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Heat Transfer Enhancement by Using Nanomaterial in Phase Change Material for Latent Heat Thermal Energy Storage System

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Abstract - **Latent heat energy storage systems using paraffin wax could have lower heat transfer rates during melting/freezing processes due to its inherent low thermal conductivity. The thermal conductivity of paraffin wax can be enhanced by employing high conductivity materials such as alumina (Al_2O_3) nanopowder. In this paper the experimental investigation has been carried out to study the performance enhancement of paraffin wax with nanoalumina (Al2O3) particles in mass fraction of 1, 3, and 5% in a Latent Heat Thermal Energy Storage (LHTES) System at constant flow rate and variable temperature of heat transfer fluid (HTF). The effect of alumina nanoparticle on total cyclic time of LHTES for different mass fraction has been studied. Commercially available paraffin wax is used as a phase change material (PCM). The present results illustrate that the suspended nanoparticles substantially increase the heat transfer rate and also the nanofluid heat transfer rate increased with an increased in the nanoparticles mass fraction. The comparative results with and without nanoalumina (Al_2O_3) enhancement indicate that the charging rate of thermal energy can be greatly enhanced using paraffin wax with alumina as compared with a simple paraffin wax as PCM. The increase of the heat release rate of the nanoparticle-enhanced phase change materials shows its great potential for diverse thermal energy storage application.**

Keywords: **Latent heat, Thermal storage, Phase Change Material, Paraffin Wax, Heat Transfer Fluid, Charging Rate.**

I. INTRODUCTION

Phase Change Materials have been used in latent thermal energy storage systems for temperature control in various applications. Applications of PCM can be divided into different groups such as thermal storage for heating/cooling (of buildings, electronic goods, automobile engines, and space craft); applications in the food industries; in medical applications; waste heat recovery; heat pump systems; cool suits; and cold storage. All storage systems should have a high thermal diffusivity to ensure rapid re-distribution of the stored energy. Slow diffusion (discharging time) and slow charging rate often limit the application of PCM. Improvement ways in the heat transfer rates including; the use of finned tubes, PCM dispersed in conductive particles, use of high conductive carbon brushes, PCM infused in an aluminum metal matrix, and expanded graphite. The configuration of the storage container also plays an important role in heat transfer; it was shown that a spherical container transfers heat faster than the cylindrical and flat plate containers. It has also been shown that the thermal stability and the thermal cycling of the paraffin are not affected by the contact metal [4]. Fan and Khodadadi [9] presented a review of experimental/computational work to promote the thermal conductivity of PCM.

