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Solidification acceleration of phase change material in a horizontal latent heat thermal energy storage system by using spiral fins

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HIGHLIGHTS

- Different spiral fins with different number of fins have been employed.
- Length of fins have been adjusted in different cases to generate equal heat transfer surface.
- The double and triple fins indicated the best performance with 15.87% and 30.43% shorter solidification process.
- The double fin with 16.25% higher *Nu* in comparison with the single fin has the most optimized performance.
- Both the number of fins and fin length play important role in heat transfer enhancement.

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Paraffin wax

ABSTRACT

One important solution for societies to overcome the energy crisis is to manage the production and storage of energy. In this regard, the latent heat energy storage systems have recently gained a remarkable attention. Hence, this work is devoted to enhance performance of a latent heat tube-shell storage system by using novel spiral fins with different geometrical characteristics. Different number of vanes have been employed on the fins with constant twisting pitch. The different cases studied include the cases with single-fin, double-fin, triple-fin and quadruple-fin. These fins have been employed to augment heat transfer from a low temperature fluid to the PCM inside the shell container during the solidification process. To model the phase change, the enthalpy-porosity technique has been adopted. Various parameters have been used to assess the functionality of the system including the Nusselt number, total solidification time, temperature, solid fraction evolution, solid fraction contours, temperature contours and etc. The results demonstrated that the triple-fin and double-fin cases took the advantage in heat transfer augmentation and discharging process while the case with single-fin showed the worst performance. The results

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indicated that fin number is not the only influencing factor and fin length also has a dominant role.

1. Introduction

While there are rapid advances in technology and the industries are developing every day around the globe, there is a rapid growth in energy demand which has raised a great concern among the scientists to develop novel methods to overcome this challenge. Depletion of natural resources, growing demand for energy among nations and the recent political conflicts in the Eurasia region has provoked the energy crisis. To overcome the energy crisis, efficient storage of energy is a key factor which can be of great help and play a significant role in supplying the required energy. In this regard, it is necessary to invent methods to enhance quality and performance of the latent heat thermal storage systems [1]. Performance augmentation of the latent heat energy storage systems have attracted a great attention in the literature and many researchers have considered different methods for accelerating the phase change process and enhancing the energy storage quality in order for better management of energy resources.

A variety of techniques have been adopted by scholars to enhance efficiency of the latent heat storage devices. These methods include adding nano additives to the PCM [2], embedding porous media inside the PCM [3–7], using several cascaded PCMs in a device [8,9] and modifying shape and geometrical characteristics of the storage unit [10–13]. However, the most prevalent method for improvement of PCM unit performance is to add high conductive fins to enhance heat transfer [14–22]. Different types of fins have been adopted in the literature with a variety of parameters which have been adjusted for the most optimized case to augment heat transfer in storage systems.

In a recent study, Alizadeh et al. [23] employed a novel fin for enhancing the solidification process in a hexagonal storage unit. The fins included triangular fins with different arrangements. They reported a considerable enhancement in solidification of PCM by changing geometrical parameters and arrangements of the fins. Jiang et al. [24] employed novel leaf-inspired bifurcated fractal fins to enhance the melting of lauric acid in a PCM enclosure. Luo et al. [25] used a novel fractal fins inside a heat exchanger for accelerating the PCM melting. They announced a great decrement in the melting duration by using the novel fractal fins which also results in a good uniformity of temperature distribution. Tiari and Hockins [26] experimentally evaluated influence of annular/radial fins on the charging/discharging of PCM in a shell and tube latent thermal energy storage system. They reported that both the radial and annular fins have great effect on the phase change process while the radial fin configuration surpassed other cases in respect of solidification and melting time of the PCM. Guo et al. [27] in a research conducted both numerically and experimentally, studied effect of upward and downward angled fins with different angles on melting of PCM in a vertical tube-shell thermal storage system. They concluded that a small range of bending the fins can make the heat transfer better however, excessive bending of the fins deteriorates the phase change process. Soltani et al. [28] used a combination of radial fins and rotation in the charging/discharging process in a horizontally oriented tube-shell latent heat thermal storage system. They reported that both rotation and fins have direct influence on the melting/solidification of PCM. Asip Khan et al. [29] evaluated effect of eccentricity of fins on the charging of a horizontal shell/tube storage unit. Tiari et al. [30] investigated effect of annular fins with different configurations and fin length on the melting of a vertical shell/tube storage unit. They concluded that in the configuration with the longer fins placed at the bottom of the enclosure, the best performance was achieved. Huang and Liu [31] numerically simulated phase change procedure in a vertical tube-shell storage unit enhanced by nature inspired fractal fins. They reported that the fractal fins have much better performance in comparison with the similar longitudinal fins in terms of melting and solidification of PCM. Another novelty inspired by nature was the honey comp meshed fins addressed by Kant et al. [32]. They tested the storage unit with different inclinations and reported that honey comb cells can significantly enhance melting of PCM. Ma et al. [33] presented a new longitudinal circular fins in a shell-tube LHTESS and reported a significant enhancement of performance in the solidification process of PCM. They also reported the energy and exergy efficiency for the unit. Joshi and Rathod [34] experimentally and numerically evaluated effect of fins in a rectangular container in the melting of PCM. They also made a comparison between the metal foam and fin as two conventional methods of enhancing PCM conductivity which are the fins and porous media. They reported in the whole phase change cycle, the porous media outperformed fins while in the melting process fins had better performance and the porous media performed better in the solidification period.

