Introduction

Sensible and latent heat storage are the primary methods for thermal energy storage. While both sensible and latent heat storage are effective, latent heat storage outperforms sensible heat storage because latent heat storage capacity per unit volume is usually 5-14 times higher than that of sensible heat storage [1]. Given the benefits of latent heat storage, researchers have shown increasing interest in PCM-based heat exchangers. PCMs have large volumetric latent heat storage capacity, suitable phase change temperatures and low volumetric changes between phase transition [2]. These characteristics offer a promising solution for improving the performance and efficiency of heat exchangers. However, the energy charging and discharging rates are limited due to relatively lower thermal conductivity of PCMs. To overcome this limitation research has generally focused on either dispersion of nano/micro particles in PCMs or use of extended surfaces (fins) to improve the overall heat transfer without significantly reducing the energy storage capacities [2]. In this synthesis essay, impact of fins geometry, spacing and positioning on heat transfer enhancement of PCM-based heat exchangers will be discussed.

Impact of Extended Surfaces on Heat transfer Enhancement in PCM-based Heat Exchangers

Agyenim et al. [3] employed PCM (Erythritol) with melting point of 117.7°C and compared three experimental configurations: horizontal concentric tube heat exchanger with no fins, circular fins and longitudinal fins. It can be clearly seen in the Fig. 1. that after 8 hours of charging, the temperatures of PCM in system with fins are higher compared to the system with no fins. And among circular and longitudinal fins, longitudinal fins show more higher and uniform temperatures, achieving almost complete melting of PCM. This behavior can be explained by nature of heat transfer involved in all three cases. For the configurations with no fins and circular fins, the dominant heat transfer mode was conduction which only allowed melting of PCM in locality of hot regions. While in case of longitudinal, convective heat transfer mode becomes dominant which results in more uniform temperatures due to mixing of PCM. From this, it can be concluded that fins increase the thermal performance of PCM heat exchangers, however, the shape of fins is equally important to reflect the impact on PCM temperatures.

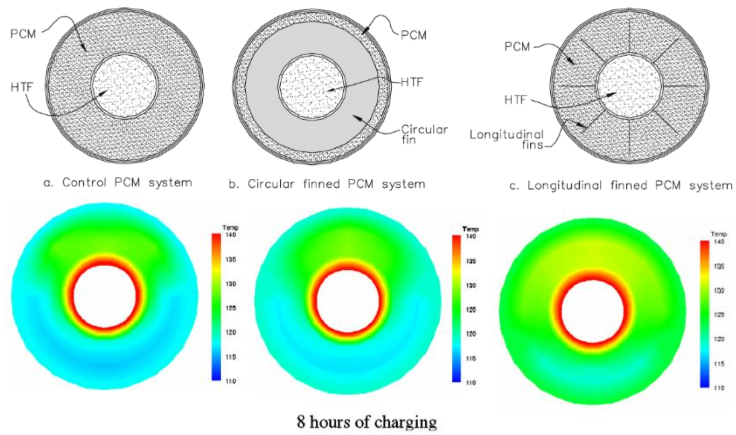

Fig. 1: Comparison of thermal performance of no fins with circular and longitudinal fins.

Another study by Abudulateef et al. [4] was focused on comparison of longitudinal and triangular fins in a Triplex Tube Heat Exchanger (TTHX). PCM with melting temperature of 78.15-82.15°C was selected and it was heated using both inner and outer tubes to charge PCM simultaneously. Three configurations – internal, internal-external and external fins – were investigated for both the geometries and the impact on PCM melting time was observed. It can be seen in Fig. 2 that compared to longitudinal fins for all three configurations, triangular fins showed significant enhancement of around 11%, 12% and 15% for internal, internal-external and external fins, respectively. It can therefore be concluded that triangular fins are better compared to longitudinal fins due to increased heat transfer area and external triangular is the most effective configuration due to reduced thermal resistance and improved natural convection.

