Enhancement the thermal characteristics of PCM By using Various Fin Configurations on the Inner Tube Surface of a Shell and Tube Latent Heat Thermal Energy Storage Unit

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Abstract

The latent heat thermal system with shells and tubes is a compact and highly efficient energy storage device. This computational research focusses on optimizing the geometry for thermal energy storage using a shell-and-tube design, taking into consideration the melting cycles and including a modified design. A modified HTF tube was employed to attach the fin, leading to an altered design. A method for thermal energy storage using a shell and tubes underwent modifications to maintain a constant surface area of the PCM and the heat transfer fluid tubes. The numerical model consisted of four separate computational model designs. In case 1, the HTF tube is simple, without any fins. In case 2, the fins have a rectangular shape. In case 3, the fins have a triangular shape. In case 4, the fins are rectangular but have different dimensions. The complete melting time was found to be 70 minutes for case 1. The melting period in cases 2, 3, and 4 has decreased by 2.85%, 4.29%, and 5.71%, respectively, compared to case 1. That PCM, or phase change material, in case 2, 3, and 4 takes 68 minutes, 67 minutes, and 66 minutes, respectively, to completely melt.

Keyword: Fins, Shell and tube latent heat thermal energy storage system, Phase change material, Heat transfer, Liquid fraction.

INTRODUCTION

In recent years, alongside India's rapid economic boom, there have been huge expansions in the industrial sector, construction, and transportation activity. The rise in per capita electricity usage will be proportional to this expansion. Electricity demand is expected to triple or quadruple, leading to a 30-60% increase from 2019 levels and a primary energy consumption spike of over 1.3 MWh in 2021 and 2022, reaching 1150-1600 Mote in 2040 [1]–[3].

In order to meet its increasing energy demands, India must strike a delicate balance between two pressing issues: energy security and climate change. Energy imports are crucial for India. Imports of about of its coal, half of its gas, and eighty percent of its oil put its energy security at risk and cost about US$165 billion per year. Coal, oil, and biomass are the main energy sources, and their usage results about emissions of carbon. Among countries with carbon emissions in 2021, India ranked third with 2.5 Gt CO_2. However, India's emissions per capita remain very modest when contrasted with the other developed nations and the global average. Disentangling economic growth from emissions is crucial for achieving sustainable development [4]–[7].

Capturing and storing heat energy for use at a later date is known as thermal energy storage (TES). You may use the thermal energy that has built up to either heat or cool your home. For the most part, TES is useful for closing the gap between energy supply and demand [8]. Using phase transitions, which don't change the chemical makeup of the material, is another way to store energy. A phase transition is induced in the material that stores heat in order for it to be released as latent heat. You may find additional options that have obvious pros and cons [9], [10]. In a solid-liquid phase shift, the melting and solidification processes may efficiently store large quantities of heat or cold, provided the material is appropriate. Many people call the materials utilized for heat storage in this method a phase-changing material (PCM) [11], [12]. An old method of storing energy involves the use of phase change materials (PCMs), particularly when gathering snow and ice from mountain, river, and lake sources. Uses for this approach include food preservation, beverage chilling, and interior space cooling. At least 350 years ago, this procedure was recorded in historical sources. Investigations in PCM TES in CSP plants are continuing at the moment [13], [14].

Solar thermal use has been a hot topic in recent years, with materials scientists focusing on ways to harness PCMs' thermally charging and discharge capabilities throughout the phase-change procedure for temperature control and storage/release. By sharing heat with the air around them, PCMs control the ambient temperature during the phase-change process [15]. The bulk of the studies have been on organic PCMs such fatty acids, polybasic alcohols, and alkanes; inorganic PCMs like crystal hydration sodium chloride, liquid minerals, or metallic alloy; and eutectic combinations that combine organic and inorganic elements [16]. Advantages of phase-change materials (PCM) include their compact size, high heat absorption density, clear effect on energy savings, constant temperature management, and broad phase-change temperature choice spectrum (20 to 1000°C). The building is dependable and easy to understand as well [17]. A phase-change material's (PCM) temperature of transition determines whether it is low, medium, or high temperature. The energy-efficient building, radiation shielding for electronics, constant-temperature wrapping of temperature-sensitive drugs, constant-temperature athletic gear, aviation systems, military technology, and countless other fields find common use over multifaceted cellular beams (PCMs) that have a phase-change the temperature listed below 100 degrees Celsius. Power peak management, industry excess heat utilisation, and CSP generating are just a few examples of the many uses for PCMs, or with a phase-change latitude greater than 100°C. These PCMs are commonly referred to as high and medium heat PCMs [18]–[20].

