Experimental Analysis of Packed Bed Sensible Thermal Energy Storage System with Small Sized Concrete Spherical Balls

Santosh Pandit Mane, Shrikant Sambhaji Kale
Mechanical Engineering, Karmayogi Engineering College
Karmayogi Engineering College Shelve-Pandharpur,
Dist-Solapur, State-Maharashtra, India

Abstract— The continuous use of fossil fuels resulted energy crisis and environmental threat. It is felt that renewable energy sources are quite capable of meeting energy demand of today’s world. The use of renewable energy sources for meeting energy needs can conserve the conventional energy sources for more number of decades. Among renewable energy sources solar energy is considered to be one of the most dominating energy sources. Conversion of solar energy into thermal energy is the easiest and the most widely accepted method. However, solar energy is a time dependent energy resource. Due to intermittent nature of solar energy, an energy storage unit is required to be attached with solar collectors to store energy for use when sunshine is not available. A storage system therefore constitutes an important component of the solar energy utilization system.

In this project the sensible heat thermal energy storage (TES) system designed and experimentally evaluated for its energy storage performance. Air as the heat transfer fluid and solid concrete made out of a high density material of spherical shapes were used for storage. Experiments performed on TES prototype system, and the results obtained. The air inlet temperature varied between 30°C to 65°C and the flow rate also varied from 0.021 kg/s to 0.0325 kg/s. The shape of the material used was sphere $\varepsilon = 0.48$. A parametric study carried out by varying the fluid flow rate, pressure drop and porosity to evaluate the charging/discharging characteristics of the system.

Keywords— Thermal energy storage, solar energy, sphericity, void fraction;

I. INTRODUCTION

1.1 THERMAL ENERGY STORAGE

Thermal energy storage (TES) systems have the potential of increasing the effective use of thermal energy equipment and of facilitating large-scale switching. They are normally useful for correcting the mismatch between the supply and demand of energy. There are mainly two types of TES systems, sensible storage systems and latent storage systems. As the temperature of a substance increases, its energy content also increases. The energy released (or absorbed) by a material as its temperature is reduced (or increased) is called sensible heat. On the other hand, the energy required to convert a solid material in a liquid material, or a liquid material in a gas (phase change of a material) is called heat of fusion at the melting point(solid to liquid) and heat of vaporization (liquid to gas), respectively. Latent heat is associated with these changes of phase. The other category of storing heat is through the use of reversible endothermic chemical reactions. Chemical heat is associated to these reversible chemical reactions where heat is needed to dissociate a chemical product. All this heat (or almost all) will be recuperated later, when synthesis reaction takes place. A complete storage process involves at least three steps: charging, storing and discharging. In practical systems, some of the steps may occur simultaneously, and each step can happen more than once in each storage cycle. In terms of storage media, a wide variety of choices exists depending on the temperature range and application.

1.2 TES classification
Thermal energy storage (TES) can be classified on the basis of storage mechanism: sensible heat storage, latent heat storage, and chemical storage.

1.2.1 Sensible heat storage
For the sensible heat storage, the storage capacity depends on the mass of the media, its heat capacity, and temperature change. The heat storage media, such as water, oil or other fluids and rocks, are very common and commercially available. However, the potential drawback of such storage is rather large volume requirement when storing or releasing large amounts of energy.

1.2.2 Latent heat storage
Latent heat storage, however, has the capacity to store energy at constant temperature during phase transition which is thermodynamically a better, reversible process. Latent heat storage has a higher storage density compared to the sensible heat storage. For a certain required amount of thermal energy, the latent heat storage can greatly minimize the volume of the materials and thus reduce the size of the storage system. Substances that can have a phase change at a certain temperature are called phase change materials (PCMs). Among several types of PCMs, solid liquid PCMs are more popular because of the relatively large latent heat and rather small volume change during transformation.

1.2.3 Chemical energy storage
Chemical energy storage, (usually a chemical reaction), which is completely reversible and endothermic, has potential to store thermal energy. As the endothermic reaction can be used for energy storage, the exothermic reaction can be used to retrieve the energy. The attractive advantages of such storage are its controllability by the catalyst and high-energy storage density. An ideal endothermic chemical reaction would be one that starts as a solid ends up as a liquid compound thus including the chemical energy as well as latent heat changes. A reverse reaction would bring things back to the original state during the energy retrieval process. Besides, uncertainties exist in the thermodynamic properties and physiochemical properties of the compounds in the reaction. Although such physio-chemical storage has many advantages, its development is still at an early stage.

