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Experimental investigation for the optimization of heat pipe performance in latent heat thermal storage †

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Abstract

We investigated the optimum performance of heat pipe in Latent heat thermal energy storage (LHTES), and compared it with copper pipe. Classical plan of experimentation was used to optimize the parameters of heat pipe. Heat pipe fill ratio, evaporator section length to condenser section length ratio i.e., Heat pipe length ratio (HPLR) and heat pipe diameter, was the parameter used for optimization, as result of parametric analysis. Experiment with flow rate of 10 lit./min. was conducted for different fill ratio, HPLR and different diameter. Fill ratio of 80 %, HPLR of 0.9 and heat pipe with diameter of 18 mm showed better trend in charging and discharging. Comparison between the storage tank with optimized heat pipe and copper pipe showed almost 186 % improvement in charging and discharging time compared with the copper pipe embedded thermal storage. Heat transfer between Heat transferring fluid (HTF) and Phase change material (PCM) increased with increase in area of heat transferring media, but storage density of storage tank decreased. Storage tank with heat pipe embedded in place of copper pipe is a better option in terms of charging and discharging time as well heat storage capacity due to less heat lost. This justifies the better efficiency and effectiveness of storage tank with embedded optimized heat pipe.

Keywords: Latent heat thermal energy storage (LHTES); Phase change material (PCM); Heat pipe; Optimization of heat pipe; Fill ratio

1. Introduction

A time-dependent energy resource relies on appropriate energy storage method to reduce the time and rate mismatch between supply and demand. Solar radiation is a time-dependent energy source with an intermittent character, hence sophisticated design of an effective heat storage device is needed. Latent heat thermal energy storage (LHTES) has been researched extensively relative to Sensible heat thermal energy storage (SHTES) and Chemical thermal energy storage (CTES). LHTES is in the developmental phase, but these types of systems are not in commercial use as much as SHTES systems because of the poor heat transfer rate during heat storage and recovery processes. The main reason is that during phase change, the solid-liquid interface moves away from the convective heat transfer surface due to which the thermal resistance of the growing layer of solidified Phase change material (PCM) increases, thereby resulting in poor heat transfer rate.

A barrier to the development of large scale LHTES is the low thermal conductivity of most PCMs; most of the previous research regarding LHTES has focused on reducing the thermal resistance posed by the PCM. Velraj et al. [1] incorporated Lessing rings within the PCM and observed increased heat transfer rates from the PCM to a coolant and reduced solidification time. Concluding fins also reduce total solidification times by approximately 75 % based upon the predictions of a numerical model. Similar results have been reported by Balikowski and Mollendorf [2]. Sparrow et al. [3] showed that small fins can triple the amount of PCM that freezes about a cold tube. Agyenim et al. [4] demonstrated that faster PCM heating can be achieved by increasing the number of heat transfer tubes embedded in a PCM. Although the preceding approaches increase heat transfer rates in LHTES systems, they all occupy volume within the PCM storage vessel.

A heat pipe is a two-phase device that allows heat to be transported over a certain length with very little temperature difference, at great speed, and is often referred to as a superconductor. The idea of the heat pipe was first suggested by Gauler in 1942 and later by Grover in the early 1960s who suggested remarkable properties of the heat pipe and serious development work took place. The usage of heat pipes for

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industrial processes was presented by Pereira [5]. The study of incorporation of heat pipes with LHTES is of considerable interest. Heat pipes may increase heat transfer rates to or from the PCM, while maintaining small temperature differences between the PCM and HTF. Faghri holds two US patents that describe the use of miniature heat pipes in small LHTES modules [6, 7]. Experimentally, Lee et al. [8] developed a low temperature LHTES system operating with a variety of PCMs that utilized a two-phase thermosyphon operating with ethyl alcohol as the working fluid. LHTES, with copper-water heat pipes embedded within a rectangular PCM enclosure was developed and tested by Liu et al. [9], Shabgard et al. [10], Tardy et al. [11], Robak et al. [12] and Sharifi et al. [13] showed improvement in both melting and solidification.