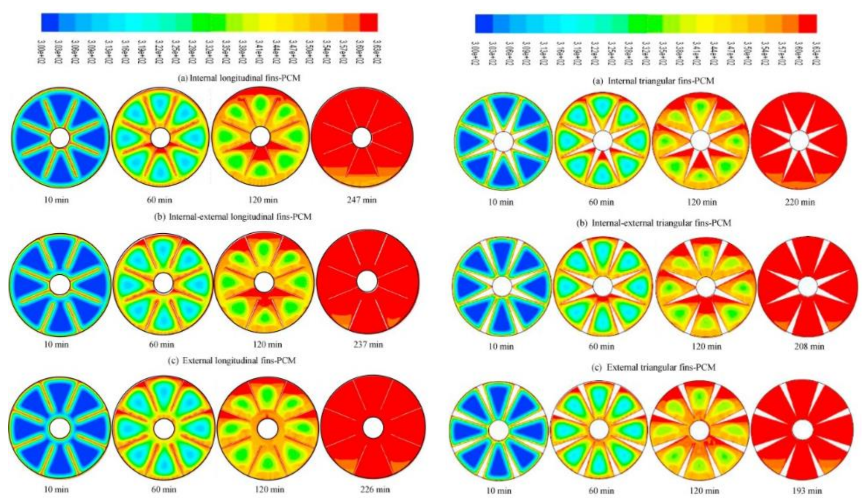

Fig. 2: Thermal performance comparison of longitudinal and triangular fins

Shi et al. [5] investigated the impact of employing fractal fins on heat enhancement of vertical triplex tube heat exchanger as shown in Fig. 3. Comparison with traditional rectangular fins was also carried out. Moreover, the impact of geometric parameters of fractal fins such as fractal fin length ratios, fractal fin width ratios and bifurcation angle were also studied. Results showed that melting rate of PCM in case of fractal fins was higher because the outward extension of secondary branches allowed uniform heat flow distribution.

Consequently, PCM melting time reduced by 27.3% compared to rectangular fins. However, it was observed that the impact of geometry was not prominent during solidification. As the solidification occurs, thermal resistance between liquid PCM and cold fluid increases, therefore, fins do not contribute much which is evident from the result that solidification time in case of fractal fins is higher than that of rectangular fins by only 4%.
Regarding the impact of geometric parameters, it was observed that when fractal fin length ratio ($L' = L_2/L_1$) is 2.5, the melting time was the shortest. At this ratio, second stage fins have a better spatial layout which allows uniform distribution of heat.
To analyze the impact of fractal fin width ratio (W_2/W_1), L' was set to 2.5. It was found that for $W' = 0.5$ is the best choice. Because when $W' = 0.5$, the width of first stage of fin is larger and allows faster heat transfer rate between fins and PCM.
In case of bifurcation angle, the angle of 60° led to an even spatial layout of second stage fins. For other angles, either the adjacent tips very close or very far making an uneven spatial layout. Therefore, it was concluded that the bifurcation angle of 60° is the most suitable choice.

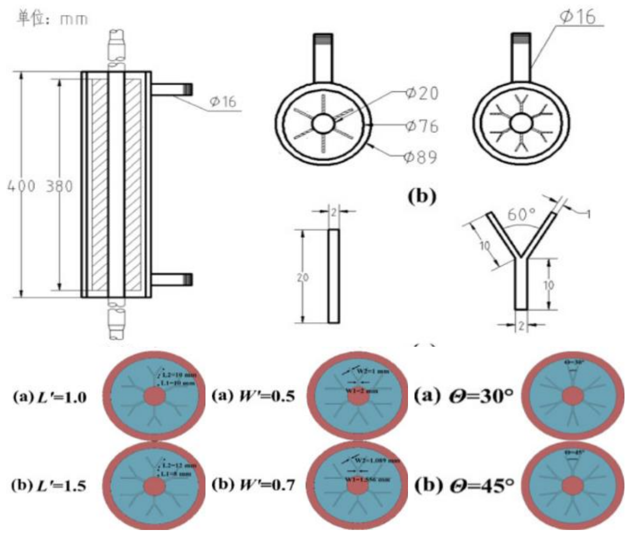

Fig. 3: Geometric representation of rectangular & fractal fins (top). Geometric representation of length ratios, width ratios and bifurcation angle (bottom).

Chen et al. [6] studied the impact circular fins in a PCM based triple tube heat exchanger on melting/solidification time. The main focus of study was to investigate the best location of fins to reach better performance by considering 5 annular fins on both inner and outer tubes. Results showed that the position of fins had big impact on melting time of PCM. The best arrangement of fins enhanced the heat transfer rate by 37.1% compared to the uniform distribution of fins shown in Fig. 4. The reason why non-uniform distribution offers better performance is because during the melting when the undergoes transformation to liquid phase, effect of convection appears which causes the circulation of molten part. Due to direction of gravity from top to bottom, the warmer liquid PCM moves in the top region causing heat transfer between this warmer PCM and solid PCM on the top part. On the other hand, since relatively colder PCM remains at the bottom, therefore it does not benefit much from the natural convection. So, the major role heat transfer in the bottom is played by conduction. This is the reason why the presence of fin in the bottom can be more effective compared to the uniform distribution.
Impact of positioning of fins was also analyzed on solidification time but since adding fins increases the surface areas for heat transfer by conduction mechanism; therefore, after the generation of solid PCM, conduction heat transfer reduces due to lower thermal conductivity of PCM. On the other hand, fins addition does not have much impact on natural convection. Therefore, the improvement in solidification time in case of non-uniform distribution compared to uniform distribution is not significant.