Among all different fin types mentioned, one of the most efficient types of fins that has been gained a considerable attention is the spiral fins and researchers have addressed various aspects of spiral fins such as the pitch, number [35], length, and thickness of spiral fins in shell/tube thermal energy storage systems. Borhani et al. [36] numerically investigated melting process in the presence of single spiral fin in a shell and tube LHTESS system. Effect of fin thickness and spiral pitch along with orientation angle of the system was assessed. Duan et al. [37] in a research conducted numerically investigated effect of number of fins in a horizontal shell and tube LHTES system. Their study involved both solidification and melting processes and the angle of distortion and fin number were the key features addressed in their work. Zhang et al. [16] made a comparison between performance of conventional annular and longitudinal fins with spiral fins and reported that spiral fins have better functionality than the conventional fins. Mehta et al. [38] worked on effect of single spiral fin on the melting/solidification process of PCM in a vertical enclosure both numerically and experimentally. In another study, Mehta et al. [39] experimentally investigated influence of the enclosure orientation angle of enclosure in the presence of single spiral fin in the melting process. They studied three angles of 0, 45 ° and 90 °. Lu et al. [40] experimentally studied effect of inlet flow rate and inlet temperature on the charging and discharging of paraffin inside a vertical enclosure. They used a single spiral fin in their work. Sun et al. [41] addressed solidification of PCM in a triple tube heat exchanger with a vertical PCM enclosure. Their work included different number of fins including 2, 4 and 6 spiral fins placed on the wall of the inner tube. They compared the performance of spiral fins with straight fins and reported a considerable augmentation of heat transfer by using spiral fins.

The previous works have addressed different features about spiral fins in the phase change process of PCM however, the present work tries to address this issue from a new point of view. In the present investigation, effect of different number of vanes having equal heat transfer area and constant mass of PCM in the enclosure has been assessed on the solidification procedure of PCM in a horizontal shell-tube container. Different considered fins include the single, double, triple and quadruple fins which have been adjusted to have equal heat transfer surface and to keep the amount of PCM material equal in all cases. The only work among previous works which had worked on solidification of PCM in horizontal enclosure was the work of Duan et al. [37] in which the spiral pitch and distortion angle was varied and the surface for heat exchange was not considered equal in all cases. However, in this work we have kept the pitch constant. Hence, in this work effect of spiral fins with different number of vanes with equal spiral pitch is investigated on the phase change process of the PCM. According to the literature review, no previous study has compared the single, double, triple and quadruple fin configurations in a horizontal shell and tube latent heat thermal energy storage system in the presence of spiral fins. The fins have been designed to have equal heat transfer area which means higher number of fins is associated with shorter length of fin to keep the area constant which is another novelty considered in this work. The main goal of the present investigation is to find the optimized number of fin in equal heat exchange surface in constant pitch.

2. Problem statement and simulation method

2.1. Problem definition and material properties

The present model is comprised of a tube-shell storage system while the PCM is filled at the shell side and water flows through the tube with lower temperature. The wall being in direct contact with the environment has been totally insulated and the PCM doesn't have any exchange of energy with the outside area. The inner tube wall is solid which is the heat transfer medium from the low temperature fluid to the PCM in the solidification process. Four different types of fins have been assembled on the solid wall which have direct contact with the PCM material which are the spiral single, double, triple and quadruple fins which have different number of vanes and have twisted around the tube with and angle of 720 ° which makes the fins to twist about the axis of the tube two times throughout the model with a twisted pitch of 230 mm. The fins have been designed in such a way that they occupy equal space in the shell side of the storage system and they all have equal heat transfer surface which makes it feasible to compare the functionality of the systems with different fins. Accordingly, the amount of PCM material used inside the shell side is equal in all cases. As all of the fins have equal heat transfer surface, increasing fin number means each fin length should decrease in constant twisted pitch. Hence, the case with four fins has the shortest length of fin. The main aim of this work is to find the case with the optimum number of fins and figure out how fin number may affect the solidification process in the PCM. Fig. 1A presents a schematic of an axial cross section of the system and the parameters that unfold geometrical dimensions of the system. These dimensions have been quantified in Table 1. Fig. 1B demonstrates the four types of fins employed in this work including the single fin, double fin, triple fin and quadruple fin configurations. Fig. 1C also shows the relevant parameters in lateral cross-section of the model.

The PCM container has been filled with PCM which was the paraffin wax. Paraffin wax is an organic PCM being prevalently used in the literature and industry due to its abundance and economic advantages. It is also a proper choice due to having a high thermal

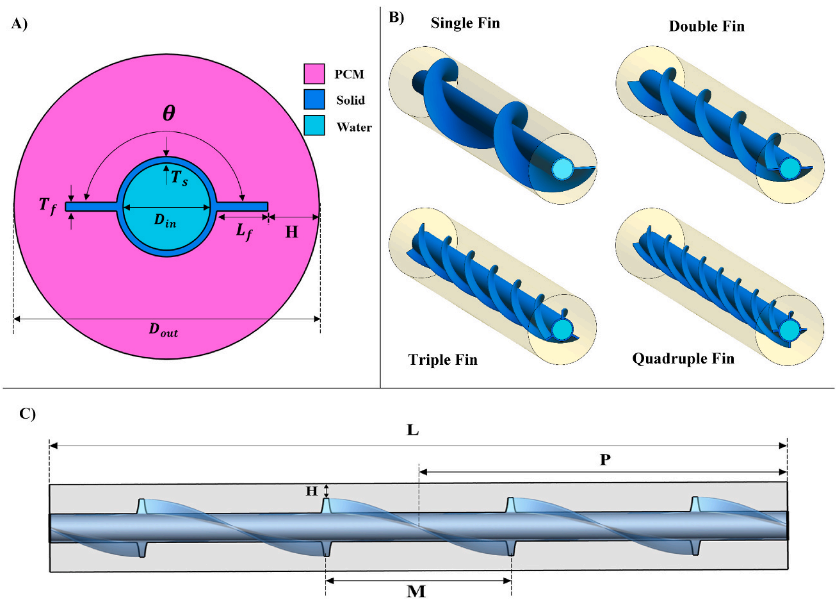

Fig. 1. Presentation of the models used for simulations and the related parameters. A) 2D schematic of the model and different morphological parameters indicated on the double fin case. B) 3D view of different configurations of fins used in this study. C) cross sectional 2D schematic of the fin in the case with double fin and the geometrical parameters in longitudinal direction.