Research and methodology

Governing equation

Here are the governing equations that are derived from the aforementioned assumptions:

Mass conservation equation:

$$\nabla \cdot \vec{V} = 0$$

Momentum conservation equation:

$$\rho \frac{\partial \vec{V}}{\partial t} + \rho \vec{V} \cdot \nabla \vec{V} = -\nabla P + \mu \cdot \nabla \cdot \nabla \vec{V} + \rho \beta \vec{g} \left(T - T_{ref}\right) + \vec{S}$$

Energy conservation equation:

$$\frac{\partial}{\partial t}(\rho H) + \nabla \cdot \left(\rho \vec{V} H\right) = \nabla \cdot (k \nabla T)$$

The density of the PCM is denoted by ρ. The vector of velocity denoted as V. "P" stands for pressure, "β" for thermal expansion coefficient, reference temperature (Tref), enthalpy (H), thermal conductivity (k), and dynamic viscosity (μ).

The momentum equation source term can be presented in the following form:

$$\vec{S} = -\frac{(1-\lambda)^2}{\lambda^2 + 0.00001} A_{Mushy} \vec{V}$$

Although the Mushy zone constant might take on values between 10^4 and 107, the present study makes use of the value 105.

Calculating the total PCM enthalpy involves adding the latent and perceptible enthalpies:

$$H = h + \Delta H = h + \lambda L$$

Where

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

A reference enthalpy $\left(h_{ref}\right)$, specific heat at constant pressure (Cp), and latent heat of fusion (L) are all used here.

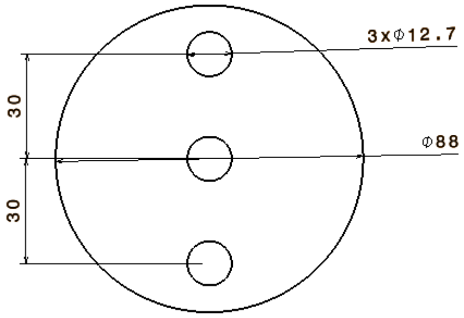
It is here that the value of the liquid fraction, represented as λ, is given.

$$\lambda \begin{cases} = 0 \; at \; T < T_{solidus} \\ = \dfrac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} \; at \; T_{solidus} \leq T \leq T_{liquidus} \\ = 1 \; at \; T > T_{liquidus} \end{cases}$$

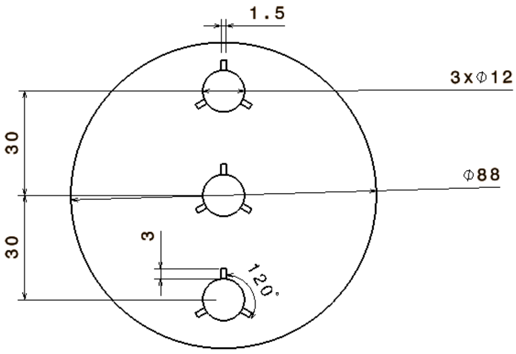
Where $T_{solidus}$ is the temperature at which the solid becomes solid and T_{liquidus} is the temperature at which it becomes liquid.

Design

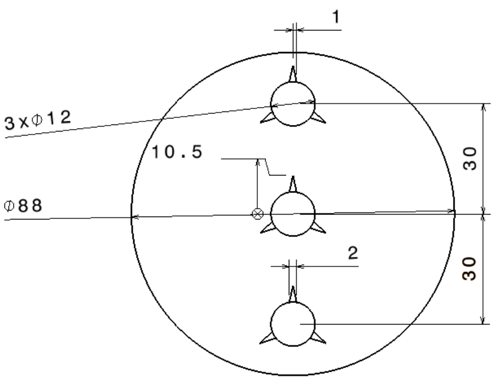
The physical model used in this work is a two-dimensional section of a horizontally shell-and-tube heat energy storage device for latent heat. As the HTF is pumped into the inner copper tubes, a PCM is placed on the side of the shell. There were four potential configurations that might enhance the heat transmission among the PCM and the fluid. One design is finless, while the other three have fins of varying shapes attached to HTF tubes. The 88 mm diameter of the shell is the same in every cases. The HTF tube has a diameter of 12.7 mm when it is finless and 12 mm when it has fins. Two fins form an angle of 120 degrees. Every HTF tube is 30 mm apart and lies along the same axis. Figure 1 shows that in case 1, there are three HTF tubes without fins, and each HTF has a diameter of 12.7 mm. Figure 1 shows that in case 2, three rectangular fins are attached to the HTF tube at an angle of 120 degrees. As seen in figure 1, case 3 features three triangle fins attached at an angle of 120°. Figure 1 shows the three rectangular firs that were used in case 2 to attach to the HTF. The dimensions of these fins differ from those in case 2. Keep in mind that the fin area is constant across the board. In cases 2, 3, and 4, the HTF tube has a diameter of 12 mm.