II. LITERATURE SURVEY

Ever since mankind used heat as an energy source, it is used stores provided by nature in natural resources such as wood, coal and oil. In principle, these represent stores for solar energy, generated during decades or thousands of years. With increased demand for energy and an increased rate of consumption, mankind, nowadays, lives exceedingly from the energy capital rather than from the growth.

The technical storage of heat is a pressing problem, therefore. Seldom is there a perfect coincidence in demand and supply of energy; formerly, in a daily life, stores for sensible heat were commonplace: heavy built houses, massive tiled stoves, or a hot brick bed in winter. The problem of technical storage has been tackled ever since energy is used in industry: regenerators with ceramic materials have been applied since more than 100 years in the metallurgic and glass industry, in order to recover high temperature heat from flue gas. In 1873, McMahon received a patent for a “storage boiler”, an early predecessor of the present day sliding pressure steam accumulator patented in 1913 by J. Ruths. For rational of energy storage in the future heat storage will be an absolute necessity.

Singh et al. [2] reviewed the studies included the design of packed beds, materials used for storage, heat transfer enhancement, flow phenomenon and pressure drop through packed beds. This paper presents an extensive review on the research carried out on packed beds. Based on the literature review, it is concluded that most of the studies carried out are on rocks and pebbles as packing material. A very few studies were conducted on large sized packing materials. Further no study has been reported so far on medium sized storage elements in packed beds.

Kuravi et al. [3] presented a review of thermal energy storage system design methodologies and the factors to be considered at different hierarchical levels for concentrating solar power plants. Thermal energy storage forms a key component of a power plant for improvement of its dispatch ability. Though there have been many reviews of storage media, there are not many that focus on storage system design along with its integration into the
power plant. This paper discusses the thermal energy storage system designs presented in the literature along with thermal and exergy efficiency analyses of various thermal energy storage systems integrated into the power plant.

III. TESTING FACILITY AND EXPERIMENTATION

As mentioned earlier the objective of this study was to carry out performance of the sensible heat storage with respect to temperature and mass flow rate experimentally.

Experiments were conducted with same materials of different shapes and size under different conditions. A hot wire anemometer was employed to measure the air velocity, temperature indicator is used for measuring the temperatures at different heights and U tube manometer is used for measurement of pressure drop. This chapter describes the experimental details concerning the characterisation of flow pattern and energy storage system.

3.1 Mathematical derivations

- Mass flow rate
  Mass flow rate is the mass of a substance which passes through a given surface per unit of time.
  \[ \dot{m} = \rho A V_a \]

- Void fraction
  Porosity or void fraction is a measure of the void (i.e., "empty") spaces in a material, and is a fraction of the volume of voids over the total volume, between 0 and 1, or as a percentage between 0 and 100%. Void of fraction, \( \varepsilon \), is given by the following equation:
  \[ \varepsilon = \frac{V_b - V_s}{V_b} \]

- Sphericity
  Sphericity is a measure of how spherical (round) an object is. As such, it is a specific example of a compactness measure of a shape.
  \[ \Phi = \frac{4}{3 \pi (6V_p)^{\frac{1}{3}}} \]

3.2 Material

The material used for experimentation was concrete. The size and shape of the material is different. Spherical shape was used for experimentation. The shapes used are sphere in Fig. 3.1. The dimensions of these shapes are for sphere average diameter \( d = 38 \) mm.

The concrete is made with the mixture of cement, silica, fine aggregate, water. The local materials volumetric ratios are water (1): cement (1): sand (1.5): rock (1.5) were used in a concrete storage system. The density of made concrete is 2000 kg/m\(^3\), thermal conductivity = 0.98 W/m/K, specific heat = 820 J/kg/K.

Table 3.1 Thermo-physical properties of concrete and estimated mass of sensible heat storage material Sphere

<table>
<thead>
<tr>
<th>Dimension (m)</th>
<th>Minimum required volume (m(^3))</th>
<th>Sphericity</th>
<th>Void fraction</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>d = 0.019</td>
<td>6.53 \times 10^{-3}</td>
<td>1</td>
<td>0.48</td>
<td>13.0 6</td>
</tr>
</tbody>
</table>

3.3 Experimental setup:

To investigate thermal energy storage of packed bed model, a storage system was constructed and tested using a proprietary material as concrete of different shapes like sphere, cylinder and cube. The shape and dimensions of concrete are shown in Fig. 3.1.

