"Heat Transfer Enhancement in Triplex Tube Latent Heat Energy Storage System Using Tree Fins and Variation on Branch Angle"

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Vishwajeet Kumar[1], Shivendra Singh[2], Dr. B. Suresh[3]

[1]*Research Scholar, Department of Mechanical Engineering, Corporate Institute Of Science & Technology, Bhopal*
[2]*Asst Prof., Department of Mechanical Engineering, Corporate Institute Of Science & Technology, Bhopal*
[3]*Prof. & HOD, Department of Mechanical Engineering, Corporate Institute Of Science & Technology, Bhopal*

Abstract
Thermal energy storage (TES) systems show great promise for using phase change material (PCM) as a material for energy storage. Nevertheless, PCM's limited heat conductivity makes it unsuitable for some uses. By enhancing PCM's heat transfer performance with a variety of fin arrangements, TES systems may have their reaction times reduced. This research delves into the various tree-shaped fin structures and the impact of HTF on melting time. It also examines the common structure used by Y-structured and tree-structured fins in nature. The enthalpy-porosity technique is the foundation of the numerical research approach employed in this investigation. The study's numerical model is checked using data from earlier experiments. The findings of the simulation, which include the shapes of the solid-liquid interface and the temperature distribution as well as the changes in the PCM liquid percentage and the temperature differential, are now available. The findings reveal that the melting process and temperature of the PCM. Two angles between two symmetric branches are considered in tree form fin. Changing the two angles may significantly shorten the PCM melting time under certain operating circumstances. Numerical findings are used to analyse the transient values of temperature and liquid percent. Findings from this research may inspire the development of innovative fin structures for use in thermal energy storage and management-related new industrial goods.

Keyword: Thermal energy storage, phase change material, conductivity, tree-shape, Y-shape, etc.

I. INTRODUCTION

Heat exchangers are employed for the purpose of facilitating the transfer of thermal energy from one medium to another. The media in question can exist in a gaseous, liquid, or hybrid state. The media can be physically divided by a solid barrier to avoid intermingling, or it can be in direct access to each other.[1], [2] Heat exchangers are essential components that are necessary in order to fulfil the thermal demands of a given process, either by providing heating or cooling. A furnace or steam boiler is the typical source of direct heat input to the system. An increased demand on the boiler or steam will follow from any inefficiency in the heat transfer process at the exchangers.[3]–[5] Because they allow heat to be transferred from systems that have more heat than they need to systems that might use it more efficiently, heat exchangers may increase a system's energy efficiency.[6] To help move heat from one process stream to another or from one process stream to a utility stream, heat exchangers are a typical piece of equipment. The temperature of these utility streams is not always constant.[7]–[9] An effective TES is necessary since the production of electricity results in a significant quantity of waste heat that may be used for subsequent cooling, heating, and other purposes.[10] Similar to how heat is recovered in CHP plants, this waste heat may be used to generate more electricity. The term "cogeneration" may also be used to describe this method.[11], [12] Exhaust gases from turbines or engines that use fuel to generate heat are routed via heat recovery devices to be reused as useful energy.

With this heat, structures may be heated or cooled as needed. Figure depicts the CHP process flow. There are a number of Thermal Energy Storage(TES) techniques that may be used to store the heat generated by a cogeneration system.[13] In all TES implementations, thermal energy is provided to storage medium, where it is then periodically consumed and

the heat extracted. The size and form of the data storage medium is the primary dividing line.[14], [15]

Heat energy storage and transmission are two of the

many applications for phase change materials (PCMs). The

phase transition in PCM materials occurs at room temperature, allowing them to store vast amounts of heat energy.[16], [17] It does this by undergoing a phase change

when exposed to temperatures above or below its melting point. Therefore, the PCM material may undergo a phase transition and either absorb or release heat when its temperature approaches a constant.[18], [19] Increased heat

transfer in a heat exchanger system may be affected by the presence of phase transition materials having a thermal

conductivity of less than 0.5 W/(mK).Accordingly, novel approaches are required to control the thermal conductivity of phase transition material at low temperatures.[20]–[22]

II. OBJECTIVES

- To study the effect of attaching Y-shape and tree shape fin to tube surface.
- To study the impact of change in angle of each two consecutive tree branches of fin
- To study the behavior of temperature and temperature difference of PCM at the end of the simulation.
- To study the effect of PCM melting by attaching the fin.
- To study the impact in heat transfer by change in angle of tree fin’s branches.

