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Experimental study of mass flow rates of HTF on PCM based solar thermal energy storage

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Abstract: Intermittency in solar energy, in case of thermal applications, it is necessary to store this energy in the form of thermal energy. It can be used when solar energy is unavailable and thus helps in minimizing the mismatch between energy demand and supply. However, it has poor heat transfer characteristics resulting in more charging and discharging times. To address this issue, various methodologies related to heat transfer enhancement have been suggested. Moreover, suitable working parameters for the best performance of this thermal storage system are also obtained. The results obtained under the present study revealed that additions of longitudinal fins improve the system efficiency significantly by reducing the charging and discharging times. Better performances were observed at a higher value of inlet temperature and mass flow rate of HTF. Moreover, suitable working parameters for the best performance of this thermal storage system are also obtained.

Keywords: solar, thermal energy storage, phase change material, PCM, heat transfer fluid, HTF

1. Introduction

The world energy consumption from 2018 to 2050 as per International Energy Outlook 2019 (IEO2019) will rise by approximately 50%. There is an increase in more than 40% of natural gas global consumption from 2018 to 2050, and it will reach nearly 200 quadrillion Btu at the end of the year 2050. But due to the non-renewability nature of natural gas, coal, petroleum, and other liquids, future fuel is renewable energy sources like solar, hydro, wind etc. and renewable energy demand will increase up to 28% from 15 % during the tenure 2018 to 2050 as shown in Fig.1 [1].

India will successfully meet the objectives of the Paris Agreement. Till June 2019, it has achieved a renewable energy capacity of 80.46 GW, which incorporates solar energy (29.55 GW), wind energy (36.37 GW), biomass (9.81GW), and small hydropower (4.6 GW). It is highly expected that 40 percent demand of the power sector will be successfully meet by 2030 through renewable sources and will reach a figure of 15,820 TWh till 2040 [2].

It significantly helps in reducing environmental pollutions directly, benefiting severe human health issues. It finds a significant role by replacing conventional fuels during space or water heating, especially power generation in rural areas and transportation. Solar energy is heat from the sun, i.e., solar or radiant energy that can be utilized in both various direct and indirect ways.

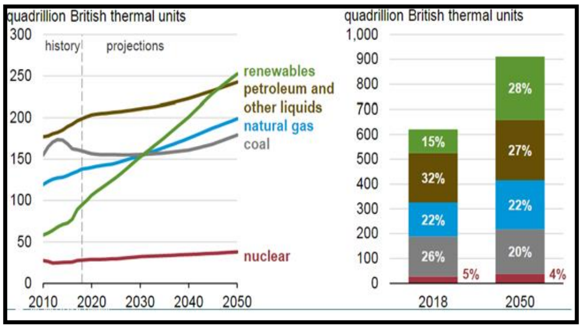

Fig. 1: Primary energy global consumption by energy source (2010-2050) [1]

The Sun generally emits approximately 1.8×10^{11} kW of energy reached to the earth's surface. It finds a vast scope in thermal applications like water heating, cooking, crop dying, etc. and power generation with the help of concentrated solar panels [3]–[22].

Thermal Energy Storage (TES): The thermal energy storage (TES) is the storage of thermal energy temporarily at high or low temperatures [14–19, 22].

It helps in reducing the mismatch between energy supply and demand in the market and follows the principle of energy conservation. In this technology, thermal energy storage done by proper heating or cooling a PCM, which is further utilized based on different heating or cooling applications like buildings and industrial sectors, as shown in Fig 2.

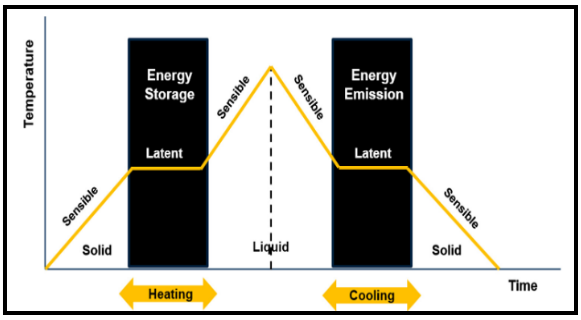

Fig 2: Working principle of TES [4]

TES technologies can be broadly classified into two major categories, namely thermal and chemical energy storage [27]–[29]. Further, thermal storage is classified into two main classes, namely sensible heat, and latent heat storage systems, as shown in Fig. 3.