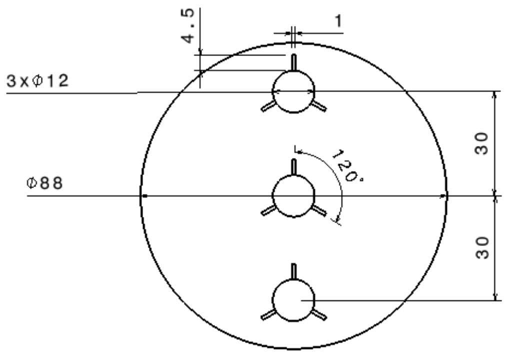
Case 1 – No fins



Case 2 – Rectangular fin



Case 3 – Triangular Fins



Case 4 – Rectangular log fins

Figure 1 Computational domain of all four cases considered

Mesh generation

In order to facilitate the computation of the PDEs ("partial differential equations") that control the physical properties of fluid flow, creation of meshes is used to discretize the physical domain in smaller subdomains (elements). The element's dimensions are 0.001 mm, and its shapes are triangular and quadrilateral. This procedure forms a large number of elements and nodes in all of the computational models that are being investigated (see table 1 for details). The computational model that is formed from the mesh is shown in Figure 2.

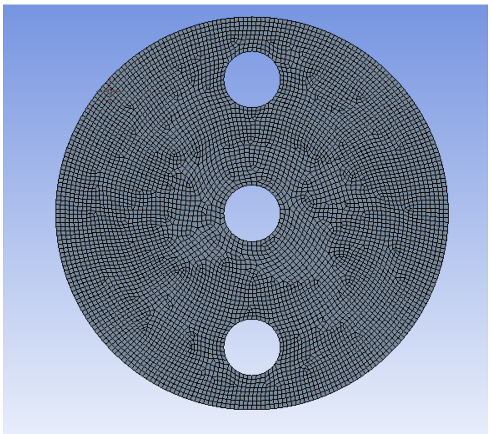


Figure 2 Mesh of computational domain

Table 1 Mesh generation detailed

	Element	Nodes
Case 1 – No fins	6364	6547
Case 2 – Rectangular fins	6461	6636
Case 1 – Triangular fins	6298	6455
Case 1 – Rectangular long fins	6294	6463

Numerical approach and Boundary condition

The commercial version of ANSYS FLUENT used to solve the governing equations. Considered the following pre-simulation procedures for this specific model. A SIMPLE method was used to implement the pressure-velocity coupling. The momentum and energy equations are solved using this second-order upwind method. In order to change the pressure term, (Mostafa M). used the PRESTO method. The values of the under relaxation solutions control factors for momentum, pressure, liquid fraction, and energy are 0.7, 0.3, 0.9, and 1, respectively. The model's stability may be enhanced by implementing a convergence requirement of 10^{-6} for the continuity and energy equations and a threshold of 10^{-5} for the momentum equation. Based on previous numerical studies, the RT44HC PCM paraffin wax was selected. For high latent heat storage applications, RT44HC is the appropriate storage material due to its substantial heat storage capacity, restricted temperature range, and absence of degradation over numerous cycles. In addition to being chemically stable, it is also non-corrosive and harmless. As for the HTF tube, it's copper. Thermophysical properties of paraffin PCM (RT44HC) and copper are detailed in Table 2. When melting begins, the starting temperature of the two-dimensional simulated PCM domain is set at 40 ◦C. A top temperature of 65 ◦C on the inner tube is necessary for the melting process. There is no need for a sliding boundary on any inner tube either. Additionally, won't take into account heat loss via the outer shell's surface. The natural convection causes the melted PCM to flow in a laminar pattern. Since the outer shell does not conduct heat, it call adiabatic.

