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Investigation of morphological characteristics of concentric tube thermals energy storage.

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ABSTRACT

This study focuses on the heat transfer intensification of concentric tube type thermal energy storage (TES). The collective influence of aspect ratio (ratio of length to diameter of the tube) and number of fins is investigated. To optimize thermal energy storage, first an optimal aspect ratio investigated. And then, optimal number of fins is obtained. Results are compared based on the amount of liquid fraction available after 120 minutes of charging and discharging. It was found that with an increasing aspect ratio, liquid fraction also increased, but up to the aspect ratio of 11. Afterwards, an increased aspect ratio showed insignificant change in the liquid fraction. Similarly, liquid fraction in case of charging was increased with increasing the number of fins up to 8. Afterward, an increased number of fins showed insignificant change in the liquid fraction.

Keywords: Aspect Ratio; Concentric tube; Phase Change Materials; Thermal Energy Storage.

INTRODUCTION

Owing to the importance of thermal energy, engineers and scientists have worked tirelessly for centuries, trying to optimize the methods of producing thermal energy. However, the methods of producing thermal energy are not without drawbacks. Some methods such as the burning of fossil fuels not only require a lot of capital owing to the different stages involved from the moment they are extracted from the earth, to when they are ultimately burnt in power plants, but they are also indirectly linked with pollution of the environment as well. Furthermore, in certain cases, external factors such as geography and climate also restrict the development of heating or thermal energy systems for use in practical situations due to which novel methods are needed to be explored. One of the solutions to many challenges related to thermal energy and its applications is thermal energy storage (TES). TES can be used in many applications ranging from thermal management of appliances, solar collectors to the solar power plants (Sharma et al. 2009).

TES is of two types - latent heat thermal energy storage (LHTES) and sensible heat storage (SHS). Sensible heating is the most common type of TES since it is based on energy transfer across a temperature difference. A simple example of this is the heating of water from room temperature. LHTES or phase change materials (PCMs) can store more energy as compared to SHS. Following factors should be considered before selecting the PCM - minimum corrosive behavior, minimum toxicity, maximum thermal conductivity, maximum values of enthalpy of phase change, maximum thermal and chemical stability (Nazir et al. 2019).

One of the major applications of TES is solar heating systems, as solar energy can’t be used all the time due to its discontinuous nature, TES in this system helps smoothen the discrepancy between the availability and need of thermal energy (Saloux and Candanedo 2020). TES based on the utilization of latent heat often perform better when compared to sensible systems since they have higher energy storage densities. TES based on concentric tube is one of the most common TES configurations (Mehling and Cabeza 2008). The most common problem of the LHTES is less thermal conductivity of PCM and inefficient transfer of heat between HTF and PCM. This poor heat transfer was showed by (Trp 2005) in the shell and tube type TES, a big portion of the heat was carried with heat transfer fluid without transferring it to phase change material. To overcome this challenge, various heat transfer methods have been proposed, amongst them addition of fins is the most common method.

(Rabbi and Asif 2021) numerically investigated the influence of various heat transfer fluids and fins made up of copper mesh on the charging/discharging time. The results revealed that HTF with higher values of thermal diffusivity will cause the less charging and discharging time, mesh type fins also decreased the charging time. Likewise, (Yang et al. 2020) studied the heat trasnsfer performance of concentric tube TES experimentally and numerically. Results showed that non-uniform arrangement of the annular fins reduced inhomogeneity of melting process and the melting duration was decreased by 62.8% as compared to the TES with uniform fins. (Lin et al. 2018) established the importance of improving heat transfer mechanics. This was done by the addition of fillers having high thermal conductivity, namely expended graphite and carbon nanotubes. The supremacy of carbon-based fillers over the metallic fillers was also observed through the results of their experiments. Similarly, (Guo et al. 2021) investigated the charging time of four types of heat exchanger type TES configurations which were tube without fins, tube with fins, tube with metal foam, and tube with fins and metal foam. Their results showed that the charging time of the tube with fins, tube with metal foam, and tube with fins and metal foam was decreased by 52.82%, 79.62%, and 83.34% compared to the bare tube.

