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Analysis of the heat transfer mechanisms during energy storage in a Phase Change Material filled vertical finned cylindrical unit for free cooling application

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ABSTRACT

The heat transfer performance of the Phase Change Material (PCM) used in free cooling application is low due to poor thermal conductivity. The addition of fins to enhance the heat transfer during solidification process is commonly employed, to address this. However for application such as free cooling, where the driving temperature potential is very less, the present experimental study is intended to investigate the sensible and subcooling phenomena during the outward cylindrical solidification of the PCM stored on the annulus side, along with 8 longitudinal uniformly spaced copper fins of different heights. The performance of the fins during solidification is analyzed, and the best suitable height is arrived at. The addition of fins plays a contradicting role during the sensible cooling of the liquid PCM, due to the suppression of free convection. The external cooling conditions along with the effect of the fin, vary the sensible cooling rate of the liquid PCM, that influences the subcooling effect, and also drifts the temperature at which major phase change occurs. In addition, the effects due to the inlet velocity of the heat transfer fluid, and its temperature on heat transfer are investigated and reported. The increase in velocity decreases the duration of solidification, and this effect is more pronounced towards the entry region, due to the higher local convective heat transfer co-efficient and a comparatively higher driving temperature potential.

1. Introduction

The thermal energy storage system (TES) employed in solar heaters, and refrigeration and air conditioning units acts as a thermal flywheel, to store surplus energy when the demand is less, and to deliver the same at other times. This reduces the peak demand, with the advantages of downsizing the capacity of the units, and also operating the same at the best suitable efficiency. In recent years, thermal energy storage systems have received greater research attention, in free cooling applications, to store the cool energy available in the ambient during the early morning hours, and to utilize the stored cool energy during the day time for space cooling, and in the thermal management of electronic devices. The latent heat thermal energy storage systems (LHTES) with PCMs are more advantageous than the sensible heat storage systems, due to their large storage capacity and near isothermal charging/discharging behavior.

During the phase change in the LHTES, the solid liquid interface moves away from the heat transfer surface. In this process, the surface heat flux decreases with respect to time, due to the increasing thermal resistance of the growing layer of the molten/solidified medium, as the thermal conductivity of the solidified PCM is abnormally low. The decrease in the heat transfer rate during solidification necessitates the usage of proper heat transfer enhancement techniques in the LHTES.

There are various techniques available to improve the thermal performance of the LHTES, such as the use of fin configurations, dispersion of high conductivity particles and nanoparticles, introduction of a metal matrix, and graphite compounded material. The various fin configurations used to enhance the performance of the thermal energy storage system employing PCM was reviewed by Jegadheeswaran and Pohekar [1] and Fan and Khodadadi [2]. Sparrow et al. [3] performed an experimental investigation of a finned tube using four fins, and concluded that the use of fins could delay the natural convection during the solidification process. According to the authors, the presence of fins could delay or interrupt the solidification process, and hence, was deemed undesirable. Sparrow et al. [4] investigated the freezing of a finned vertical tube, when either conduction in the solid or natural convection in the liquid controlled the heat transfer, using n-eicosane paraffin as a PCM. The authors concluded that the presence of

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fins brought an enhancement of freezing heat transfer on the tube surface between the fins. Padmanabhan and Krishna Murthy [5] studied the phase change process occurring in a cylindrical annulus, in which rectangular, uniformly spaced axial fins spanning the annulus are attached to the inner isothermal tube, while the outer tube is made adiabatic. They performed the parametric analysis, and based on the results, they suggested a working formula to obtain the volume fraction solidified at any time for this fin configuration.

Velraj et al. [6] performed an experimental and numerical analysis of the enhancement of heat transfer in a PCM storage system, consisting of a cylindrical vertical tube with an internal longitudinal fin arrangement. A theoretical model that also accounts for the circumferential heat flow through the tube wall was developed, using the enthalpy formulation, and employed in conjunction with the fully implicit finite difference method, to solve the solidification problem in a convectively cooled vertical tube. The numerical model was validated with the experimental data. Lacroix and Benmadda [7] noticed that the onset of natural convection was gradually prevented during the melting of the PCM, as the distance between the fins was decreased. It was concluded that natural convection would occur, if less number of fins were used. They also found that too large a distance between the fins led to a reduction in the total heat transfer surface area, and hence, they optimized the number of fins for a fixed size of the module. Ismail and Melo [8] developed a two-dimensional axi-symmetrical model for the formulation of the problem of the fusion of PCM around a vertical cylinder in the presence of natural convection. The model was extended to produce charts and correlations for the mean heat transfer rate, total solidification (or fusion) time in terms of the geometrical parameter, and the modified Rayleigh and Stefan numbers.