An experimental setup was planned and made up to achieve the desired objective. Fig. 5 represents the schematic fabrication setup. A tank made of mild steel pipe was used for storage. The bed was 0.50 m high with 0.15 m long inlet and exit manifolds, which accounted to the total height of 0.80 m. The diameter of bed was 0.20 m. The thermocouple wires were put in the tank with holes made on pipe the bed for measurement of temperature at different locations.

Pipes were fitted on the tank for the flow of air into or out of the storage. The top cover of the tank could be lifted with the help of handles and gasket packing was provided upper and below the cover for tight fitting with nuts and bolts. Glass wool insulation of 0.05 m was used to reduce the heat losses.
For supplying the hot air to bed, a circular cross section pipe with U shape air heater mounting on both equal sides of pipe and in the centre of pipe was done and one J hook with the help of nut bolt arrangement air heater stopper was created where the air heater stop also there were mounted at centre of the pipe and having its topside as electric heater has been provided. The heater was capable of supplying a heat flux of 1000 W/m$^2$. A blower with a control valve was used and supplied the hot air to the bed. The blower was a centrifugal fan driven by a 1 kW, single phase, 230V and 2880 rpm motor. The inlet hot air temperature was held constant at a value of 65°C.

3.4 Instrumentation

A hot wire anemometer is employed to measure the air velocity. A control valve was used to vary flow rate. The bed pressure drop was determined using a U tube manometer. Copper-constantan thermocouples were used to find the temperatures in the bed with the help of two temperature indicators. PID Temperature controller was used to control the temperature.

Before packing, total 22 thermocouples were fixed. They were arranged in such a way that the air temperature was measured at centres of the pipe, at the surface of the pipe and in between centre on the surface of elements by boring shallow grooves. These elements were put at desired pre-determined locations in the bed, as also similar numbers of thermocouples were located in air for measurement of air temperature near these locations in the voids. The details of the locations of thermocouples are shown in Fig. 3.3

3.5 Methodology

As mentioned above, the void fraction with spheres $\phi = 0.48$ was obtained with the bed of spheres. Sphericity of these materials for sphere $\psi = 1$.

With the height of the bed and the calculated number of elements, the elements were filled in the tank to obtain the required void fraction. The packing of the elements was done by placing the elements in one layer and then the elements in the next layer were placed on the gaps created in the first layer and hence the third layer was replica of the first layer, fourth layer the replica of second layer and so on, as in Fig. 3.6 for a typical packing.

For packing of material elements, number of elements of storage material to be packed is calculated before packing in the tank. From the total number of material elements and number of layers, the number of elements to be put in each layer is calculated. The elements have been packed with great care in order to have approximate uniform distribution of voids in the bed and to avoid formation of flow channels. Care has also been taken to keep the minimum possible surface contacts of material elements for having the maximum possible heat transfer.
The top cover of the tank was fitted tightly and the tank was connected to the air supply. The measuring instruments were checked and the U tube manometer levelled and marked. The liquid level in the U tube manometer was precisely marked before the start of air supply. The fan was started by fully opening the control valve and then the heater was given electric supply. The airflow rate was controlled with control valve and the input to the heater was controlled with the temperature controller. The system was run continuously for 2 h for each set of experimentation. During supply of hot air to the bed, flow rate of air and energy input to the heater were checked continuously. If required, these were adjusted accordingly to maintain them at the fixed desired value. For each run of experimentation the following parameters were calculated:

i) The air velocity was measured by a hot wire anemometer.
ii) Head loss in the bed (Δh) from U tube manometer.
iii) Air temperature at different locations.
iv) Surface temperature of material elements at different locations.

3.6 Summary
The packed bed unit mainly depends on the parameters such as inlet temperature of air, shape of material, packing arrangement, void fraction and sphericity of the material, pressure drop of the test section. The experiments are performed using three different shapes and are compared.

IV RESULTS AND DISCUSSION
A test facility was developed to study the sensible heat storage system and performance of different concrete shapes like sphere, cylinder and cube at different mass flow rates of air. System performance depends on various operating parameters; mass flow rates, shapes of material, heat transfer areas and ambient conditions. Heat and mass transfer takes place simultaneously. Experiments were conducted at various operating conditions to evaluate the performance and identification of the critical operating parameters.