Table 1
Geometrical characteristics of the model with symbols presented in Fig. 1

	L_F (mm)	H (mm)	θ	M (mm)	T_F (mm)	T_S (mm)	D_{in} (mm)	D_{out} (mm)	P (mm)	L (mm)
Single Fin	22	1.5	–	230	2	1.5	20	70	230	460
Double Fin	11.7	11.8	180 °	115	2	1.5	20	70	230	460
Triple Fin	7.96	15.54	120 °	76.6	2	1.5	20	70	230	460
Quadruple Fin	6.05	17.45	90 °	57.5	2	1.5	20	70	230	460

storage capacity and good operating temperature [42]. Accordingly, in this work, paraffin wax has been employed as the PCM material. The fluid flow inside the tube at the center of the enclosure is water and steel is used as the solid material for fins and the tube wall which is according to the study of Mahdi et al. [43]. The thermophyscial properties of the material used in this work have been presented in Table .2.

2.2. Numerical method

The PCM has been considered as Newtonian and incompressible, and the change in the physical properties of the PCM is assumed negligible in the range of working temperature. In order to simulate the phase change process, in this work the Enthalpy-Porosity method has been employed. According to this technique, the volume fraction in each cell is regarded as the porosity of that cell in which porosity equal to 0 is taken as the solid state and porosity equal to 1 is regarded as liquid state. The volume fraction of the PCM is calculated according to the following equation:

$$\alpha = \begin{cases} 0 & T < T_s \\ \dfrac{T - T_{so}}{T_{li} - T_{so}} & T_s < T < T_l \\ 1 & T > T_l \end{cases} \tag{Eq.1}$$

As in a porous media, porosity of 0 is equivalent with a great pressure loss in that cell which is a representative of solid material presence in that cell and porosity of 1 generates no pressure loss in that cell which means the cell is filled with liquid PCM. The porosity between 1 and 0 is regarded as the mushy region in which the transition from one state to another state occurs. The simulation of phase change is calculated by summation of a term to the equation of the momentum acting as the source term according to the volume fraction of melted PCM in each cell. To calculate the source term, the following equation is used:

$$S = A_{Mushy} \frac{(1-\alpha)^2}{\alpha^3 + \varepsilon} u \tag{Eq.2}$$

In the above equation the parameter A_{Mushy} is a constant parameter that determines how fast the velocity reaches zero and the PCM turns to solid state. According to the former studies in the literature, an amount of 10^5 for the mushy constant parameter can provide the best results and higher values may result in undesired errors [43,44]. In the above equation, volume fraction equal to zero ($\alpha = 0$) is associated with the solid state which returns a high quantity of the source term which totally damps the velocity of PCM and volume fraction equal to 1 ($\alpha = 1$) eliminates the source term as if there is no barrier in the path of the liquid PCM and is associated with liquid PCM. The source term in Eq. (2) is added to the momentum equation. The parameter ε at the denominator in Eq. (2) is a negligible constant to avoid having zero in the denominator. The governing equations for calculating the motion of PCM which is considered as a Newtonian and incompressible fluid with constant properties and negligible volume change are as follows:

Continuity equation:

$$\nabla \bullet \vec{V} = 0 \tag{Eq.3}$$

Table 2
Thermophysical Properties of the different materials used in the study.

Paraffin Wax [43]	Range of Melting Temperature (° C)	Unit	48.3–62
	Enthalpy of Fusion	(kJ/kg)	114
	Specific Heat	(J/kg. ° C)	2000
	Density	(kg/m^3)	820
	Thermal Conductivity	(W/m. ° C)	0.14
	Viscosity	(Pa.s)	0.033
	Thermal Expansion Coefficient	1/K	$6*10^{-4}$
	Mushy Zone Constant	–	10^5
Water [43]	Specific Heat	(J/kg. ° C)	4190
	Density	(kg/m^3)	996
	Thermal Conductivity	(W/m. ° C)	0.66
	Viscosity	(Pa.s)	0.001
Steel	Specific Heat	(J/kg. ° C)	502
	Density	(kg/m^3)	8030
	Thermal Conductivity	(W/m. ° C)	16.27

Momentum equation:

$$\rho\frac{\partial\vec{V}}{\partial t}+\rho\vec{V}\left(\nabla\bullet\vec{V}\right)=-\nabla p+\mu\nabla^2\vec{V}+\rho\beta g(T-T_L)+S \quad \text{(Eq.4)}$$

Energy equation:

$$\frac{\partial}{\partial t}(\rho H)+\nabla\bullet\left(\rho\vec{V}H\right)=\nabla\bullet(K\nabla T) \quad \text{(Eq.5)}$$

In Eq. (5), H is the total enthalpy which is the sum of sensible and latent energy and is calculated based on the following equations:

$$H=H_{SE}+H_{Lh} \quad \text{(Eq.6)}$$

$$H_{SE}=H_{ref}+\int_{T_{ref}}^{T}C_p dT \quad \text{(Eq.7)}$$

$$H_{Lh}=\alpha L_m \quad \text{(Eq.8)}$$

The buoyancy force in this work has been calculated by adopting the Boussinesq approximation which declares that effect of the buoyancy driven forces due to gravity and temperature change can be calculated by summation of the momentum equation with a source term. The source term related to the Boussinesq approximation has been added as the third term to the right side of Eq. (4).

The governing equations used to solve the fluid flow inside the tube which is an incompressible, Newtonian fluid with constant thermos-physical properties are as follows:

Continuity equation:

$$\nabla\bullet\vec{V}=0 \quad \text{(Eq.9)}$$

Momentum equation:

$$\rho_f\frac{\partial\vec{V}}{\partial t}+\rho_f\vec{V}\left(\nabla\bullet\vec{V}\right)=-\nabla p+\mu_f\nabla^2\vec{V} \quad \text{(Eq.10)}$$

Energy equation:

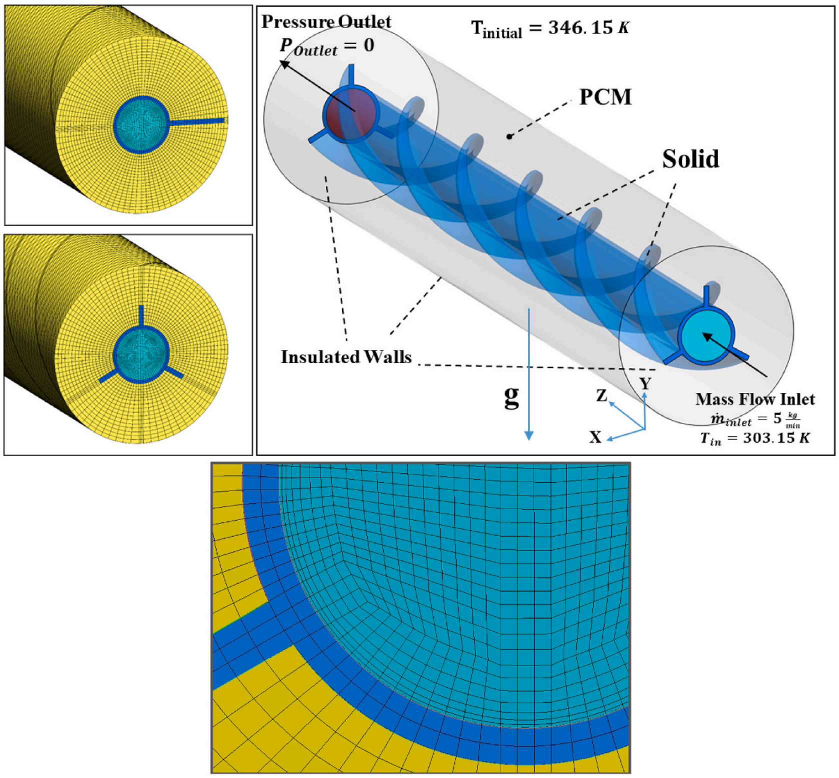

Fig. 2. Generated mesh on two of the models (single fin and triple fin) (left), schematic of the boundary and initial conditions (right) and the close view of the boundary layer mesh on the wall of the water tube (bottom).

$$\rho_f c_{p_f} \frac{\partial T}{\partial t} + \rho_f c_{p_f} \vec{V} \bullet \nabla T = \nabla \bullet (k_f \nabla T) \quad \text{(Eq.11)}$$

As the inlet Reynolds number is about 5300 which totally falls within the turbulent flow regime, in order to simulate the water flowing within the tube, the k-ε turbulence model has been used with the Enhanced Wall Treatment (EWT) as the wall function which solves the flow parameters near the wall and more properly captures the near wall phenomenon including the heat transfer and boundary layer and generates more accurate results in the near wall regions. The SIMPLE algorithm has been adopted for the pressure/velocity coupling and the PRESTO scheme has been used for discretization of the pressure term and Second order upwind scheme has been selected for discretizing the momentum, energy and turbulence terms. In order to insure the convergence, 10^{-4}, 10^{-5} and 10^{-7} have been set for the convergence criteria for the continuity, momentum and energy equations.

2.3. Boundary and initial conditions

Fig. 2 depicts schematically the various boundary conditions set on different boundaries of the model. The inlet of the tube has been set to "mass flow rate" and the water with low temperature flows inside the tube with flow rate of 5 kg/min and temperature of 303.15 K. The outer walls of the PCM enclosure are insulated and the PCM has no thermal exchange with the environment. The inside walls which encompasses the fin walls are set as the coupled walls which have heat transfer from both the water and the PCM side. The outlets of the tube are set to be "pressure outlet" with atmospheric pressure at the outlet boundary. Fig. 2 also depicts a view of the generated structured mesh on the single fin and the triple fin cases. The solid and PCM and water regions in the meshed model have been designated with different colors as different computational domains.

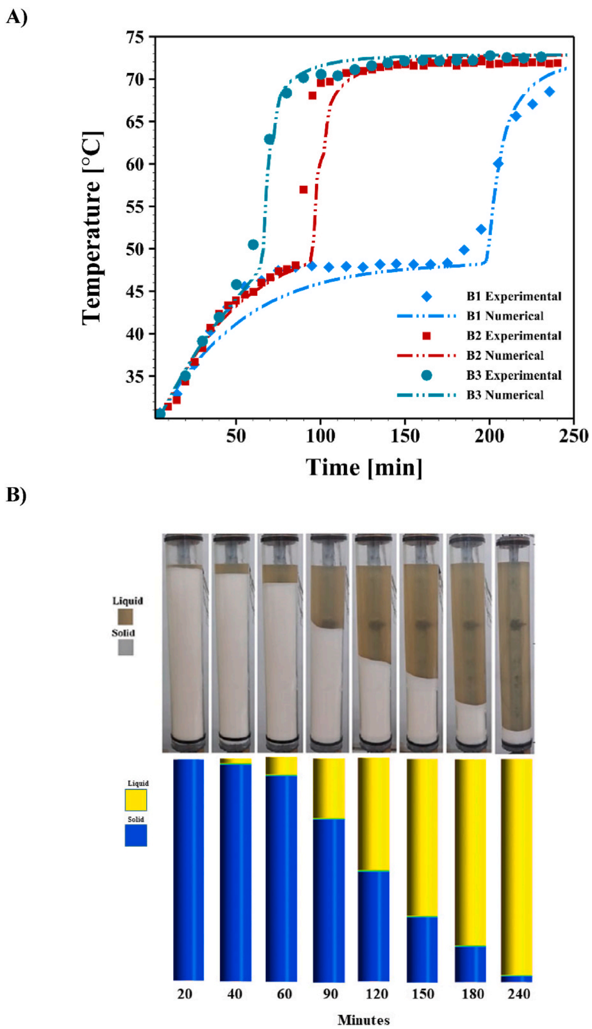

Fig. 3. Validation of the numerical method. A) Comparison of evolution of temperature of three distinct points in the domain in this work and that of Mahdi et al. [43] B) Comparison of liquid fraction at various times during the phase change in the work of Mahdi et al. [43] and the present numerical work.