ElGhnam et al. [14] studied the effect of parameters like the size and material of the spherical capsule, the volume flow rate and temperature of the HTF on the time for complete charging/discharging. Wang et al. [15] saw the effect of evaporation section and condensation section length on thermal performance of flat plate heat pipe. Prasher [16] put forward a conduction based model to assess the heat transport capability of heat pipes and vapor chamber for various configurations. Tan et al. [17] introduced an analytical approach to study the liquid flow performance inside the wick structure of a flat plate heat pipe under different heat source conditions. Koito et al. [18] investigated heat transfer characteristics of heat sinks with flat plate heat pipe. Thuchayapong et al. [19] analyzed the effect of capillary pressure on performance of a heat pipe using numerical approach with FEM. Gui et al. [20] investigated the influence of void ratio on thermal performance of heat pipe receiver. Patil and Ladekar [21] experimentally investigated LHTES using embedded heat pipes in comparison with LHTES with embedded Copper Pipes. LHTES with embedded heat pipe is found to be more effective that LHTES with embedded copper pipe. Shandilya and Ladekar [22] tested performance of LHTES experimentally with use of PCM of different grades and found charging and discharging time decrease with PCM with low melting point, but at the same time the storage capacity decreases also LHTES with embedded heat pipe is found to be more effective that embedded copper pipe. Ladekar et al. [23] critically reviewed all the parameters of heat pipe for its effect on heat transfer in LHTES and suggested suitable materials for LHTES. Chan et al. [24] reviewed diverse types of heat pipes, types of wicks, working fluid and emphasis that all these topics are relevant to the improvement of heat pipe performance. Tsai et al. [25] developed dynamic test method for determining the thermal performances of heat pipes and tested the effect bending angle, fill ratio and shape of pipe. Comparison between the steady-state test and the dynamic test are found to be remarkably analogous. Ladekar et al. [26] investigated effect of heat pipe fill ratio and found significant effect on performance of heat pipe embedded in latent thermal energy storage.

However, no such literature is reported so for which has attempted to optimize major parameters of heat pipe using systematic way of experimentation for enhancing LHTES performance.

Table 1. Heat pipe test parameters with its range.

Parameter	Iteration 1	Iteration 2	Iteration 3
Fill ratio	80 %	100 %	120 %
Ratio of heat pipe evaporator section length to condenser section length (Le /Lc) (HPLR)	0.9	1	1.1
Diameter of heat pipe (D)	14 mm	16 mm	18 mm

2. Experimental design

2.1 Design of experimentation

Design and selection of heat pipe components is based on the literature review and plan of experimentation. Classical plan of experimentation was used to design the experimentation. Number of variable were studied for their effect on the performance of heat pipe from the literature and segregated as dependent and independent parameters. Dimensional analysis using Bucking Π theorem was performed and grouped in the dimensional groups for optimization of rate heat transfer though the heat pipe.

The internal volume of the heat pipe is fixed, when the heat pipe is operated, the sum of the liquid and vapor volume is fixed; therefore, the fill ratio is the ratio of mass of liquid filled in the heat pipe to the designed value of mass of liquid to be filled in the heat pipe. The ability to reach uniformity of temperature of a heat pipe is mainly affected by the instant heat and mass flow rate of the working fluid. A higher heat and mass flow rate of vapor would lead to a faster response of the condensation section, and a higher mass flow rate of condensate would cool the evaporation section more efficiently. As can be conjectured, if the vapor tunnel is blocked or shrunk, it would be harder for the vapor to flow to the condensation section, and easier for the instant vapor flow rate to attain maximum. Besides, the instant flow rate of working fluid is also limited by the fill ratio of working fluid. The production rate of vapor would no longer be increased if there were no more liquid working fluid to absorb the heat.

Three parameters were chosen for test: Fill ratio, HPLR, and diameter of heat pipe. Every time, the performance of the test run was compared with the result of copper pipe. Heat pipe parameters are listed in Table 1 variables with their value.