III. RESEARCH AND METHODOLOGY

A. Governing equations and assumptions

An enthalpy-porosity model, often used to describe PCM melting processes, has been used in this investigation. The model accounts for the phase transition region with a porosity and also accounts for the local liquid fraction of the PCM with a porosity equal to its value. Between zero and one, porosity triggers the phase transition, which changes the material's state from solid to liquid. According to the enthalpy-porosity model, the fluid velocity & temperature distribution in the tube are defined by the following equations:

“Continuity equation:

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}=0$$

Momentum equation:

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho uu)}{\partial x}+\frac{\partial(\rho vu)}{\partial y}=-\frac{\partial\rho}{\partial x}+\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)+uA$$

$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho uv)}{\partial x}+\frac{\partial(\rho vv)}{\partial y}$$

$$\partial\rho \quad \partial \quad \partial v \quad \partial \quad \partial v$$

$$= -\frac{}{\partial y} + \frac{}{\partial x}\left(\mu \frac{}{\partial x}\right) + \frac{}{\partial y}\left(\mu \frac{}{\partial y}\right)$$
$$+ vA + \rho g\beta(T - T_m)$$

B. Physical model

The study's triplex-tube TES system, which includes fins in both Y-and tree-shaped configurations, is shown in Figure as a cross-section. The heat exchanger is positioned horizontally and is 500 mm in length. “The TES system is made up of three interconnected copper tubes that have inner, middle, and outer diameters of 50.8, 150, and 200 mm, respectively. All three tubes that make up the TES system have a thickness of 2 mm; the inner tube has a thickness of 1.2 mm.” The three flow channels of the TES system are designed to accommodate the incoming HTF, PCM, and HTF, in that order. In this experiment, RT82 is used as the PCM material and water as the HTF. For this investigation, the PCM material is RT82 since it has a virtually unlimited lifespan, doesn't have a super cooling effect, and is therefore chosen. You may find RT82's thermophysical and chemical characteristics in Table 3.2. Table 3.1 provides the precise measurements of the fins, which are Y-shaped and tree-shaped and uniformly distributed throughout the tubes. In example 1, the fin surface area fraction (φ) is set at 0.02 whereas in the other situations, it is set at 0.028. Natural Y- and tree-shaped structures are thought to enhance heat transmission when applied. As may be seen in Figures 3.2 and 3.3, the computational domain included this investigation.

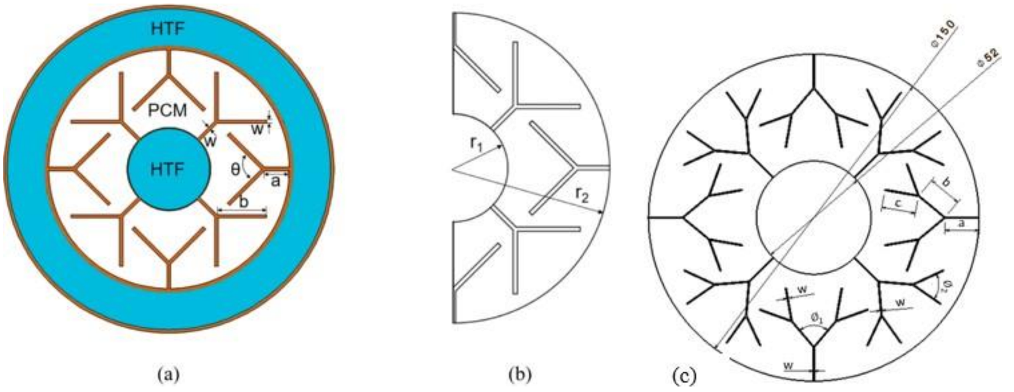


Figure 1 Two-dimensional view of the triplex tube: (a) the physical domain, (b) Y-shape fin, and (c) Tree-shape fins.

Table 1 Fin dimension with case nomenclature

Cases	W (mm)	a (mm)	b (mm)	c (mm)	$\emptyset_1$	$\emptyset_2$
Case 1	0.05	15.44	15.44	15.44	60	-
Case 2 – 80/60	0.05	15.44	15.44	15.44	80	60
Case 3 – 80/90	0.05	15.44	15.44	15.44	80	90
Case 4 – 60/60	0.05	15.44	15.44	15.44	60	60
Case 5 – 60/90	0.05	15.44	15.44	15.44	60	90

C. Mesh generation

In generating the mesh for the computational model, a consistent element size of 0.0009 meters was employed throughout. The elements were of two shapes: triangular and quadratic. Each case utilized a constant element size and shape configuration. The mesh was structured such that the number of elements and nodes varied depending on the specific case, as outlined in a table. These computational models were design for 2D simulations, ensuring that the mesh adequately represented the geometry and features of the system under analysis show in the Figure. The use of triangular and quadratic elements allowed for accurate representation of complex geometries and behaviors within the computational domain.