3. Results

3.1. Validation

In order to assess the validity of the results and the numerical method adopted, the data acquired by the present simulation have been compared against the published data in the literature. The work of Mahdi et al. [43] has been used to evaluate reliability of the present numerical method in association with the experimental data. Fig. 3A demonstrates the comparison between the temperature at three distinct points of in the domain derived by the present work and that of Mahdi et al. [43]. Fig. 3A clearly shows that there is a good compatibility between the current results and the results of the experimental work. Although there are some minor deviations at some points, however, it is observed that the results of the numerical simulation follow the experimental results closely during the whole period of experiment. Fig. 3A clearly proves the validity of the present numerical method. However, in order to have a more comprehensive comparison between the numerical/experimental data, contours of melt fraction reported in the work of Mahdi [43] et al. have been compared with the contours obtained by the numerical work at different times within the melting process in Fig. 3B. Despite Fig. 3A which proved validity of the solution method more quantitatively, Fig. 3B proves the validity of the results more qualitatively. It is discovered that the melt fraction contours in the numerical work are mostly similar to the ones in experimental work. Hence, according to Fig. 3, it could be concluded that the present numerical method is reliable and provides accurate results.

3.2. Results

Fig. 4A presents the PCM solid fraction in the solidification process in different cases having different fin numbers. It is observed that the finned cases essentially affect the solidification speed and the solid fraction reaches to 1 in the finned cases much earlier than the no fin (base) case. Among the finned cases, it is observed that the case with single fin has the worst performance for heat transfer among all finned cases and its performance is far away from other finned cases. The triple, double and quadruple fins have relatively better functionality than single fin case although the double and triple fins have rather equal performance which is better than others. According to Fig. 4B, it is observed that the double and triple fin cases outperform other cases with the fastest solidification time followed by the quadruple fin case with a minor difference than the double fin and the fourth placement is the single fin. Among all finned cases the single fin has the longest period of solidification and the triple and double fins equally have the least period of solidification. In comparison to the weakest case with fin and the base case, the triple and double fins have 15.78% and 30.43% shorter phase change period respectively. According to the present data, it could be concluded that the fin number is not the main influencing factor for heat transfer optimization and the length of the fins also plays an important role. According to Fig. 1 and Table s 1 and it was stated that the length of fins varies with fin number and as it increases, the length of each of the fins reduces to keep the total heat transfer surface constant. Hence, the cases with higher number of fins have the least fin length. As the single fin has the longest length

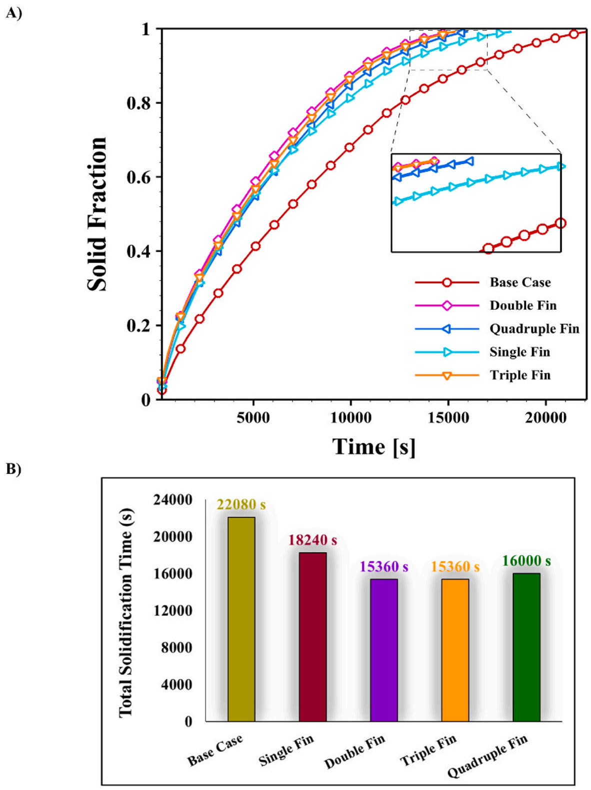

Fig. 4. A) Evolution of PCM Solid fraction against time in different cases, B) Total Solidification time of PCM in different cases.

among all cases, the fin can better penetrate toward the PCM container wall and cover a farther distance in the PCM which is an advantage for augmentation of heat transfer. On the other hand, in the single fin case, lower number of fins results in further distance in between the successive fins and the fin cannot properly fill the whole surrounding of the tube which remains a negative impact of the heat transfer. In the cases with higher fin number, the opposite is true and there is less penetration inside the PCM enclosure in exchange for better distribution of fins on the periphery of the tube. As it is clear in Fig. 4, the best case is result of a trade-off between the fin number and the fin length. According to Fig. 4, it is observed that the single fin case which has the longest fin and the quadruple fin case which has the highest number of fins do not have the best functionality while the case with double and triple fin outperform other cases. It indicates that these cases can better transfer the heat to both the near wall regions and the periphery of the tube at the same time and perform better. The single fin although can better increase the heat transfer in the near wall regions, on the other hand cannot properly cover the area around the tube thus shows a weaker performance.

There are two important parameters in each of the fin configuration that affect the heat transfer and phase change speed, one of which has a positive effect and the other remains negative impact. These two parameters are the number of fins and length of each fin. Number of fins is important as higher number of fins results in more equal heat transfer around the inner tube. It is evident in Fig. 6 that the cases with higher number of fins have more uniform solidification front which is resulted by the uniform transfer of energy from the PCM enclosure. On the other hand, length of fins is important as longer fins can better extend inside the PCM enclosure and sweep the heat from all regions particularly the near wall regions which are the farthest regions from the inner tube. Hence, longer fins result in better transfer of energy from the farther areas. In this work, as the heat transfer area in all fins have been taken to be equal, the fins' length has an inverse relationship with the number of fins and as the number of fins increases, the length of fins gets shorter. This means that improvement of one parameter results in weakening of the other parameter. When increasing the fin number from 1 to 2, although fin length gets shorter but the heat transfer occurs better around the tube. In fact, effect of fin number prevails over the effect of fin length. This is due to the fact that presence of fins on the both sides of the inner tube is much more effective than being only on one side of the inner tube (See Fig. 1). However, when increasing the fin number from 2 to 3, the presence of fins on three sides of the inner tube doesn't remain the influence as much as the influence of increasing the fin number from 1 to 2. Hence, in the double fin and triple fin cases, the two mentioned factors neutralize each other and perform equally in terms of phase change speed. It is to be noted that by increasing the fin number from 3 to 4, again the effect of length of fins prevails over fin number and the heat transfer becomes weaker.

