Experimental and Numerical Investigations on Sensible Heat Storage Systems

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By

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Abstract

Energy plays a major role for the existence of mankind. It is necessary to adopt human development and economic growth of any nation with secure, affordable, reliable, clean and sustainable energy supply. Today, the world is facing several challenges such as global warming, depletion of natural resources, population growth, increase in energy demand and price and unequal distribution of energy sources. All these factors contribute to the urgent need to transform the energy sector, which primarily depends on fossil fuels, to the one that uses renewable energies and energy efficient technologies. Renewable energy is one of the key solutions to the current challenges facing by the world. Many countries have already explored various options of generating power from the renewable energy through different approaches.

Concentrated solar power (CSP) is one of the promising large-scale power generation technologies among the renewables, which is being widely commercialized now. The CSP technologies exist in four common forms namely parabolic trough, central tower, and parabolic dish and linear fresnel reflector. The major problem faced by all types of CSP plants is the intermittent solar radiation, which halts the generation of electricity during night and overcast day. This issue can be solved by incorporating a thermal energy storage (TES) system. TES systems are broadly classified into sensible heat storage (SHS), latent heat storage and thermochemical heat storage. TES systems using SHS solid materials are highly attractive due to their high thermal storage capacity, abundant availability, cheap, compatibility with container materials, and chemical stability.

In general, SHS system consists of a regenerator type heat exchanger wherein the heat transfer fluid (HTF) is passed through the storage media for charging and discharging processes. During charging, the high-temperature HTF transfers the heat to the storage medium. The stored energy is released during discharging as the low-temperature HTF passes through it. Design and optimization of SHS prototypes require extensive analysis on heat transfer characteristics between the SHS medium and HTF. The number of HTF tubes and fins on the HTF tube's outer surface play a major role in transferring the heat between them. Un-optimized prototype with more number of HTF tubes and fins would lead to higher material account. In addition, the overall weight of the system will increase too. Hence, a detailed optimization study is

needed to have a cost-effective SHS system. In view of the above, the major objectives of the present work are formulated as

(i) To develop a 3D thermal model for predicting the charging and discharging characteristics of the solid SHS prototype with the optimized number of tubes and fins at different operating conditions

(ii) To test the various mix designs of the concrete mix design to fill inside the designed tube matrix of the SHS beds (M2 and M3)

(iii) To measure thermo-physical properties of the selected concrete mixture samples

(iv) To test the thermal storage performances of the solid SHS prototype at various operating conditions.

A numerical study of conjugate heat transfer in a shell-and-tube type prototype of 15 MJ capacity filled with a SHS material is presented. The materials used in the present study are cast steel and concrete (Mix Design M30 grade). Mix design of M30 grade is a mixture of cement, fine aggregate (sand), coarse aggregate (gravel) and Water in the weight proportion of 1:1.52:3.21:0.49. The governing equations involved in the thermal model are1solved using a finite element based software product, COMSOLTM Multiphysics 4.3a.

The thermo-physical properties of the concrete such as volumetric heat capacity and thermal conductivity were measured with the help of a thermal property analyser, Hot Disk TPS 2500 S by using the transient plane source technique. Two concrete specimens of diameter 25 mm and length 20 mm were prepared for testing the thermo-physical properties at different temperatures. It is observed from the measurements that the thermal conductivity and diffusivity of concrete decrease and the volumetric heat capacity of concrete increases with temperature. The maximum uncertainty in the estimation of thermal conductivity, volumetric heat capacity and diffusivity were ±3 %, ±5% and ±3.5 %, respectively.

Employing optimization configuration of the storage module, three number of lab-scale shell-and-tube based SHS prototypes (i) cast steel prototype (termed as M1), (ii) concrete prototype with copper finned tubes (termed as M2) and (iii) concrete prototype with mild steel finned tubes (termed as M3) of 15 MJ capacity each were fabricated. Five different concrete mix designs were studied and the mix design M30 was selected for thermal storage, as they possess high compressive strength-cost ratio. Charging and discharging characteristics were tested at different operating temperature ranges viz. 343 K – 403 K/353 K – 413 K/363 K – 423 K for M1 prototype and 333 K – 413 K/343 K – 423 K/353 K – 433 K for M2/M3 prototypes during charging and discharging. The storage prototypes were also tested at different velocities of the heat transfer fluid (v = 0.1, 0.25, 0.5 m/s). It is observed that the charging/discharging rate is faster for lower/higher HTF inlet temperature. Similarly, the charging/discharging rate is faster for higher HTF flow velocities. The numerically predicted average bed temperature variation of the storage module is in good agreement with experimental data. It is observed that the charging process is faster than the discharging process due to the domination of preliminary convection heat transfer (during charging) over the preliminary conduction heat transfer (during discharging). For an HTF inlet temperature of 353 / 413 K during charging/discharging and HTF velocity of 0.25 m/s, it took about 1263 / 1803 s, for charging/discharging of the M1 prototype in the experiments. Similarly, it took about 1106 / 1572 s, for charging/discharging in the numerical simulations.

It is observed that partial charging/discharging process is efficient than complete charging/discharging process for the SHS material having less thermal conductivity (concrete ceramic, rock, etc.) They take more time to completely charge/discharge due to lesser heat transfer rate between the SHS materials and the HTF. Hence, partial charging/discharging is better in M2/M3 prototypes and this is addressed using a parameter named, effective charging/discharging time. Effective charging/discharging time is the time taken by the storage prototype's volume average temperature to reach a temperature, which is 5 K lower/higher than the HTF inlet temperature during charging/discharging cycle. Experimentally observed effective charging/discharging time of the M2 and M3 prototypes for the temperature range of 353-433 K are 5210/6297 s and 7160/7780 s and the respective values predicted from the numerical study are 4371/5196 s and 6155/6360 s.

In addition to the major objectives of the thesis, different high temperature lab scale SHS bed configurations are compared numerically. The numerical model used for the performance evaluation of the high temperature SHS beds is slightly modified to study the storage characteristics. Employing concrete, cast steel and cast iron heat storage beds, numerical investigations have been carried out for different geometrical configurations viz., square, circular and hexagonal. The storage volume and heat transfer area of the beds were kept same in thermal modeling for the different configurations. It is found that the cylindrical bed is storing the required heat in less time when compared with other geometries due to the symmetrical heat transfer rates. Simulations have been carried out at the temperature range of 523 K -583 K (cast iron & cast steel) and 523-593 K (concrete) in laminar flow regime. It is also found from the numerical study that the charging time of cast iron (1357 s) and cast steel (1552 s) are much less than that of concrete bed (6183 s) in circular bed designs. Charging time of circular concrete bed (6183 s) is less when compared to its hexagonal (6755 s) and square (6667 s) configurations.

Based on the above discussions, one can conclude that the shell-and-tube based SHS prototype with fins can be effectively used for storing the heat. Further, the results presented in this thesis will be useful for developing the commercial SHS devices for industrial applications. Using the developed thermal model, one can predict the performances of shell-and-tube based SHS prototype with fins filled with different solid SHS materials without performing the expensive experimental studies.