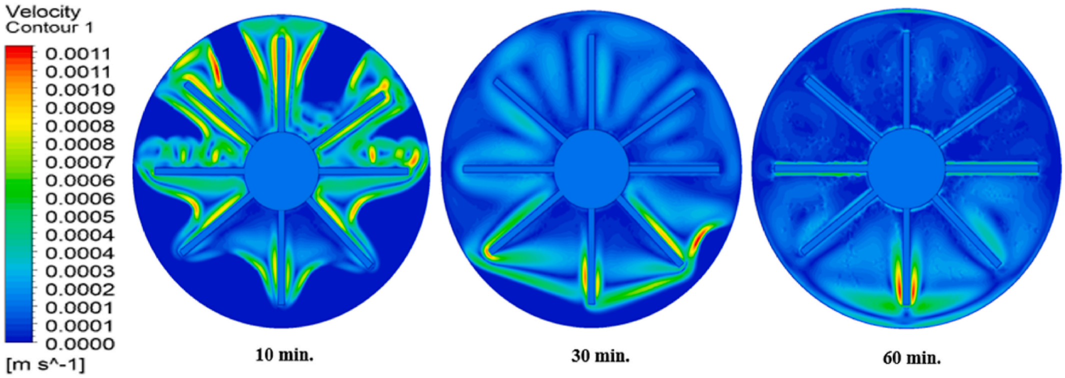

Fig. 12. Velocity distributions with eight fins.

4.4. Comparison of the three investigated cases

By examining the melting process, we see that fins have a significant impact on heat transport, which shortens the time needed to complete melting. We can see in Fig. 13 that the melting process is strongly impacted by the presence of falciparum. Fig. 14 demonstrates how the heat transfer is significantly influenced by the natural load after the conduction load at the beginning of melting. Moreover, fins have a significant impact on heat transport. Fig. 15 illustrates the significance of fins in the process of heat transfer by showing that melting occurs more quickly as the fin count rises.

It was investigated how the fin number affected the process of melting. Figs. 16 and 17 show the melting percentage and temperature curves, respectively, in comparison to cases with and without fins, with varying numbers of fins (four and eight). It is clear that the melting percentage rose monotonically with the fin number, and the overall trend of the curve was high at first, then sluggish. When more PCMs became molten, the melting rate decreased and the thermal resistance between the solid-liquid interface and the heat transfer surface increased.

Fig. 18 illustrates how the fin number significantly influenced the total time of melting. Under the same heat storage effect, the highest time difference was 236 min, and the maximum time difference induced by the number of fins was as high as 81.4 %. When there was a certain fin number, the time of melting and heat transfer was quickest when there were 8 fins. Research demonstrated that appropriately adding fins may significantly enhance heat transfer during melting. While there were just four fins, the total melting time essentially reduced as the number of fins increased. The neighboring fluid flow between the fins may slow down

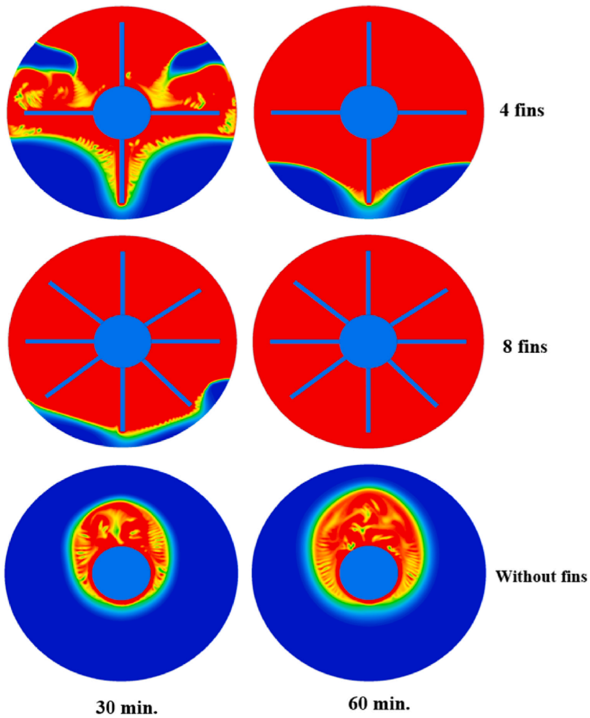

Fig. 13. Comparison of the melting process between the three cases.

