Industrial Engineering Journal
ISSN: 0970-2555
Volume : 52, Issue 7, No. 5, July : 2023

ENHANCING THE MELTING RATE OF RT-50 PCM BY USING VARIOUS FINS IN TRIPLE TUBE HEAT EXCHANGER

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Abstract

The intermittent availability of solar energy is a concerned issue for the user from a long period of time. This issue can be resolved by storing the solar energy in the day time and using it in the night time. The usage of thermal energy storage and storing this energy in the form of latent heat is one of the relevant solutions for the same. The phase change material (PCM) with the highest potential for this application is RT-50 since at a steady temperature, it has a large amount of latent heat storage capacity. The melting rate of the PCM in a triple tube heat exchanger (TTHX) has received special attention in the current work. In Ansys 2019 R3, a two-dimensional (2D) numerical model was created. Due to the PCM's extremely poor thermal conductivity, so to enhance the melting-rate three different arrangements of triangular fins have been considered. The study's primary goal is to maintain the packing factor (PF) of the TTHX between 90 - 95 % because P.F. is crucial. The analysis shows that with the usage of triangular fins the melting rate has been enhanced by 64% as compared to without fins TTHX.

Keywords: Packing factor, Triplex tube heat exchanger, phase change material, Melting rate and Fins

I. Introduction

1.1 Latent Heat Storage

Efficient thermal energy storage is a critical concern in modern energy conversion systems due to the depletion of conventional energy sources and rising energy demands. Thermal energy storage is essential for enhancing the effectiveness of thermal energy utilization in various energy sectors. Sensible-heat-storage (SHS), latent-heat-storage (LHS), and thermo-chemical-heat-storage are the three most important methods of thermal energy storage. SHS involves storing energy through change in temperature, where energy is stored as a material's temperature rises and released as its temperature falls without any phase change. LHS, on the other hand, involves energy storage during a material's transition from one state to another, such as from solid to liquid or liquid to gas. Thermo-chemical storage utilizes chemical reactions to store reaction-generated energy. Of these methods, latent heat storage in a phase change material (PCM) is the most desirable due to its numerous advantageous qualities. PCM-based LHS provides a heat source with a constant temperature during the phase change process, allowing for efficient thermal energy storage. Additionally, PCM-based LHS can recover heat with a minimal temperature drop and has a low vapor pressure at its operating temperature. Moreover, PCMs are chemically stable and non-corrosive, making them a practical choice for a range of thermal energy storage applications. The following equation can be used to calculate how much heat is stored in an LHS system:

$$\boldsymbol{Q_{Latent}} = \int_{T_{\mathrm{i}}}^{T_{ii}} \boldsymbol{mC_{ps}\,dT} + \boldsymbol{mL} + \int_{T_{\mathrm{ii}}}^{T_{\mathrm{iii}}} \boldsymbol{mC_{pl}\,dT} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where *L* is the phase-change material's latent heat of fusion or vaporisation in the LHSU, The specific heats of the solid and liquid phases of the phase-change material are denoted by *Cps* and *Cpl* respectively and *m* represents the mass of the material in the LHSU (in kg). The energy that is stored as solid sensible heat when a material's temperature rises from its initial temperature T_i to its melting point T_{ii} is represented by the first term in Equation (1). The energy that is stored as latent heat during the transition from solid to liquid at a constant temperature T_{ii} is represented by the second term. As the material's temperature is raised from T_{ii} to the final temperature T_{iii}, the energy that is stored as liquid sensible heat is represented by the third term. Equation (1) provides a means of quantifying the amount of thermal energy that can be stored or released using an LHSU and can be used to optimize the design and performance of thermal energy storage systems.

1.2 Phase Change Material (PCM)

Phase Change Materials (PCMs) are typically stored in containers that have a rectangular or cylindrical shape. The LHSUs mainly comprise of shell and tube heat-exchangers. Yet, due to their improved energy storage capability, a unique technology known as Triple Tube Heat Exchangers (TTHX) has recently acquired favour. This unique type of heat exchanger is equipped with three annular tubes, out of which the middle tube serves the purpose of PCM storage, while the remaining two tubes are used for the movement of Heat-Transfer Fluid (HTF). The TTHX design incorporates an additional tube, which increases the heat-transfer surface area and, consequently, enhances the efficiency of the storage unit when compared to conventional shell and tube heat exchangers.