Velraj and Seeniraj [9] reported that the internal fin configuration gives the maximum benefit of the fin to the PCM, farther away from the convectively cooled surface. The necessity to include the effect of the circumferential heat flow through the tube wall for a higher value of the Biot number, in order to correctly predict the heat transfer behavior, was also emphasized. Further, for a given quantity of heat to be extracted uniformly, a combination of a lower Biot number and a higher Stefan number (within the practical range) was recommended. Velraj et al. [10] investigated three different heat transfer enhancement techniques, such as fin configuration, lessing rings and bubble agitation in a latent heat storage system, using paraffin. They compared the total solidification time and the total quantity of heat stored for the above said three configurations. They further reported that, comparing the volume fraction occupied by the fins and the lessing rings in their respective storage system, the latter contribute more volume, without a proportionate reduction in time for complete solidification. A numerical model, for the solidification of the PCM around a radially finned tube with a constant wall temperature, was developed by Ismail et al. [11]. They developed correlations for the time taken for complete solidification based on the aspect ratio, number of fins and half the phase change temperature range. Ismail et al. [12] carried out numerical and experimental investigations to model a thermal storage system, with paraffin as the PCM, for solidification around a vertical axially finned isothermal cylinder. They inferred that the number of fins, fin length, fin thickness, the degree of super heat and the aspect ratio of the annular spacing are found to influence the time taken for complete solidification, solidified mass fraction and the total stored energy. The results confirmed the importance of the fins in delaying the undesirable effects of natural convection during the phase change process. The fin thickness had a relatively lesser influence on the solidification time, while the fin lengths as well as the number of fins had strongly affected the time taken for complete solidification and the solidification rate. The aspect ratio of the annular space had a strong effect on the time taken for complete solidification.

Radhakrishnan and Balakrishnan [13] carried out an analytical heat transfer study with a surface heat flux of 500 W/m^2 and above, on the freezing of the PCM and reported that the rate of growth of the freeze thickness was rapid up to 20% of the distance from the wall, and then it slowed down due to the increased conductive resistance from the increasing solid layers. Also, the solidification time decreased with the increasing heat flux, and then remained constant beyond a heat flux of about 1000 W/m^2. An experimental study of the enhanced heat transfer in melting and solidification with 32 longitudinal fins was carried out by Stritih [14] on paraffin, whose melting temperature is 30 °C, for thermal storage applications in buildings. Time-based variations of the temperature distribution and heat flux were explained from the observations of the melting and solidification layers. The effectiveness of the fins was calculated from the quotient of the heat flux, with fins and without fins. Lamberg [15] used an approximate analytical model, to analyze the two phase solidification problem in a finned PCM storage system, and concluded that the solidification was dominated by conduction, while natural convection exists only during the beginning of the solidification process. The natural convection effect diminishes with respect to time and reaches almost zero, as compared to the effect due to conduction.

Castell et al. [16] studied the performance enhancement of LHTES during solidification, by adding external longitudinal fins to the HTF, while the PCM was stored in the inner tube. The study focused on the calculation of the heat transfer coefficient, and it was found, that the heat transfer coefficient was not increased by the introduction of vertical fins; however, the time needed to solidify the PCM decreased. When using small fins, a lower temperature difference was sufficient to achieve the same heat transfer coefficient as with no fins. When longer fins were used, there was a decrease in the heat transfer coefficient due to the dampening effect on natural convection. Agyenim et al. [17] designed an energy storage system using a horizontal concentric tube heat exchanger, incorporating erythritol as the PCM with a melting point of 117.7 °C. Three experimental configurations, a control system with no heat transfer enhancement, a system augmented with circular fins and one with longitudinal fins, were studied. They reported that the system with longitudinal fins gave the best performance, with increased thermal response during charging, and reduced subcooling in the melt during discharging.

The subcooling effect of PCM-RT 21 was studied by Solomon et al. [18] in a vertical concentric tube heat storage unit. They observed that the PCM experienced different cooling rates at different axial heights, with the highest rate near the heat transfer fluid entry region. They reported that the higher cooling rate increased the subcooling effect and lowered the solidification temperature of the PCM. The free convection observed during the liquid sensible cooling commenced the nucleation process at all the radial locations of the PCM at a particular axial height, at the same time, without much difference in the onset of the solidification temperature. Further, on increasing the radial location of the PCM from the heat transfer surface, the time span of the temperature plateau during the latent heat release increased as the heat transport rate decreased.

In recent years, cool thermal storage systems, have become very popular in large scale central air conditioning applications, where water or other PCM material in the range of −5 °C to 5 °C, are being used. Further, the concept of free cooling has gained momentum in recent years in the field of Heating Ventilation and Air Conditioning and green buildings. Since the temperature difference available for free cooling application is quite less, in the range of 3–4 °C, for both the discharging and charging sides, the subcooling, suppression of free convection in sensible cooling, and the addition of fins