The performance of different types of heat exchangers used as latent heat thermal storage units has been investigated by many researchers. Zalba *et al.* [1], Sharma *et al.* [2] have reviewed various kinds of PCMs, Heat Exchangers and Applications proposed by researchers. Among the Heat Exchangers shell and tube/concentric double pipe heat exchangers have been proved as high efficient for minimum volume. Among the nanoparticle, Alumina (Al_2O_3) is one of the most common and inexpensive nanoparticle used by many researchers in their experimental investigations [3]. Following are the reviews of PCMs, Heat Exchangers, Experiments and Thermal Conductivities enhancement techniques used. Abhat *et al.* [4] has presented experimental investigation of melting & freezing behavior of different PCMs using thermal analysis and differential scanning calorimetry. Results from thermal cycling tests and corrosion investigations are presented to illustrate their importance in the appropriate choice of materials from the standpoint of the life of a latent heat store. Different stages that may be involved in the development of an LTES system and of the specialized Problems that need to be tackled are also discussed with the help of a flow chart. Velraj *et al.* [5] carried out a detailed investigation of the different heat transfer enhancement methods for the LHS system. Three different experiments to augment heat transfer were conducted and the findings are reported. In heat transfer enhancement with fin configuration for storage tubes and by using Lessing rings in storage tanks suitable for solidification enhancement. Sari and Kaygusuz [6] studied experimentally the thermal performance and phase change stability of stearic acid as a LHS material. In this study, parameters such as transition times, temperature range and propagation of the solid–liquid interface as well as the effect of the heat flow rate on the phase change stability of stearic acid as a phase change material were studied. Trp A. [7] analyzed the LHS system of the shell-and-tube type during charging and discharging. In order to provide guidelines for system performance and design optimization, unsteady temperature distributions of the heat transfer fluid (HTF), tube wall and the PCM have been obtained by a series of numerical calculations for various HTF working conditions and various geometric parameters, and the thermal behavior of the LHS unit during charging and discharging has been simulated. Waghmare and Pise [8] studied experimentally enhancement of heat transfer using high thermal conductive material in thermal storage system. Experimental investigation has been carried out in order to study melting (i.e. charging) and solidification (i.e. discharging) characteristics of paraffin as a phase change material with respect to time period with fin and without fin. Das *et al.* [10] investigated the increase of thermal conductivity with temperature for nano fluids with water as base fluid and particles of Al_2O_3 or CuO as suspension material. It has been observed that the enhancement is considerably increased for nanofluids with Al_2O_3 as well. Kim *et al.* [11] investigated high latent heat storage and high thermal conductive PCMs using exfoliated graphite nanoplatelets. Using exfoliated graphite nanoplatelets (xGnP), paraffin/xGnP composite PCMs were prepared by the stirring of xGnP in liquid paraffin for high electric conductivity, thermal conductivity and latent heat storage. It was observed that xGnP can be considered as an effective heat-diffusion promoter to improve thermal conductivity of PCMs without reducing its latent heat storage capacity in paraffin wax. Zhao et al. [12] experimentally investigated that the addition of metal foam can increase the overall heat transfer rate by 3–10 times (depending on the metal foam structures and materials) during the melting process. Sebti *et al.* [13] presented a numerical study of heat transfer enhancement during solidification in concentric cylindrical horizontal annulus through dispersion of nanoparticle. The study illustrates that the suspended nanoparticles increase the heat transfer rate and substantially decrease the solidification time. obtained numerical results were validated with available mathematical model results. It was observed that increasing nano particle volume fraction, increases the heat transfer rate then significantly reduces the total solidification time. Sinus *et al.* [14] examined experimentally the effect that graphite nanofibers (GNFs), aspect ratio and power density have on both thermal storage and solidification time of a PCM which is embedded between two sets of aluminum fins. It was shown that as aspect ratio of the thermal containment unit (TCU) increases, the difference in heat-up time between the pure and GNF-enhanced PCM also increases. This has important implications for the total usable time of the PCM during the active power state in the thermal cycle. Arasu *et al.* [15] studied numerically the effects of nanoparticle volume fraction on melting and solidification rates of paraffin wax. These are analyzed and compared for Al_2O_3 and CuO nanoparticle. Results showed that dispersing nanoparticle in smaller volumetric fractions increase the heat transfer rate. The enhancement in thermal performance of paraffin wax is greater for Al_2O_3 compared with that for CuO nanoparticles.

This paper explores the augmentation of heat transfer using Al_2O_3 Nanopowder of 20nm size with paraffin wax as a phase change material in latent thermal storage system. This study helps to design a LHTES for solar thermal application with reduction in time to charge and discharge the process. As far as the authors are aware, detailed experimental or theoretical work on LHTES System at constant flow rate and variable temperature of HTF with experimental set up presented in this study are seems to be limited and the present results with nanomaterial enhanced in paraffin wax for increasing the heat transfer rate of phase change material and reduce the charge time.

II. EXPERIMENTAL METHOD

Experimentation is done in order to get the performance of the latent heat thermal energy storage (LHTES) during Melting (Charging). Trial extended for addition of Al_2O_3 of 20 nm size and 99% pure particles is purchase from a commercial company (Nanoshel By Intelligent Material Pvt. Ltd.) are chosen as a source nanomaterial and has to added in by mass concentration 1, 3 and 5% by mass fraction of paraffin wax which is to be used as a phase change material in LHTES and observations recorded on Data acquisition is an integral part of the system.