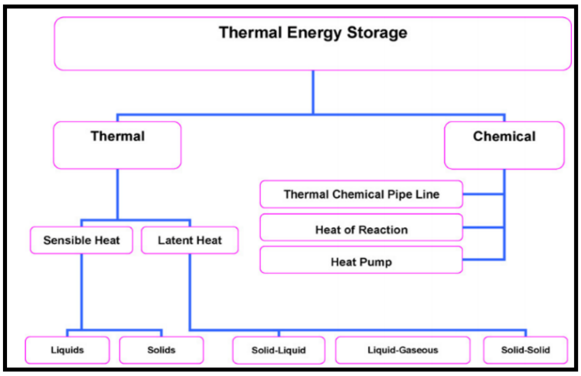

Fig. 3: Major techniques of thermal energy storage [30].

Sensible Heat Storage (SHS): Sensible heat storage is the most common form of heat storage and widely used in the industrial and domestic sectors. It is the storage of sensible energy by heating a liquid or a solid media without a change in phase. Water, molten salts, sand, or rocks are typical examples of sensible heat storage. Specific heat characteristics of medium, their mass quantity, and change in temperature during sensible heat transfer play a vital role in storing the amount of heat. General equation for SES is expressed in following equation.

$$Q = \int_{ti}^{tf} m\,Cp\,dT$$

Where, Q is the amount of heat stored , C_p is specific heat of material, t_i is the initial temperature, and t_f is final temperature.

Latent Heat Storage (LHS): Latent heat storage (LHS) is working on the principle of heat absorption or release when a storage medium changes its phage from liquid to gas, solid to liquid, or vice- versa. Thermal energy storage occurs when material changes its phase from solid to liquid or from liquid to vapor in the form of latent heat of vaporization. The extraction of stored heat occurs due to the application of external load while restoring the storage medium into its initial phase. Recently, it is researched more as compare to sensible heat storage due to its several advantages. Moreover, there is an issue of incomplete reversal cycle in the thermo-chemical storage system during charging and discharging cycles. General equation for LHS is expressed in following equation.

$$Q = \int_{ti}^{tm} MCp\Delta T\,dt + M(LH) + \int_{tm}^{tf} MCp\Delta T\,dt$$

Where, Q is quantity of heat stored, m is mass of heat storage medium, C_p is specific heat of the material, t_i is initial temperature, t_f is final temperature, t_m is the melting temperature, LH is latent heat of fusion .

Range of Working Parameters: System and operating parameters are identified based on literature studies. Operating parameters of this system are inlet temperature and mass flow rate of HTF. The system operates at 70°C, 80°C and 90°C of HTF `s inlet temperature and mass flow rate at 0.066 kg/s and 0.085 kg/s.

2. Experimental Setup of Latent Heat Storage System

Schematic and photographic views of this experimental setup are shown in Fig. 4 and Fig. 5 respectively. The setup is used to carry out the performance analysis of phase change material storage system. The performance is analyzed based on the variation of inlet temperatures and mass flow rates of HTF during each charging and discharging cycle. Paraffin wax is used to store heat, and water is used as HTF.

The setup consists of a heat storage system, K-type thermocouples, data logger, water- heater, storage tanks for water, rotameter, control valves, and pump. Paraffin wax is filled inside the shell through a window provided. Water is permitted to flow through a central tube from the upper plenum section.

