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Advancing the Freezing Rate in a Triplex-Tube Ice Storage Unit Using Axial Bent Fins

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***Abstract*—**Fins are widely recognized as a highly effective solution to address the poor thermal conductivity of phase change materials (PCMs) and enhance the efficiency of phase transition processes in thermal energy storage units. Despite the development of numerous advanced novel fin designs in academic research, their practical application in industry is often limited by the complexity of manufacturing. This study proposes a non-complex yet efficient axial bent fin design aimed at accelerating ice formation in a triplex-tube ice storage unit, with no intricate fabrication techniques. Using time-dependent computational simulations, the impact of key fin variables, including bend angles and directions are thoroughly investigated on the freezing process. The results demonstrate that although the presence of bends weakens the heat exchange in some cases, in the majority of the cases, they lead to improved performance. The findings demonstrate that the bent fin design can increase the freezing rate by up to 42.37% compared to the system without fins and by 6.13% in comparison with the case with traditional straight fins while maintaining identical heat transfer areas and PCM volumes. Given the simplicity of this design, it presents a viable option for real-world implementation in thermal energy storage applications.

Keywords-phase change materials; ice storage systems; heat transfer; freezing; triplex tube heat exchanger

I. INTRODUCTION

The rising global energy demand and the pressing need to reduce carbon emissions have made efficient energy management systems a top priority. Renewable energy sources like solar and wind are inherently intermittent, creating challenges in maintaining a stable energy supply. To address this, energy storage solutions that can balance supply and demand are essential. Latent thermal energy storage (LTES) units, which store energy through phase change processes, offer a promising solution due to their high energy density. Among these, ice storage systems are particularly effective for cooling applications, such as air conditioning, by shifting energy use to off-peak periods. However, the limited thermal conductivity of PCMs remains a significant limitation in these systems, prompting researchers to explore methods to enhance their performance.

One widely studied approach involves the use of extended surfaces, or fins, to elevate heat exchange. Fins increase the surface area for heat exchange, accelerating the charging and discharging of LTES units. Recent innovations in fin design have shown significant potential. For example, Zheng et al. [1] introduced a fin shaped like a spiderweb, which reduced the time needed for PCM solidification by nearly 90% compared to straight fin designs; however, the improvement was not obtained at identical heat exchange surface areas. Similarly, Nie et al. [2] investigated helm-shaped fins, demonstrating a 22.1% improvement in melting time compared to conventional annular fins of the same volume (but not the same heat exchange surface). Li et al. [3] explored leaf-shaped fins and tried to optimize such fins, but did not compare their results with any conventional or even finless cases to prove the superiority of these novel fins.

Fractal-based fin designs, such as those mimicking tree branches or leaf veins, have further advanced heat exchange. In a study by Rostami et al. [4], vein-like fins were introduced in a PCM container shaped like a maple leaf. The reason for selecting such an unconventional container or fin shape was not disclosed and no comparison was made to show their superiority compared to their conventional counterparts in any way. They reported that these fins are able to enhance the freezing time by around 42% compared to systems without fins. However, since neither the heat exchange area of the fins nor the PCM volume was maintained fixed during their experiments, such improvement is not meaningful.

Overall, regarding these novel fin designs it can be said that, despite their academic promise, these complex geometries face practical hurdles. Manufacturing such intricate designs with precision is challenging, especially for large-scale industrial applications. This limits their practicality, as the performance gains often do not justify the increased costs and manufacturing complexity compared to simpler, traditional fin designs. Given these challenges, this investigation is shifting toward simpler yet effective fin configurations that are easier to produce and scale. For instance, studies are now focusing on bent fins in triplex-tube LTES systems, which are straightforward to manufacture and optimize. By using computational models, researchers are investigating how factors like bend angle, orientation, and placement influence phase change dynamics. Importantly, these studies maintain consistent PCM volume and heat exchange surface area to ensure fair comparisons. This approach aims to balance practicality and performance simultaneously, paving the way for more widespread adoption of LTES systems in industrial and commercial settings.