1.3 Literature Survey

The heat needs of Phase Change Materials (PCMs) during the melting and solidification processes in energy storage devices have been studied by numerous authors. Zalba et al. [1] conducted a comprehensive review of thermal energy storage technologies, which encompassed the study of PCMs, heat transmission investigations, and various applications. Farid et al. [2] offered in their publication a thorough review of the analysis, hermetic encapsulation, and use of phase change materials (PCMs). The examination of PCMs, encapsulation methods, and applications in many sectors were just a few of the topics that this review essay explored. In a numerical examination conducted by Khodadadi et al. [3], Investigated was the consequences of density-driven flow on the limited liquefy of PCM in a sphere container. According to the study, enhanced conduction caused the rate of melting in the top portion of the sphere to be higher than in the bottom portion. The energy equation was expressed using an enthalpy formulation by Duan et al [4] in their experimental investigation of the Pure n-hexadecane PCM solidification processes in a rectangular container. The researchers analysed the effects of the aspect ratio of the enclosure, initial liquid superheat, and cold wall temperature. For a geometry with a greater aspect ratio, It was observed that the phase front's slope was only evident at the enclosure's top. Khillarkar et al. [5] conducted a numerical analysis of the phase change material's melting process in two different tube geometries, both (I) a circular tube inside a square exterior tube and (II) a square tube inside a circular external tube. According to the study, natural convection was the cause of the temperature stratification in the cavity's upper portion. Assis et al. [6] used both numerical and experimental techniques to analyse the melting of a spherical shell. The researchers proposed a link between the melting percent and a sufficient number of Fourier, Stefan, and Grashof numbers. Medrano et al. [7] investigated the solidification of PCM inside a spherical shell with various diameters using experimental and computational methods. The study involved five small heat exchangers that served as thermal storage systems for latent heat. The heat transfer characteristics during the charge and discharge procedures were experimentally characterized by the researchers. Seeniraj et al. [8] conducted analysis on the short-term behaviour of PCMs held at high temperatures in shell and tube heat exchangers. When an unfinned tube was employed, the researchers found that some PCM closer to the tube's exit stayed in the solid state. This was attributed to the minimal temperature difference between the PCM's melting point and the HTF temperature closer to the exit. However, it was discovered that adding a few annular fins allowed melting to take place everywhere along the axial direction while maintaining a respectably high temperature difference between the melting point and the HTF. The highest values were obtained for a PCM-embedded double pipe heat exchanger with a graphite matrix, according to the results obtained. Castell et al. [9] carried out an experimental investigation to investigate how in a domestic hot water (DHW) tank, PCM modules function. The scientists discovered that the PCM modules' external fins sped up heat transfer to the nearby water. Also, they noticed that larger fins accelerated heat transfer even when the heat transfer coefficient dropped. Sari and Kaygusuz [10] a Melting and solidification of dual pipe energy storage system were the subject of an experimental inquiry The consequences of natural convection was shown to have the greatest impact on the typical heat transfer coefficient and heat flow rate during the melting process. Ettouney et al. [11] did an experimental inquiry to learn more about the melting and solidification in a shell and tube setup. In their experiment, a phase transition substance was stored on the shell side, while the heat transfer fluid (HTF) flowed in the inner tube. The researchers found that natural convection and conduction dominated the melting processes, respectively. Vyshak and Jilani [12] a numerical analysis was carried out to examine the effects of different latent heat thermal storage (LHTS) layouts with the same volume and heat transfer surface area. Three separate geometrically unique containers—a rectangle, a cylinder, and a shell and tube—had their overall melting times compared. The researchers discovered that cylindrical shell containers retained energy in the quickest duration, and that as PCM mass increased, this geometric effect got more pronounced. In a study conducted by Al-Abidi et al. [13], Three different methodologies were used to conduct an experimental investigation into the melting of phase change material (PCM) in a triplex tube thermal energy storage (TES) system: the inner heat transfer fluid (HTF) tube, the outer HTF tube, and both sides HTF tubes. Both the radial and axial directions were used to examine the thermal performance. The findings showed that the third method, which used HTF tubes on both sides, resulted in the quickest time for full PCM melting. Vertical TTHX was examined experimentally and numerically by Almsater et al. [14] With water acting as the PCM, melting and solidification were seen. The effectiveness and length of the phase transition were compared, and they were found to be in good accord with the predictions of the computational fluid dynamics model.