A. Experimental Set-up

The schematic of experimental set-up is shown in Fig.1. The dimensions of the test unit and the radial and axial positions of the temperature probes are shown in Fig. 2. Temperature sensors with their axial and radial positions are given in Table I. As is shown in Figures, the test unit has a vertical concentric double pipe configuration, where the heat transfer fluid (HTF) pipe is introduced into the PCM pipe, and the PCM in the annular space. The inner and the outer pipes are made of Copper and SS-304 respectively. The HTF flows through from bottom to the top of the HTF pipe. Temperature probes of PCM are Pt100 having measuring accuracy of 0.1˚C. In the heat storage unit, four temperature probes were set up in longitudinal from the bottom (at the positions of 100, 200, 300, 400 mm), and radial direction (at the positions of 5, 14, 25 mm) from the outer wall of the HTF pipe toward the inner wall of the PCM container in order to measure the temperature field in the PCM. Additional measurements include the temperatures of the inlet and outlet HTF temperatures. Insulation of asbestos rope is wounded to prevent heat loss from the system to the surroundings. The mass flow rate of HTF is measured by a calibrated flow meter with a measuring accuracy of 0.01 kg/s.

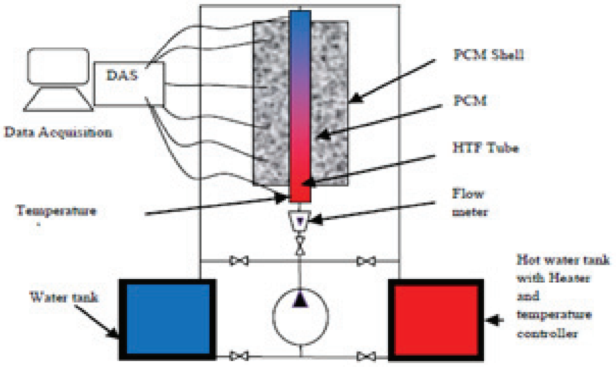

Fig. 1 Schematic of experimental setup

Insulated hot water tank with temperature controller to provide HTF to the test unit. Cold water tank of the same size provided as well. Two industrial heaters are in combination with temperature controller are fixed in hot water tank. One pump to circulate hot water and cold water in the test unit along with necessary piping. Data acquisition is an integral part of the system.

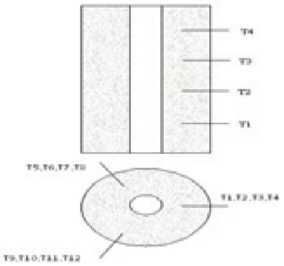

Fig. 2 Sectional views of test unit

TABLE I TEMPERATURE SENSORS POSITIONS

Temperature sensor	Axial Position from bottom, mm	Radial Position, mm
T1	100	5
T2	200	5
T3	300	5
T4	400	5
T5	100	14
T6	200	14
T7	300	14
T8	400	14
T9	100	25
T10	200	25
T11	300	25
T12	400	25

B.Experimental Procedure

Operation of the system for the first time involved loading of solid chunks of the PCM (3.0 kg) in the PCM container. The system is heated to a high temperature of 90 °C to allow for melting of solid pieces. The melting run was started at room temperature, where the PCM is in the solid phase. Throughout melting run, the hot HTF with a constant mass flow rate and temperature over the melting range of the PCM was passed into the HTF pipe. The melting process was finished as soon as all the radial temperatures were above the melting temperature range. Temperature data were recorded at intervals of 1 min. The solidification period was initiated directly by passing the cold HTF into the HTF pipe at a constant mass flow rate and temperature below the solidification range after completing the melting process. Temperature distributions in the PCM and the inlet and outlet temperatures of the HTF were measured and recorded in the same way as in the melting period. Melting and solidification processes of the PCM were repeated at different initial HTF temperatures and mass flow rates.

C.Thermophysical Properties of PCM and HTF

The Differential Scanning Calorimetry (DSC) provides quick and reliable results in the form of Energy-Time diagrams (Thermograms) using very small quantities of the sample (1-10 mg). Thermogram of Paraffin of 1 mg is shown in Fig. 3 containing peak, onset and endset temperatures. DSC analysis of Paraffin shows that the material taken as PCM in this study is suitable for medium temperature application.