In another study, (Rabbi, Asif, and Bibi 2021) studied the aspect ratio of packed bed type thermal energy storage and results indicated that by increasing aspect ratio charging time was decreased. Similarly, (Eslamnezhad and Rahimi 2017) numerically studied the effect of fins on heat transfer in triplex tube heat exchanger, they suggested the optimal arrangement to raise the efficiency of TES and decrease the time of charging of the phase-change material. Likewise, (u Mekrisuh et al.

2021) investigated the influence of geometric parameters on thermal parameters in the shell and tube type TES while keeping same storage capacity for all cases. Results revealed that after geometric optimization melting time reduced to 44 mins from the 244 mins as compared to the basic configuration.

After the literature review, it is obvious that the addition of fins in the concentric tube type TES and optimal aspect ratio of TES can improve heat transfer from HTF to the PCM. According to the authors' knowledge, the collective impact of aspect ratio and optimal number of fins in concentric tube on the TES has not been investigated. The main objective of this study is to analyze the influence of aspect ratio and fins in the concentric tube type TES on the liquid fraction of PCM.

MODEL DESCRIPTION

Governing equations of the LHTES:

The design consists of a simple concentric tube heat exchanger. The length of heat exchanger tube is 1m, the inner mean diameter and outer mean diameter of tube is 0.06m and 0.16m, respectively. Hot water flow inside the inner tube and PCM is kept between inner and outer tube. Simulation of heat transfer is performed for heat exchanger and the liquid fraction is noted down after the 120 minutes. Geometry of the concentric tube TES with fins is shown in Figure 1.

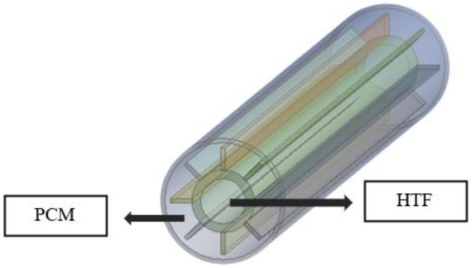


Figure 1. Geometry of the concentric tube TES with fins

The energy, momentum and continuity equations are given by equation 1-3, respectively (Dabiri, Mehrpooya, and Nezhad 2018; Al-Maghalseh 2017).

$$\partial_t(\rho h) + \partial_i(\rho \Delta H) + \partial_i(\rho u_i h) = \partial_i(k\,\partial_i T) \quad (1)$$

$$\partial_t(\rho u_i) + \partial_i\left(\rho u_i u_j\right) = \mu\,\partial_{jj} u_i - \partial_i p + \rho g_i + S_i \quad (2)$$

$$\partial_t(\rho) + \partial_i(\rho u_i) = 0 \quad (3)$$

The sensible enthalpy is the sum of reference enthalpy at reference temperature and increase in enthalpy from reference to Temperature T (Dabiri, Mehrpooya, and Nezhad 2018)

$$h = h_{ref} + \int_{T_{ref}}^{T} c_p \Delta T \quad (4)$$

The complete enthalpy is given by the addition of sensible and latent enthalpy.

$$H = h + \Delta H \quad (5)$$

The liquid phase is calculated by the following equation.

$$\gamma = \frac{T - T_s}{T_l - T_s} \quad (6)$$

The source term S_i in the momentum equation is given by (Brent, Voller, and Reid 2007)**.**

$$S_i = C(1-\gamma)^2 \frac{u_i}{\gamma^3 + \varepsilon} \quad (7)$$

Here, C shows that how the velocity is decreased to zero when the PCM is in solid state. The value of C for PCM varies between 10^4 to 10^7 and ε is a smaller value (0.001) introduced in Ref. (Ye, Zhu, and Wang 2011).

PCM Properties

The simulation is performed for using ANSYS FLUENT 18.1, hot water flows in inner tube at the flow rate of $0.01 m^3/s$, with constant inlet temperature of 340 K in case of charging. PCM of mass 12.5 kg is placed in between the tubes. The convergence criterion was 10^{-5} for momentum equations and 10^{-10} for the energy equation. The maximum number of iterations for each time step was 60, properties of PCM are stated in the table 1 (Groulx and Ogoh, n.d.).