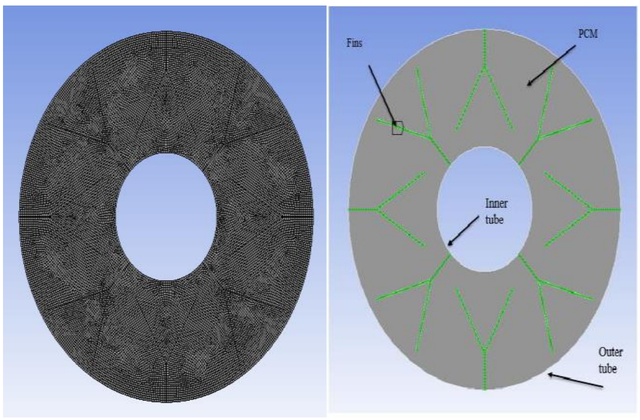


Figure 2 Mesh generation and domain representation

D. Boundary conditions and simulation methods

At 300 K, the PCM is at its starting condition inside the calculation domain. The HTF's temperature remains constant at 373 K throughout the computation, which takes gravity into account for natural convection purposes. Commercial software ANSYS-Fluent 2021 is use for the simulation. The pressure-velocity coupling is implemented using the SIMPLE method, and then presto! The equation for pressure correction is designed to use the scheme. The first-order upwind technique was used for the momentum and energy equation. Both the fin wall and the consecutive tube wall have been connected. The author has previously presented research that provide access to the numerical methodology's comprehensive technique (Yan et al., 2022)[23]. Copper material are using for both outer and inner tube and RT-82 use as thermal energy storage material (PCM). Properties of the both material copper and RT-82 (PCM) mention in table.

Table 2 Thermo-physical properties of PCM and copper

Properties	Unit	RT-82 (PCM)	Copper
Density	Kg/m3	770	8920
Specific heat	J/kg/K	2000	381
Thermal conductivity	W/mK	0.2	387.6
Viscosity	Pa.s	0.03499	-
Latent heat capacity	J/kg	176000	-
Solidus temperature	K	350.15	-
Melting temperature	K	358.15	-
Thermal expansion	1/K	0.001	-

E. Validation

Validation of the simulation model in this work was done using previously published experimental data from, and the simulation was run with the identical boundary conditions and beginning circumstances as the experiment. (Yan et al., 2022)[23] Both the inner and exterior tubes maintain a constant temperature of 373K. There is an initial state of 300K and PCMs in a solid state in the simulation. tubes were connected to their surfaces by fins. The section above provides the design parameters. Figure clearly indicates that the simulation model agrees well with experimental data, suggesting that this model may be used to investigate melting enhancement in the TES system.

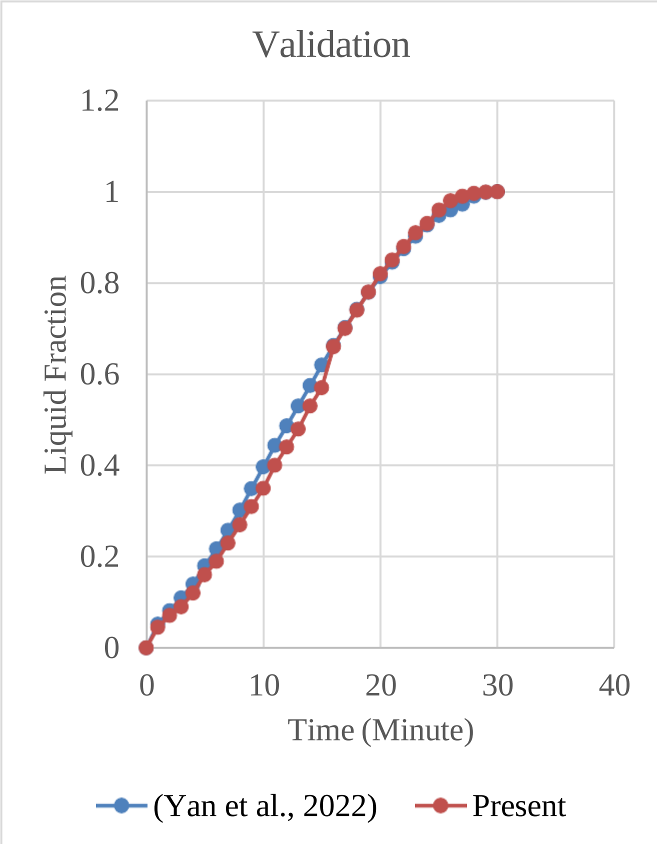
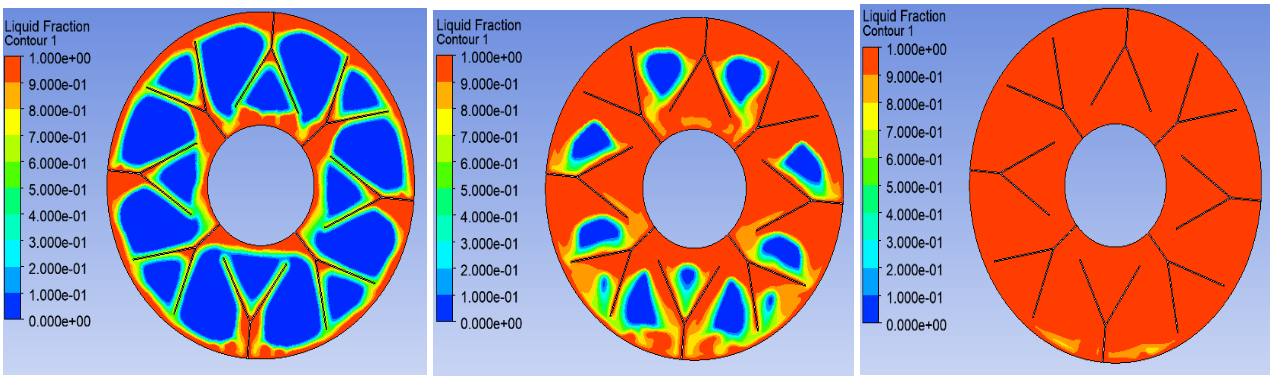