II. Methodology

A. Physical Model

This study focuses on a horizontally-aligned Triplex Tube Unit (TTU). The TTU includes three concentric tubes: a central tube measuring 12.7 mm in diameter, a middle tube with a diameter of 50.8 mm, and an outer tube with a diameter of 63.5 mm, all with a 1 mm thickness. Water is used as the PCM and fills the gap between the middle and central tubes. The coolant flows through the space between the middle and outer pipes as well as the central pipe. The pipes and fins are constructed from C12200 copper alloy, selected for its high thermal conductivity and availability. The study compares the performance of straight and bent fins, ensuring that the PCM volume and heat exchange surface area remain the same across all finned setups. The TTU has ten fins, with five on the outside of the central pipe and five on the inside of the outer pipe. Figure 1 shows a three-dimensional (3D) visualization of the bent fins in the aforementioned unit, along with the examined domain and sizing details. Table 1 lists the thermophysical properties of water and C12200 alloy, and Table 2 outlines the cases analyzed in the research.

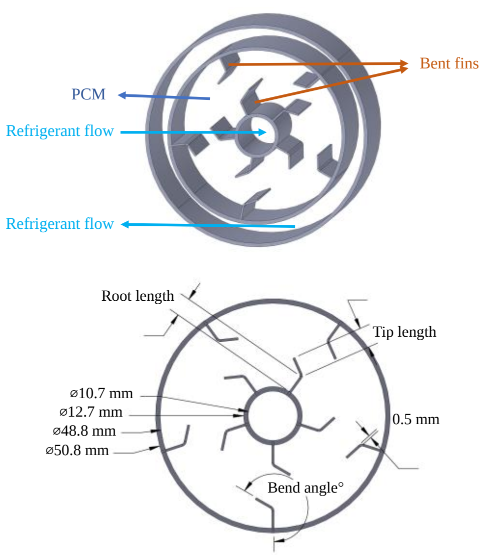

Figure 1. 3D visualization of the TTU with bent fins, and the computational domain details

TABLE I. MATERIAL PROPERTIES USED IN THE SIMULATION [5, 6]

Property	**Material**		
	C12200	***Water***	
		Solid	***Liquid***
Freezing point [K]	-	273.15	
Thermal Expansion Coefficient [1/K]×10^7	-	-6.733	
Latent heat of fusion [kJ/kg]	-	334	
Viscosity [Pa·s]×10^2	-	-	0.162
Density [kg/m³]	8940	958.4	
Thermal Capacity [J/(kg·K)]	386	2217	4180
Thermal Conductivity [W/(m·K)]	330	1.918	0.578

TABLE II. CONFIGURATIONS ANALYZED IN THE PRESENT RESEARCH

Studied Parameter	**Specifications**			
	Case	***Bend angle (°)***	***Bend direction***	***Added heat exchange surface (cm^2/m)***
	A	-	-	0
Bend angle	B	0	-	1700.35
	C	30	Unidirectional	
	D	60		
	E	90		
Bend direction	B	0	-	
	D	60	Unidirectional	
	F	60	Bidirectional	

B. Assumptions and Conditions

To simplify the complex physics of PCM container simulations, several assumptions are applied:

- The liquid PCM is modeled as incompressible fluid in a laminar flow, with negligible viscous dissipation in transient mode.
- The PCM is homogeneous, with no irregularities or impurities.
- The solidification process is simulated using Voller and Prakash's enthalpy-porosity method [7].
- Thermophysical properties of the PCM are kept constant within each phase (solid or liquid) but differ between phases.
- Thermal contact resistance between tubes and fins is neglected.
- Volume changes during phase transition are disregarded. The natural convection is modeled employing the Boussinesq approximation.
- Supercooling effects are ignored.
- A fixed wall temperature (270.65 K) is imposed on the inner and outer tube surfaces, assuming rapid coolant flow with negligible temperature variation in the axial direction [8, 9].
- Initially, the computational domain is stationary at 277.15 K.

