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Thermal conductivity enhancement of PCMs in annular tube heat storage: A review

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Abstract: This paper reviews previous work on thermal conductivity enhancement of phase change materials (PCMs) filled in cylindrical annulus. Two aspects have been covered under this review: PCM materials, thermal conductivity enhancement techniques. The present paper reviewed the different configuration of high conductivity inserts/structures to increase heat transfer during charging and discharging of heat storage system. Different forms of thermal conductivity promoters (matrix, fins,etc.) were suggested in previous studies. The reviewed research studies covered verity of the annular PCM storage units with heat transfer enhancement.
Keywords*: *Phase change materials (PCMs), Fins, heat storage, Heat transfer

I. INTRODUCTION

Energy is the backbone of human activities. There is strong relationship between energy and economic development of any country. Scientists all over the world are in search of new and renewable energy sources to minimize the mismatch between the supply and demand of energy. Thermal energy storage systems can improve the efficiency and reliability of thermal systems based on conventional and non conventional energy sources, Thermal energy storage systems provide the potential to attain energy savings, which in turn reduce the environmental impact related to energy use. Infact, these systems provide a valuable solution for correcting the mismatch that is often found between the supply and demand of energy. Thermal energy may be stored in the form of sensible and latent heat. Latent heat storage has a high energy storage capacity per unit volume compared to sensible heat storage. PCMs have low thermal conductivity in the range of 0.1-0.7 W/m-K [1]. The present review of literature, focus on the thermal conductivity enhancement of PCMs.

II. MATERIALS FOR THERMAL ENERGY STORAGE

Thermal energy can be stored in the form of sensible and latent heat. In sensible heat storage (SHS), thermal energy is stored by raising the temperature of a liquid or solid. These systems utilize the heat capacity of the material.SHS has a low heat storage capacity per unit volume of the stored material, and heat transfer during charging and discharging also does not take place at a constant temperature. Water, rock, brick, concrete and engine oil are some of the materials that are generally used in SHS. Latent heat storage (LHS) is based on the absorption or release of latent heat at a constant temperature when a storage material undergoes a change of phase from solid to liquid, liquid to gas or vice versa. Materials used in LHS are the phase change materials (PCMs). Paraffin wax ,fatty acid, glycol's, alcohol's and esters are examples of latent heat storage materials or Phase change materials (PCMs) LHS has a high heat storage capacity due to the high value of latent heat compared to sensible heat and due to minimum heat losses from the system during charging and discharging of heat. Farid et al. [2] reviewed the LHS systems and their materials that have been used for different research applications during the last 40 years. These materials are paraffin's, non-paraffin, hydrate salts, eutectics, etc. These materials are available in temperature range from 0 ˚C to 150˚C.

III. TECHNIQUES FOR THERMAL CONDUCTIVITY ENHANCEMENT OF PCMs IN ANNULAR TUBE HEAT STORAGE

Most of PCMs have low thermal conductivity and the problem of super cooling. Low thermal conductivity leads to less effective heat transfer during charging and discharging of heat storage media. In order to improve the thermal conductivity of phase change materials, extensive investigation have been carried

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Table 1 Thermophysical properties of some PCMs used in previous research studies

Heat Storage Material	Melting Temperature (^oC)	Heat of Fusion ^oC (KJ/Kg)	Thermal Conductivity (W/mK)	Specific Heat	References
Parraffin 44	44	167	N/A	N/A	[3]
Parraffin 53	53	200	N/A	N/A	[3]
Parraffin 64	64	210	N/A	N/A	[3]
Paraffin wax	32	251	0.514 (solid) 0.224 (liquid)	1.92(solid) 3.26(liquid)	[4,5]
Paraffin wax	40-53	N/A	N/A	N/A	[6]
P116-Wax	46.7–50	209	0.277 (liquid) 0.140 (solid)	2.89 (liquid) 2.89 (solid)	[4,5]
Commercial paraffin wax	52.1	243.5	0.15	N/A	[7]
Paraffin RT60/RT58	55 to 60	214.4–232	0.2	0.9	[7,8]
Medicinal paraffin	40–44	146	2.1 (liquid) 0.5 (solid)	2.3 (liquid) 2.2 (solid)	[9]
Paraffin 56	56	72-86	0.75	N/A	[10]
Paraffin 57	57	98	0.7	N/A	[10]
Paraffin natural wax 79	79	80	0.63	N/A	[10]
Paraffin natural wax 106	106	80	0.65	N/A	[10]

out to improve the thermal response of PCM through the addition of high thermal conductivity materials. Many researchers proposed nonmoving structure like metal foam, fins, wool, graphite matrix to improve thermal conductivity of PCMs.