Table 2 Thermo-physical properties of Paraffin and copper

Properties	Unit	Paraffin (PCM)	Copper
Melting temperature	$(°C)$	42.13-43.28	-
Latent heat	kJ/kg	218.110	-
Specific heat	$J/kg \cdot K$	2000	381
Density	kg/m^3	800 (solid), 700 (liquid)	8978
Thermal conductivity	$W/m \cdot K$	0.2	387.6
Dynamic viscosity	$kg/m \cdot s$	0.0008	-
Coefficient of thermal expansion	K^{-1}	0.00259	-

Numerical model validation

The current numerical results are based on a validated CFD model that was used in earlier numerical work. (Zaytoun et al., 2023) [21] consistent numerical work was used to do the validation. The computation model is validated without fins on the HTF tube. The 88 mm shell diameter and the 12.7 mm HTF tube diameter are identical. There is a 30-millimeter gap between each HTF tube. In this simulation, the following setup processes were taken into account. For the coupling between pressure and velocity, a SIMPLE method was used. Apply the second-order upwind technique to the momentum and energy equations. The pressure term adaptation scheme called PRESTO has been put into place. For both the current study and (Zaytoun et al., 2023) [21] the liquid fraction contours at 25 minutes of melting. Compare the numerical findings shown in Figure 3 from earlier iterations of the CFD model with the present model, which incorporates the full paraffin melting period. A difference of approx. one percent was shown in the comparison results.

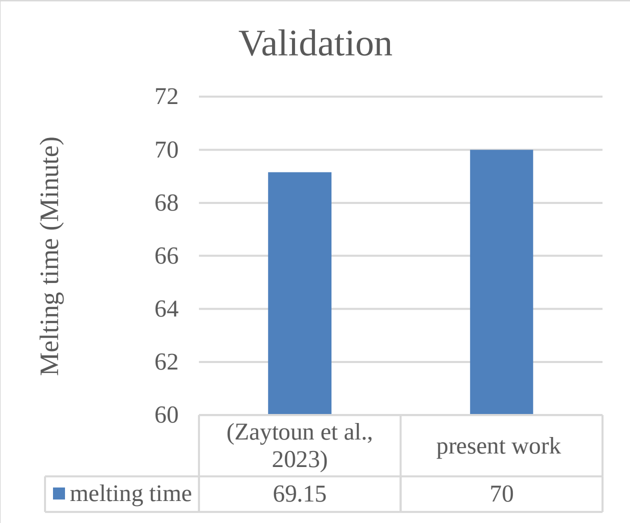


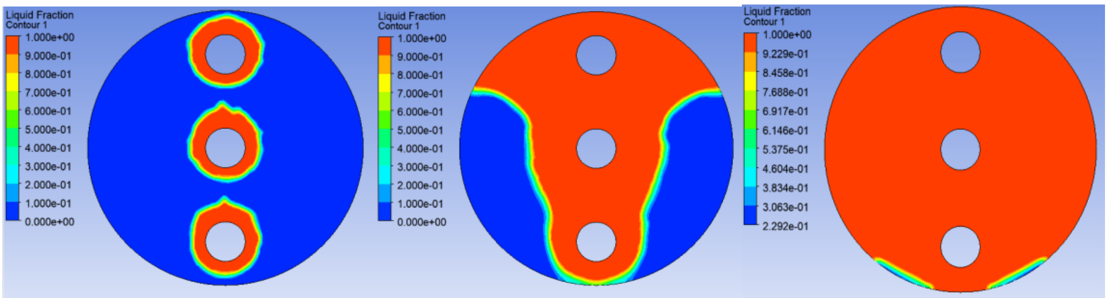
Figure 3 Validation with complete melting time

Result and discussion

Here discussed the PCM's actions in relation to the liquid fraction and temperature distribution inside the shell and tube latent heat thermal storage unit. Zero to one is the range of values for a liquid fraction, which represents the percentage in PCM volume that is liquid. Fraction zero at the liquid phase represents PCM in its solid form, whereas fraction one represents the full melt state.