C. Governing Equations

The simulation solves governing equations for mass, momentum, and energy conservation.

Continuity equation:

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

Navier-Stokes equations:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\frac{1}{\rho}\frac{(1-\gamma)^2}{\gamma^3+\varepsilon}A_{mush}u \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\frac{\mu}{\rho}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{(\rho\beta)}{\rho}g(T-T_{ref})+\frac{1}{\rho}\frac{(1-\gamma)^2}{\gamma^3+\varepsilon}A_{mush}v \tag{3}$$

In Equations (1) to (3), ρ denotes density, P represents pressure, μ indicates dynamic viscosity, β is the volumetric thermal expansion coefficient, k is thermal conductivity, g is the gravity vector, and γ represents the liquid fraction. The flow velocity is defined by components u and v in horizontal and vertical directions, respectively. Moreover, A_{mush} symbol is employed to indicate the mushy zone constant, which models the damping effect caused by the solid-liquid interface during phase change. A value of 10^5 is used for this parameter in this study, consistent with prior research on water solidification [5, 10]. Additionally, ε is a small constant added to avoid creating a division by 0 in the equations.

Energy equation:

$$\rho\left(\frac{\partial H}{\partial t}+\frac{\partial(uH)}{\partial x}+\frac{\partial(vH)}{\partial y}\right)=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

Equation (4) governs the energy balance within the system, incorporating the total enthalpy (H) of the PCM, which combines sensible enthalpy (h_{sens}) and latent enthalpy (h_{lat}). The liquid fraction (γ), representing the proportion of molten PCM, is determined using Equation (5). This fraction depends on the PCM temperature relative to its solidus (T_s) and liquidus (T_l) temperatures, resulting in a value between 1 (fully liquid) and 0 (fully solid). Moreover, latent and sensible enthalpies are computed employing Equations (6) and (7), respectively.

$$\gamma=\begin{Bmatrix} 0 & \text{if } T<T_s \\ (T-T_s)/(T_l-T_s) & \text{if } T_s<T<T_l \\ 1 & \text{if } T>T_l \end{Bmatrix} \tag{5}$$

$$h_{lat}=\gamma\cdot\Gamma \tag{6}$$

$$h_{sen}=h_{ref}+\int_{T_{ref}}^{T}c_p\,dT \tag{7}$$

Here, T represents the temperature of the cell, T_{ref} and h_{ref} correspond to the reference temperature and enthalpy under initial conditions, c_p denotes the specific heat capacity, and Γ represents the enthalpy of fusion for the solid-liquid phase transition.

D. *Solver Configurations*

The development of the computational model was carried out using ANSYS 19.2 using the finite volume approach. For spatial discretization of convective terms in the momentum and energy equations, the QUICK scheme was utilized. Pressure interpolation was performed using the PRESTO! scheme, while the SIMPLE algorithm addressed pressure-velocity coupling. Discretization of the momentum and energy equations was carried out with a first-order upwind scheme. Convergence thresholds were set at 10^{-4} for momentum and continuity, and 10^{-6} for energy.

E. *Validation*

To validate the numerical simulations, results underwent a comparison with experimental data from Ezan et al. [11], who investigated the charging process in a shell-and-tube unit for storing ice. Their setup involved water in the shell and an ethylene glycol solution in the tube. For validation, their fourth geometric configuration was used, featuring a 190 mm shell diameter, a 25 mm outer tube diameter, and a 15 mm inner tube diameter, with both shell and tube lengths set to 400 mm. Polythene (PE-32) was chosen as the tube material; on the other hand, the shell was made of Plexiglas for phase change observation. The heat transfer fluid (HTF) temperature was maintained at 263.15 K, with a flow rate of 4 LPM. A comparison between the numerical results and experimental data revealed a maximum error of 5.79%, as shown in Figure 2. The numerical model accurately predicted the solidification trend, demonstrating its reliability for further analysis.