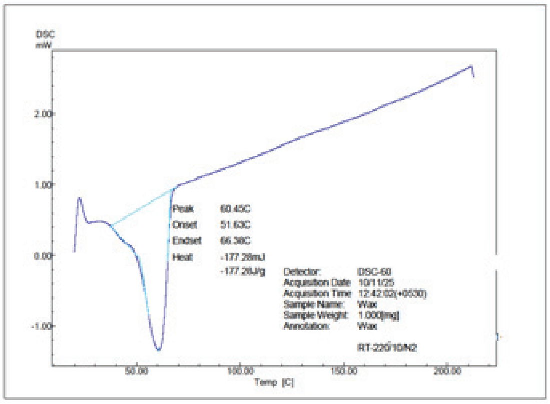

Fig. 3 DSC Thermogram of sample Paraffin

Values are as follows: Peak temperature is 60.45 ˚C, Onset temperature is 51.63 ˚C and Endset is 66.38 ˚C. Latent heat of PCM is 177.28 kJ/kg. Here phase change does not occur at one temperature which was expected. Further observe that there is no effect of thermal cycling on the properties of PCM. Water is the HTF whose properties are standard. Specific volumes of liquid PCM and Solid PCM measured. These values are different as phase changes. This is one of the reasons of selecting shell vertically instead of horizontal. When PCM becomes solid total volume reduces and upper portion of the shell is free from PCM. During solidification of PCM, relatively cold water flows through tube. Solidification of PCM starts near to surface of tube and then it proceeds towards inner portion of outer tube.

TABLE II THERMOPHYSICAL PROPERTIES OF PARAFFIN WAX

Property	Value
Density of liquid PCM	870 kg/ m^3
Density of solid PCM	960 kg/ m^3
Cp (solid/liquid)	2000 J/kg K
Onset temperature	51.63 °C
Latent heat of fusion	177 kJ/kg
End set temperature	51.63 °C
Peak temperature	60.45C

III. RESULTS AND DISCUSSION

In order to establish thermal behavior of the PCM, several experiments were performed at various initial temperatures and constant mass flow rate of the HTF. Only some temperature data, which exhibit obviously the melting behaviors, are considered here. Due to symmetrical geometry and symmetrical boundary conditions, symmetrical temperature distributions inside the PCM has been considered. Thermal behavior of PCM.

Experiments are conducted for the concentric cylinder geometry. For this geometry, it is observed that PCM in the lower outer region of the annulus take much longer times than the other regions to melt. Therefore, the total melting time of the whole PCM prolongs. Melting starts in the lower region of the storage container close to the inner wall and, then, molten PCM ascends to the top part of the storage container as a result of natural convection currents. The melt region extends radially upward (i.e. boundary layer develops along the inner wall). This type of melt region extension leads to a shape of truncated conical annulus at the intermediate steps of melting. In order to have a better view on the melting characteristic of the PCM the without enhancement of nanomaterial at 90^{0}C (Stefan's No= 0.3610) and 85^{0}C (Stefan's No= 0.3050) variation of the temperature with respect to time period for charging is shown in fig. 4 and fig. 5 at different times.

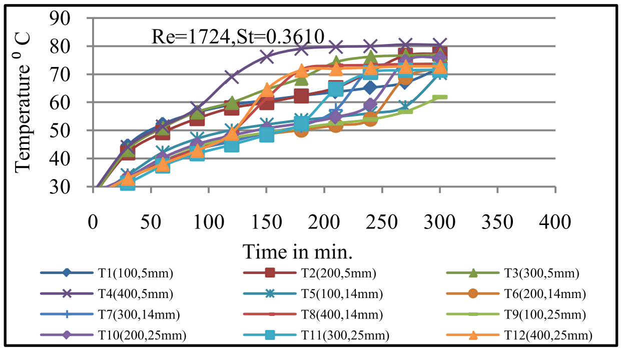

Fig. 4 Charging process without Nanomaterial at St=0.3610

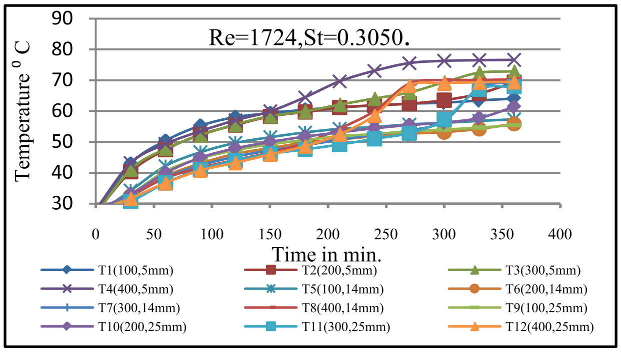

Fig. 5 Charging process without Nanomaterial at St=0.3050

With an increase in time, PCM goes through heating of the solid matrix due to conduction, melting, and heating of the molten PCM to temperatures above its melting point. As seen and expected, higher temperatures are observed near the HTF tube surface as a result of immediate melting of the PCM. Flow in the melt region is driven by buoyancy forces.