2.2 Design of experimental setup

Setup was designed, considering need for of hot water for a small family of five persons (i.e., 100 ltr/day), at an temperature of 45 °C for various purposes of domestic use such as bathing, cloth washing, dish washing etc. Average inlet temperature of water was 35 °C as per the Pune average water temperature and average hot water temperature through Flat plate collector (FPC) was considered to be maximum 70 °C. Amount of energy storage required to get outlet temperature (required) of 45 °C considering losses was calculated as 4187 kW/day using below correlation.

$$Q_r = m_r C_p \Delta T \ . \tag{1}$$

For designing of capacity of collector considering inlet water temperature of 35 °C and maximum outlet water temperature of 50 °C (required water temperature is 45 °C). Quantity of water required was calculated as 66.6 kg/day. FPC of 100 ltr./day was selected with collector efficiency of 60 %. Considering 10 % losses Q_C found to be 5709 kW/day as per the Eq. (2).

$$Q_C = m_C C_p \Delta T \ , \tag{2}$$

where Q_r and Q_C is amount of energy required and amount of energy collected in the storage tank, m_r and m_C is mass flow rate required and collected in the storage tank. C_p is specific heat of water and ΔT is the temperature difference between inlet and outlet temperature of storage tank.

Considering maximum storage temperature of 70 °C, mass of water required to store was 39 ltr. and storage tank was designed accordingly. To store required amount of energy with minimum loss, LHTES tank required amount of PCM was calculated as 20 kg using heat stored in three different phases of PCM (Solid sensible, latent and liquid sensible).

$$Q = mC_{sp}(T_m - T_i) + a_m L_{pcm} + C_{lp}(T_f - T_m) \tag{3}$$

Table 2. Design specifications.

Material of storage tank	Stainless steel
Length of storage tank	466 mm
Diameter of storage tank	233 mm
Insulation used	Glass wool
Thickness of insulation	50 mm

Table 3. Thermophysical properties of PCM.

Melting temperature of PCM	50 °C
Density of PCM (Liquid phase)	775 kg/m^3
Specific heat of PCM (Solid phase)	2.384 kJ/kg °C
Thermal conductivity	0.15 W/m k
Prandtl no.	1001.23
Latent heat of fusion	184.48 kJ/kg
Density of PCM (Solid phase)	833.60 kg/m^3
Specific heat of PCM (Lq. phase)	2.44 kJ/kg °C
Viscosity	6.3*10^{-3}
Thermal expansion coefficient	7.14*10^{-3}
Kinematic viscosity	8.31*10^{-5} m^2/sec

Where m is the mass of PCM, C_{sp} is specific heat of PCM in solid phase, a_m is the mass fraction of PCM and C_{lp} is specific heat of PCM in liquid phase, L_{pcm} is latent heat of PCM.

Insulation for the tank was designed accordingly and design outcomes are shown in Table 2. PCM was selected as per design requirement, and thermophysical properties of PCM are tabulated in Table 3.

For effective heat transfer from Sensible heat storage (SHS) of the tank to latent storage of the tank, the heat pipe and copper pipes rewe designed. Design specifications of heat pipe and copper pipe are given in Table 4.

For rate of heat transfer inside heat pipes is given as in Eq. (4)

$$Q = \mu h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/4} , \tag{4}$$

where μ is the dynamic viscosity of fluid in heat pipe, hfg is the enthalpy of working fluid, ρl and ρv is the density of fluid in liquid and vapor phase, respectively.

2.3 Construction details of experimental setup

To evaluate the performance of the proposed LHTES device, an experimental system was set up. The main components of the experimental setup are as shown in Fig. 1 and the schematic explanation of the operation is shown in Fig. 2.