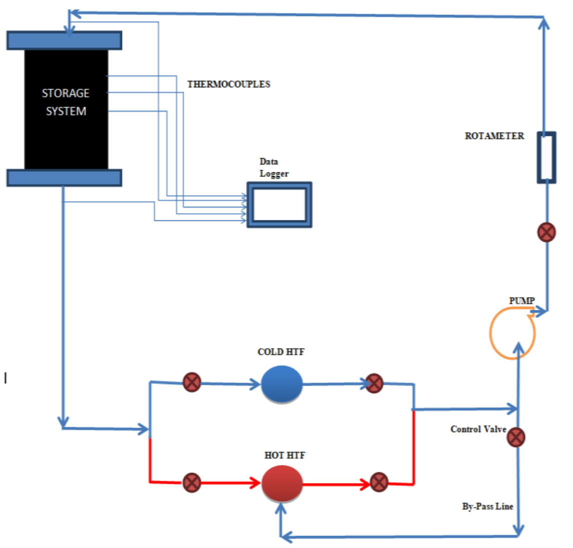

Fig. 4: Major techniques of thermal energy storage [30].

Table 1: Properties of PCM (Paraffin Wax)

Property	Value
Melting Temperature Range	50.29°C to 59.17°C (54.9°C)
Latent Heat	176 kJ/kg
Specific Heat	1.92 kJ/kg K
Density	845.4 kg/m^3
Thermal Conductivity	0.18 W/mK
Viscosity	0.004416 Ns/m^2

Table 2: Properties of HTF (Water)

Property	Value
Density	997 kg/m^3
Specific Heat at 90°C	4.199 kJ./ kg K
Specific Heat at 80°C	4.197 kJ./ kg K
Specific Heat at 70°C	4.191 kJ/kg K

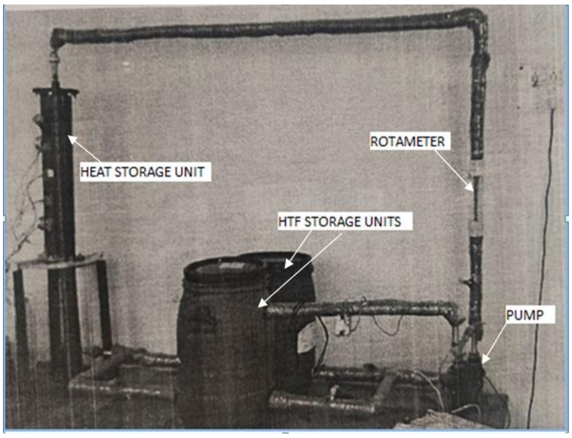

Fig. 5: Photographic view of an experimental setup.

The temperature of PCM, inlet, and outlet temperatures of the HTF is measured with the help of thermocouples located at different radial and axial positions, as shown in Fig. 4 and Fig. 5. These thermocouples are connected to a computer through a data logger. A rotameter measures flow rate of heat transfer fluid. The outer surface of heat storage system, HTF carrying pipelines, joints, etc. are properly insulated by using polyethylene foam to prevent heat loss. An electric heater of 1 kW capacity is placed into a hot storage tank to heat the HTF at the required temperature. Control valves positioned at different locations are used to control the flow rate of HTF [27].

Modelling of Longitudinal Fin Configuration: Longitudinal fin is adapted to enhance the heat transfer rate in the system. Design and modeling of this fin configuration have been done with the help of SOLIDWORKS and AUTOCAD software. The comparison of system performance parameters under different operation conditions is carried out for two different cases i.e., without fin and with longitudinal fin, as shown in Fig. 6 and Fig. 7, respectively.

