Design Development of a Heat Storage System at Small Scale for Solar Thermal Collectors

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1 Introduction

The clean and long-lasting sources of the energies are the present need. Solar thermal energy is a promising source to meet-up the thermal energy demand of the world for low to high-temperature requirements. The solar thermal energy storage (STES) systems have special relevance in the solar thermal systems (STS). There are various types of STSs that directly collect the heat and serve the purpose of any heating applications in the range of 60–1000 °C. The variable, intermittent and unpredictable nature of solar radiation limit the operation of these systems due to the heat collection mismatch between the load and the supply. These storage systems provide heat backup for the system application in the absence of daylight or during insufficient solar radiation. Thermal energy storage (TES) systems are being widely used in solar thermal collectors for water heaters and as building heating systems [1, 2]. Among three kinds of storage systems (i) sensible heat storage (store energy while heating and release energy when cooling of a liquid or solid material), (ii) latent heat storage (store or release energy during phase change of material) and (iii) thermo-chemical storage (TCS) (uses chemical reactions to store and release thermal energy), the sensible method is the most useful. Due to the low density, the sensible heat storage requires a larger volume than that of PCM and TCS systems, respectively [2]. The properties of various storage materials are summarized in Table 1 [3–14].

Although various mediums have been tested and reported, water is the most used medium for storing sensible energy to use at low or medium temperature solar thermal systems. Storage at more than the boiling temperature of water needs pressure vessels which makes the system costly. For this, other liquids, viz. octane, isopentanol and

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Table 1 Storage materials and their properties

Medium	Type	Melting point (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/mK)	Specific heat capacity (kJ/kg K)	References
Mineral oil	Sensible	310 (boiling point)	–	0.12	1.966	[3]
Concrete	Sensible	–	–	1.5	0.85	[3]
Rocks	Sensible	–	–	0.48	0.96	[4]
Sand	Sensible	–	–		0.8	[5]
Parrafin wax	PCM	64	173	0.167 (liq.) 0.346 (solid)	–	[6]
Palmitic acid (C-16)	PCM	64	185	0.162	–	[7]
Stearic acid (C-18)	PCM	69	209	–	2.07	[7]
KNO_3/KCl	PCM	320	74	0.5	1.21	[8]
$MgCl_2$/KCl	PCM	435	351	0.81	0.8(solid) 0.96(liq.)	[9]
Al-Si	PCM	576	560	160	1.038	[10]
LiF/CaF_2	PCM	767	790	–	–	[11]
Acetamide	PCM	82	263	–	1.94	[12]

butanol with lower density and specific heat than water are used, but, those are flammable, so requires additional safety of the system [13, 15]. The present work is emphasized for low-temperature, so water is used as storage medium. A significant number of research work has been published on the design of heat storage systems for solar thermal collectors. Parsad and Muthukumar [16] have numerically investigated a sensible heat storage unit for high-temperature application using a 3D mathematical model. The storage is configured with cast steel, iron and concrete. The predicted values are in good match with the reported values. Nkhonjera et al. [17] discussed in detail various storage units for cooking in different research work and presented a good review on STSs. Celador et al. [18] described a methodology to select the different design parameters for thermal storage systems to decrease the system cost.

It is understandable that a small-scale solar thermal system, a heat storage system with reasonable cost will increase the utility and adoption of this technology among potential users. The present work is aimed to design an effective small capacity storage tank at low cost. Two storage tanks are designed for this purpose, and a thermal performance study is conducted with the help of a lab scale experimental set-up.

2 Development of Heat Storage System

A storage system extracting heat from a heat source is depicted in Fig. 1. This heat source is a solar collector when the storage is used to provide thermal backup or diurnal storage of solar energy. In the present study, this heat source is an electric heater with a controlled energy input to a metallic heat exchanger immersed in a heat transfer fluid. This arrangement is analogues to the solar thermal energy system for testing of heat storage system under indoor laboratory conditions.