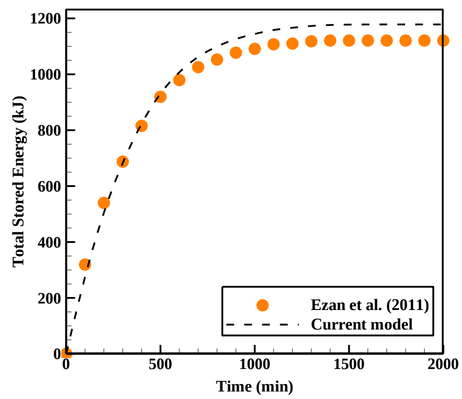

Figure 2. Model validation against experimental data from Ezan et al. [11]

F. *Solution Independence Tests*

To ensure simulation reliability, time-step, and grid independence analyses were conducted. Figure 3 shows the results of these analyses. The results with three different time-step sizes were compared, with results for 0.25 s and 0.5 s showing minimal differences. A 0.5 s time step was selected for its balance between accuracy and computational efficiency. For meshing the computational domain, an unstructured triangular mesh was used, with finer resolution near the fins and tubes to capture curvature and enhance precision in critical areas. A comparison of various grid systems revealed that grid independence was achieved with 33,151 cells, as further refinement to 48,229 cells yielded negligible improvements. Consequently, the 33,151-cell grid was selected for its optimal combination of accuracy and computational cost. The selected grid is illustrated in Figure 4.

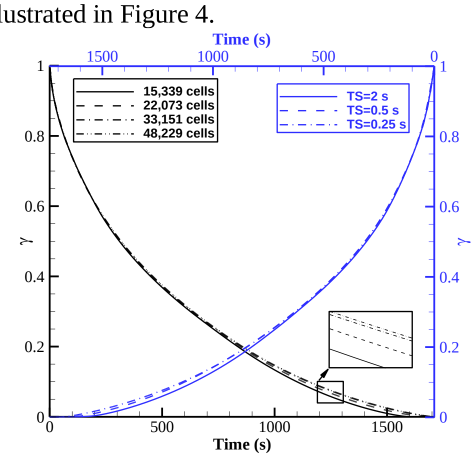

Figure 3. Grid and time-step sensitivity analyses

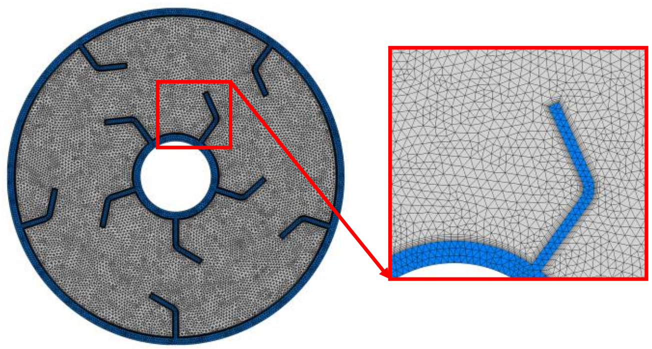

Figure 4. Example of the mesh grid for Case F

III. Results and Discussions

This study introduces a practical and efficient fin design that balances thermal performance with ease of manufacturing. Bent axial fins with varying geometric features are examined and compared to traditional straight fins. Key parameters, including bend angle and orientation, are evaluated based on their influence on the freezing process. Performance is assessed through changes in average liquid fraction, temperature reduction in the PCM, and graphical phase change contours. Each parameter is examined sequentially, with the best-performing geometry from one step serving as the baseline for the next. This approach ensures the identification of the optimal fin configuration within the tested range.