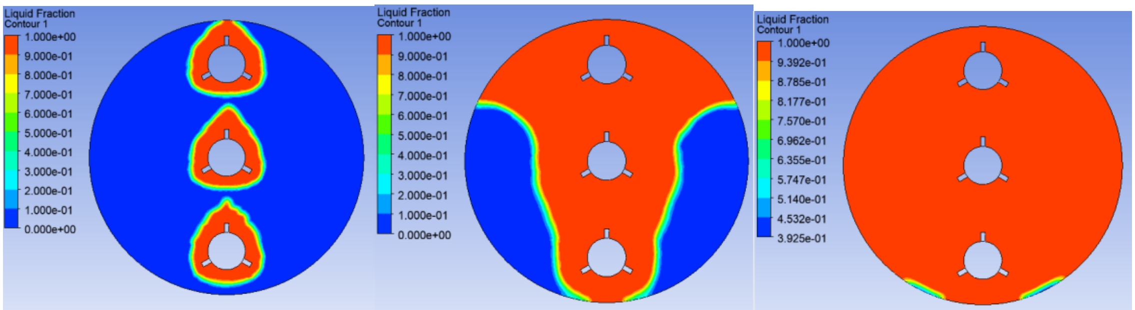
Liquid fraction

In all four cases, the melting fraction profile is shown in Figures 4–7 as the melting time varies. Approximately two minutes during the melting process, a little upward wave appears in each HTF tube due to natural convection. As time progresses (t = 10 min), an uneven melting pattern is noticed around the HTF tubes. This pattern of uneven melting is created by the regulation of circulation, which mainly help the heat-conduction process. These vortices are produced by the buoyant force that results from the motion of both cold and hot liquid PCM. After twenty-five minutes of melting, the upward convection phenomenon becomes less prominent, depending upon the angular direction of each case. When compared to the upper convection currents, the lower zone's melting is proceeding at slowly. The function of natural convection disappears after around 50 and 70 minutes, and the melting rate drops significantly when the conduction transfer of heat process takes over. How much solid PCM melts in the lower area, where natural convection is prevalent (the melting dead zone), is greatly affected by the size and form of the fins.