The energy balance equation for this set-up is written as:

$$q_{\mathrm{us}} = q_{\mathrm{af}} - q_{\mathrm{ls}} \tag{1}$$

$$q_{\mathrm{us}} = (m_w C_w + m_s C_s)\frac{\Delta T_s}{\mathrm{dt}} \tag{2}$$

$$q_{\mathrm{ls}} = U_{\mathrm{ls}} A_s \left(\overline{T_s} - \overline{T}_a\right) \tag{3}$$

$$q_{\mathrm{af}} = q_{\mathrm{ah}} - q_{\mathrm{lh}} = m_f C_f \frac{\Delta T_f}{\mathrm{dt}} \tag{4}$$

$$q_{\mathrm{ah}} = q_e \eta_e \tag{5}$$

$$q_{\mathrm{lh}} = (m_h C_h)\frac{\Delta T_f}{\mathrm{d}t}. \tag{6}$$

where q_{us} is the rate of energy utilization by the storage system. q_{af} and q_{ah} are the rates of available heat to the heat transfer fluid and the heat source, resptively. q_{ls} and q_{lh} are the rates of energy loss from heat storage and heat source, respectively. q_e is the rate of electric energy supplied to electric heater and η_e is the conversion (electric

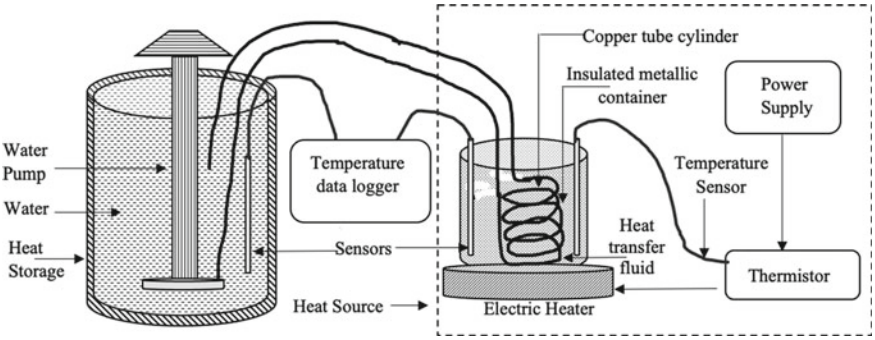

Fig. 1 Charging set-up (heat extraction) of heat storage systems from a heat source

energy to thermal energy) efficiency. m_w, m_s, m_f and m_h are masses of water (sensible storage medium), storage tank, heat transfer fluid and heat exchanger, respectively. C_w, C_s, C_f and C_h are the specific heats of water (sensible storage medium), storage tank material, heat transfer fluid and heat exchanger material, respectively. ΔT_s and ΔT_f are the rise of temperatures of storage system (i.e. water) and heat transfer fluid in dt time interval. U_{ls} and A_s are overall heat loss coefficient and total area of the storage system, respectively. $\overline{T_s}$ and $\overline{T}_a$ are average storage and ambient temperatures during the time period Δt. In the above equation, temperature stratification is neglected due to low capacity of storage system.

Using Eqs. (1)–(6)

$$q_{\text{us}} = q_e \eta_e - m_f C_f \frac{\Delta T_f}{\text{d}t} - U_{\text{ls}} A_s \left(\overline{T_s} - \overline{T}_a \right) \tag{7}$$

The above equation is for charging cycle of the system. For discharging cycle energy balance equation is:

$$q_{\text{ls}} = m_s C_s \frac{\Delta T_s^{'}}{\text{d}t} \tag{8}$$

where $\Delta T_s^{'}$ is decrease in storage system temperature in the dt time period. Clearly, charging and discharging of a the heat storage system are govern by the various heat losses occurred in a storage system. For low charging and high discharging time, these losses should be minimized while keeping the cost of the system reasonably fair. These heat losses mainly depend on the (i) storage structure elements, (ii) operation temperature range, (iii) temperature stratification and (iv) thermal losses [19, 20].

Here, focus is on minimize the heat losses by keeping (i) low operation temperature range (50–90 °C), (ii) low capacity of storage system to avoid temperature stratification and (iii) use of locally available material for base and layered insulation material to reduce fabrication cost. Design parameters of the system are given in Table 2. All the systems are cylindrical in shape having a maximum water capacity of 8 L.