Fig. 5 elucidates the phenomenon presented in Fig. 4 by depicting the solid fraction contours on different cross sections of the model at different times during the solidification period. In all cases, the PCM at the vicinity of the tube turns to solid earlier than other regions at the onset of the phase change and later the solid region expands to other regions. Due to presence of convective flows and the accumulation of the cold fluid gathered at the lower side of the tube, the solid region extends below the tube further than the upper parts and it is observed that there is an accumulation of PCM in its liquid state at the top of the enclosure at the subsequent stages of the solidification process. Although this incident is also observed in the finned cases, unlike the base case, the solid region extension in finned cases is not uniform around the tube and presence of fins alters the solidification pattern. In the single fin case, the solidification is strengthened around the fin itself which eliminates the uniformity of solid front around the tube. The same phenomenon is observed in other cases either with less importance. By increasing the number of fins, the periphery of the tube gets properly occupied by the fins and the heat at the periphery of the tube gets better transferred which results in more uniform expansion of the solid front. This incident is better presented in Fig. 6 where the solid front in the single and quadruple fin cases has been depicted at various times during the solidification process. It is figured out that in Fig. 6 that extension of the solid front in the base case and the quadruple fin case is more uniform than the single fin case. It is also notable that the expansion of the solid front at the lower side of the tube is more

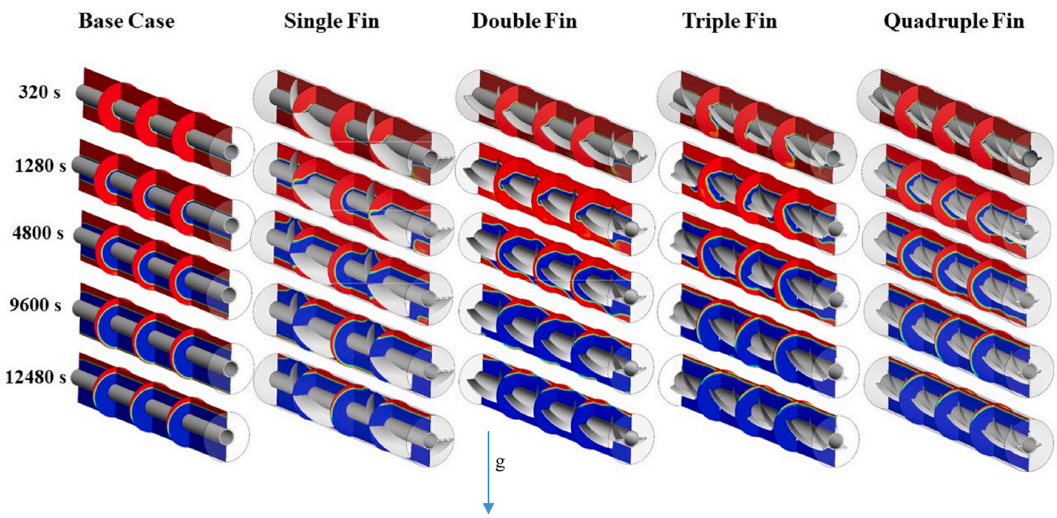

Fig. 5. Contours of solid fraction in various cases at different times during the solidification procedure.

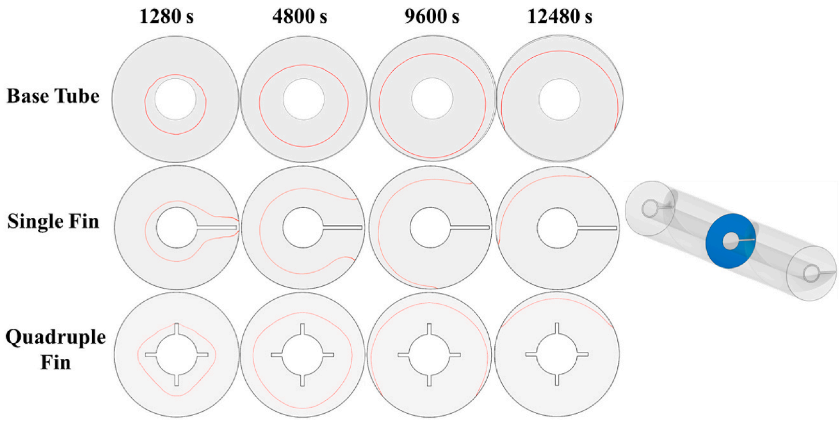

Fig. 6. Solid interface in the single fin and quadruple fin cases at different times on the mid plane of enclosure. Position of the plane has been ascertained with blue color in the model. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

considerable than the top side of the tube which is due to the downward orientation of the cold currents and development of solid front toward the bottom of the enclosure which is why cumulation of molten PCM in Fig. 5 is evident at the top of the enclosure at the final stages of the solidification.

Fig. 7 depicts the temperature contours on three transverse and one axial cross-section of the PCM container at different time steps in the solidification process in different cases including the finned cases and the base case. It is observed that there is a temperature gradient at the beginning of the heat transfer process but over the course of the time, the thermal energy is swept from the environment and the domain temperature decreases more uniformly in cases with higher number of fins. One important point to mention is that the energy depletion in the single and double fin cases is more affected by the presence of the fins but in cases with higher number of fins the heat transfer is more uniform for the reason mentioned previously in the solid fraction contours.