Figure 3 Liquid Fraction Validation

IV. RESULT AND DISCUSSION

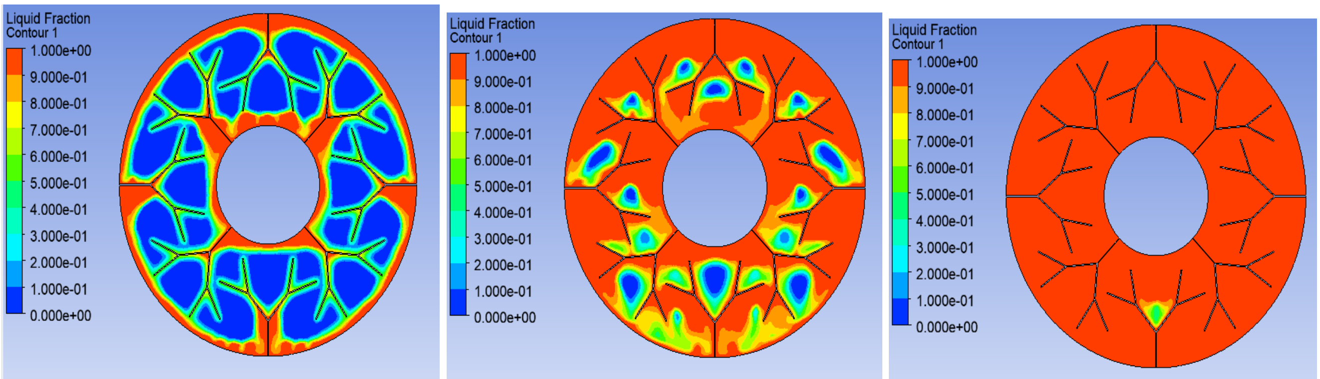
A. Liquid fraction Contour

In this study, analysis was done in 2d so, concentric triplex tube heat exchanger optimize into concentric double tube heat exchanger with constant temperature in inner and outer tube surface. PCM material filled between outer and inner tube at initial state, which is solid. Different type of fin arrangement are consider, which is couple with consecutive tube wall. Each case having different shapes of fins are as case 1 - Y-shape fin, case 2, 3, and 4 having tree shape fins where each case have different angle. Therefore, due to convection between fins, tube surface and PCM transfer the heat to the PCM. From the liquid fraction contour of the computation domain examine the optimal design of fins. Liquid fraction vary 0 to 1, which denote that when PCM at solid state its value is 0 and when complete melt then its value is 1. Liquid fraction contour illustrate that the initial 5 minutes of simulation PCM melt at near the tube wall and fins wall. In the liquid fraction contour red part represent that melted PCM and blue part represent that solid PCM. PCM melting time is "30 minute, 30 minute, 29 minute, 28, minute, and 27 minute in case 1, case 2, case 3, case 4, and last case 5 respectively."