With addition of an 1% nano alumina by mass concentration in PCM and at constant flow rate of HTF a better view on the melting characteristic of the PCM the axial and radial variation of the temperature is shown in fig. 6 and fig. 7 at different times.

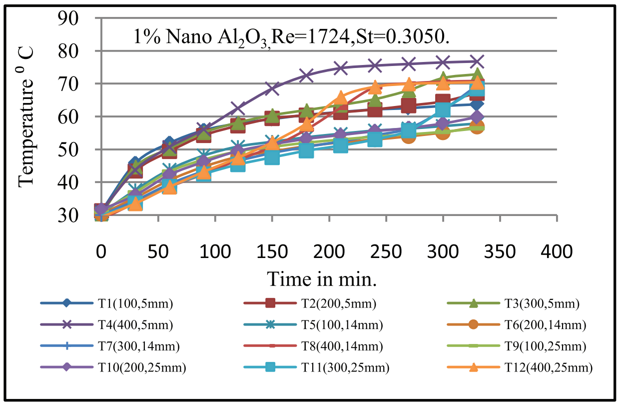

Fig. 6 Charging process with 1% Nanomaterial at St=0.3050

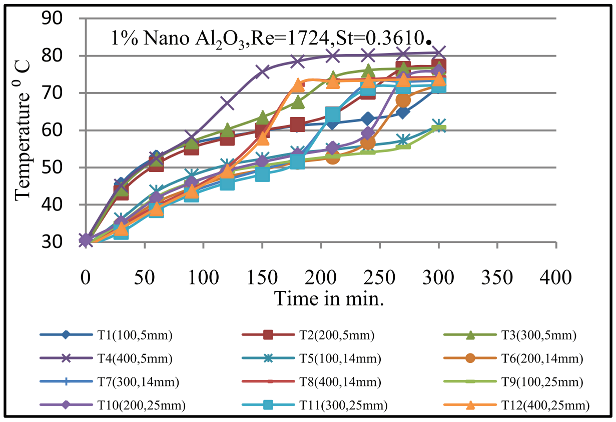

Fig. 7 Charging process with 1% Nanomaterial at St=0.3050

The melting (Charging)rate of nanoparticle enhanced paraffin wax is examined for various mass concentrations viz. 1%, 3% and 5% of Al_2O_3 nanoparticles. The time evolution of melting of paraffin wax without and with nanoparticles is shown in Fig. 8 and Fig. 9. The total melting time is defined as the time required for all the points inside the PCM to reach the upper limit value of melting temperature range from the identical solid state temperature. Table no. III and Table no. IV indicates time required to Melt PCM at different locations for without & with Nanomaterial at 85^0C (St=0.3050) and 90^0C (St=0.3610) HTF respectively in LHTES gives an idea about time required to melt PCM at different locations.

It is expected that additional nanoparticle into paraffin wax enhances the heat transfer performance; this is indeed the case for low nanoparticle concentration of 1%, as can be inferred from Fig. 8 and 9. It is noted that the nanoPCM melts faster only marginally by 5% and 3% for 1% Al_2O_3 respectively, compared to that for pure paraffin wax (Figs. 5 and 6). This exemplifies the enhancement, albeit small, in the thermal conductivity of paraffin wax with Al_2O_3 nanoparticle]

Table III Time Required to Melt Pcm at Different Locations For Without & With Nanomaterial At 85^0C HTF in Lhtes

Thermocouple	With out Nano	With 1% Nano	With 3% Nano	With 5% Nano
T1	60	52	53	50
T2	77	65	70	63
T3	76	59	55	56
T4	67	52	48	43
T5	127	109	101	92
T6	187	155	145	139
T7	203	166	153	145
T8	186	143	132	127
T9	169	132	119	107
T10	152	128	116	111
T11	224	186	173	164
T12	196	138	131	129