The HTF Temperature in case of charging and discharging at inlet was 330 K and 300 K. The initial Temperature of PCM for charging and discharging was 312 K and 320K

Table 1. Thermal Energy Storage, (Groulx and Ogoh, n.d.)

Density	Cp	Conductivity	Heat of fusion	Solidus melting temperature	Liquids melting temperature
(Kg/m^3)	(kJ/kg)	(W/m k)	(kJ/kg)	(K)	(K)
900	2.5	0.21	174	313	316

Numerical Model Validation:

The results obtained from the simulations performed on Ansys Fluent® are validated with the aid of experimental results available in the literature (Jesumathy et al. 2014). The mass flow rate used for this experiment was 8L/min and the inlet temperature of heat transfer fluid was 72°C. The parameters and dimensions of the model are modified according to the above-mentioned reference and the simulation is performed at points T1 and T4 for 200 minutes. Results that are obtained from simulation are depicted in Figure 2.

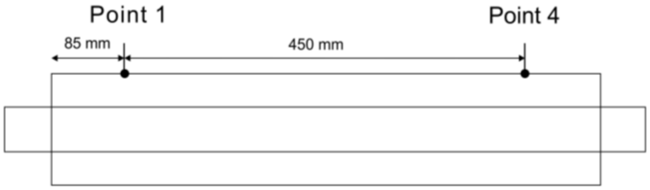


Figure 2. Locations at which melting curves were plotted for validation.

By comparing Figure 3 it is obvious that the trend of results at point T1 and T4 are very close to that of experimental results. Therefore, the simulations results obtained are validated and model can be used for further research work.

RESULTS AND DISCUSSION:

Simulations are carried on concentric tube type LHTES, to find the optimal aspect ratio and optimal number of fins. Afterwards, this optimal TES configuration is compared with TES without fins in terms of liquid fraction.

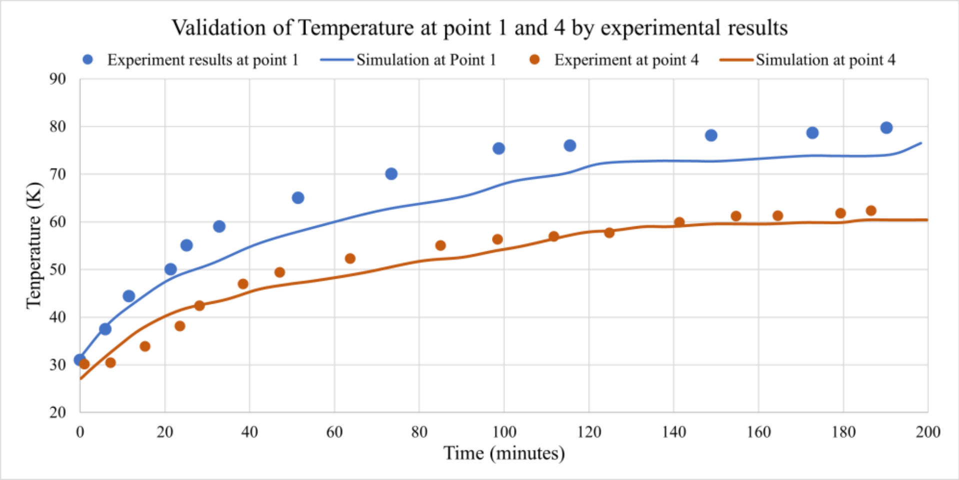


Figure 3. Temperature of paraffin wax in axial direction at point 1 and 4 during melting.

Effect of aspect ratio on TES Performance:

To improve the heat transfer, aspect ratio of TES is studied. It is the ratio of the length of the TES and the outer diameter of the tube. As the aspect ratio increases the liquid fraction rises. Initially the rate of increase of the liquid percentage is higher but as the aspect ratio increases beyond 11 the rate of increase of the liquid fraction decreases. Therefore, optimal aspect ratio for TES is found to be 11. Results are shown in Figure 4.