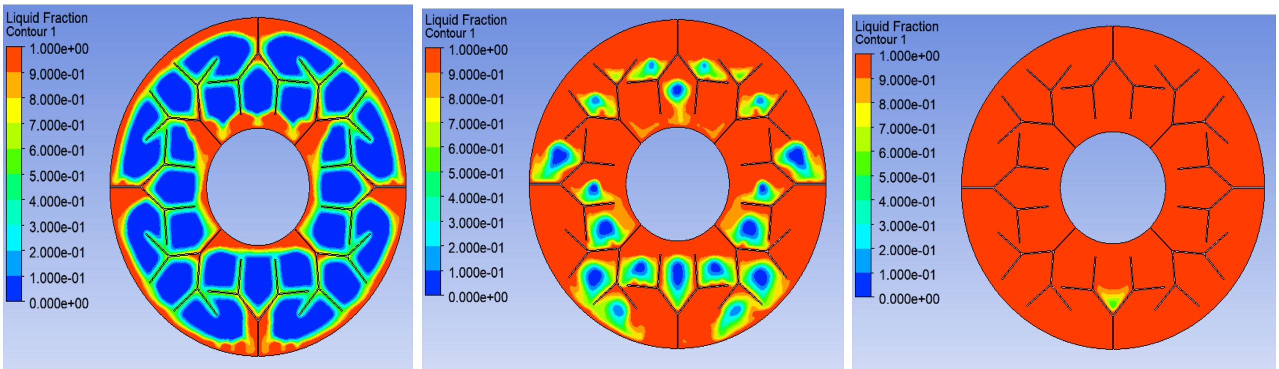
10 Minute 20 Minute 29 Minute

Figure 4 Liquid fraction of case 1



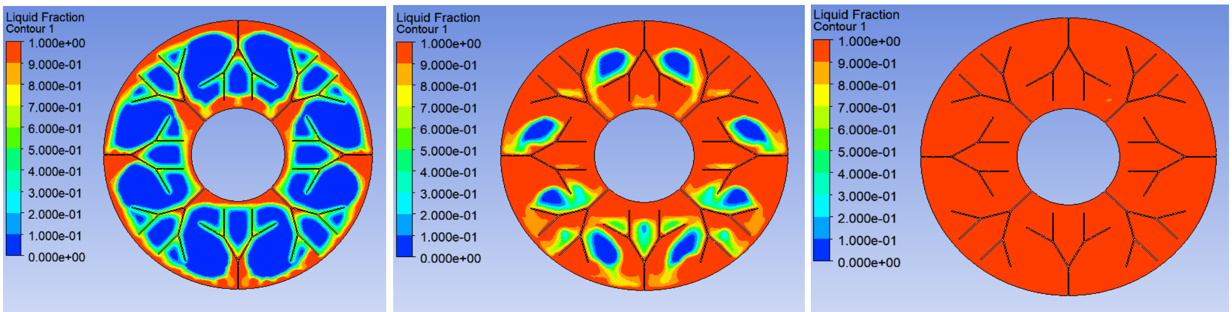
10 Minute 20 Minute 29 Minute

Figure 5 Liquid fraction of case 2 – 80/60



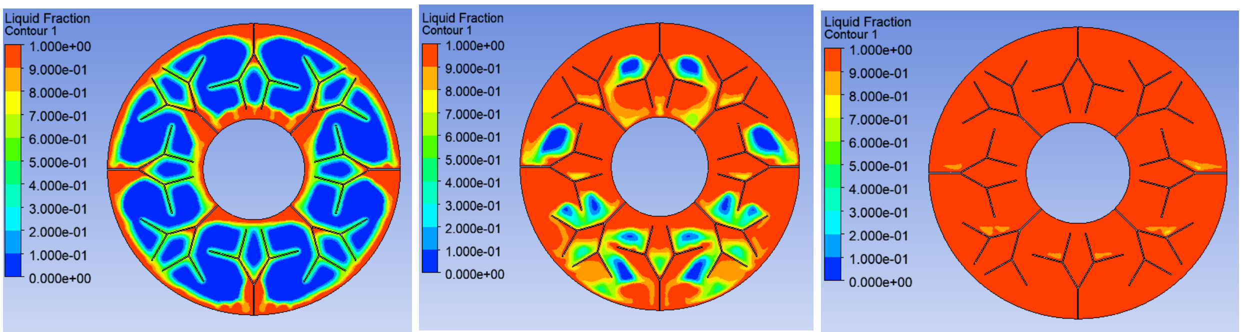
10 Minute 20 Minute 28 Minute

Figure 6 Liquid fraction of case 3 – 80/90



10 Minute 20 Minute 27 Minute

Figure 7 Liquid fraction of case 4 – 60/60



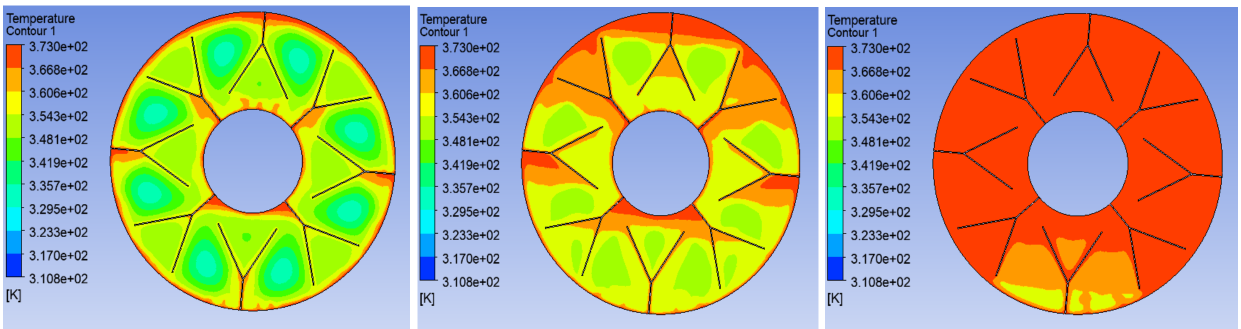
10 Minute 20 Minute 26 Minute

Figure 8 Liquid fraction of case 5- 60/90

B. Temperature contour

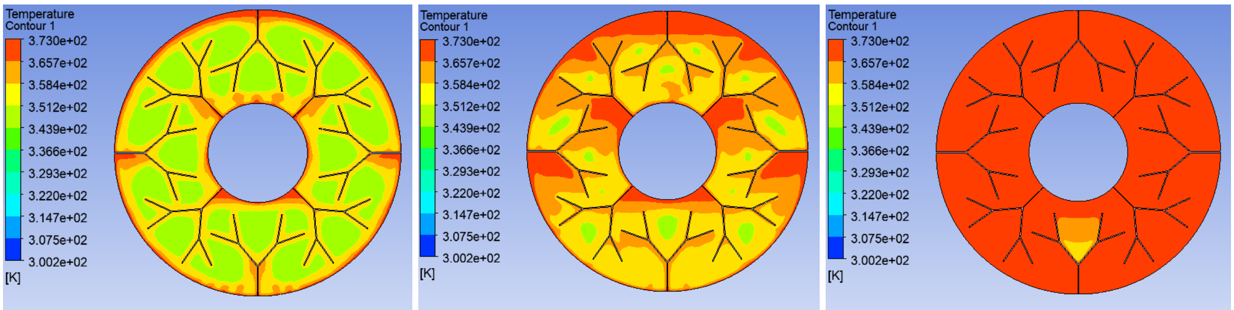
When examining the temperature contour across the computational domain revealed insights into the optimal design of fins for enhanced heat transfer. The temperature varied between 300 K and 373 K, representing the solid state of the PCM at 300 K and the hot tube walls at 373 K, transferring heat to the PCM. Initially, within the first 5 minutes of simulation, the PCM began to melt near the tube and fin walls, with an average temperature ranging from 340 K to 345 K. The temperature contour showcased regions of red denoting melted PCM and blue indicating solid PCM.

As the simulation progressed, the PCM continued to absorb heat, reaching an average temperature of 370 K by the end of the simulation. This gradual increase in PCM temperature illustrated the effectiveness of the heat transfer process facilitated by the optimized fin configurations. The findings from this analysis provide valuable insights for the design and optimization of double tube heat exchangers with PCM, offering potential advancements in thermal management systems for various applications.