Shell and tube heat exchangers have been used in the bulk of LHSU's research projects. Because there hasn't been enough research on triple tube heat exchangers, the current study's objective is to thoroughly understand the melting process in such a system by examining the thermal performance of triple type LHSU (TTHX). Several fin types are offered to improve heat transfer, and the location of the fins' impact on the LHSU's thermal performance is determined during the melting process. For this investigation, we are looking at four different cases.

II. Physical Model

The triple tube heat exchanger's geometric depiction is shown in Figure 1. The inner, middle, and outer tubes are 22mm, 85mm, and 115mm in diameter, respectively. The PCM, RT50 is stored in middle portion of TTHX while the HTF water flows through the inner and outer pipe. The latent heat storage in thermal heat storages uses RT50, a commercial PCM, which is used globally. RT50 melts at a temperature of 50oC. In the Table 1, the Characteristics of RT50 has been mentioned. Triangular fins were added to the PCM in TTHX to improve heat transfer, but instead of doing it the conventional way, a circular tube with triangular fins inserted on its circumference was used. The tube measures 52 mm on the inside and 54 mm on the outside. The fin is 10 mm long. A, B, C, and D are the four diverse cases under investigation in the melting process as shown in Figure 2. The simplest case, Case-A, one

Table 1. PCM RT-50's Thermo-Chemical Characteristics

Property	Value	Unit
Density, ρ	780	Kg/m3
Latent heat of fusion, L	168000	J/kg
Specific heat, C_p	2000	J/kg K
Solidus temperature	45	ºC
Liquidus temperature	51	ºC
Thermal conductivity, k	0.2	W/m K
Dynamic viscosity, μ	0.0042	Kg/m s
Thermal Expansion coefficient, β	0.0006	1/K

without fins. Case-B features a circular tube with four triangular fins that are lie on circular ring supported by 4 supporting rods, as shown in Figure 2. The zig-zag type rod, which has a 1 mm width and a 45° bend angle, is utilized in place of the straight supporting rod. On the diameter of the round tube, case C has four identically shaped rectangular fins spaced 90 degrees apart from one another. Case D is new type of fins called as Novel fins inspired from the leaf of tree. The packing factors for cases A, B, C, and D are 100%, 93.84%, 93.44%, and 92.77%, respectively.

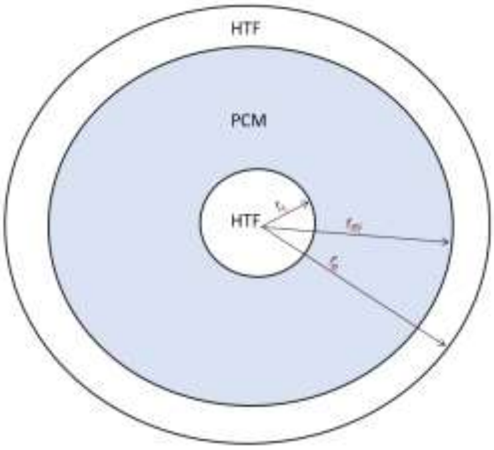
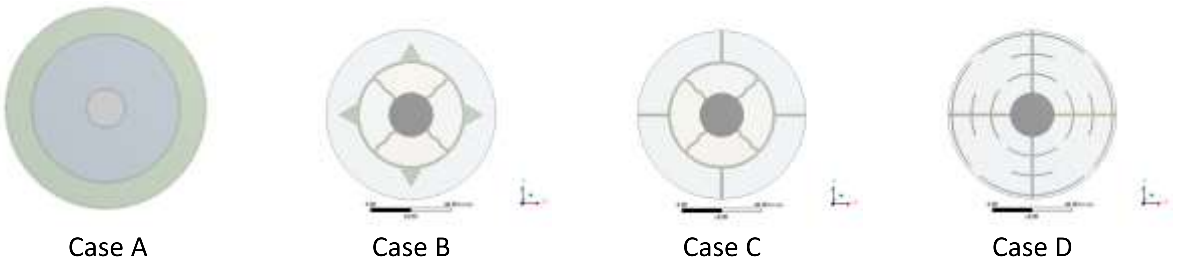