Setup consisted of an FPC, two LHTES tanks. These LHTES tanks consisted of two compartments: upper was Latent heat storage (LHS) and bottom was SHS. Both the LHTES tank were of 300 mm*550 mm (Internal) made of stainless steel with capacity of about 36 liters, 18 liters was stored in LHS with PCM and the remaining half was stored in water in sensible form. Third tank was SHS tank; this SHS tank was built in with the setup to test the performance of LHTES over SHTES and to test the heat losses. Out of two LHTES, one LHTES was with copper rods, and the other had heat pipes. It housed the PCM and copper/heat pipes and allowed for heat transfer between the copper /heat pipes inserted half inside PCM and half in water. Copper plate of 10mm thickness and 300 mm diameter separated the compartment

Table 4. Design specification of pipes.

Parameters	Heat pipe	Copper pipe
No. of pipes	7	7
Length of pipe	500 mm	500 mm
Diameter of pipe	16 mm	16 mm
Thickness	2 mm	Solid
Material of pipe	Copper	Copper
Thermal conductivity	-	380 W/m K
Mesh	Wired mesh	--
Working fluid	Distilled water	--

Fig. 1. Actual photograph of experimental setup.

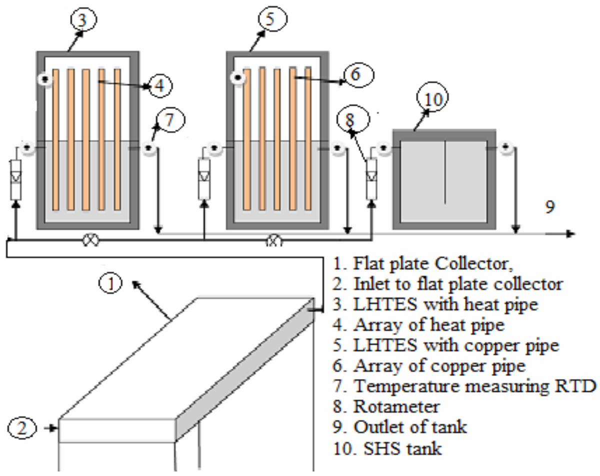

Fig. 2. Schematic diagram of experimental setup.

between SHS and LHS. Copper/heat pipe 7 in number was arranged in the same fashion. One pipe was placed at the center and remaining six at the radial distance of 200 mm. All six pipes were equidistant and equiangular with the central pipe. Glass wool insulation of 50 mm thickness with density 48 kg/m^3 was provided with an aluminum cladding externally.

Four RTDs were provided on each LHTES tank and two on SHS tank. RTDs were located at four different locations in the LHTES tanks. One RTD was at radial 100 mm from center and axial 180 mm from bottom of LHS, Second RTD radial was 250 mm from center and axial 350 mm from bottom of LHS, third and fourth RTD at inlet and outlet of SHS. This arrangement was the same for both LHTES. Two RTDs were provided at the inlet and outlet of third SHS tank. Care was taken while placing RTDs so that it would not touch the pipes.

The flow rate of the HTF through the system was measured using a rotameter. Water level indicator with solenoid valve was provided and pipe with proper insulation was used to minimize the intermediate heat loss. The orientation of the flat plate collector was in south-west direction. The PCM used in the Tank was industrial grade granulated paraffin wax with a melting point range of 50-55 °C and water was used as the HTF. RTD inputs which were calibrated were used on each tank. Good quality temperature indicator was used for recording temperatures of the PCM and the HTF. All thermocouples were calibrated and the estimated thermocouple error was ±0.1 °C. Rotameter was calibrated for correctness and estimated mass flow error with 4 %. As will become evident, temperature differences were utilized for data reduction, and to minimize bias error all thermocouples were constructed from the same spool of wire. Thermocouple voltages were measured using a calibrated temperature indicator manually with error ±0.1 °C.

An uncertainty analysis for the experimentation was carried out. Uncertainty in the experimental measurement in the HTF temperature change (from the inlet to the exit of the LHTES) was calculated using the sequential perturbation method [27], yielding uncertainties between ±6 and 10 % of the measured temperature difference. To quantify the uncertainty in charging and discharging rates, reproducibility trials were conducted for both charging and discharging experiments, from which 90 % confidence intervals were calculated using small-sample statistics.