Each experimental run represents a thermal cycle of either charging followed immediately by discharging or charging followed by standby mode, in which the blower was turned off and the inlet and outlet manifolds were plugged with insulation. Each thermal cycle used ambient air to charge or discharge the system; therefore, continuous cyclic operation was not conducted. A manometer was used to measure the pressure drop across the bed based on the volumetric flow rate of the blower. Pressure drop values were provided in Table 4.1. It can be observed that the pressure drop decreases with decrease in mass flow rate.

The mass flow rates used in the experimental study were restricted by the capacity of the blower and the heater’s temperature limitations. Heater had heating capacity up to 75°C. For this study, charging mass flow rates of 0.021 kg/s and 0.0325 kg/s were used. The maximum temperature achieved from the bed was 65°C. As expected, the lower mass flow rate provides greater air temperatures to the bed, and the thicker insulation reduces heat loss from the air, producing higher inlet air temperatures into the bed.

4.1 Temperature distribution performance on sphere
The concrete spheres were tested under the packed bed test section. The spheres were arranged in such a manner the void fraction is minimum and it was found ε = 0.48. The spheres were tested for charging and discharging for two different mass flow rates 0.021 kg/s and 0.0325 kg/s. The pressure drop was measured with the help of U Tube manometer and shown in Table 4.1. For charging and discharging the results are as below.

Table 4.1 Pressure drop in sphere, cube and cylinder

<table>
<thead>
<tr>
<th>Mass flow rate (kg/s)</th>
<th>Pressure drop (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.021</td>
<td>6</td>
</tr>
<tr>
<td>0.0325</td>
<td>10</td>
</tr>
</tbody>
</table>
4.1.1 Charging of sphere

As described earlier, following are the results for charging of sphere at two different mass flow rates. The results obtained for mass flow rate 0.021 kg/s are shown in Fig. 4.1. The temperature distribution of model at different level for charging modes is represented. It can be seen that for distance 100 mm the temperature increment was gradual and it was happening due to temperature gradient. For distance 500 mm temperature was distributed in the packed bed and so it takes a time to achieve maximum temperature. The same trend is obtained for mass flow rate 0.0325 kg/s shown in Fig. 4.2.

The results of charging at two mass flow rates 0.021 kg/s and 0.0325 kg/s are obtained. The comparison of charging for two mass flow rates with time and average temperature at distance 500 mm is shown in Fig. 4.3. At the distance 500 mm was taken because it takes total volume of packed bed material. The results found shows that as the mass flow rate increases the temperature distribution is increased with time and when mass flow rate is reduced the temperature distribution in the bed was slow as seen in Fig. 4.3.

4.1.2 Discharging of sphere

For same packing arrangement the following results were found for discharging of sphere at two different mass flow rates 0.021 kg/s and 0.0325 kg/s. The discharging of sphere for mass flow rate 0.021 kg/s is shown in Fig. 4.4. For discharging the ambient air was used. The temperature distribution at the distance is shown in Fig. 4.4. At initial time, discharging takes place suddenly due to temperature gradient. For level 100 mm the discharging was fast and for level 500 mm initially the temperature drops suddenly and after that it drops gradually as seen in Fig. 4.4. The same trend is obtained for mass flow rate 0.0325 kg/s shown in Fig. 4.5.

The comparison of air temperature with two different mass flow rates Fig. 4.6. For comparison level 500 mm is selected for discharging, because it takes the total volume of packed bed. The results show that when mass flow is high the packed bed is discharged in the early minutes as compared to low mass flow rate.
Fig. 4.5 Air temperature at mass flow rate 0.0325 kg/s.

Fig. 4.6 Comparison of air temperature at two different mass flow rates.

CONCLUSIONS

Sensible heat storage is a good energy storage system. It can be used easily. The material is available in local place. The energy storage is environment friendly. The material can be used for a long time of period. It is low cost energy storage.

An in-house test facility is developed to carry out the experimentation on sensible heat storage in concrete of different shape. The first step is the packing arrangement of material for minimum void of fraction. The second step is the charging of cylinder. The final step is a discharging of packed bed. The test facility facilitates the variation of operating parameters such as air flow rate and void fraction.

Results shows that the temperature distribution with respect to time in packed bed for material concrete of shape sphere $\varepsilon = 0.48$. The mass flow rates are 0.021 kg/s and 0.0325 kg/s. The pressure drop for these flow rates and material are obtained. It is seen that the void fraction is more the charging process and discharging process is quick, the void fraction is less the charging and discharging process is slow and vice versa. The energy storage in packed bed is more for void fraction is less and energy storage is less where void fraction more. The pressure drop considers the void fraction is more then pressure drop is less and void fraction is less the pressure drop is more.

References