Figure 1. Schematic of triple tube heat exchanger



Case A Case B Case C Case D

Figure 2. Schematic of triple tube heat exchanger for Case A, Case B, Case C and Case D

III. Computational Method

Pressure-velocity coupling is achieved by using the semi-implicit pressure linked equation. The momentum and energy equations are discretized using the first order of the upwind approach, and the

pressure equation is discretized using the Pressure Staggered Option (PRESTO). The PRESTO approach uses a discrete continuity balance for a "staggered" control volume around the face to determine the pressure. For pressure, velocity, energy, and liquid percent, the under-relaxation value factors are set to be 0.3, 0.7, 0.9, and 0.9, respectively. While 10^{-4} is chosen for the other governing equations, 10^{-6} is the convergence criterion for the energy equation. Mesh independence is examined for numerical simulations before to the analysis. In Case B, four distinct grid sizes with the following cell types are examined: 5311, 10626, 13468 and 17940.The comparison and validation of all different grid sizes are displayed in the Figure 3. Because the results from 13468 and 17940 the two grid sizes are nearly identical, the smaller grid size is chosen to decrease the simulation duration.
Due to which, this grid size is selected for all 4 cases during this study.

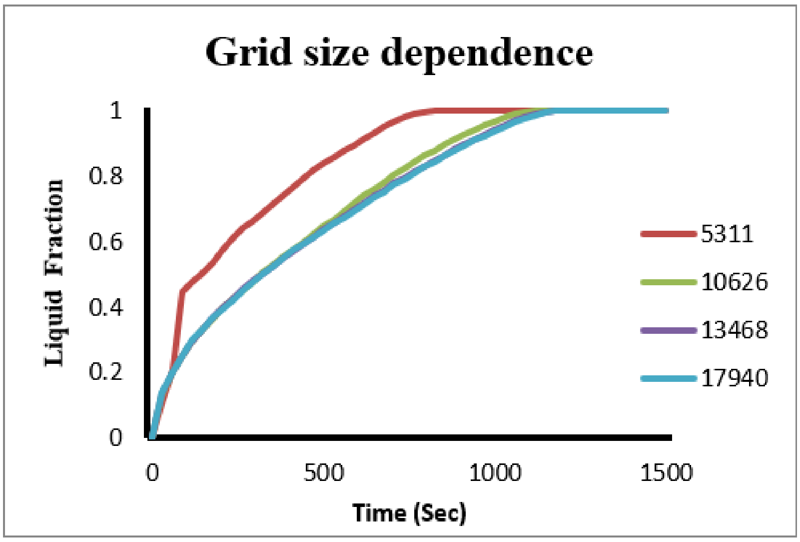


Figure 3. Grid size dependence for numerical solution

IV. Validation

The melting numerical model used in this study was created using Ansys 2019 R3The current study has been initially validate with [15]. The heat transfer fluid, water, is flowing from the inner-outer

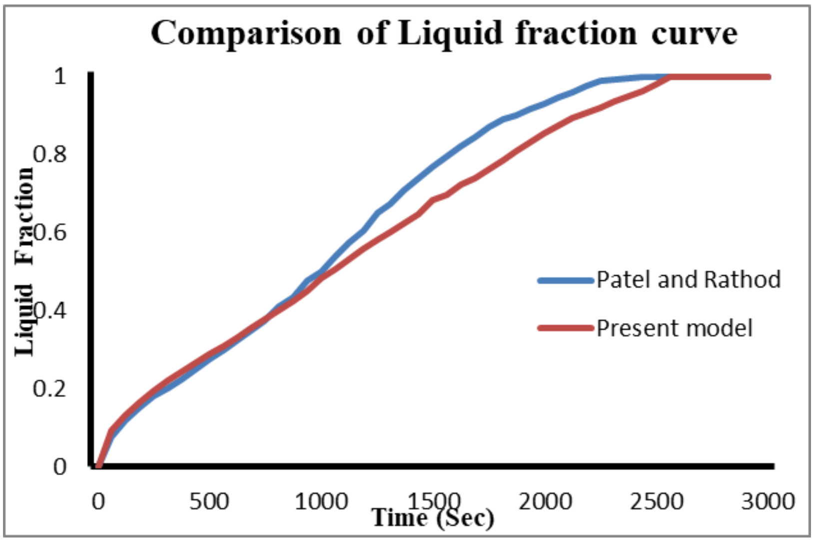


Figure 4. Comparison of liquid fraction curve of present study with results by Jay Patel[15]

tubes of the triple tube heat exchanger (TTHX), while PCM paraffinic wax RT50 is stored in the centre portion of the TTHX. The inner diameter of the TTHX is 22 mm, and the middle and outer diameters are 85 and 115 mm, respectively.