3. Experimental procedure

3.1 Test trial

To test the performance of heat pipe in the LHTES from the parametric analysis, three parameters were chosen: Fill ratio, heat pipe length ratio, and diameter of heat pipe.

During every trial before start of experimentation, the setup was tested for leaks. The storage unit was filled with molten paraffin and hot water passed through the coil till the PCM in the storage unit melted. When the complete fusion of PCM was reached, the solidification process was initiated by passing cold water into the pipe of heat exchanger. Trial experimental run was conducted and test result was validated. Experimentation was carried for charging and discharging separately and observations were recorded manually.

3.2 Charging and discharging

Charging process trial conducted during sunshine for 3 hrs. continuously from 11.00 am to 2.00 pm and repeated several times. HTF was circulated through the Thermal energy storage (TES) tank and the solar collector unit continuously. After complete melting was achieved, further heat addition from the HTF caused the liquid PCM sensible heat storage. The charging process continued till the PCM and the HTF attained thermal equilibrium. Discharging process was conducted with covering on FPC. Using bypass a certain quantity of hot water was withdrawn from the TES tank and mixed with cold water to obtain a nominal temperature of 45 °C to 50 °C for direct use and the tank was refilled with cold water to maintain a constant amount of water in tank. This was then repeated for

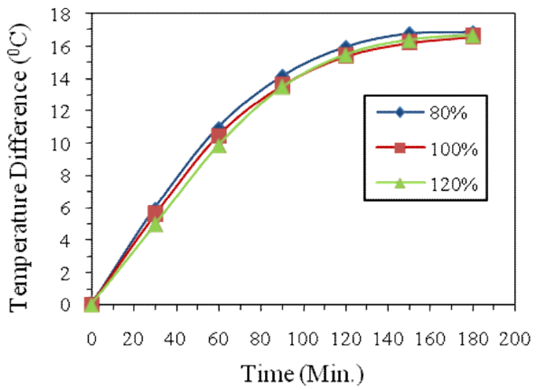

Fig. 3. Response of temperature difference at different fill ratios in heat pipe embedded LHTES during charging.

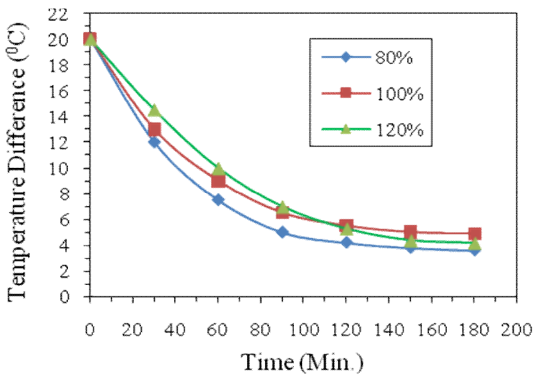

Fig. 4. Response of temperature difference at different fill ratios in heat pipe embedded LHTES during discharging.

intervals of 10 minutes several times. Volume flow rate of 10 ltr./min. was kept constant [21]. Results were reported in terms of temperature difference to take care of differences in environmental and inlet temperature of water. Trial 1 was for fill ratio 80 %, trial 2 for fill ratio of 100 % and trial 3 for fill ratio of 120 %. Similar trials were conducted for different HPLR (0.9, 1 and 1.1) and for heat pipe of different diameters (14 mm, 16 mm, 18 mm). Test specimens were manufactured as per the design and tested for their dimensions.

4. Results and discussion

4.1 Effect of fill ratio on charging and discharging

The temperature history of the storage tank with heat pipe at different fill ratio (80 %, 100 % and 120 %) was recorded during charging and discharging. Figs. 3 and 4 represent the variation of temperature difference with time for different fill ratio in heat pipe during charging and discharging of storage tank, respectively. HPLR = 1 and diameter of 16 mm were fixed for the trial on different fill ratio (80 %, 100 %, 120 %). Result reported for charging and discharging during different fill ratio indicates that the charging and discharging is faster for fill ratio of 80 % compared to 100 % fill ratio and 120 % fill ratio.