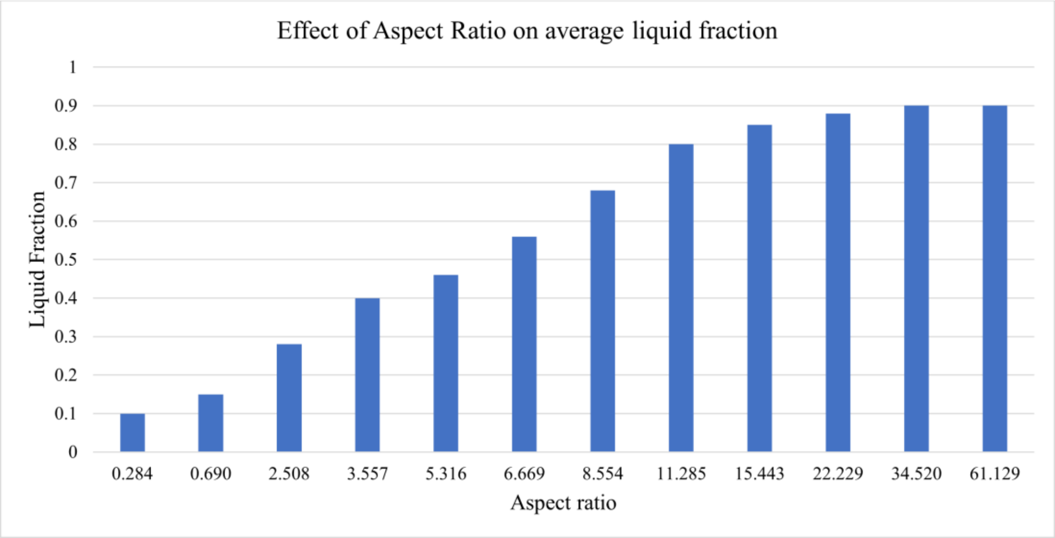


Figure 4. Effect of aspect ratio on liquid fraction for time = 120 minutes

Influence of number of fins on TES Performance:

Fins are incorporated to enhance heat transfer by conduction. This addition of fins comes at the expense of reducing heat transfer by convection, as fins will resist flow of melted PCM. Therefore, optimized number of fins is found by performing simulations with varying number of fins. The resulting liquid fraction after 120 minutes is observed in each case. Liquid fraction is an indicator of the amount of the PCM that has melted in specific amount of time, a larger liquid fraction indicates a higher amount of heat transfer. Figure 5 indicates that as fins are increased the liquid-fraction increases which means heat transfer increases. However, it is visible from the Figure 5 that as the fins are increased beyond 8, the increase of the liquid fraction is not significant. Therefore, 8 fins are considered as the optimal for enhancing the heat transfer.