The heat transfer fluid is flowing at 70 degrees Celsius, although the initiation temperature for their study is 25 degrees Celsius. Comparing the liquid fraction curve from the current investigation with the findings from Patel and Rathod is shown in the following Figure. As a result of the element's meshing, there is a 2% error in both the current study and the study by Patel and Rathod, which is acceptable. When the liquid fraction counter from this study is compared to those from Patel and Rathod, as shown in Figure 4, it is discovered that the liquid fraction contours are likewise similar. As a result, the current model can be utilized to examine the melting process in more detail.

V. Results and Discussion

5.1 Melting Liquid Fraction

Conduction is the mechanism by which heat is transferred from the tube wall to the PCM during melting. The temperature of PCM is rising, and when it reaches melting point, it begins to liquefy. Initially due to conduction, a homogeneous layer of liquid PCM forms around the tube walls.

However, when liquefaction progresses due to density differences, the phenomenon known as natural convection occurs. The upper area of the PCM melts more quickly than the bottom region due to a density-driven flow that begins in the liquid zone.

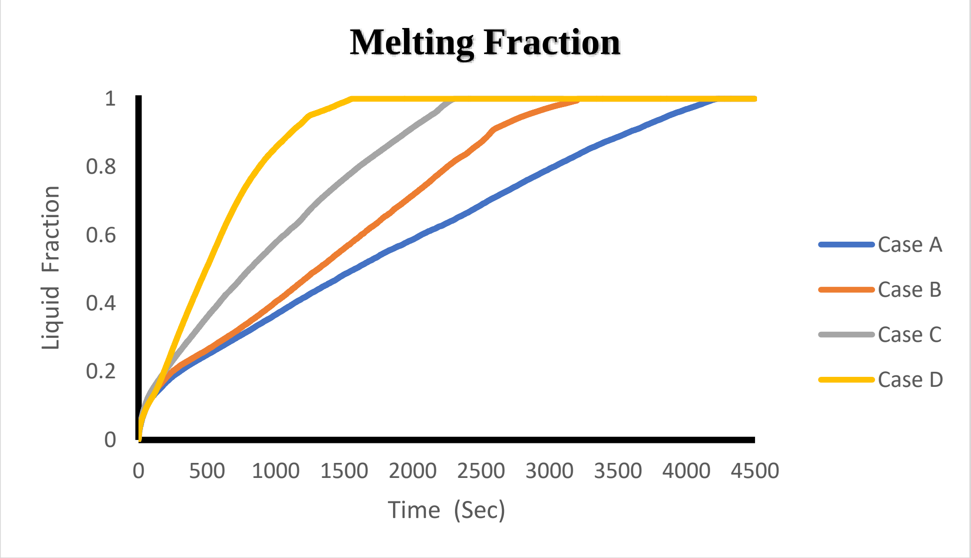


Figure 5. Comparison of liquid fraction curve

The addition of fins shortens the melting time, as is seen from cases B, C, and D. The time it takes for the entire melting process in the normal case to occur is 4240 seconds, whereas, in the case of B, it only needs 3170. With the addition of triangular fins, the melting time is reduced by 26%. Due to the addition of supporting rod the heat from the HTF reach to fins at higher rate compare to normal fins because the thermal conductivity of the copper is higher than PCM.

In Case C, there are 4 supporting copper rod to support the fins' geometry; instead of a straight pipe, a curved rod is used. Unlike in Case B, in Case C rectangular fins are used. Copper has a higher thermal conductivity than PCM, hence the heat transfer rate is faster. As a result, the time required to heat the fins is shorter than in case B, resulting in a shorter melting time. As a result, 47% less time is consumed for melting, bringing the total time necessary to completely melt PCM down to 2280 seconds.