Charging time required for preheating PCM from 35 °C to

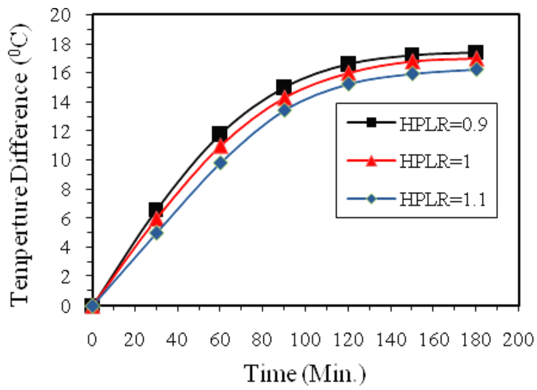

Fig. 5. Response of temperature difference at different HPLR in heat pipe embedded LHTES during charging.

50 °C for fill ratio of 100 % and 120 % is almost the same and is approximately 120 min, whereas for 80 % fill ratio during charging for preheating of PCM from 35 °C to 50 °C was 105 min. The time required for charging for the fill ratio of 100 %, 120 % was approximately same, whereas for 80 % fill ratio it was less.

During discharging with 80 % fill ratio discharging time for cooling PCM in liquid sensible phase from 65 °C to 50 °C took 90 min as compared to 100 % and 120 % fill ratio, which took 110 min for both fill ratios approximately.

For the specific application of the heat pipe in transferring the heat in PCM, the condenser section heat transfer rate depends on the convective heat transfer between the walls of condenser section and surrounding PCM properties as well the geometrical parameters of the condenser section. A higher vapor temperature at the condenser will enhance the rate of heat transfer. Increasing the fill ratio beyond a certain design value will lead to chocking condition and will not change the performance compared to 100 % fill ratio. Decreasing the value of fill ratio will maintain higher temperature of vapor flow, such that vapor flow and condensate flow will be properly balanced and dry out situation will be avoided. This needs further investigation for critically optimized fill ratio for specific application.

4.2 Effect of evaporator and condenser section length of heat pipe

Heat pipe with fill ratio of 80 % and diameter of 16 mm was selected for optimization of HPLR according to design of experimentation. Heat pipe was tested for its performance using HPLR = 0.9, HPLR = 1, HPLR = 1.1 (Heat pipe with evaporator length of 250 mm and condenser length 250 mm was called as HPLR = Le/Lc = 1) by dipping in the SHS and LHS tank. The temperature history of storage tank was recorded during charging and discharging process. Figs. 5 and 6 represent the variation of temperature difference with time for different HPLR in heat pipe during charging and discharging of storage tank, respectively.

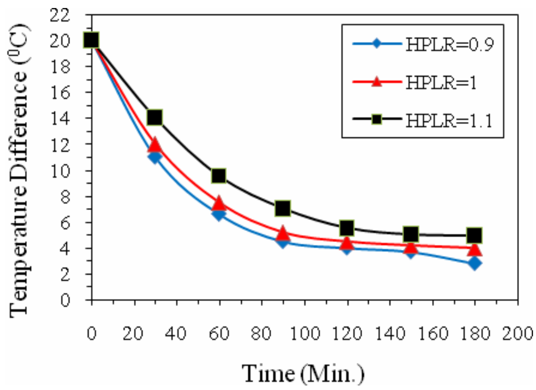

Fig. 6. Response of temperature difference at different HPLR in heat pipe embedded LHTES during discharging.