A. Bend Angle

The study begins by examining the effect of bend angle on fin performance. Fins are bent at 30°, 60°, and 90° at their midpoint, and their performance is compared to cases without fins and with traditional straight fins (with identical heat exchange areas). Figure 5 shows the impact of the bend angle on the average liquid fraction. Without fins, complete freezing takes 2960.5 s, while straight fins and bent fins at 30°, 60°, and 90° reduce this time to 1817.5 s, 1797 s, 1786 s, and 1854.5 s, respectively. Fins generally accelerate freezing by increasing heat exchange surfaces and reducing PCM volume, cutting freezing time by 38.61%, 39.30%, 39.67%, and 37.35% for straight and bent fins at 30°, 60°, and 90°, respectively. However, comparing finned cases with equal heat exchange areas reveals that 30° and 60° bends reduce freezing time by 1.13% and 1.73%, while a 90° bend increases it by 1.99%. Thus, the 60° bend performs best and is selected for further analysis. The difference and the reason behind it will be explained using liquid fraction contours.

Figure 6 shows the influence of fin bends on average temperature changes of the PCM. Based on the figure, temperature reduction trends align with liquid fraction changes. Initially, PCM temperature drops rapidly due to the absence of latent heat barriers. As phase change begins, temperature reduction slows, closely tied to the freezing process. Once freezing is complete, the temperature decline accelerates again. These findings highlight the importance of bend angle in optimizing fin performance for LTES units.

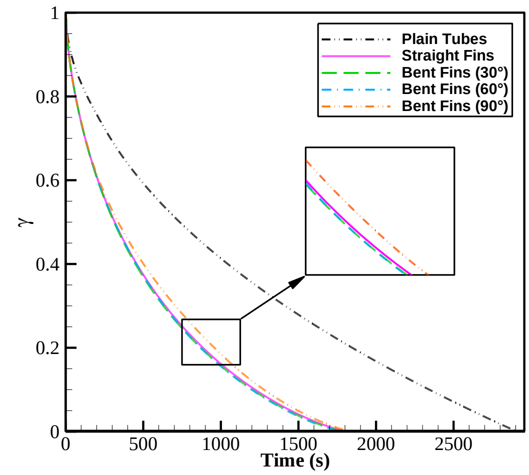

Figure 5. Influence of the bend angle on the temporal evolution of the liquid fraction

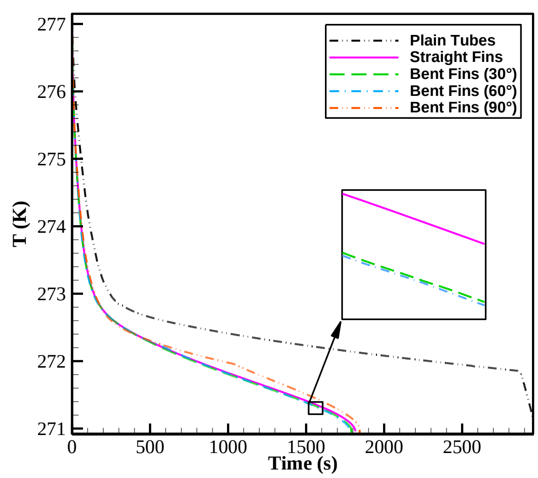

Figure 6. Influence of the bend angle on the temporal evolution of the average PCM temperature

The superior performance of 30° and 60° bend stems from their ability to distribute coldness more effectively across the container, particularly in slower-freezing regions. In contrast, a 90° bend sacrifices radial coverage, failing to address these areas efficiently. Figure 7 illustrates liquid fraction contours during freezing, showing that at 1080 s, the 90° bend case retains the most unfrozen water, while 30° and 60° bends outperform straight fins slightly. Additionally, bent fins create an asymmetrical freezing front, unlike the symmetrical front seen with straight fins and plain tubes.