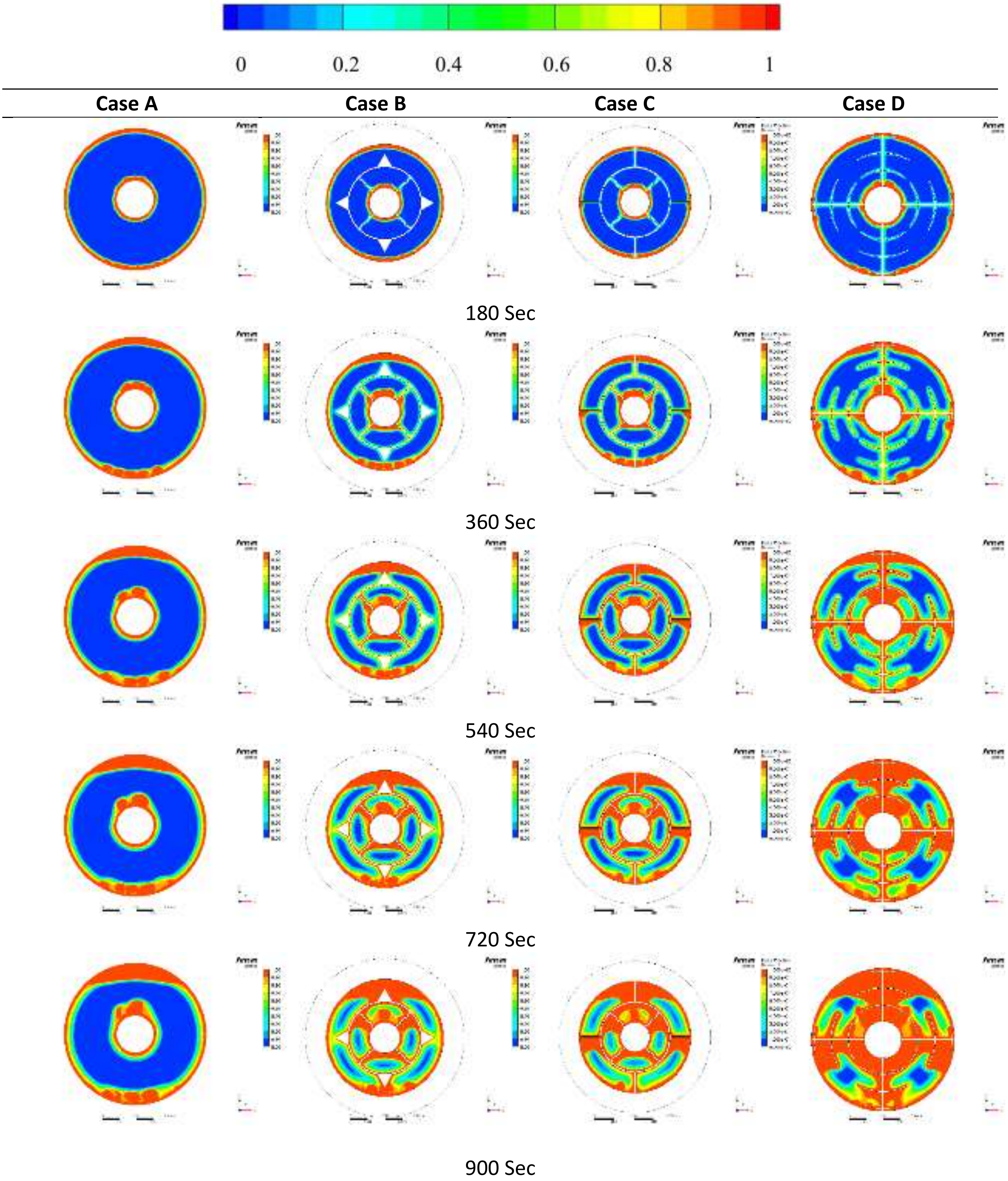


Figure 6. Comparison of liquid fraction contours for Case-A, Case-B, Case-C and Case-D

In case D, there are 4 identically shaped novel fins are placed 90o from each other. The outcome was achieved when the melting time was reduced to 1520 Sec, which is 64% less than Case A. Owing to this modification, heat is transported from the fins to the copper rod because of which the heat transfer area rises, and the melting time decreases.