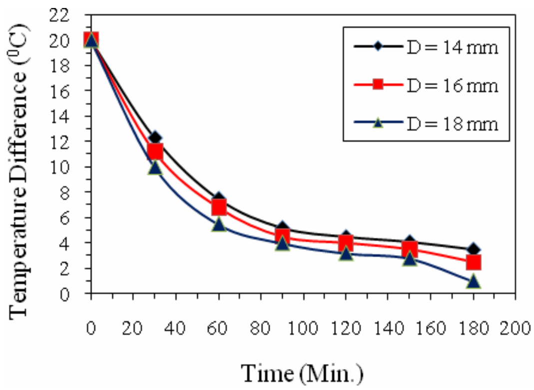

Fig. 8. Response of temperature difference with diameter in heat pipe embedded LHTES during discharging.

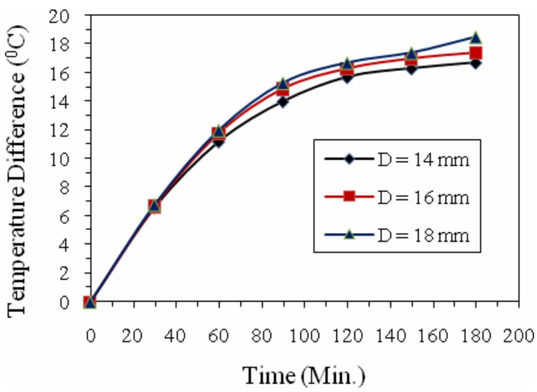

Fig. 7. Response of temperature difference with diameter in heat pipe embedded LHTES during charging.

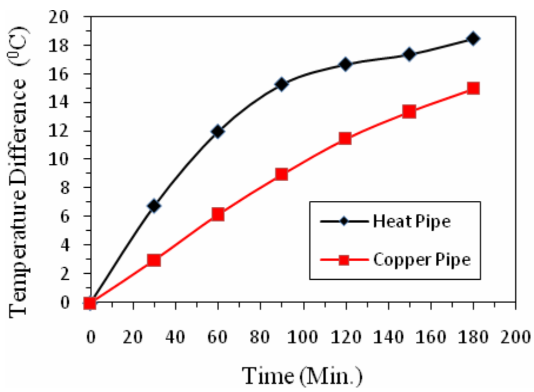

Fig. 9. Performance comparisons of optimized heat pipe and copper pipe embedded LHTES during charging.

Result for different HPLR indicates that the charging and discharging time improved with HPLR 0.9. During charging for preheating of PCM from 35 °C to 50 °C, charging time changed from 105 min. to 90 min. for HPLR 0.9 compared with HPLR 1. Charging time for HPLR 1.1 was much higher. During discharging with HPLR 0.9, time for cooling PCM in liquid sensible phase from 65 °C to 50 °C discharging time changed from 90 min. to 80 min. in comparison with HPLR 1. Discharging time for HPLR 1.1 was much higher in comparison with HPLR 1 and HPLR 0.9.

Decrease in HPLR gave better charging and discharging because of increasing area of heat transfer in heat pipe. Solid PCM sensible cooling phase transformation was reported at 150 min. Constant variation in the temperature was found. This is because of load variation in SHS and LHTES tank and needs further investigation to find optimum ratio.

4.3 Effect of heat pipe diameter

According to result reported in the result of fill ratio and HPLR, heat pipe with 80 % fill ratio and 0.9 HPLR having different diameter was selected. Heat pipes with diameter of 14 mm, 16 mm and 18 mm were tested for their performance in LHTES. Thickness of heat pipe wall for all the test specimen was 2 mm. The temperature history of storage tank was recorded during charging and discharging process. Figs. 7 and 8 represent the variation of temperature difference with time for different diameter of heat pipe during charging and discharging of storage tank, respectively.

Result reported during the test for different diameter shows the further enhancement in the time of preheating PCM from 35 °C to 50 °C. Charging time decreased to 85 min. for diameter of 18 mm, compared with diameter of 16 mm and 14 mm which was 90 min. and 120 min., respectively.