Abhat et al. [11] performed experimental study to evaluate the thermal performance of latent heat storage system. A finned-annulus heat exchanger, in which aluminum metal fins were positioned radially, was used as the container filled with PCM. A small test model with a length of 0.1 m that was proportionally similar to a practical system was built.Both the transient melting and freezing processes were visually investigated through the transparent covers made of Plexiglas flanges. In this experiment, eicosane, lauric acid and CaCl2_6H2O were selected as storage materials. Although the existence of fins suppressed natural convection, it is shown clearly that heat convection still occurred,especially in the upper part of the sector.Symmetric frozen interface fronts in each segment were observed during the entire solidification process suggesting dominance of heat diffusion. Ettouney et al. [12] conducted experimental

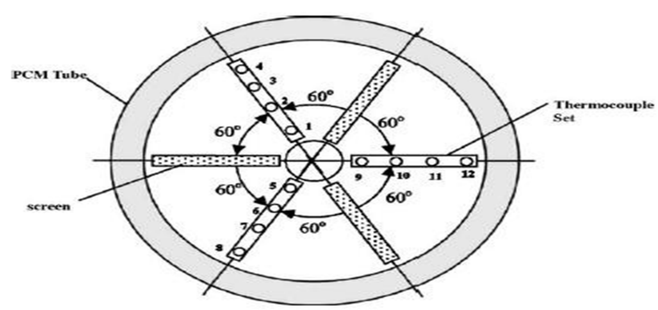

Fig.1 Cross section view of annulus of heat storage system (Ettouney et al. [12])

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study for thermal conductivity enhancement of paraffin wax within a cylindrical annulus. The metal screens and spheres of three different diameters, made of stainless steel were selected for thermal conductivity enhancement. The volume fraction of the metal screens and spheres was changed from 0.1% to 3.4%.Temperature history and progress of melt interface is predicted by 38 thermocouples. Thermocouples were mounted at three different horizontal levels inside the annulus. The comparison among the results demonstrated that the metal spheres with a volume fraction of 2% led to the best enhancement effects. Results are presented in terms of variations in the PCM Nusselt number and the melting Fourier number. Results indicate three-fold decrease in the Fourier number and similar increase in the Nusselt number.

Agyenim et al.[13] conducted an experimental study to explore the effectiveness of using radial and longitudinal fins to provide extended heat exchange area and enhanced thermal conductivity for a latent

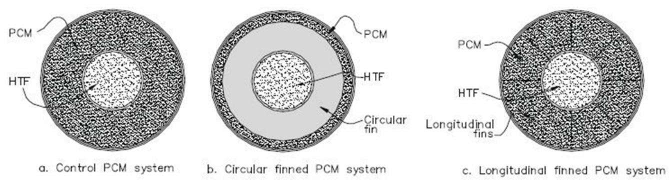

Fig.2 Control, radial & longitudinal finned Heat storage system (Agyenim et al. [13])

heat thermal energy storage unit. Erythritol, with a melting point of 117.7 ^{o}C was selected as heat storage material.The experiments were conducted for three configuration of heat exchanger:(1) a control system with no heat transfer enhancement (2) system with radial fins (3) system with longitudinal fins. The storage vessel was 1 m long,inside diameter of 146.4 mm and a wall thickness of 3 mm.HTF flow through a copper tube of 54 mm diameter.. Complete melting was achieved in the longitudinal finned system but not in the control and circular finned systems for an imposed 8-h charge time. Solidification times for control, radial & longitudinal finned system were 80,100 and 130 min respectively. Time average temperature gradient along the axial ,radial and angular directions of the PCM systems during charging was minimum for the longitudinal finned system. The system with longitudinal fins gave the best performance with increased thermal response during charging and reduced subcooling in the melt during discharging

Liu et al. [14] reported results of their experimental investigation on the melting characteristics process of stearic acid in an annulus and its thermal conductivity enhancement by fins. The unit mainly consists of an electrical heating rod and an outer tube, and the space between is an annulus that is filled with stearic acid. A new type of fin was designed and fixed to the electrical heating rod to enhance the thermal response of the stearic acid. The thermal performance of the unit is measured, and the heat transfer characteristics of the melting processes of stearic acid are studied under different heat flux conditions to determine the influence of heat flux on the melting processes. The experimental results show that the fin can improve the heat transfer of the melting process of the thermal storage unit greatly. The analysis of the experimental results shows that the enhancement mechanism of the fin is attributed to its ability to improve both heat conduction and natural convection very effectively. The influences of the fin size and pitch on the enhancement are also studied and analyzed and it is found that these two parameters can both affect the thermal conductivity enhancement significantly.It was found that by reducing the fin width there is effective enhancement of the PCM thermal conductivity.