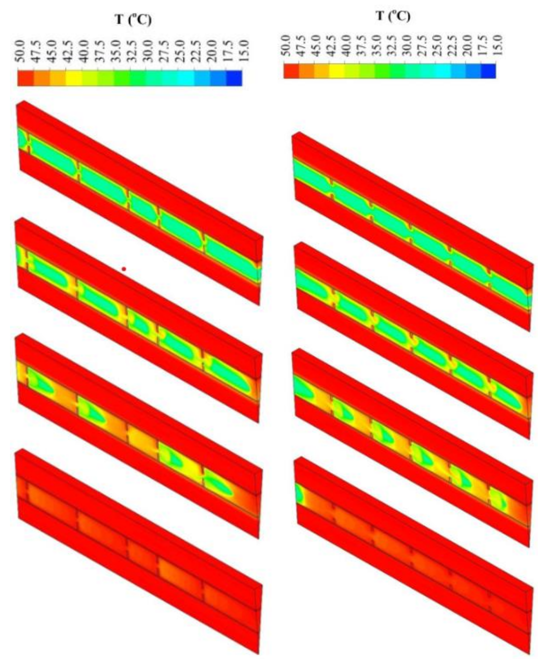

Fig. 4: Temperature profile for non-uniform (left) and uniform (right) distribution of fins.

Palmer et al. [7] evaluated different design concept of fins as shown in Fig. 5 integrated with PCM in a novel triplex-tube heat exchanger. He first simulated the melting process with no fins and analyzed the positions where the fins should be placed. As already mentioned during previous discussion, PCM usually takes longest time to melt at the bottom compared to top part of heat exchanger, therefore, all the concept geometries except 3 focused to improve the heat transfer in this region Concept 3 was rather used to strengthen his point that optimal positioning of fins is also important to improve the thermal performance by showing that concept 3 geometry performed the least. With concept 5 achieving the lowest melting time of 66 mins, results showed that compared to straight fins, curved fins concept is superior due to their profile fitting better with circular tubed TTHX.

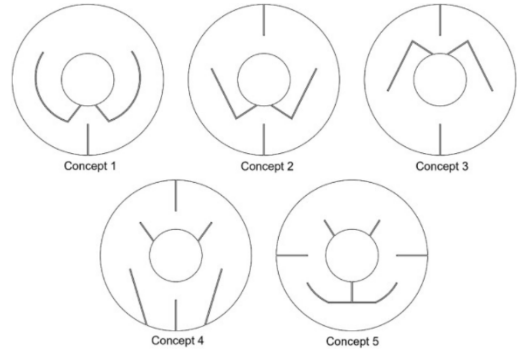

Fig. 5: Concept designs of fins.

Conclusion

Heat transfer process in PCM-based heat exchangers is limited due to poor thermal conductivity of PCMs. Many studies have been conducted to overcome this challenge. One of the promising methods is using the fins in heat exchangers to improve the overall heat transfer by increasing heat transfer area. Therefore, this synthesis essay has explored the impact of fins' geometry, spacing, and positioning on the heat transfer performance of PCM-based heat exchangers. Key findings from the reviewed studies include:

1. Heat transfer performance of the heat exchangers with fins is significantly higher compared to that with no fins.
2. Geometry plays a huge role in improving the heat transfer performance as evident from comparison of circular with longitudinal fins where longitudinal exhibits better performance and comparison of longitudinal with triangular fins where triangular showed relatively better thermal performance.
3. Considering the same geometry of fins; changing the geometric parameters of fins such as length, width and bifurcation angle can significantly change thermal performance of heat exchangers as discussed in the example fractal fins.
4. Addition of fins to heat exchangers has huge impact on melting process, as they significantly increase heat transfer rate and reduce thermal resistance.
5. There is relatively very low or insignificant impact of fins during the solidification process which is driven by natural convection currents.
6. Optimizing the fin position is another crucial factor in enhancing the thermal performance of PCM-based heat exchangers as shown by comparison of uniform with non-uniform distribution of fins and by the example of concept fins.

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