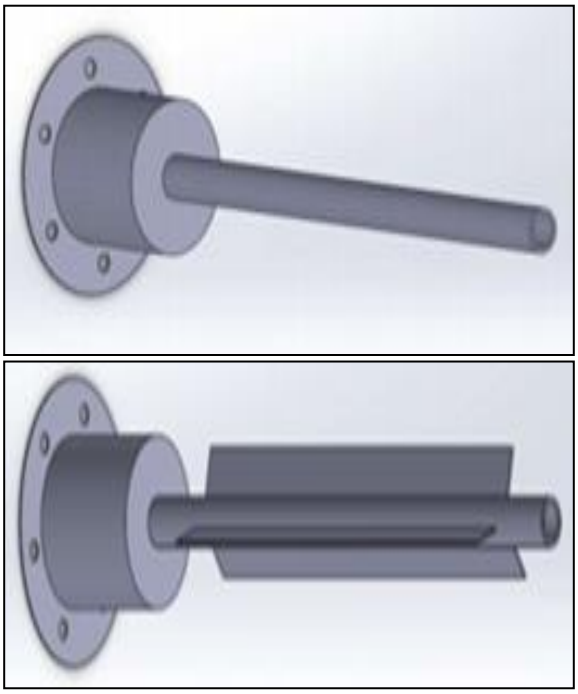

Fig. 6 (a) Without fin and (b) With longitudinal fins.

The detail dimensions of a longitudinal fin configuration are shown in Fig. 7

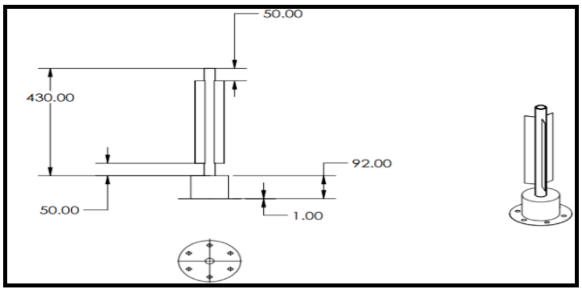

Fig. 7: Longitudinal configuration of a fin arrangement.

Thermo-Physical Properties of PCM And HTF Used: Various thermo-physical properties of paraffin wax and water were studied and tested using an instrument Differential Thermal Analyzer (DTA).The properties of paraffin wax & water are obtained as tabulated in Tables 1 and 2.

3. Fabrication, Calibration and Positioning of Thermocouples

K-type thermocouples are used with having a range of temperature measurements is from -75°C to 400°C. Fabrication of thermocouple is done by using mercury dip. Calibration of thermocouples is carried out using FLUKE 9142 Field Meteorological Well. A calibration curve is plotted, which is shown in Fig. 8. It was found that for the working temperature range of the experiment (70°C - 90°C), the maximum error in temperature was found to be around 2.71°C, which is about 3.01 % error in the temperature reading.

Twelve thermocouples are inserted into the storage unit at 04 at axial positions and 03 radial positions at each of the axial locations. Three thermocouples are grouped at a particular axial position. A thermocouple is inserted at the inlet and exit of a storage unit to determine the HTF temperature.

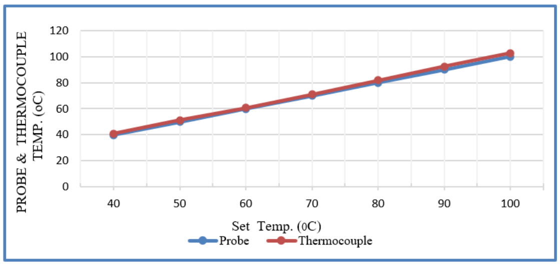

Fig. 8: Calibration curve of thermocouples.

4. Results and Discussion

A series of experiments were performed for defined operating parameters, namely inlet temperature and mass flow rate of HTF for both charging and discharging cycles. The system operates at HTF inlet temperatures of 70°C, 80°C, and 90°C and mass flow rates of 0.066 kg/s and 0.085 kg/s. Based on various system parameters like charging and discharging times, the total energy stored by PCM, charging, and system efficiencies, the performance of a vertical shell and tube type LHESS is defined and discussed in the following sections.

Effect of Mass Flow Rates of HTF: The effects of varying mass flow rates of HTF on charging and discharging times, cumulative/total energy stored in the PCM, charging, and system efficiencies have also been assessed for a shell and tube type LHESS with and without incorporation of longitudinal fins. The experiments were carried out by varying mass flow rates at 0.066kg/s and 0.085kg/s.