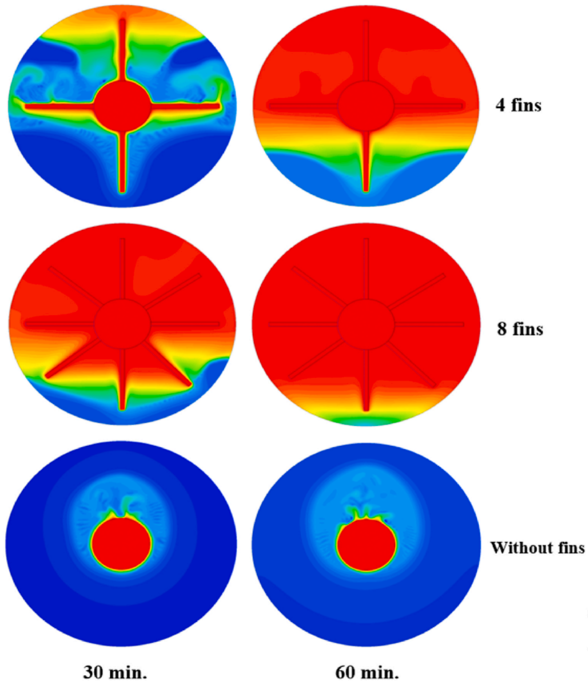

Fig. 14. Comparison of the temperature between the three cases.

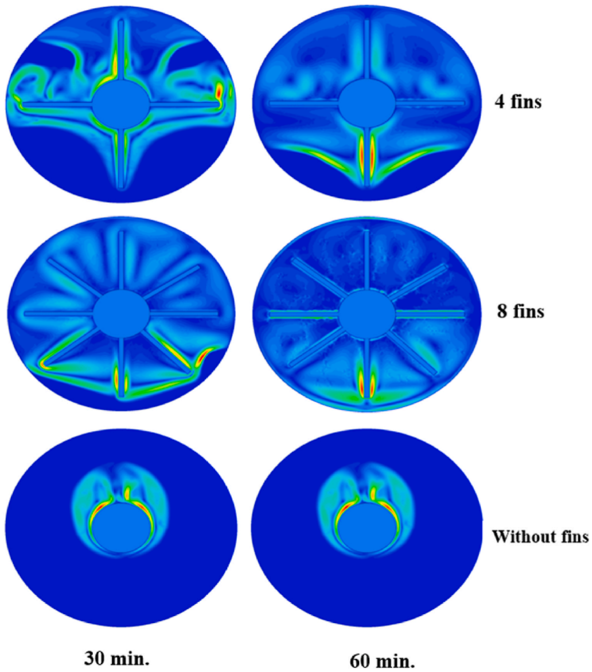

Fig. 15. Comparison of the velocity between the three cases.

or even stall if the fin number is blindly increased while the spacing between fins is reduced, which will diminish the influence of natural convection between nearby locations.

It is crucial to maintain the capacity of the fins and PCM consistent while changing the fin arrangement to guarantee an accurate comparison between various instances. Eight straight fins (A), eight opposing fins (B), and eight fan-shaped fins were compared to one another while maintaining the capacity of the fins and PCM consistent. As shown in Fig. 19, case (A) has the potential to greatly improve the melting process by reducing the total melting time and increasing melting homogeneity independent of the heat transfer

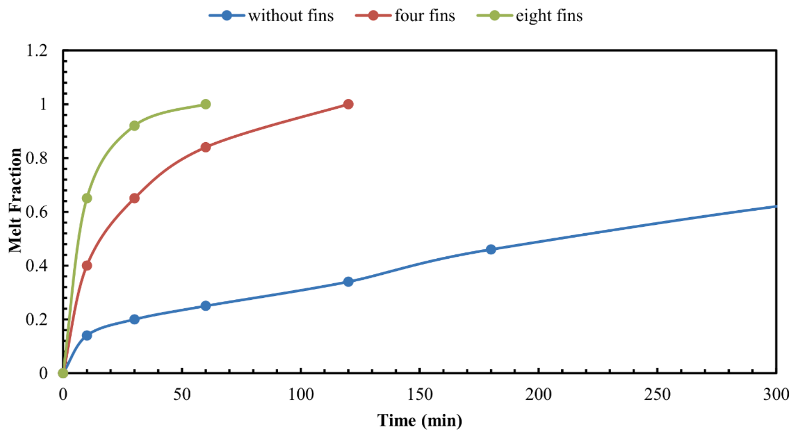

Fig. 16. Melting fraction for different numbers of fins.