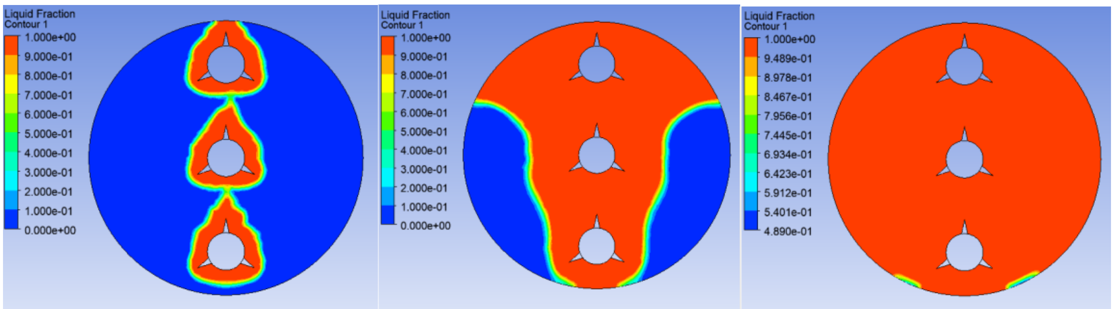
2 Minute 25 Minute 70 Minute

Figure 4 Liquid fraction contour of Case 1 – No fins



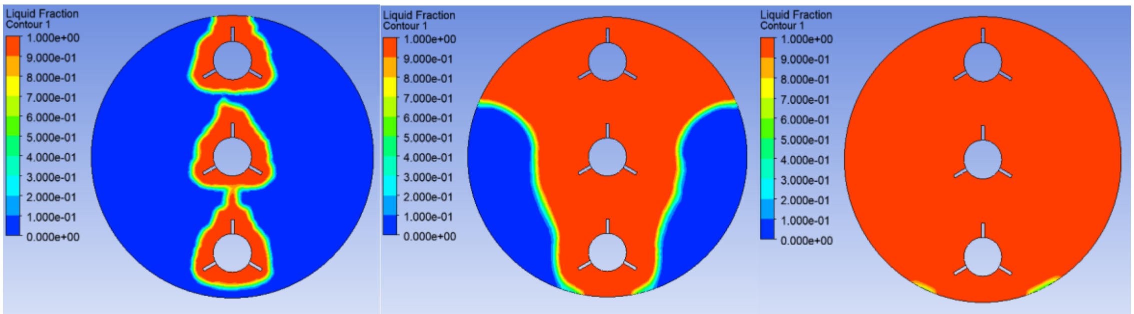
2 Minute 25 Minute 68 Minute

Figure 5 Liquid fraction contour of Case 2 – Rectangular fin



2 Minute 25 Minute 67 Minute

Figure 6 liquid fraction contour of case 3 – Triangular fins

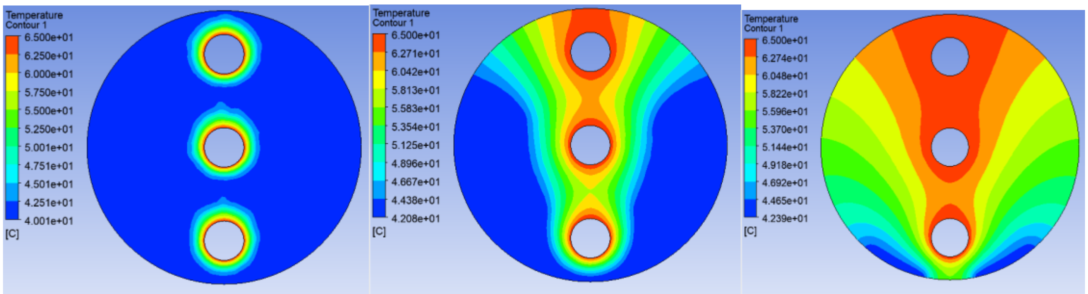


2 Minute 25 Minute 66 Minute

Figure 7 Liquid fraction contour of Case 4 – Rectangular long fins

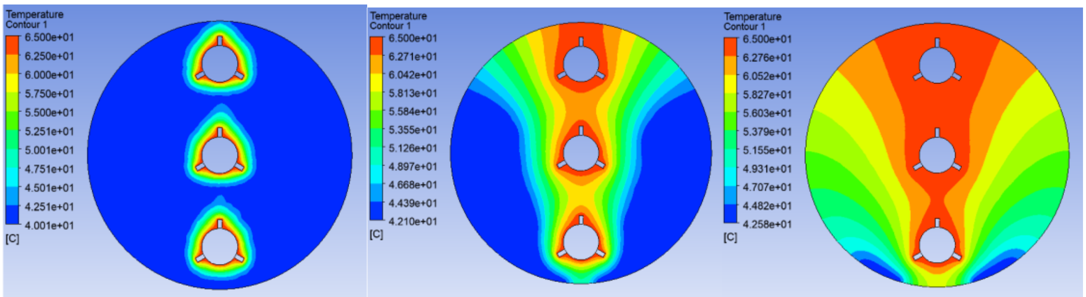
Temperature distribution

The four case's PCM temperature contours vary at distinct melting time intervals, as shown in Figure 8-11. Compare the fundamental case (HTF tube without fin) to three distinct fin, PCM temperature contours for every melting time period by connecting them to HTF tubes. Different heat transmission techniques are used at each stage of the multi-step melting process: At the outset of melting, conduction is the primary mechanism of heat transport. A mix of conduction and natural convection defines the second phase, during which melting proceeds. Third Level: Conduction is the primary mechanism for heat transport even at the last stage of melting. A consistent temperature contour around each HTF tube is seen during the first two minutes of melting. While the HTF tube was still in its early stages of melting, the firm PCM around it aided the conduction process. Once two minutes have passed during the melting process, the second phase may begin. Upon leaving the HTF tube, the heated PCM liquid begins to transmit heat via natural convection. When the PCM around the HTF tubes experiences a temperature difference, a natural convection process begins. The buoyant force caused by the rising and falling of the hot and cold liquid PCM drives natural conduction currents, which in turn cause the creation of circular natural currents. The subsequent stage of melting, as seen at ten minutes, involves the slow but steady strengthening of natural convection by means of streams of hotter temperatures moving upwards. The top portion of the PCM melted the fastest due to these natural convection currents. During stage three, the hot PCM zones are located in the top half and its cool PCM areas are concentrated in the bottom half. There is less activity from natural convection and less noticeable temperature change since temperature are more uniformly distributed. Moving heat from the warmer upper PCM zone to the colder lower PCM zone is more efficiently accomplished via conduction due to the more uniform distribution of temperatures throughout the PCM. The cold PCM downward melting zone grows when the fin is linked to the HTF tube, as has been seen by many. As the melting process nears its end, this helps the remainder of hard PCM at the bottom zone to melt more easily.