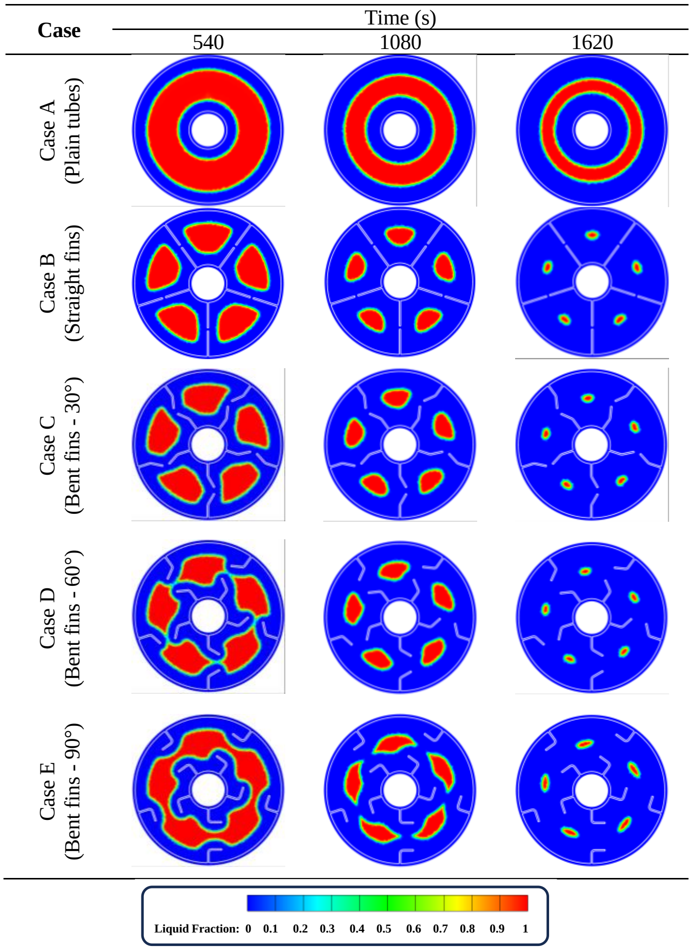

Figure 7. Liquid fraction contours for different bend angles

B. Bend Direction

This section investigates how bend direction influences the solidification rate in TTUs. The container features two rows of fins on the central and outer tubes, which can be bent in the same (unidirectional) or opposite (bidirectional) directions. Based on prior findings, fins with a 60° bend, which outperform straight fins, are used to test bend direction effects. Figure 8 shows the impact of bend direction on liquid fraction changes. Without fins, solidification takes 2960.5 s, while straight fins, unidirectional bent fins, and bidirectional bent fins reduce this time to 1817.5 s, 1786 s, and 1706 s, respectively. Compared to the finless case, these configurations improve solidification rates by 38.61%, 39.67%, and 42.37%. When comparing finned cases with equal PCM volume and heat exchange area, unidirectional and bidirectional bends enhance solidification rates by 1.73% and 6.13%, respectively. Although these improvements may seem modest, the simplicity of bending fins makes them significant.

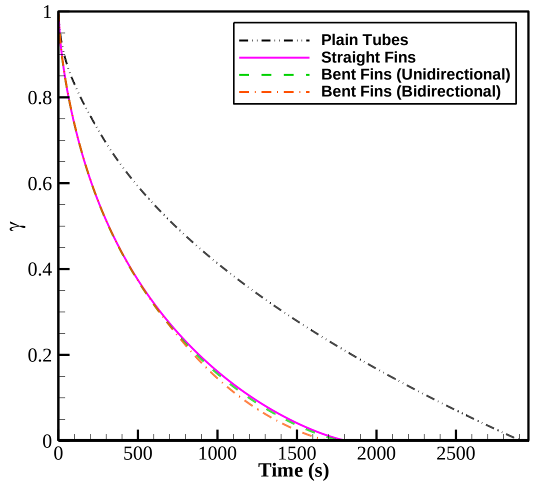

Figure 8. Influence of the fin's type on the temporal evolution of the liquid fraction

Figure 9 shows the effect of fin bend direction on the average PCM changes. According to the plot, the average PCM temperature trends with different bend directions align with liquid fraction changes. After an initial rapid drop, the temperature stabilizes near the freezing point as latent heat is absorbed, reflecting a similar trend to that of the liquid fraction pattern. These results highlight the importance of bend direction in optimizing fin performance for LTES units.