3 Experimental Method

The charging and discharging curves of storage systems are compared with a commercial storage system. The component details of these systems are given in Table 2. The laboratory set-up consists (Figs. 1 and 2) of mainly four sections (i) a heat source that is an electric heater with a controlled energy input, (ii) a metallic heat exchanger to receive direct heat from the heat source, (iii) a heat storage system that receives heat from the heat exchanger and (iv) the temperature data logger that records temperature through the sensors which are kept at various positions in the system. An electric

Table 2 Design parameters of the heat storage systems

System	Material	Diameter (m)		Useful Height (m)	Insulation and casing material	Insulation thickness (m)
		Inner	Outer			
Commercial HS	Steel	0.215	0.285	0.275	Polyurethane, Plastic casing	0.035
Designed HS-1	Aluminium	0.24	0.31	0.31	Glass wool, cardboard casing	0.035
Designed HS-2	Aluminium	0.24	0.30	0.32	Cardboard, and theramcole, cardboard casing	0.03

heater (power consumption 1.5 kWh) is used to give thermal energy to HTF. The heat exchanger is an insulated metallic cylinder container (capacity 2 L) made of copper and it contains the heat transfer fluid. A copper tube cylinder is immersed in it for heat exchange from HTF. The metallic container is an insulated container with an inner diameter of 0.115 m, outer diameter of 0.18 m and height of 0.175 m.

In the present study, Hytherm (1 L) is used as HTF. The copper tube cylinder (CTC) is designed using a copper tube of 1 m length. The tube is rounded keeping the diameter 0.10 m to make spiral rings of height 0.08 m. This copper tube cylinder is kept in the HTF container. This heat exchanger having HTF and CTC is placed upon

Fig. 2 Lab scale testing set-up with commercial heat storage system

the electric heater to receive the heat directly from the electric heater. By this heat, the temperature of HTF increases continuously. To obtain the constant temperature of HTF, an auto cut of power supply is set using a thermistor (±5 °C). In the present study, this temperature is kept at 150 °C in all the experiments. The water is chosen as a heat storage material. The water in the heat storage is circulated through the copper tube cylinder. Both the ends of this cylinder is connected with silicon tubes, and these tubes are immersed in the heat storage system. A water pump is dipped in the storage tank to circulate the water in the copper tube cylinder and exchange the heat from HTF. The temperatures of HTF and HS are measured by using k-type thermocouples dipped in the respective containers. The sensors' inputs are recorded through a data logger (85XX + Masibas data logger, LC 0.1 °C). For the charging experiments, the temperatures are recorded in 01 min interval while for the discharging set-up this time interval is 15 min.

4 Results and Discussion

The representative thermal profiles are shown in Figs. 3, 4, 5, 6 and 7. Figure 3 and 4 depict the charging of heat storage systems (HS, HS-1, HS,2) up to 90 °C while keeping all experimental conditions identical, i.e. HTF material and its temperature (initial and saturation), power source (heat input), initial room temperature and flow rate. The load capacity is 6 L and 8 L in the charging cycle. The discharging cycle under environmental conditions is also recorded for the different load capacities of the heat storage systems. These are depicted in Figs. 5 and 6. The temperature of heat transfer fluid (hytherm) is plotted in Fig. 7 for the different sets of experiments.

A comparative curve (Fig. 3) for charging of heat storage tank up to 90 °C indicates that the lab designed heat storage systems (HS-1 and HS-2) took around 6–10 min extra to reach 90 °C in comparison with the commercial HS for 6 L water, while for 8 L (Fig. 4), the time taken by systems HS and HS-1 is almost same. For all the systems, the heating of the 8 L water load took a larger time (5 to 8 min) than the 6 L load. The discharging plots shown in Fig. 5 infer that after 15 h, the temperatures of HS, HS-1 and HS-2 are 51.1 °C, 42.9 °C and 39.6 °C, respectively, for 6 L water load. The temperature difference of about 10–12 °C is found in this. In the other experiment for higher load capacity (8L), the temperature falls after 15 h are found 53.1, 47.6 and 44.5 °C for systems HS, HS-1 and HS-2, respectively. Overall, in the 15 h discharging time period, a little difference of about 6–12 °C is noted in the comparison with the commercial system. The rate of increase of the temperature for HS-1 is better than HS-2 due to good insulation material, and this rate is also equal to the commercial system (HS). The rate of decrease in temperature for both the developed system is slightly higher than HS. This is due to the marginally larger diameter of HS-1 and HS-2 about 0.03 m than the commercial one (HS). Using Eq. (8), Table 2, Figs. 5 and 6, the overall loss coefficients for the designed systems are computed and are given in Table 3. The curves between ΔT_s and$\left(\overline{T_s} - \overline{T}_a\right)$ are plotted to obtain the curve slopes for each system under 6 and 8 L water conditions.