During discharging with diameter of 18 mm, time for cooling PCM in liquid sensible phase from 65 °C to 50 °C discharging time changed to 75 min. which was much less than cooling time required in case of 16 mm diameter pipe and 14 mm diameter pipe. Liquid PCM sensible heating phase transformation was reported at 150 min. during charging, and solid PCM phase transformation was reported at 140 min. for heat pipe with 18 mm diameter. Since increase in the diameter of heat pipe charging and discharging time was reduced, but the volumetric heat storage capacity of the tank was reduced due to increasing the total area of the heat pipe.

4.4 Comparison between storage tank with heat pipe and copper pipe

Figs. 9 and 10 represent the variation of temperature differ-

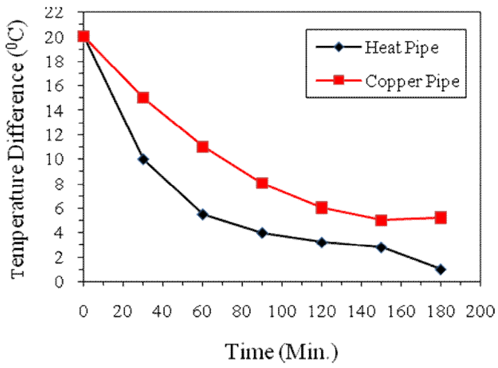

Fig. 10. Performance comparisons of optimized heat pipe and copper pipe embedded LHTES during discharging.

ence with time for both storage tanks during charging and discharging, respectively.

Heat pipe with 80 % fill ratio, HPLR 1 and having diameter of 18 mm was selected for performance comparison of heat pipe embedded LHTES with copper pipe embedded LHTES. Copper pipe of 16 mm diameter immersed 250 mm in SHS and 250 mm LHS was used for experimentation. Both the LHTES were tested simultaneously by fixing the flow rate of 10 ltr./min. for charging and discharging. The temperature histories of storage tanks were recorded during charging and discharging process.

During charging, solid sensible heating of PCM was for 80 min.; after that, phase transformation of PCM for next 80 min, and liquid sensible heating started at 150 min in case of embedded heat pipe LHTES. In copper pipe embedded LHTES solid PCM sensible heating required 180 min.

During discharging liquid, sensible cooling from 65 °C to 50 °C required 75 min. Further liquid to solid phase transformation continued till 140 min., and after that solid sensible cooling continued. In case of copper pipe embedded LHTES sensible cooling of liquid PCM takes 140 min. and then phase transformation started.

Storage tank with optimized heat pipe embedded LHTES showed 187 % improvement in charging time and nearly same improvement in discharging time in comparison with copper pipe embedded LHTES. Charging and discharging rate drastically improved; however, volumetric storage capacity was reduced due to increasing in area of heat pipe.

5. Conclusions

We present an experimental comparative performance study of the charging and discharging process of the embedded copper pipe LHTES with optimized heat pipe embedded LHTES. Also presented is the experimental performance improvement charging and discharging due to change in fill ratio, HPLR and diameter of heat pipe in the LHTES.

Fill ratio of 80 % shows the better charging and discharging in the storage tank. Resistance to heat flow during two-phase boundary after certain period creates the situation of dry out to a certain extent due to less condensation in the LHTES tank. Optimum fill ratio in heat pipe maximizes the heat transfer. HPLR 0.9 shows better result during charging and discharging. Increasing the diameter of the heat pipe from 16 mm to 18 mm also improves charging and discharging time. This is due to increasing the area of heat transfer in LHTES in both the cases increases the heat transfer but volumetric storage capacity of tank decreases.

Comparison between storages tank with heat pipe and copper pipe shows the heat pipe embedded LHTES is a better option for all types of LHTES.

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Nomenclature

Lc : Length of heat pipe condenser section
Le : Length of heat pipe condenser section
C_{sp} : Specific heat of PCM in solid phase
C_{lp} : Specific heat of PCM in liquid phase
L_{pcm} : Latent heat of PCM
g : Acceleration due to gravity
min. : Time in minutes
°C : Degree Celsius
W : Watt
m : Meter
kg : Kilogram
kJ : Kilo-joule
ltr./day : Liters per day

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