INVESTIGATION ON PERFORMANCE OF A PACKED BED SOLAR ENERGY STORAGE SYSTEM

A THESIS

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HARMEET SINGH

ALTERNATE HYDRO ENERGY CENTRE
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE-247 667 (INDIA)

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ABSTRACT

Solar energy is the most important energy resource among all renewable energy resources due to its quantitative abundance. Conversion of solar energy into thermal energy is the easiest and the most widely accepted method of utilization of this abundant renewable energy resource. However, due to intermittent nature of solar energy availability, an energy storage system is required to be attached with solar collectors to store energy for use when solar energy is not available. A storage system therefore constitutes an important component of the solar energy utilization system.

The heat energy may be stored as sensible heat or latent heat. The energy storage taking place without the phase change is the sensible heat storage, in which the heat is stored by raising the temperature of the storage medium, whereas in case of latent heat storage phase change of the material takes place. Sensible heat storage may be used with solar water heating as well as solar air heating systems. Rocks or pebbles packed in insulated containers known as packed or rock beds are most commonly used with solar air heaters for thermal energy storage systems for use with solar air heating collectors.

A packed bed storage system consists of loosely packed solid material through which the heat transport fluid is circulated. Heated fluid (usually air) flows from solar collectors into a bed of particles from top to bottom in which thermal energy is transferred during the charging phase. Recovery of this stored energy is usually achieved in discharging mode by circulating cold air from bottom to top.

Literature reveals that properties of the packing material and its size and shape affect the performance of the packed beds. Majority of the research work has been carried out on rocks and pebbles. Materials other than rocks and pebbles have been

studied in few of studies. There have been few studies on the stratification of the packed beds. The high stratification in packed beds can lead to better thermal performance of solar collector and in order to have higher stratification the void fraction should be low. Further, to reduce the pressure drop in the packed bed the size of the elements should be relatively large.

Keeping this in view, it was proposed to investigate the heat transfer and pressure drop characteristics of a packed bed solar energy storage system having packed elements of relatively large size and of different sphericity values in a lower void fraction range. Such a study will be helpful in predicting the best performance of the bed parameters on the basis of thermal performance, friction loss and stratification considerations. Accordingly, research work with the following major objectives was taken up:

(1) Experimental investigation of heat transfer and friction characteristics of storage system as a function of system and operating parameters.

(2) Development of correlations for heat transfer coefficient and friction factor based on the experimental data.

(3) Investigation of performance of the storage system with respect to the thermal energy stored, available energy stored and thermal efficiency of solar collector as function of system parameters of the bed.

(4) Investigation of thermal stratification and its effect on the solar energy collector-storage system to predict optimum values of system parameters.

In order to achieve the above-mentioned objectives an experimental investigation was planned. An experimental set up comprising of sensible heat storage tank containing bed elements, a heating system, a fan, temperature and fluid flow measuring devices has been designed, fabricated and commissioned. The set up has been planned to collect extensive data on heat transfer and fluid flow characteristics of packed bed.

The material elements of five different shapes i.e. sphere, cube and three types of rectangular elements were used in order to collect the experimental data on heat transfer and fluid flow characteristics of the packed bed. The range of the system and operating parameters is listed in Table 1.

Table 1: Range of system and operating parameters

S.No.	Parameter	Range
1.	Void fraction (ε)	0.28-0.48
2.	Sphericity (Ψ)	0.65-1.0
3.	Mass velocity of air (kg/s m^2)	0.155-0.266
4.	Reynolds number	503-866

An error analysis as per the procedure proposed by Klein and McClintock [140] was carried out to determine the uncertainties in the values of major parameters of the investigation, namely, Nusselt number and friction factor. The values of maximum uncertainties were found to be 6.3% and 3.5% for Nusselt number and friction factor respectively.

Nusselt number has been found to increase with increase in Reynolds number for the given values of system parameters. The Nusselt number decreases considerably with increase of sphericity from 0.65 to 0.80 and then increases as the value of sphericity increases from 0.80 to 1.00. The bed comprising of cubical elements ($\psi = 0.80$) has the minimum values of Nusselt number while the spherical shaped elements yield maximum value of Nusselt number. As the value of sphericity increases from 0.65 to 0.80, the flatness of the surface decrease resulting in reduction in the turbulence and hence a decrease in Nusselt number is obtained. In case of spherical shaped elements there is point contact between the spheres and it appears that during flow of air in the bed, air film may remain in contact with the maximum portion of the surface of elements of spherical elements as compared to that for the non-spherical elements. Further, it has also been observed that the bed having lowest void fraction has the maximum values of Nusselt number. It appears that with an increase in void fraction the volume/amount of material packed in the bed decreases and the contact area of flowing air and the material reduces which may lead to a decrease in the value of heat transfer coefficient.