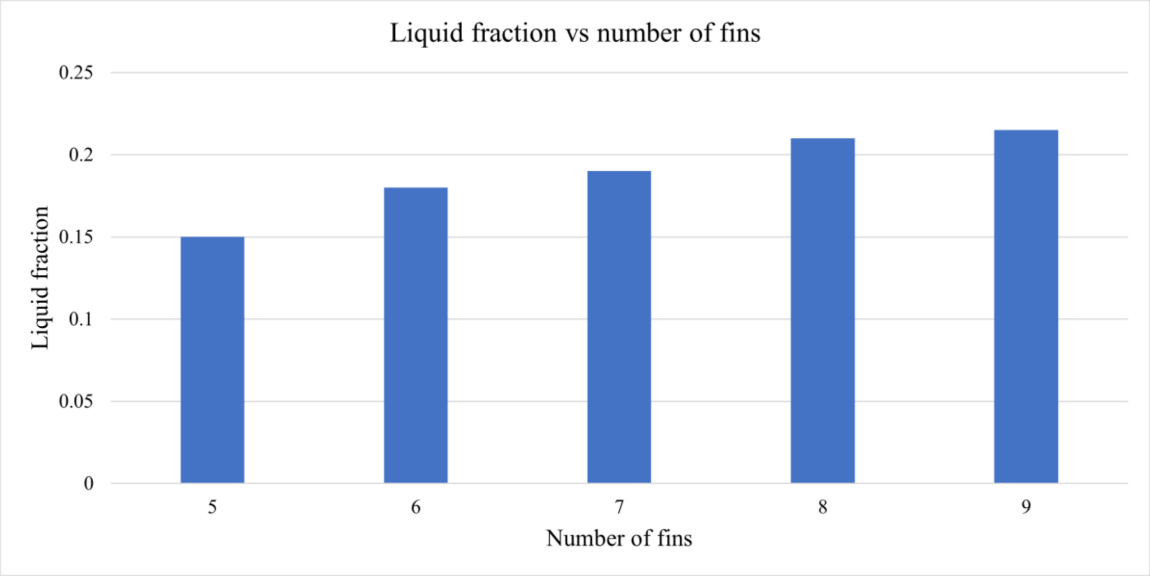


Figure 5. Impact of number of fins on liquid fraction at time = 120 minutes

Comparison of charging between optimal configuration and TES without fins.

Temperature of water at inlet boundary is kept constant at 330 K to maximize the heat transfer. Water flows with mass flow rate of 0.01m/s. After simulation, the PCM temperature for concentric tube TES without fins has reached about 317 K after 120 minutes. Similarly, for optimal configuration having aspect ratio of 11 and with 8 number of fins the PCM temperature has reached about 324 K after 120 minutes, this comparison is shown in Figure 6. The average liquid fraction for concentric tube TES without fins has reached about 0.4 which indicates that 40 % of the PCM has melted after a time of 120 minutes**.** Similarly, for optimal configuration having aspect ratio of 11 and 8 number of fins. The average liquid fraction has reached about 0.8 which indicates that 80 % of the PCM has melted after a time of 120 minutes as shown in Figure 7. In 120 minutes 100% more PCM is melted by using optimal TES configuration.

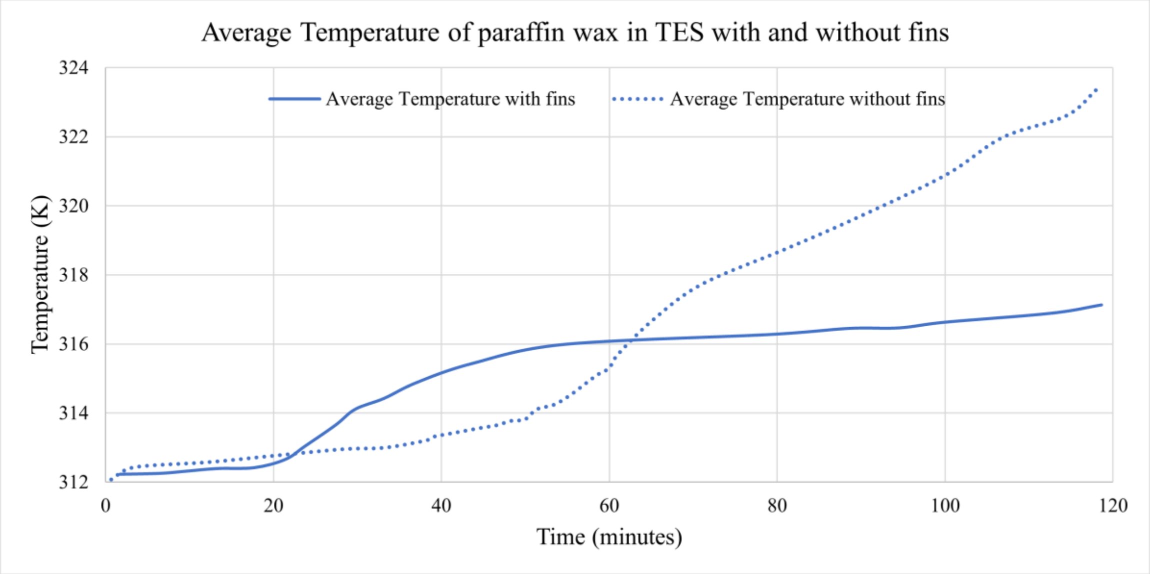


Figure 6. Average temperature of paraffin in TES with and without fins for charging

As mass average temperatures do not show clear picture of sensible and latent heating therefore temperatures at a particular point (a) are plotted for both with and without fins. The location of point (a) is shown in Figure 8. The comparison between temperature with and without fins at point (a) is shown in Figure 9. It can be clearly seen that temperature of point (a) without fins has not reached melting temperature in 120 minutes and is still in sensible heating portion. While temperature of point (a) for TES with fins has reached melting point and is in latent heating portion.