5.2 Heat-Transfer Enhancement Ratio

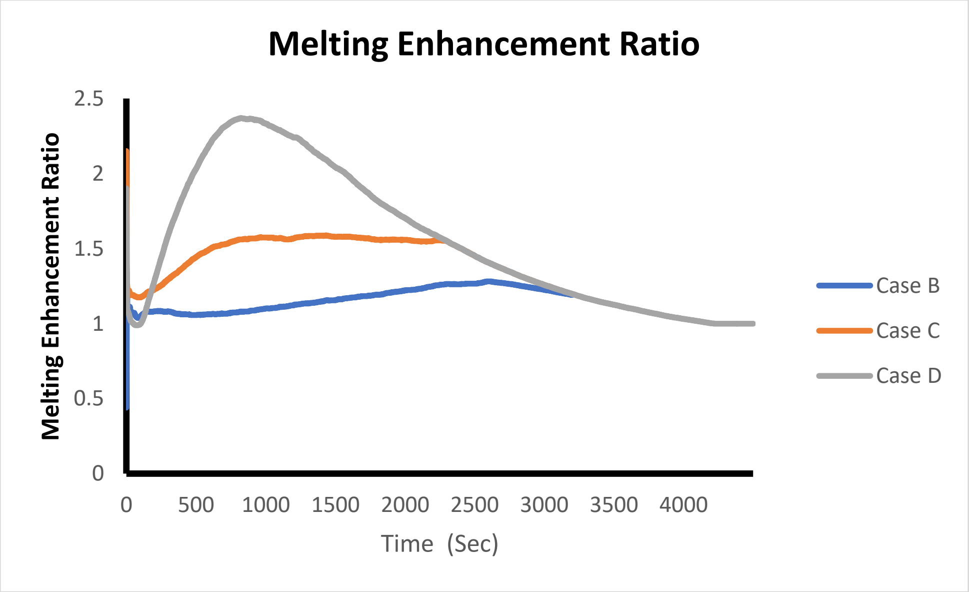


Figure 7. Comparison of Enhancement Ratio (ER_m)

It is obvious that fins are improving the melting process from liquid fraction contours and brief fluctuations in liquid fraction. A new parameter, the heat-transfer enhancement ratio, is added to allow for the analysis of the fins' features in terms of heat-transfer enhancement at various melting phases. The melting enhancement ratio (ER_m) is the proportion of the melting fraction that has fins compared to one that does not.

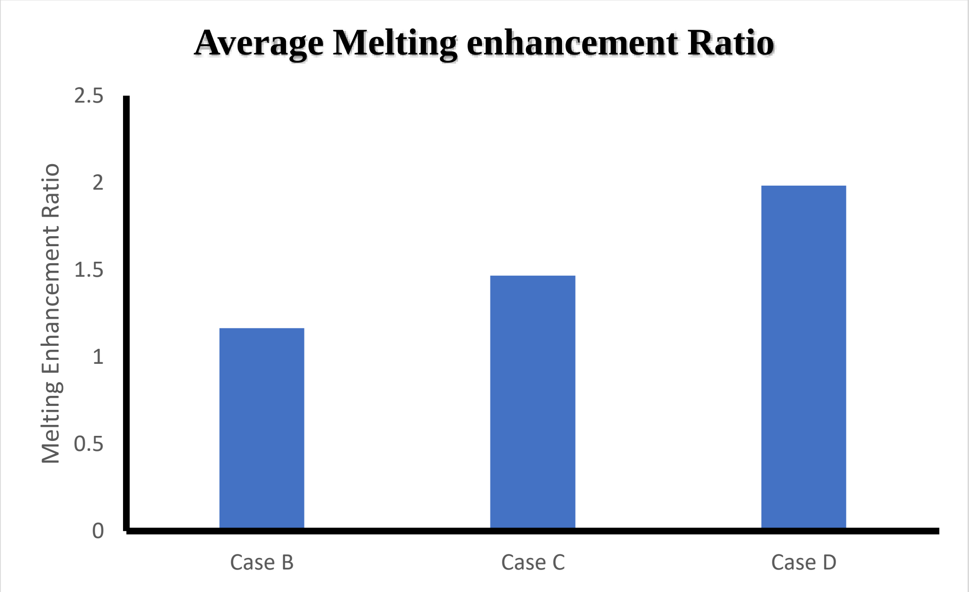


Figure 8. Comparison of Average Enhancement Ratio (ER_m)

$$E_{Rm} = \frac{\lambda}{\lambda_0}$$

where the PCM liquid fraction with and without fins are represented by λ and, λo respectively.