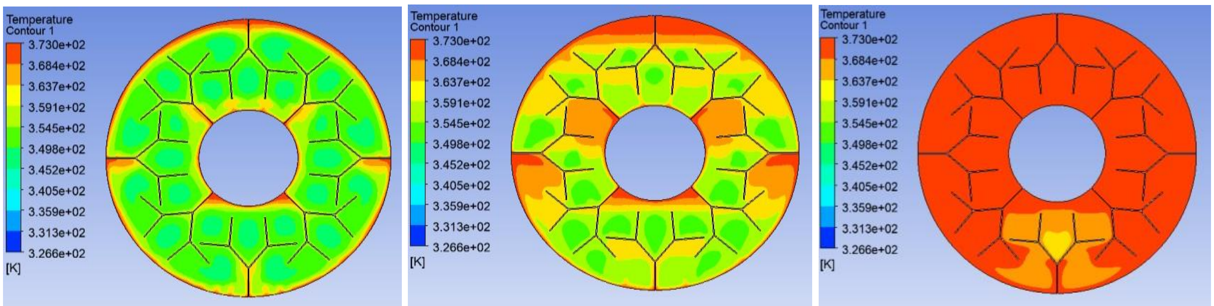
10 Minute 20 Minute 30 Minute

Figure 9 Temperature contour of case 1



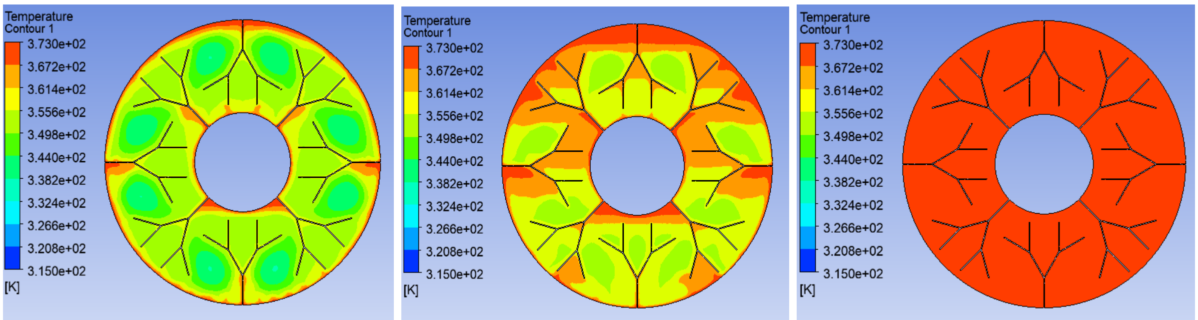
10 Minute 20 Minute 30 Minute

Figure 10 Temperature contour of case 2 – 80/60



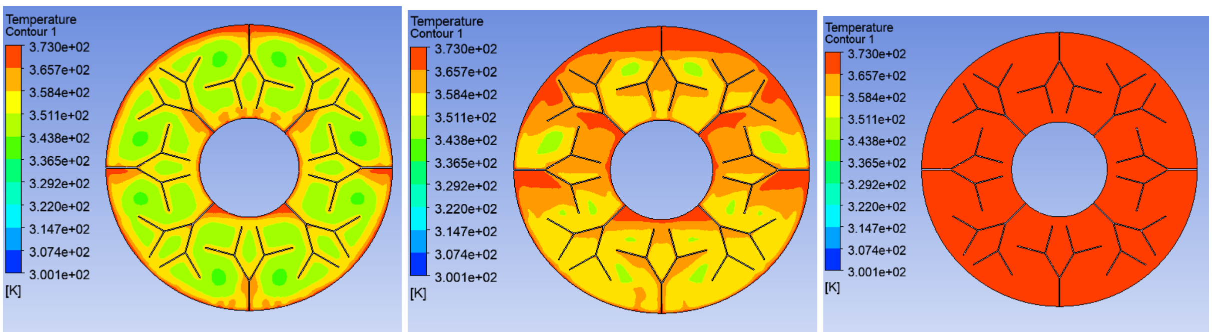
10 Minute 20 Minute 30 Minute

Figure 11 Temperature contour of case 3 – 80/90



10 Minute 20 Minute 30 Minute

Figure 12 Temperature contour of case 4 – 60/60



10 Minute 20 Minute 30 Minute

Figure 13 Temperature contour of case 5 – 60/90

C. Result Comparison

The figure illustrates the temperature differences among different cases at the end of a 30-minute simulation. Case 1 shows a notably low temperature difference compared to the other cases, with a value of 69.2 K. Cases 2, 3, and 4 exhibit approximately similar temperature differences, while Case 5 stands out with a higher temperature difference compared to the rest. This discrepancy in temperature differences suggests that the angle of the tree fin branches plays a significant role in heat transfer.

The figure indicates that altering the angle of the tree branches enhances heat transfer in the phase change material (PCM). Cases 1 and 2 both experience complete melting within the 30-minute timeframe, indicating a rapid heat transfer. Case 5, on the other hand, reaches complete melting in 27 minutes, which is comparatively faster than the other cases. These observations underscore the importance of geometry and design in optimizing heat transfer processes, particularly in PCM systems where heat absorption and release rates are crucial factors.