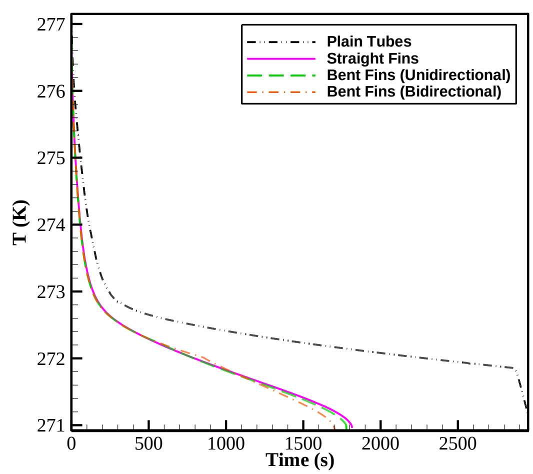

Figure 9. Influence of the fin's type on the temporal evolution of the average PCM temperature

Figure 10 illustrates liquid fraction contours with different fin bend directions. Observing the contours at 1080 s indicates that bidirectional bent fins leave less liquid water than other configurations. Unidirectional bends cause fin tips to overlap regions closer to each other, leaving some areas inadequately covered, while bidirectional bends ensure even coverage on both sides, accelerating freezing without altering PCM volume or fin surface area.

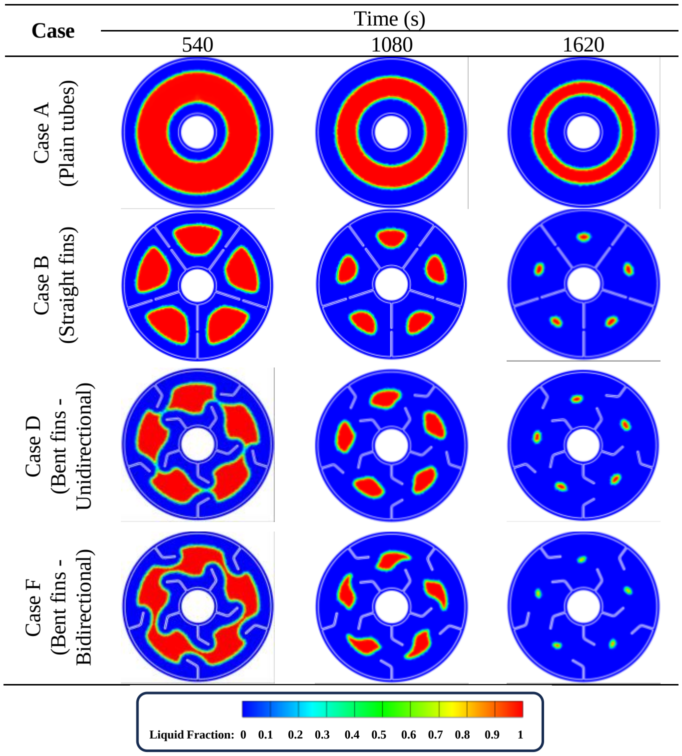

Figure 10. Liquid fraction contours for different types of fins

IV. CONCLUSIONS

This research focused on optimizing fin designs to enhance heat exchange in triplex-tube ice storage systems using axial bent fins. Transient simulations were conducted to evaluate the impact of bend angle, direction, and location on phase-change performance, measured through liquid fraction, PCM temperature, and solidification front behavior. The study aimed to develop a fin design that improves thermal efficiency while remaining easy to manufacture. Key insights include:

- Not all bends improve performance. At a constant heat exchange surface, while 30° and 60° bends increased solidification rates by up to 6.13%, a 90° bend reduced freezing rate by 1.99%, showing that excessive bending can reduce heat exchange.
- Raising the bend angle of the fin does not have a straightforward trend in reducing the complete freezing time. A 60° bend in the middle of the fin provided a better solidification rate compared to that with 30° and 90° bends.
- Bidirectional fin arrangements outperformed unidirectional ones, boosting freezing rates by 6.13% compared to straight fins. Unidirectional setups improved rates by only 1.73%, as bidirectional designs distribute cooling more evenly across the PCM.

These findings highlight that simple geometric adjustments to fins can significantly improve thermal performance in ice storage systems without requiring complex manufacturing processes. The proposed bent fin design offers a practical and efficient solution for enhancing heat exchange in triplex-tube units.

REFERENCES

[1] Zheng Z.-J., Yin H., He C., Wei Y., Cui M., and Xu Y., Parameter optimization of unevenly spiderweb-shaped fin for enhanced solidification performance of shell and tube latent-heat thermal energy storage units. *Journal of Energy Storage*, **72**: 108495, 2023.

[2] Nie C., Liu X., Rao Z., and Liu J., Discharging performance evaluation and optimization of a latent heat thermal energy storage unit with helm-shaped fin. Applied Thermal Engineering, **236**: 121595, 2024.

[3] Li C., Li Q., and Ge R., Assessment on the melting performance of a phase change material based shell and tube thermal energy storage device containing leaf-shaped longitudinal fins. *Journal of Energy Storage*, **60**: 106574, 2023.

[4] Rostami A.K., Alizadeh M., Fazlollahtabar A., and Ganji D.D., Performance enhancement of a maple leaf-shaped latent heat energy storage unit by adding nanoparticles and leaf vein fins. *Journal of Energy Storage*, **43**: 103159, 2021.

[5] Afsharpanah F., Mousavi Ajarostaghi S.S., and Arıcı M., Parametric study of phase change time reduction in a shell-and-tube ice storage system with anchor-type fin design. *International Communications in Heat and Mass Transfer*, 2022. **137**: 106281, 2022.

[6] KME Germany GmbH & Co., *Copper Alloy C12200 (Cu-DHP) Data Sheet*, 2023, Available from: https://www.kme.com/fileadmin/DOWNLOADCENTER/COPPER%20DIVISON/4%20Industrial%20Rolled/3_Datasheets/05_2023_C12200_Cu-DHP_e.pdf.

[7] Voller V.R. and Prakash C., A fixed grid numerical modelling methodology for convection-diffusion mushy region phase-change problems. *International Journal of Heat and Mass Transfer*, **30**(8): p. 1709-1719, 1987.

[8] Kumar A., Maurya A., Haque Siddiqui I., Alnaser I.A., and Ashraf I., Transient analysis of PCM discharging in a rotary triplex tube with wave-shaped fins. *Journal of Energy Storage*, **79**: 110178, 2024.

[9] Vahidhosseini S.M., Esmaeili Z., Rashidi S., Rafee R., and Yan W.M., Effects of novel fins on PCM melting/solidification in triplex tube heat exchangers. *Applied Thermal Engineering*, **262**: 125217, 2025.

[10] Afsharpanah F., Pakzad K., Mousavi Ajarostaghi S.S., Poncet S., and Sedighi K., Accelerating the charging process in a shell and dual coil ice storage unit equipped with connecting plates. *International Journal of Energy Research*, **46**(6): p. 7460-7478, 2022.

[11] Ezan M.A., Ozdogan M., and Erek A., Experimental study on charging and discharging periods of water in a latent heat storage unit. *International Journal of Thermal Sciences*, **50**(11): p. 2205-2219, 2011.