Figure 7 shows the change in ER_m over time for cases B, C, and D. When melting advances, ER_m rises to a maximum and then begins to fall. Since PCM is initially solid, using fins to expand the heat transfer area aids in the conduction method of heat transfer. Because the initial local temperature differential is the highest, improvement in heat transportability is seen early on. Then PCM begins to melt. A thin layer of liquid PCM arises due to natural convection brought on by density differences, and hot, molten PCM starts to circulate. This quickens the transport of heat. Yet after a while, the rate of improvement stabilises and achieves a maximum value. Following that, the melting rate reduces because the usage of fins causes the majority of the PCM to melt. Yet, at the same time frame, PCM continues to melt in the absence of fins. As a result, as the melting process progresses, ER_m gradually lowers.

5.3 Total Energy Stored

PCM serves as a form of energy storage during melting. This energy consists of latent heat as well as sensible heat. The following equation can be used to determine the total amount of energy in PCM at any given moment.

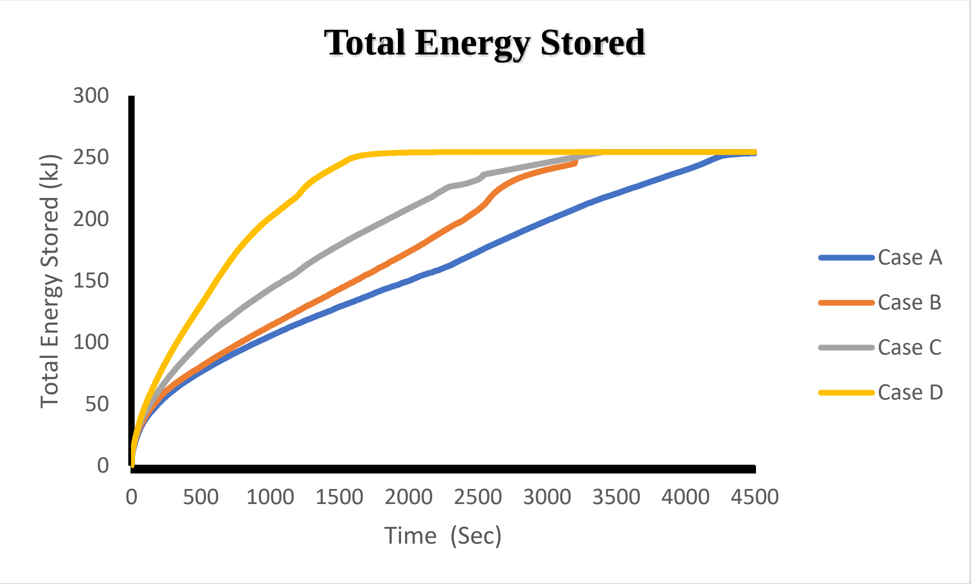


Figure 9. Comparison of Energy stored

PCM's mass, m, is indicated here. The specific heats of solid and liquid PCM are denoted by Cps and Cpl respectively. PCM has an initial temperature of Ti and a melting temperature of Tm. The simulation results are used to determine the average temperature, Tpcm and the liquid fraction λ of PCM. The total energy held by the PCM in TTHX as it melted is shown in the Figure 9 as a function of time. Energy storage happens rapidly at first during the melting process, and then it becomes nearly uniform and gradually slows down towards the finish. For cases A, B, C, and D, the energy stored in PCM after 1000 seconds is approximately 105, 114, 143, and 202 kJ/kg, respectively. This demonstrates that case D is the most effective at storing energy.

VI. Conclusion

This paper has been presented the numerical simulation of the melting of PCM within a triple tube heat exchanger. The effect of the fins geometry on melting rate have been discussed. Result demonstrates that the melting rate at the top portion of pipe is much more than bottom section of pipe due to presence of natural convection effect. During melting the heat transfer through conduction is more dominant in initial stages afterward the heat transfer through the convection becomes dominant. Case D greatly improves the melting process, with a melting time reduction of about 60% as compared to Case A and a packing factor of between 90 and 95%. Hence, of all the situations mentioned above, Case D provides the most efficient energy storage.

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