Figure 10 (a) and (b) shows phase of PCM in TES with and without fins after 120 minutes, respectively.

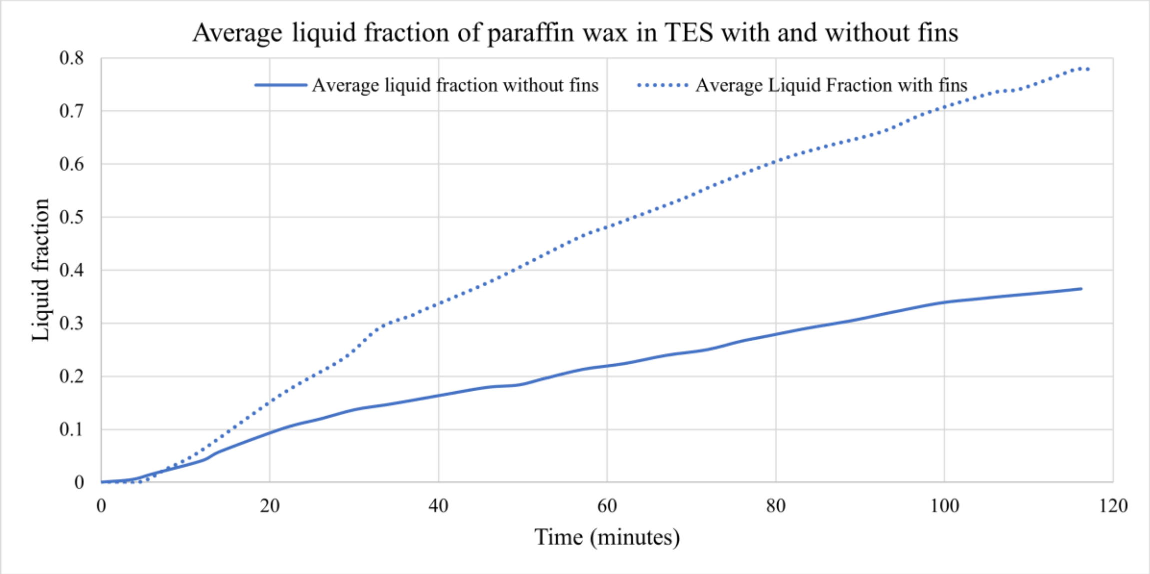


Figure 7. Average liquid fraction of paraffin in TES with and without fins for charging.