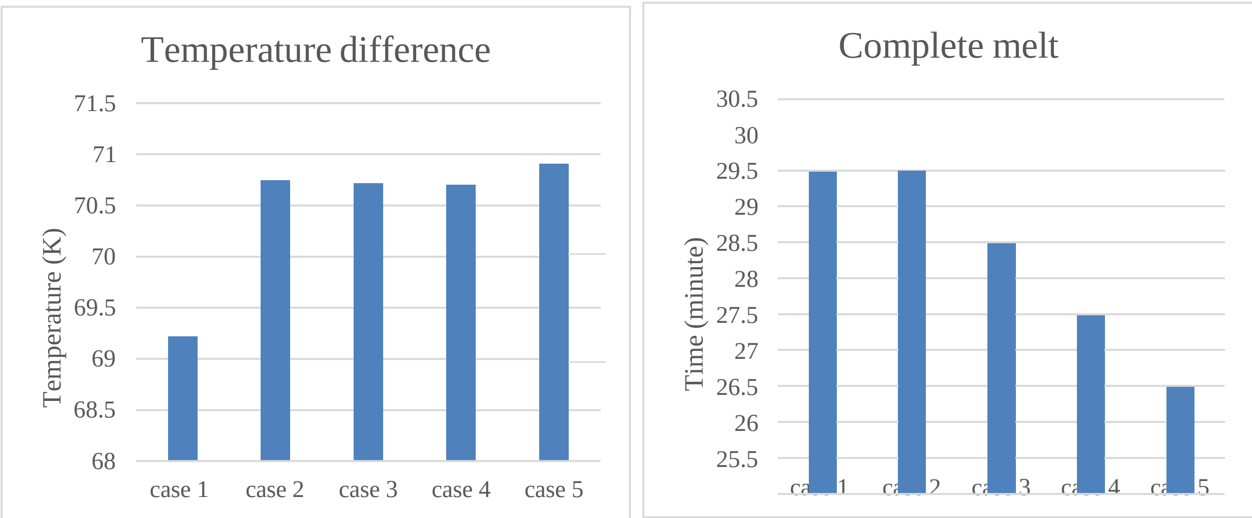


Figure 14 Temperature Difference and complete melting of PCM comparison

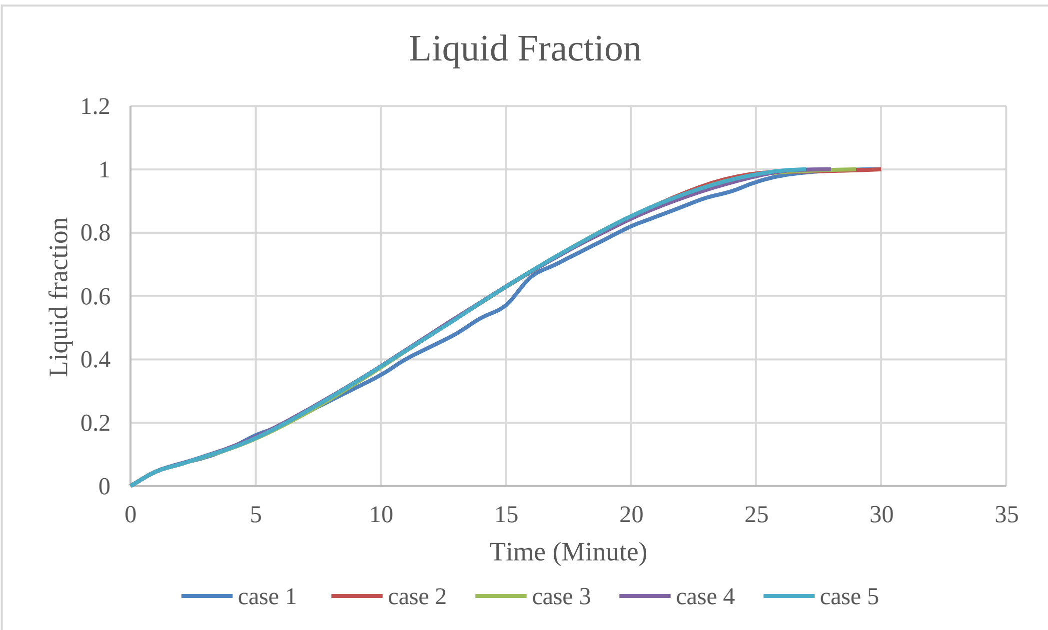


Figure 15 Liquid fraction comparison

V. CONCLUSION

In the present research, the triplex-tube thermoelectric storage system is equipped with Y-shaped and tree-shaped fins. Additionally, the impact of various factors on the heat transfer performance is examined in order to evaluate the melting enhancement of the triplex-tube thermoelectric storage system. This study's overarching goal is to better understand the anatomy of this fin type so that it may be more appropriately included in any future TES models. A number of findings have been derived from the investigation.

- The melting process is efficiently facilitated by the employment of fins with Y and tree shapes. Preventing the buildup of solids is equally crucial.
- Changing the angle of the fin branches shortens the melting time when the percentage of fins in the triplex-tube system's cross-section remains constant.
- Temperature difference is very low in case 1, and very high in case 5, which is 69.2 K, and 70.9K respectively. But in case 2, 3, and 4 temperature difference obtain same.
- Complete melting time in case 1 is high, which is 30 minute and in case 5 is low, which is 27 minute as compare to each cases.

The future scope in concentric triplex tube heat exchangers for enhancing heat transfer and performance lies in several promising areas. Firstly, advancements in computational modeling techniques, such as three-dimensional simulations coupled with optimization algorithms, can aid in designing optimized geometries and configurations to maximize heat transfer efficiency while minimizing pressure drop. Secondly, the integration of advanced materials with superior thermal conductivity and phase change capabilities, such as phase change materials (PCMs) or high thermal conductivity fluids, cansignificantly enhance heat transfer rates and enable efficient thermal energy storage within the heat exchanger. Additionally, exploring innovative fin designs, surface coatings, and flow enhancement techniques can further improve heat transfer performance in concentric triplex tube heat exchangers. Furthermore, incorporating smart control systems and sensors for real-time monitoring and adaptive control can optimize heat transfer under varying operating conditions, enhancing overall system performance and energy efficiency. Collaborative interdisciplinary research efforts involving experts from fields like fluid dynamics, materials science, and control engineering will be crucial for advancing the capabilities of concentric triplex tube heat exchangers and unlocking their full potential in thermal energy storage and heat transfer applications.

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