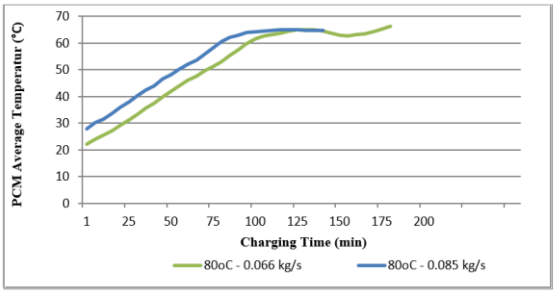

Fig. 9: Effects on charging times by varying HTF`s mass flow rates without incorporation of fins.

Charging/Melting Time: The influence of varying mass flow rates of HTF on charging time for both the cases, i.e., with and without fins, was found to be lesser when the mass flow rate is higher. It took charging times, when no longitudinal fins were incorporated, of around 180 minutes, and 135 minutes as shown in Fig. 9, for complete melting of the PCM with mass flow rates of 0.066 kg/s and 0.085 kg/s, respectively, while with use of longitudinal fins, charging time reduces from 180 minutes to 160 minutes at 0.066kg/s of the mass flow rate of HTF as shown in Fig. 10.

Various technologies are there to reduce the charging time; varying mass flow rates of HTF with the application of fin is one of them. Varying mass flow rates of HTF had a significant influence on charging times; likewise, variation in the inlet temperatures of HTF Longitudinal fins enhance the surface areas of heat transfer resulting a faster heat transfer rate.

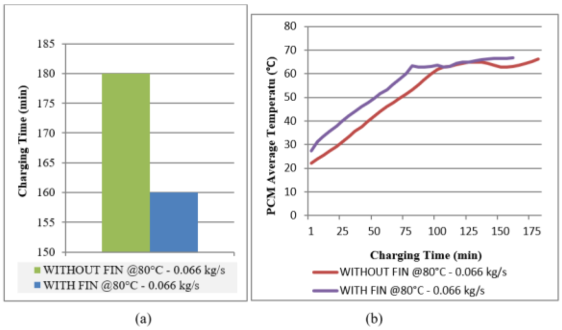

Fig. 10: Effect of fins on discharging times at 0.066 kg/s of HTF`s mass flow rate.

Discharging/Solidification Time: In order to have effective thermal energy storage, the lesser the discharging time means, the faster the heat transfer and discharge rates. It took discharging times when no longitudinal fins were incorporated, of around 135 minutes, and 115 minutes as shown in Fig. 11, for complete melting of the PCM with mass flow rates of 0.066 kg/s and 0.085 kg/s, respectively. While with the use of longitudinal fins, charging time reduces from 135 minutes to 115 minutes at 0.066kg/s of the mass flow rate, as shown in Fig. 12.

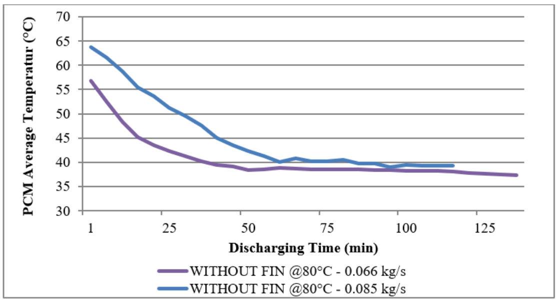

Fig. 11: Influence on discharging times by varying HTF`s mass flow rates.

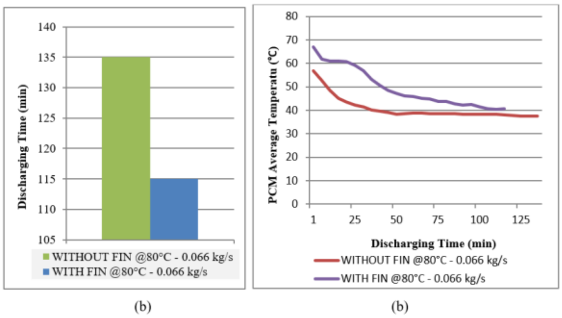

Fig. 12: Effect of fins on discharging times at 0.066 kg/s of HTF`s mass flow rate.