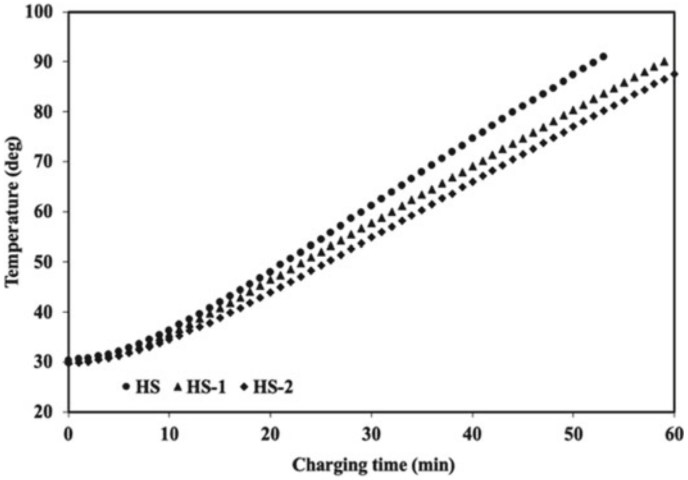

Fig. 3 Charging time period vs temperature curve for heat storage systems (HS, HS-1 and HS-2) for 6 L water load capacity

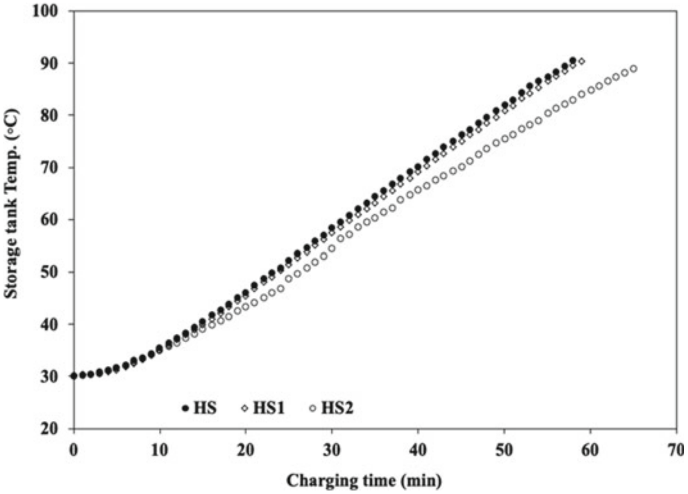

Fig. 4 Charging time period vs temperature curve for heat storage systems (HS, HS-1 and HS-2) for 8 L water load capacity

The time interval to compute ΔT_s is taken 1 h. The specific heat of water is taken to be 4186 J/kg °C.

Table 3 infers that the minimum heat loss coefficient is found for HS-1 system, while highest value is obtained for HS-2. This is a clear indication of better performance of the system HS-1 in comparison with the HS and HS-2. The costs of developed systems are about 60–65% less than the commercial ones due to use of different