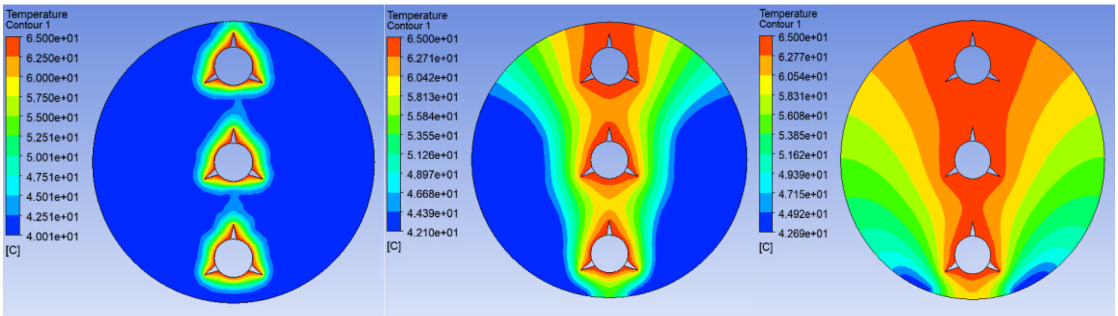
2 Minute 25 Minute 70 Minute

Figure 8 Temperature contour of case 1- No fins



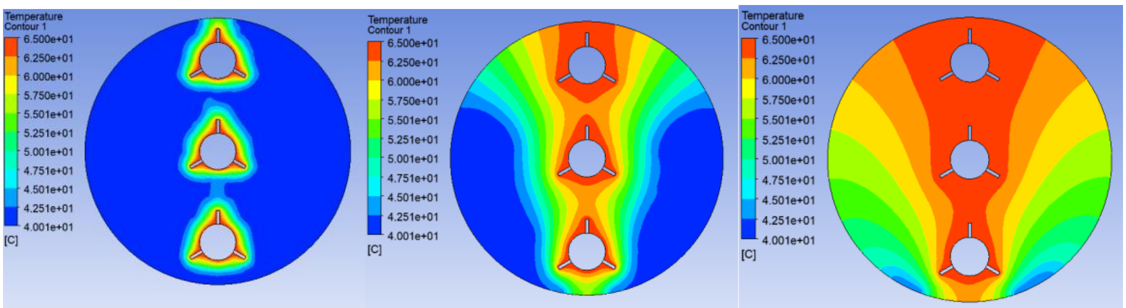
2 Minute 25 Minute 68 Minute

Figure 9 Temperature contour of case 2 – Rectangular fins



2 Minute 25 Minute 67 Minute

Figure 10 Temperature contour of case 3 - triangular fins



2 Minute 25 Minute 66 Minute

Figure 11 Temperature contour of case 4 – Rectangular long fins

Discussion

A vertically-aligned HTF tube devoid of fins is seen in the initial situation. Phase change material fills in the void between the outer shell and inner tube. In case 1, the PCM fully melts after seventy minutes. Many different shaped fins may be mounted on the surface of the HTF tube to accelerate the heat transmission through PCM or to shorten the time required for PCM to melt entirely. It is possible to connect the fin to a smaller HTF tube while maintaining a consistent PCM surface area. In case 2, 3, and 4, the heat transfer fluid tube's diameter is 12 mm; however, in case 1, it is 12.7 mm. Fins with a rectangular and triangular shape are seen in Case 2 and Case 3 respectively. Utilization of rectangular fin in case 4, but with proportions that vary from case 2. It takes 68 minutes for case 2, 67 minutes for case 3, and 66 minutes for case 4 for the PCM to completely melt. Assign an amount of PCM and HTF tube surface area, and then find the PCM melting point as a function of time due to fin attachment to the tube surface.