Fig. 8 indicates the temperature evolution on three distinct points inside the domain as indicated in this figure. The temperature evolution on point 1 in different cases and temperature on points 1, 2 and 3 in the single fin (worst performance) and triple fin (best performance) cases have been demonstrated. In Fig. 8A, the comparison of the temperature on point 1 in different cases has been presented. It is obvious that the performance of each fin has direct impact on the temperature because as the heat transfer gets enhanced, there is a more rapid temperature change in the domain. It is observed in Fig. 8A that the slope of the temperature curve for triple and double and quadruple fins are steeper while temperature on point 1 in base case and single fin case has more mild slope which is due to the heat transfer behavior in different cases. Fig. 8B presents a comparison between the temperature evolution among the points 1–3 which are for the single fin and triple fin cases. It is observed that at all points, the reduction of temperature in all three points is faster in the triple fin case in comparison with the single fin case which is result of better heat transfer characteristic of the triple fin. It is observed that at the initial steps of the process, the slope of the curves is too high which is to the sensible heat removal from the domain and reduction of the temperature in PCM. After a while, when the temperature of the PCM gets close to the

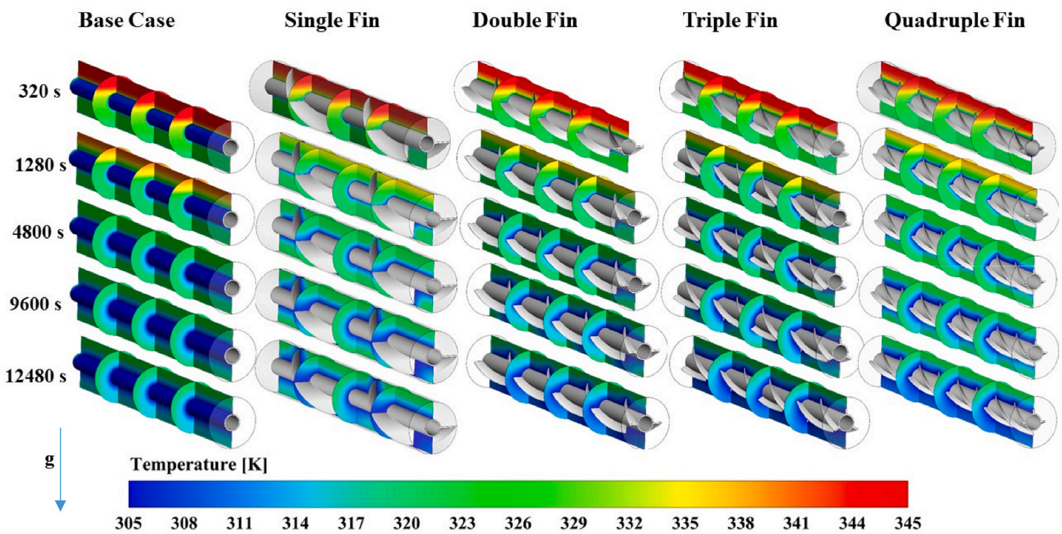

Fig. 7. Temperature contours in different cases at different times during the solidification process.

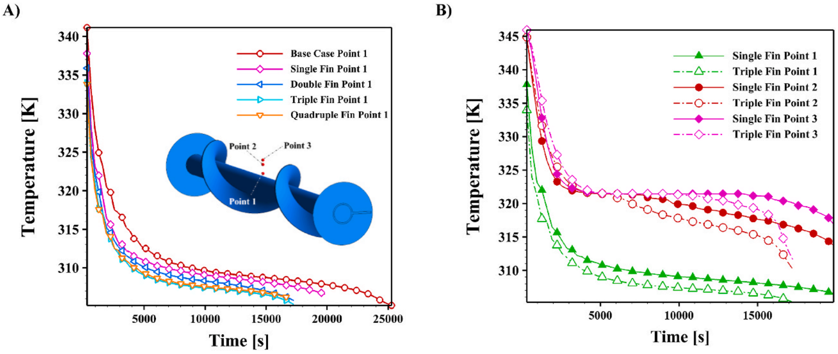

Fig. 8. Temperature evolution on different points inside the PCM enclosure. A) Comparison of temperature on point 1 in different cases, B) comparison of temperature on points 1–3 in the cases with single fin and triple fin.

solidification temperature, the reduction of the temperature which was due to sensible energy loss is stopped and the solid front starts to develop to the surrounding. This is the stage that the temperature at points 2 and 3 remains constant at about 321 K which is the onset of solidification temperature of PCM. As points 2 and 3 are further distant from the surface of the fins, it gets longer than the point 1 for these points to fall below 321 K while point 1 which is the closest to the surface of the fin loses temperature rapidly until it reaches to the same temperature as the solid walls temperature. In all points, the higher performance of the triple fin is evident as the points in this case have lower temperature in comparison with the single fin case.

As a general conclusion about the performance of the different cases studied in this work, average Nusselt number as a dimensionless parameter can properly express the influence of the fins used. The average *Nu* during the solidification period is calculated based on the following equation:

$$\overline{Nu_{avg}} = \frac{1}{t_{full}} \int_0^{t_{full}} \frac{q_w\,(t) L_e}{A_w t\,(T_w - T_m) k}\, dt \qquad \text{(Eq. 12)}$$

In Eq. (12), t_{full} is the total phase change period, A_w is the surface area of the heat transfer wall, L_e is the characteristic length, T_w is the average wall temperature, T_m is the mean temperature of the domain and k is the thermal conductivity of the PCM. According to Fig. 9, the same conclusion about the performance of fins could be made more evidently. It is observed that the double fin and triple fin cases with a minor difference have the highest performance in comparison with other cases and the quadruple fin and single fin cases are in the next positions. It is also evident that the double, triple and quadruple fin cases demonstrate rather better performance with minor differences however, the performance of the single fin case is far below the other finned cases which is because of higher distance of fins in the single fin case when comparing with other cases. It was stated before that as the fin number increases, the length of fins decreases and vice versa. Although in the single fin case, the fin has the longest length among other cases, but the fins have occupied surrounding of the tube with a low frequency and this can significantly weaken the heat transfer in the PCM which is why performance of single fin is much lower than other cases. The double fin with 16.25% and 41% higher heat transfer performance in comparison with the single fin and the base tube has the optimized performance among all cases.

Fig. 10 represent the released energy during the solidification process which includes both of the latent energy and sensible energy. Latent energy is related to the energy released during the phase change and sensible energy is the energy released without phase change which is accompanied with variation of temperature in the domain. As observed in Fig. 10, the rate of sensible and latent energy release for different cases is relative to the performance of each fin. It could be seen that the triple and double fin cases show rather equal rate of energy release which is followed by the quadruple and single fin cases. The slowest rate of energy release is related to the base case in both the latent and sensible heat energy. Another point to mention based on Fig. 10 is that as there is a great difference between the temperature of the inlet flow and the PCM region, the PCM starts to lose its energy at a greater pace at the initial stages of the heat transfer process and the slope of sensible energy curves are higher in this period. Hence, as the process elapses and the temperature difference between the fluid flow and the PCM reduces, the rate of sensible energy release also reduces and the rate of latent energy release overtakes the sensible energy release.