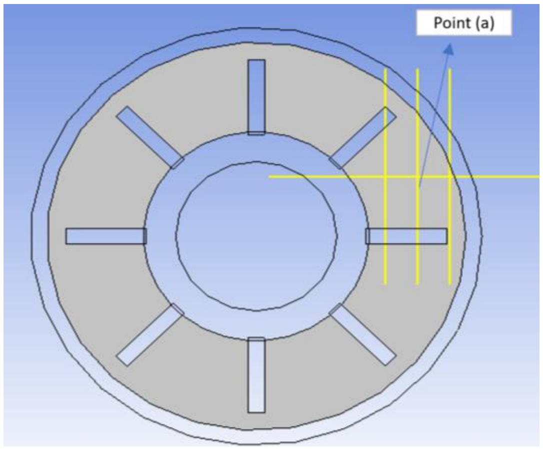


Figure 8. Location of point (a) in TES

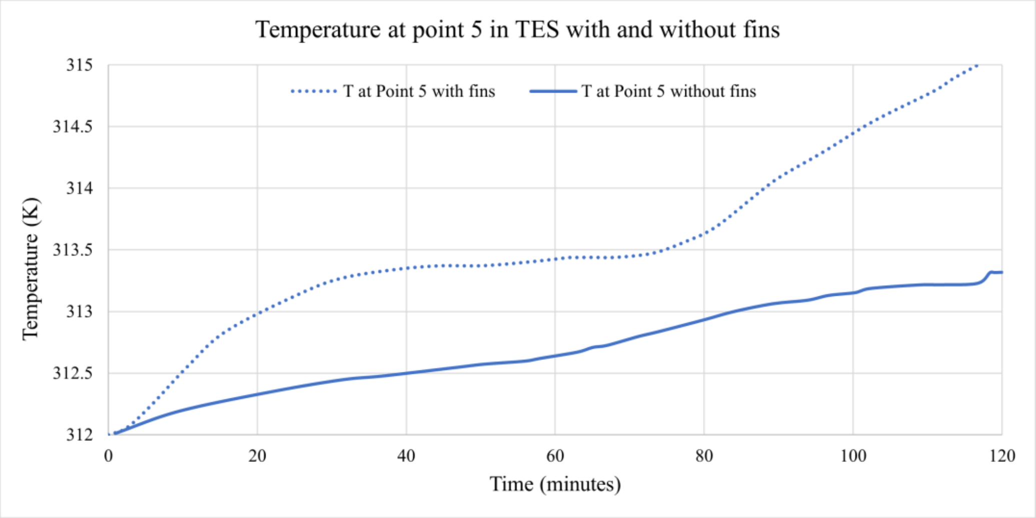
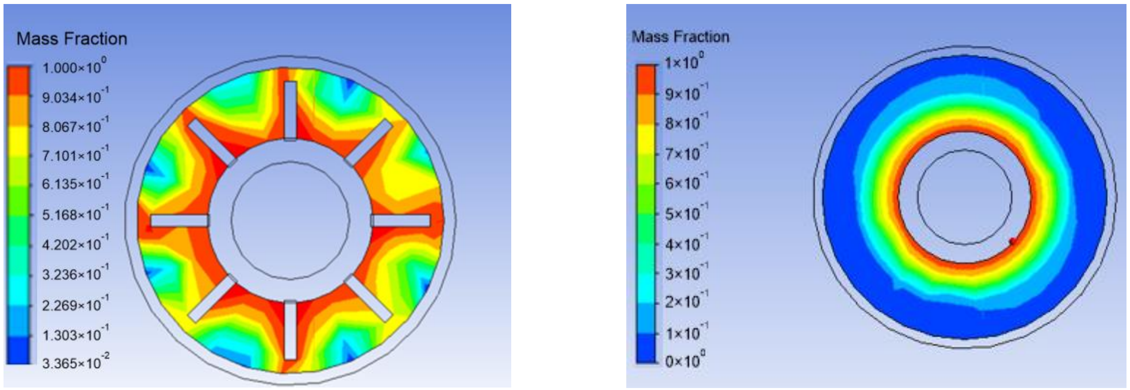


Figure 9. Temperature of paraffin in TES with and without fins at point (a) for charging



(a) (b)

Figure 10. Contour of liquid Fraction of TES **(a)** with fins **(b)** without fins

Comparison of discharging between optimal configuration and TES without fins.

Temperature of water at inlet boundary is kept constant at 300 K and initial temperature of PCM is kept at 320K to maximize the heat transfer and the water flows with mass flow rate of 0.01m/s. The PCM temperature for concentric tube TES without fins has reached about 314 k after 120 minutes. Similarly, for optimal configuration having aspect ratio of 11 and with 8 number of fins the PCM temperature has reached about 313.5 K after 120 minutes, this comparison is shown in Figure 11. The average liquid fraction for concentric tube TES without fins has reached from 1 to about 0.8 which indicates that 20 % of the PCM has solidified after a time of 120 minutes. Similarly, for optimal configuration having aspect ratio of 11 and 8 number of fins. The average liquid fraction reached from 1 to about 0.65 which indicates that 35 % of the PCM has solidified after a time of 120 minutes as shown in Figure 12. In 120 minutes 75% more PCM is solidified by using optimal TES configuration.