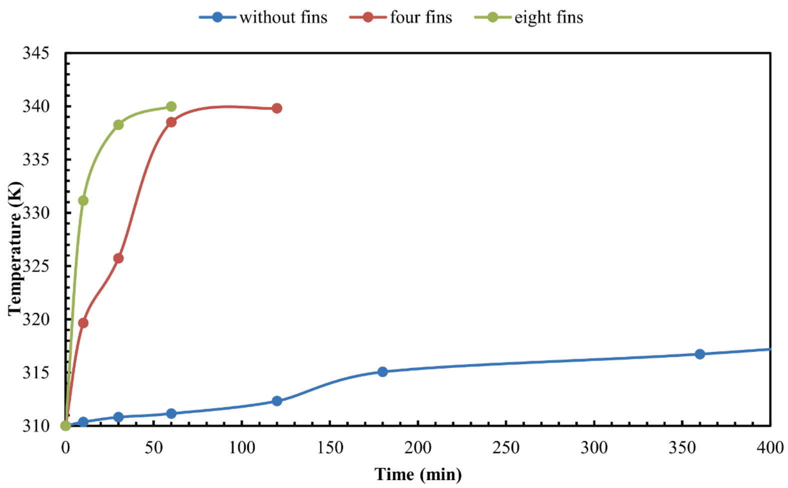

Fig. 17. Temperature profile with and without fins.

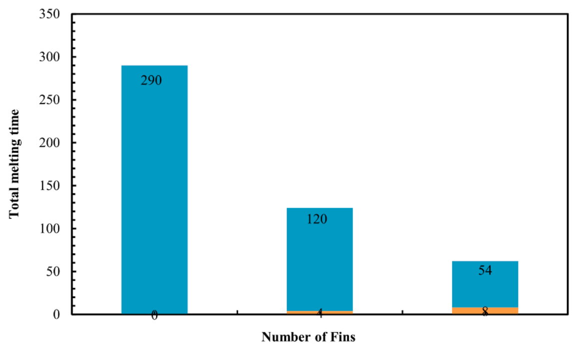

Fig. 18. Complete melting time against the number of fins.

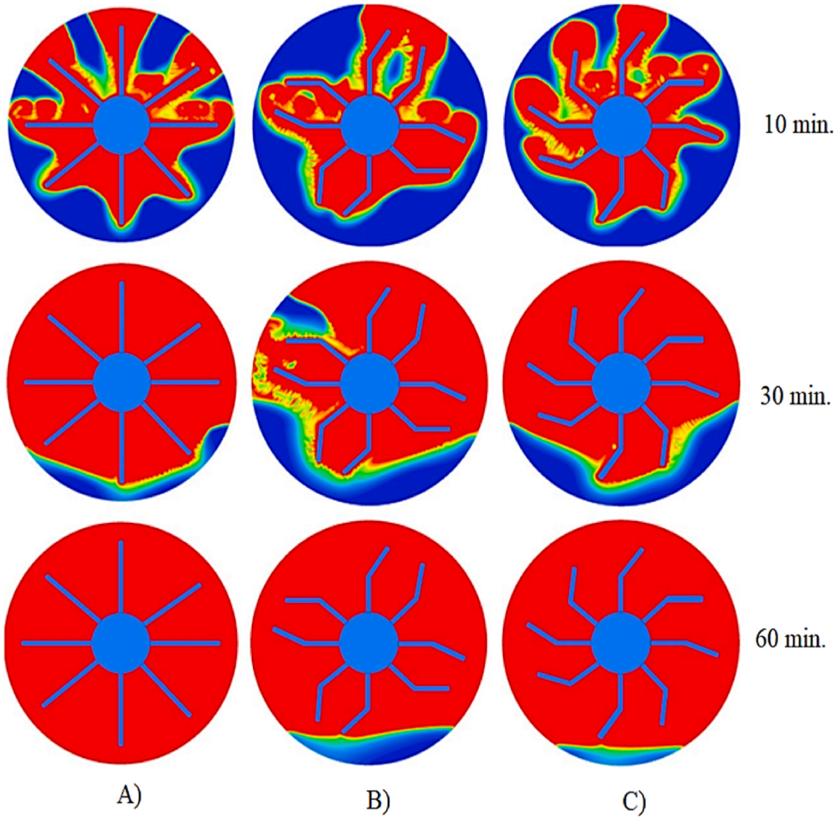

Fig. 19. Comparison of the melting process between the three fin configurations.

fluid temperature, while case (B) has the least amount of melting improvement. The vertical fins provide a more uniform heat transfer than the other arrangement, which accounts for the disparity.