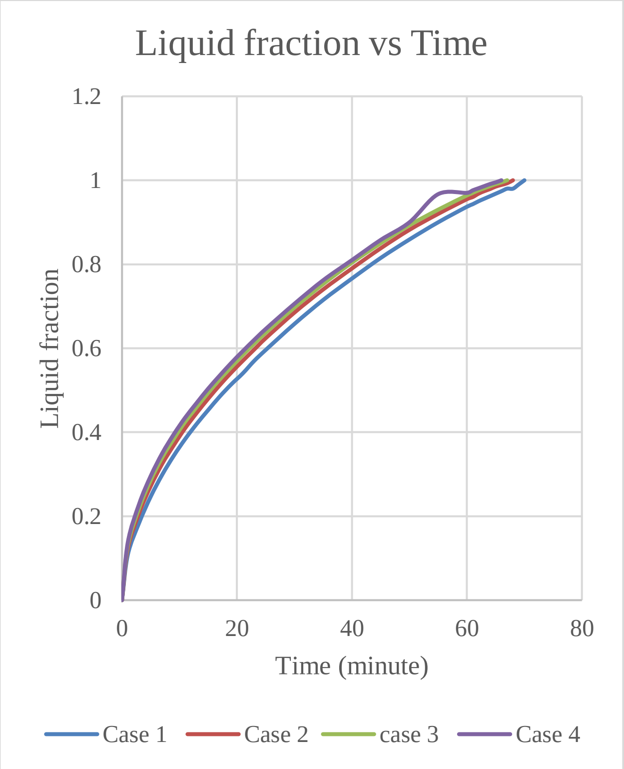


Figure 12 Complete melt of PCM for all cases

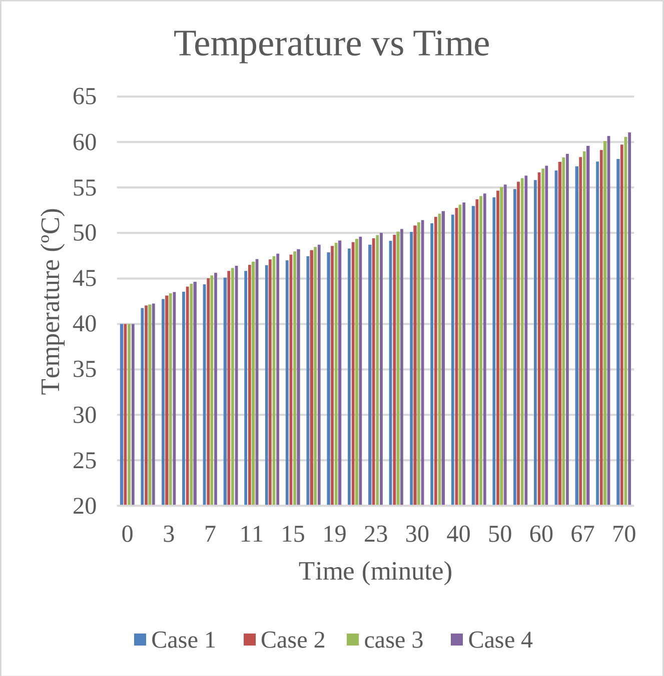


Figure 13 Temperature of PCM at various time in all cases

Conclusion

Renewable energy has emerged as a viable alternative to traditional energy sources due to rising global energy demand and the associated environmental concerns. The unreliability of renewable energy sources is their main drawback. To get around this problem, another option is to use thermal energy storage (TES) systems. All three forms of thermal energy storage—thermochemical heat, sensible heat, and latent heat—are real and distinct. Latent heat thermal energy storage systems (LHTES) are quite popular because of their large and effective storage capacity. Within a shell-and-tube latent heat thermal energy storage system, the present numerical investigation focuses on an enhanced hat transfer between PCM and HTF fluid. This study suggests attaching different shape fins to the outer surface of HTF tubes in order to improve heat transfer between PCMs and HTF tubes. The gradient fins are at 120^{o} angles to each other. Fins are designed with shapes like rectangular and triangles to enhance heat transmission. The presence or lack of fins does not affect the consistency of the HTF tube and PCM surface. The primary inferences drawn from this analysis are as follows:

- Research demonstrates that by attaching fins to the surface of HTF tubes, heat transfer can be enhanced without an increase in the tube surface area.

- To fully melt the PCM, Case 1, which does not have a fin, takes 70 minutes.
- It takes 68 minutes to fully melt the PCM in case 2, 67 minutes in case 3, and 66 minutes in case 4, correspondingly.
- The PCM's temperature in cases 1, 2, 3, and 4 is 58.136 ºC, 59.739 ºC, 60.583 ºC, and 61.072 ºC, respectively, at 70 minutes of the melting process.
- From case 1, the melting times reduce for cases 2, 3, and 4 are 2.85%, 4.29%, and 5.71%, respectively.

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