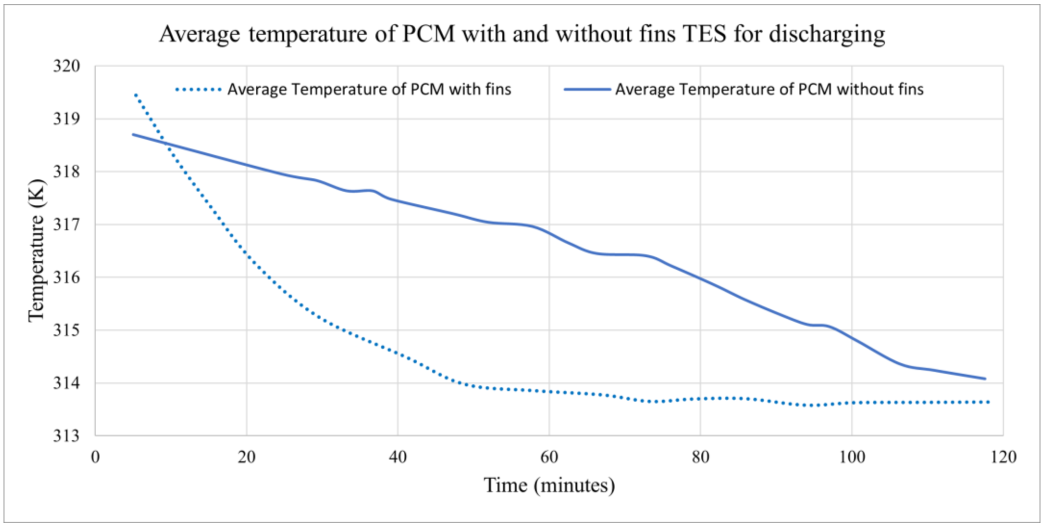


Figure 11. Average temperature of paraffin in TES with and without fins for discharging

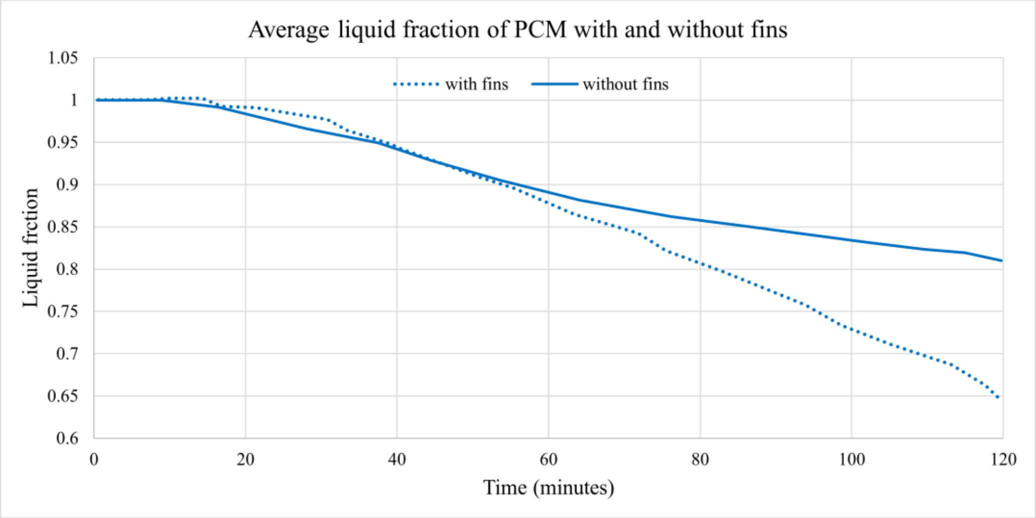


Figure 12. Average liquid fraction of paraffin in TES with and without fins for charging

CONCLUSION

In this research, the design of concentric tube heat exchanger based on PCM is investigated numerically. Several configurations to improve heat transfer such as various aspect ratios and fins are investigated and compared. Simulation results prove that the application of finned heat exchanger is more effective in utilizing the latent heat energy. It was found that by using 8 number of fins in TES and with aspect ratio of 11 liquid fraction was maximum after 120 minutes. Charging of this optimal configuration caused 100 % more liquid fraction in 120 minutes while in discharging solidification was increased by 75%.

ABBREVIATIONS

HTF	Heat Transfer Fluid
LHTES	Latent Heat Thermal Energy Storage
PCM	Phase Change Material
SHS	Sensible Heat Storage
TES	Thermal Energy Storage

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