5. Critical analysis of the associated results

Referring to the associated results (discussed in section 4) that entail the influence of fin number on PCM melting in a shell-and-tube thermal energy storage system, the following can describe the conceptual physics behind the obtained results;

- The existence of fins has enhanced the heat transfer from the hot water in the inner tube to the PCM in the outer tube due to increasing the available surface area. Also, the fins aid in promoting the convection within the PCM as a result of creating a greater temperature gradient between the hot water and the PCM. Indeed, increasing the fins number would enlarge the available surface area and that faster melting rate. However, it should be realized that increasing the number would reduce the space between fins, i.e., reduce the convection rate. Regarding the temperature contours, it has been ascertained that the melting starts from the inner tube wall to the outer tube wall. In this regard, the existence of fins helps to enhance the temperature distribution within the PCM as a result of creating a uniform melting front. Also, the velocity distribution contours of the case without fins show negligible natural convection within the PCM compared to those with fins of increased circulation, i.e., enhanced natural convection. Consequently, one can expect an increase in melting rate due to the presence of fins in a shell-and-tube thermal energy storage system using PCM. However, a careful balance between the number of fins, surface area, natural convection, and cost should be considered when designing these systems.

6. Conclusions

The current study concentrated on how the number of fins can affect the PCM melting in a shell-and-tube thermal energy storage system. A PCM of the Rubitherm RT42 type filled the outer tube and sent hot water (340 K) into the inner tube to provide heat. In this regard, the study introduced three cases: one without fins, one with four fins, and one with eight fins. The software for numerical simulation was ANSYS-Fluent 16.0. Two-dimensional simulations were performed using an algorithm called SIMPLEC with velocity-pressure coupling and the correlation equation of pressure in the PRESTO scheme on the foundation of the finite volume method. The following conclusions can be drawn from this investigation:

- Without fins, the melting process requires natural convection, which has a sluggish rate of heat transfer. As a result, the process of melting takes longer. The process of melting is finished in 900 min.

- Without fins, the PCM has a sluggish heat transfer since it relies on natural convection for heat transfer.
- The speed of the process of melting (with the absence of fins), which begins with the part in contact with the heat source and subsequently moves to the higher part as a consequence of acceleration, is caused by the movement of the liquid portion to the top.
- The melting fraction grew monotonically with the number of fins, and the curve had an initial sharp trend followed by a gradual one. As more PCMs changed from solid to liquid over time, the thermal resistance between the solid-liquid interface and the heat transfer surface rose, and the rate of melting slowed.
- The number of fins had a big effect on the total melting time. Under the same heat storage effect, the biggest difference in melting time was 236 min, which was caused by the number of fins at 81.4 %.
- Case (A) of eight straight fins can significantly enhance the melting process by shortening the complete melting time and improving the melting uniformity regardless of the heat transfer fluid temperature. However, case (B) of eight opposing fins, and case (C) of eight fan-shaped fins have a minimum melting enhancement.

Referring to the above conclusions, it can be ascertained that the findings of this study apply to a wide range of PCMs and shell-and-tube thermal energy storage systems. More importantly, these findings can guide the design and optimization of thermal energy storage systems for different applications, including solar thermal energy storage, waste heat recovery, and building heating and cooling.

Nomenclature

Symbol	**Description**	**Units**
c	Specific heat	J kg^{-1} K^{-1}
β	Melting fraction	
h	Average heat transfer coefficient	W m^{-2} K^{-1}
k	Thermal of conductivity	W m^{-1} K^{-1}
L	Latent heat melting	kJ kg^{-1}
t_e	Test run elapsed time	s
T	Temperature	K
Greek symbols		
Symbol	**Description**	**Units**
α	Thermal diffusivity	m^2 s^{-1}
β_f	Expansion coefficient of liquid	K^{-1}
ρ	Density	kg m^{-3}
ν	Kinematic of viscosity	m^2 s^{-1}
Subscripts		
Symbol	**Description**	
H	Hot water	
l	PCM of liquid	
M	Process of melting	
PCM	Phase-changing material	
s	PCM of solid	

CRediT authorship contribution statement

Farhan Lafta Rashid: Supervision, Writing – review & editing, Conceptualization, Data curation, Formal analysis. **Abbas Fadhil Khalaf:** Investigation, Writing – original draft. **As'ad Alizadeh:** Formal analysis, Writing – original draft. **Soheil Salahshour:** Writing – review & editing, Conceptualization, Data curation, Formal analysis. **Mudhar A. Al-Obaidi:** Investigation, Writing – original draft. **Choon Kit Chan:** Supervision, Writing – review & editing.

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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