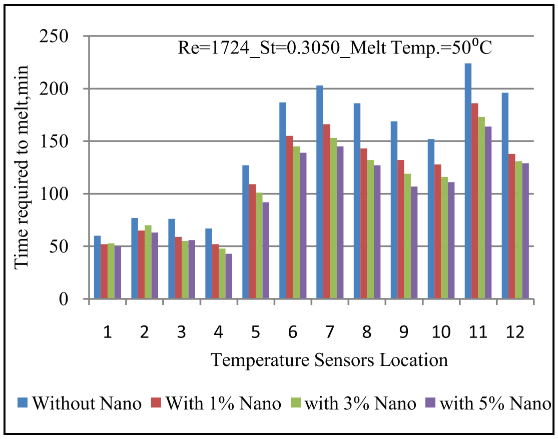

Fig. 8 Melting Process time Without & with Enhancement of Nanomaterial in Paraffin Wax at St=0.3050

From the foregoing analysis, it is found that 1% volumetric concentration of nanoparticle enhances the performance of paraffin wax compared to higher concentrations.Intuitively, adding larger amount of nanoparticle in the PCM enhances thermal conductivity; however, care has to be taken as it also increases the friction factor (viscosity), reduces the available latent heat of PCM and may reduce the stability of nanoPCM due to agglomeration and sedimentation. Thus, selecting a proper nanoparticle material and its concentration is essential to improve heat transfer performance of PCM in term melting process.

IV. Conclusion

In the present work an experimental investigation has been carried out in order to study melting (i.e. charging) characteristic and estimate the effect on thermal performance of paraffin wax due to the enhancement in thermal conductivity using alumina (Al_2O_3) nanoparticles of paraffin as a phase change material.

Table IV Time Required to Melt PCM at Different Locations For Without & With Nanomaterial at 90^{0}C HTF in Lhtes

Thermocouple	Without Nano	With 1% Nano	With 3% Nano	With 5% Nano
T1	52	47	44	42
T2	67	56	51	49
T3	57	52	43	56
T4	55	50	41	49
T5	121	110	104	97
T6	176	157	149	138
T7	162	153	145	157
T8	125	118	113	125
T9	164	138	123	115
T10	142	128	125	119
T11	165	161	156	150
T12	125	123	116	110

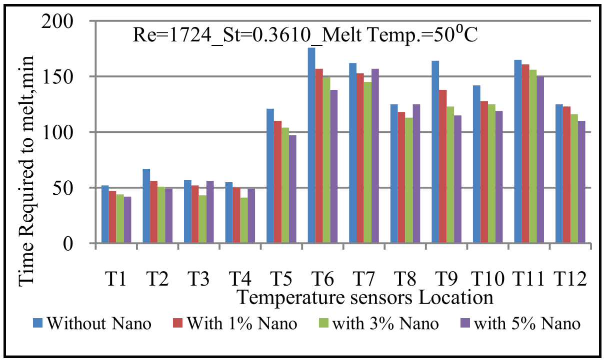

Fig. 9 Melting Process time Without & with Enhancement of Nanomaterial in Paraffin Wax at St=0.3610

1. The effect of mass concentration of the nanoparticles on the melting performance is examined and compared between with and without enhancement of nanoparticles.

2. From the present study it has been confirmed that the thermal performance of paraffin wax is enhanced only marginally with the dispersion of Al_2O_3 nanoparticles. The overall performance of melting process of paraffin wax is better for lower concentration of nanoparticles.

3. Melting started in the below region close to the wall of the inner tube and then molten PCM ascended to the top part of the PCM container as a result of natural convection currents.

4. With enhancement of nano alumina (Al_2O_3) in PCM by mass concentration of 1,3 and 5% reduces approximately 20, 25, 29% at 85^{0}C HTF temperature and 8, 14, 14% at 90^{0}C HTF temperature time to melt (Charging) the PCM.

5. Phase separation layer works as a barrier to transfer heat. To break it, enhancement of heat transfer in PCM is required.

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