Total Energy Storage by PCM: The influence of the mass flow rate of the HTF without the incorporation of longitudinal fins on cumulative/total energy storage by PCM is shown in Fig. 13. Total energy storage got influenced by varying mass flow rates for both the cases, but there was more energy storage in longitudinal fins as compared to simple shell and tube type units. The total energy storage initially for lower mass flow rates had a higher value of energy storage as compared to the higher value of mass flow rate. In contrast, at the end of the melting cycles, higher mass flow rates had a higher value of cumulative energy storage. The cumulative energy storage decreases with the decrease in the mass flow rates of HTF, considered as 0.085 kg/s, and 0.066 kg/s. The cumulative/total energy storage by PCM for without fin case, nearly 768.29 kJ, and 783.34 kJ at 0.066 kg/s and 0.085 kg/s, respectively, of mass flow rates.

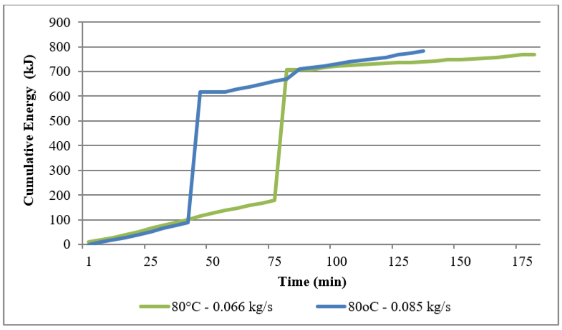

Fig. 13: Effects of varying HTF`s mass flow rates on the cumulative energy storage without incorporation of fins.

The effect of longitudinal fins on total energy/cumulative energy storage in PCM is shown in Fig. 14. A higher value of cumulative energy stored with the use of fins, which was around 782.64 kJ as compared to without fin, was around 768.29 kJ at 80°C, inlet temperature, and 0.066 kg/s of a mass flow rate of HTF.

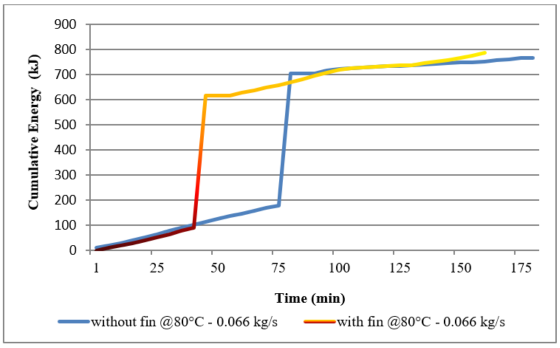

Fig. 14: Effects of longitudinal fins on the cumulative energy storage.

5. Conclusions

Under the dissertation work, two different cases are studied, and a series of experiments are carried out while varying two operating parameters, i.e., inlet temperature and mass flow rates of HTF i e. (a) shell and tube type without fins and (b) shell and tube with longitudinal fins. Based on the experimental study following conclusions are draw.

i) The inlet temperature of heat transfer fluid plays a vital role in governing the performance of this system. The performance in terms of thermal energy storage (744.86 kJ at 70°C and 789.36 kJ at 90°C) is higher at higher values of inlet temperatures with less charging time (255 minutes at 70°C and 150 minutes at 90°C) and higher system efficiency (35.69 % at 70°C and 41.32 % at 90°C)

ii) The influence of varying mass flow rates of the HTF was not as prominent as by varying inlet temperatures of the HTF (system efficiency: 41.32 % at 0.066 kg/s and 42.36 % at 0.085 kg/s).

iii) Increasing heat transfer rate by incorporation of longitudinal fins plays a vital role in improving system performance. Charging cycles (255 minutes and 210 minutes at 70°C) had more profound results than the discharging cycles (135 minutes and 115 minutes at 70°C).

Based on a series of experiments carried out on shell and tube type LHESS, it is recommended that incorporation of other shapes of fins configurations and number of fins should also be tested which can further enhance the system performance. Other materials for heat transfer may be investigated incorporation with additives (metal matrix) into the paraffin wax to have higher heat transfer rates.

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