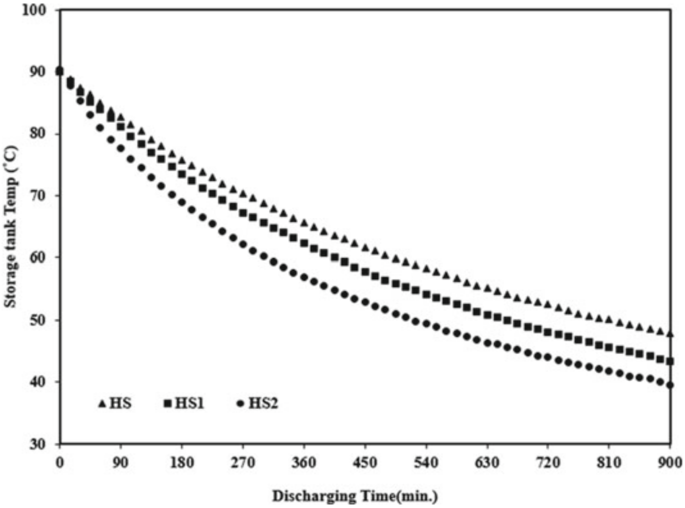

Fig. 5 Discharging time period vs temperature curve for heat storage systems (HS, HS-1 and HS-2) for 6 L water load capacity

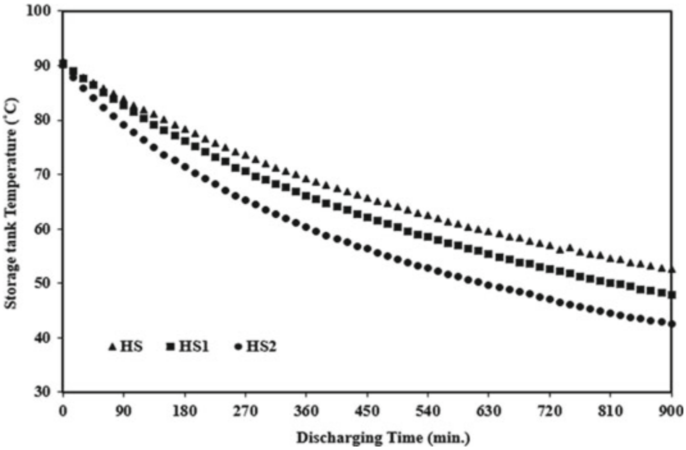

Fig. 6 Discharging time period vs temperature curve for heat storage systems (HS, HS-1 and HS-2) for 8 L water load capacity

layers of cost-effective insulation materials. These initial results obtained at the lab scale infer that the lab designed systems have significant potential.

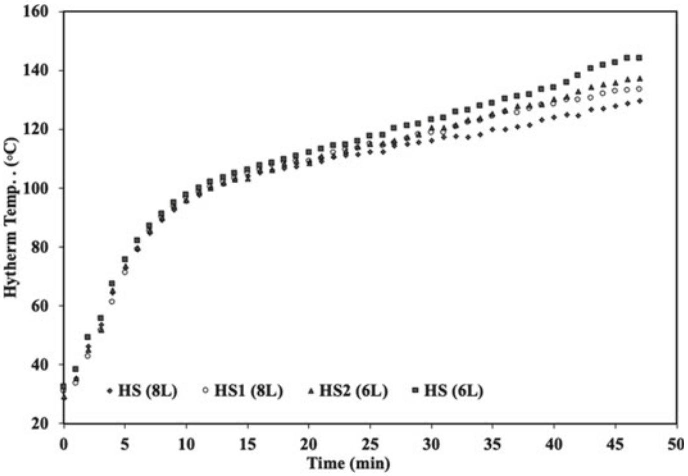

Fig. 7 Temperature profile of Hytherm (HTF) in different set of experiments

Table 3 Heat loss coefficients of heat storage systems

System	A_s (total area m^2)	Curve slope		Regression coefficient of curve		U_{ls} (overall heat loss coefficient (W/m^2 °C)	
		6 L	8L	6 L	8L	6 L	8L
Commercial HS	0.25	0.1126	0.1027	0.96	0.99	3.14	3.82
Designed HS-1	0.32	0.1255	0.1124	0.99	0.98	2.73	3.26
Designed HS-2	0.33	0.1768	0.1589	0.97	0.97	3.73	4.47

5 Conclusion

The heat storage systems are the important segment of any solar thermal collector system. Two low-cost solar thermal storages are fabricated to test low-temperature applications, and their experimental studies are performed and compared to the commercial one. The different charging and discharging tests are performed with the systems with water as heat storage material. The load capacities of all the systems are the same. The thermal performance of the fabricated systems are found to be competitive to commercial ones. The costs of the fabricated systems are reasonable.

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