Velraj et al [15] experimentally studied the enhancement of thermal response of a latent heat storage system. Experimental setup consists of the vertical cylindrical storage tube made of aluminium, with an outside diameter of 6 length of 60 cm. The tube is, placed inside another cylindrical vessel with 25 cm diameter and having the same height as the tube, containing water and the vessel is well insulated. In the present work three different heat transfer enhancement methods are investigated. The first enhancement technique uses internal longitudinal fins inside a cylindrical vertical storage tube containing paraffin.In the second method the tube is filled with lessing rings of 1 cm diameter which are commonly used in the chemical reactors to enhance the surface contact and the molten paraffin is poured into the tube. These lessing rings are made of steel and have a thin walled hollow cylindrical structure with a partition. A photographic view of the lessing rings is shown in Fig. 3. The molten paraffin occupies 80% of the storage volume. The heat transfer enhancement with fin configuration for storage tubes and by using lessing rings in storage tanks is appreciable, and these two methods are highly suitable for solidification enhancement.

Experimental study during solidification of vertical

Fig. 3 photographic view of the lessing rings (Velraj et al. [15])

latent heat storage, has been conducted by Sparrow et al.[16].Longitudinal fins were used as thermal conductivity promoter. Auxiliary experiments were also performed with an unfinned tube to obtain comparison data. The phase change medium was a paraffin, 99% pure *n*-eicosane, with a fusion temperature of 36.4°C. It was reported that the conduction is the controlling mode when the liquid is at its fusion temperature, whereas natural convection controls when the liquid is above the fusion. It is concluded that for conduction control, the enhancement of freezing due to finning is less than the area ratio of the finned and unfinned tubes, whereas for natural convection control, the enhancement is very nearly equal to the area ratio. It is also stated that when conduction controls, freezing continues more or less indefinitely, whereas natural convection severely retards the freezing and ultimately terminates it altogether in the vertical tube arrangement.

Lacroix [17] has presented a theoretical shell-and-tube storage test unit having annular fins externally fixed on the inner tube with the PCM on the shell-side and the HTF flowing inside the tube. The numerical results have also been validated with experimental data for various parameters like shell radius, mass flow rate and inlet temperature of the HTF. Results show that the annular fins are most effective for moderate mass flow rates and small inlet temperatures.

Padmanabhan and Krishna Murthy [18] have also studied the phase change process occurring in a cylindrical annulus in which (i) rectangular, uniformly spaced longitudinal fins, spanning the annulus (ii) annular fins are attached to the outer surface of the inner isothermal tube, while the outer tube is made adiabatic. They have performed parametric analysis and based on the results they have suggested working formulae to obtain the volume fraction solidified at any time for both the cases.

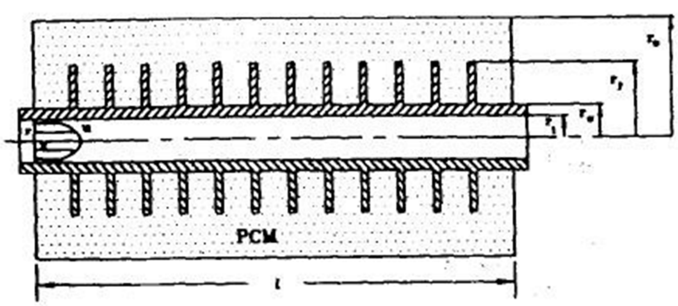

Fig 4 Diagram of PCM energy storage system with transverse finned tube [19].

Yuwen zhang and Amir faghri [19] performed numerical investigation for heat transfer enhancement in latent heat thermal storage system. Transverse fins were used as thermal conductivity enhancer. It was reported that the transverse fins is a more efficient way

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to enhance the melting heat transfer if the initial subcooling exists in the PCM. The height of the fins only have a significant effect on the melting front on the two sides of the fins, but have no significant effect on the melting front between the transverse fins. The MVF can be significantly increased by increasing the heights of fins.