4. Conclusion

In the present study, influence of twisted-fins on the solidification performance of the PCM inside a tube-shell LHTESS has been evaluated. Five cases with different fin number including the single, double, triple and quadruple fins and the base case have been simulated and compared together. Enthalpy-porosity method along with the k-e turbulent model have been used to simulate the phase change process and the water flow inside tube. The fins have been set to have equal heat transfer surface in all cases to make it feasible to be compared. Hence length of the fins is adjusted according to the fin number to keep the heat transfer surface equal. The method has been validated by using the experimental data present in the literature. The data have been evaluated in terms of the solid fraction evolution, total solidification time, time averaged Nusselt number, solid fraction and temperature contours and temperature evolution inside the domain. The key points observed in the study are as follows:

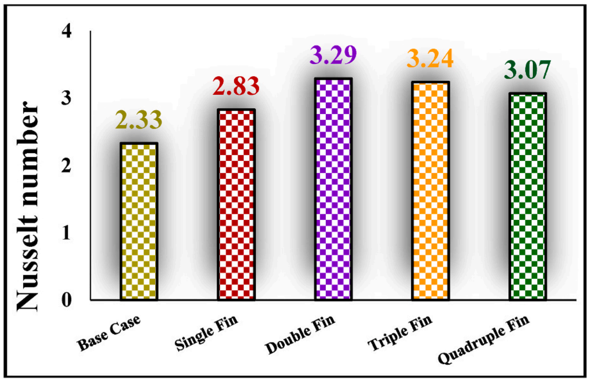

Fig. 9. Average Nusselt for different cases throughout the solidification period.

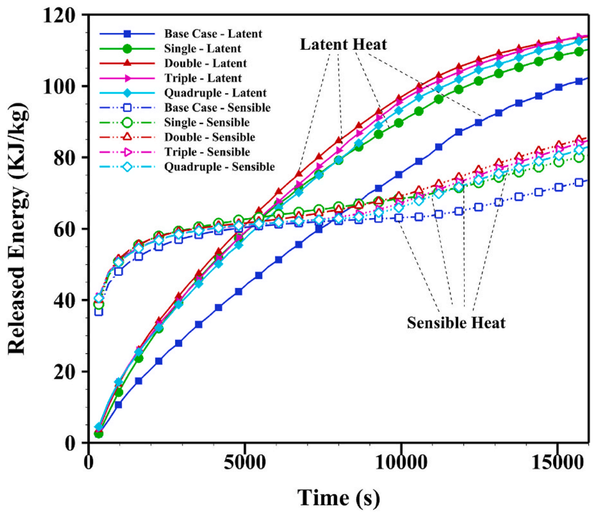

Fig. 10. Released energy per unit mass of the PCM for different cases including the sensible energy and latent energy.

- Presence of fins substantially influences the phase change process. In addition, number and length of fins are both influential and there is not a direct relationship between the number of fins and phase change acceleration.
- By increasing number of fins, the fins occupy more space around the tube which is beneficial for phase change acceleration however, on the other hand higher number of fins is associated with reducing the fin length which is a drawback for heat transfer process which is why increasing the fin number from triple to quadruple the solidification process takes longer to finish.
- The triple and double fin cases have the best performance among all cases and the single fin has the worst functionality among the finned cases. The triple and double cases have equal solidification period each of which being 15.78% and 30.43% shorter when being compared with the single fin (worst finned case) and base case respectively.
- As the solid front develops faster in the vicinity of the fins, presence of fins affects the solid front development. It is observed that in the triple and quadruple fin cases, due to more uniform presence of fins around the tube, the solid front advances more uniformly around the tube however, in the single and double fin cases, the solid front is more oriented toward the fin and the solid front extends more asymmetrically.
- The uniformity of heat transfer is also observed in the temperature contours where in the triple and quadruple fin cases the temperature around the tube is more uniform and the heat is absorbed from around the tube more uniformly.

Author statement

Kamel Guedri: Resources, Formal analysis, Investigation, Writing and editing-revised draft, Supervision; Pavitra Singh: Writing - review & editing, Methodology, Formal analysis, Data curation; Fahid Riaz: Methodology, writing original draft. Project management, Investigation; Abrar Inayat: Methodology, Writing original draft, Investigation; Nehad Ali Shah: Writing - review & editing, Methodology, Formal analysis, Data curation; Bandar M. Fadhl: Writing - review & editing, Formal analysis, Resources; Basim M. Makhdoum: Methodology, Formal analysis, Data curation, Investigation, Writing - review & editing, Resources, Project management; Akbar Arsalanloo: Formal analysis, Investigation, Methodology, Data curation, Writing and editing-revised draft, Supervision.

Declaration of competing interest

There is No Conflict of interest for the submitted paper titled as "Solidification Acceleration of PCM in a Horizontal Latent Heat Thermal Energy Storage System by Using Spiral Fins".

Data availability

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

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Nomenclature

T_F	Thickness of Fin (mm)
L_F	Fin Length (mm)
D_{out}	Diameter of PCM container (mm)
D_{in}	Diameter of HTF tube (mm)
T_S	Thickness of the Solid (mm)
P	Twist pitch (mm)
L	Length of Tube (mm)
t	Time (s)
T_L	Temperature of Melting (K)
C_p	Specific Heat (J/kg.K)
Nu_{avg}	Time Averaged *Nu*
H	distance between the fin and the outer shell
M	periodic distance between two consecutive points on fins
T_{So}	Solidification temperature
T_{Li}	Liquefying temperature

Greek symbols

θ	Fin Angle
ρ	Density (kg/m^3)
μ	Dynamic viscosity (Pa.s)
β	Coefficient of Thermal expansion (1/K)
α	Volume fraction

Abbreviations

EWT	Enhanced Wall Treatment
PCM	Phase Change Material
LHTESS	Latent Heat Thermal Energy Storage System
HTF	Heat Transfer Fluid

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