IV. CONCLUSION

A review of research works on thermal conductivity enhancement of Annular PCM storage was presented. Copper, nickel, aluminum and carbon fiber was used in different form to increase thermal conductivity of PCMs. The reviewed research works focuses on: variety of PCMs, heat exchange between HTF and PCMs during charging and discharging, arrangement of heat storage system. It is concluded that due to insertion of high conductivity non moving structure, there is effective enhancement of the PCM thermal conductivity. Further research is required to improve charging and discharging time of heat storage system.

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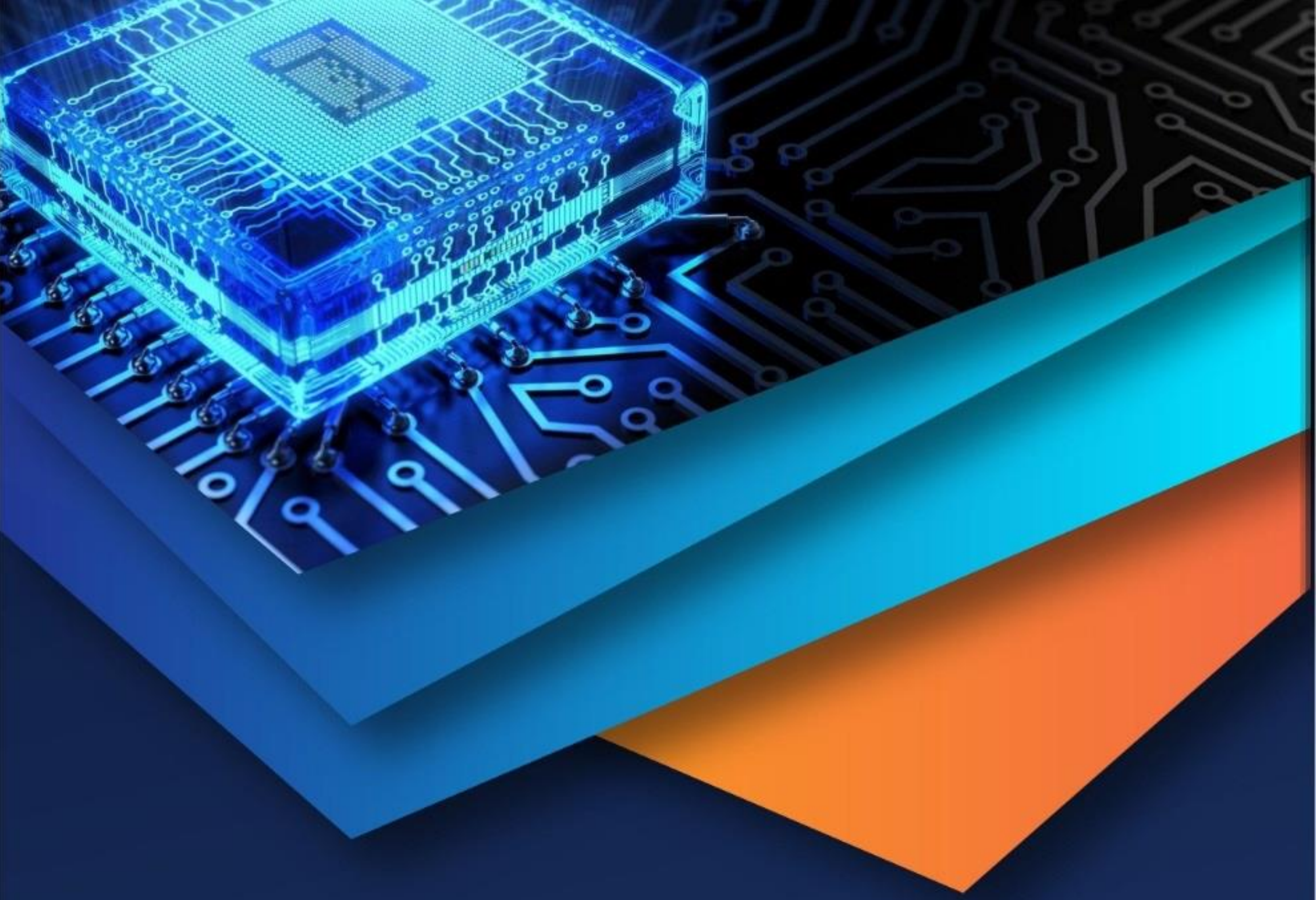

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