The friction factor has a maximum value corresponding to sphericity of 0.65 and it decreases as the sphericity increases from 0.65 to 0.80 and it further increases slightly with increase of sphericity to 1.0. The increase in the flatness of the surface seems to be predominating effect that results in higher level of turbulence and hence an increase in friction factor as the sphericity is decreased from 0.80 to 0.65. With increase in sphericity from 0.80 to 1.0 there is considerable change in solid-fluid contact and hence a likely increase in friction factor. It has been observed that friction factor increases with decrease in void fraction and is found to be maximum for a void fraction of 0.28. An increase in voids may give rise to the channeling of fluid flow i.e. the reduction in tortuousness of the flow through the bed and hence a reduction in contact area occurs. The number of sharp corners per unit volume also reduce with an increase in void fraction of the bed. These conditions reduce the frictional losses between fluid and solid and consequently the friction factor decreases.

It is revealed from the experimental data that Nusselt number and friction factor are strong functions of system (sphericity and void fraction) and operating (Reynolds number) parameters. Hence experimental data have been used to develop the following Nusselt number and friction factor correlations.

Correlation for Nusselt number:

$$Nu = 0.06\,(\mathrm{Re})^{1.12}(\varepsilon)^{-1.02}(\psi)^{2.51}\exp[(5.30\,(\ln\psi)^{2}]$$

The regression of data for the correlation was found to have:

(i) Regression coefficient value of 0.96

(ii) Average absolute deviation of 3.20%

Correlation for friction factor:

$$f = 374.76\,(\mathrm{Re})^{-0.65}(\varepsilon)^{-0.79}(\psi)^{2.52}\exp[(9.75\,(\ln\psi)^{2}]$$

The regression of data for the correlation was:

(i) Regression coefficient value of 0.98

(ii) Average absolute deviation of 4.82%

It has been observed that the experimental values and the values of Nusselt number and friction factor predicted by the above correlations are in good agreement.

The Nusselt number and friction factor correlations developed in this work have been used to investigate the thermal and hydrodynamic performance of the packed bed solar energy storage system using a mathematical simulation technique. The performance study of the packed bed solar energy storage system has been carried out to determine the temperature distribution, thermal and available energy stored in the bed, energy consumption by fan, thermal efficiency of the solar collector and stratification coefficient during charging of the bed as function of sphericity and void fraction.

It has been observed that the bed having spherical elements (sphericity of 1.00) has the lowest temperature at the lower most layer of the bed for maximum period of time and as such is found to be the most stratified while the least stratified bed is constituted by elements having sphericity of 0.80. It can be observed that the bed with elements yielding maximum heat transfer coefficient lead to higher stratification because more energy is transferred in the upper regions leading to higher temperatures there. The stratification of the bed reduces with increase in void fraction because with increase in void fraction of the bed, the temperature in the lower portion of the bed increases. Thermal and available energy stored in the bed have been found to be maximum for elements with sphericity of 1.00. Thermal energy stored in the bed decreases with an increase in the void fraction for a given value of the sphericity whereas the stored available energy has been found to increase with increase in the void fraction due to higher grade of energy stored. The energy consumed by the fan is found to be maximum for the elements with sphericity of 0.65 and is minimum for the elements having sphericity of 0.80. The thermal efficiency of the collector is found to be maximum for sphericity of 1.0 and void fraction of 0.28.

The stratification coefficient has been determined in order to investigate the effect of void fraction and sphericity on the stratification and it has been seen that stratification is strongly affected by the bed conditions. The stratification coefficient has been found to be maximum for sphericity of 1.0 and a lower value of void fraction yielding considerably more stratified bed. The thermal efficiency of the collector is found to increase with an increase in the stratification coefficient. It has been observed that the thermal efficiency and the stratification are maximum for sphericity of 1.0 and void fraction of 0.28.

Summarizing, it can be stated that an experimental investigation has been carried out in order to collect data related to heat transfer and fluid flow characteristics of an energy storage system consisting of large sized material elements in low void fraction range. Nusselt number and friction factor correlations have been developed on the basis of the experimental data. Mathematical simulation has been

utilized to investigate the effect of system parameters on the values of energy stored, available energy stored, collector thermal efficiency, bed stratification and the effect of stratification on the solar energy collector-storage system. Optimum values of bed parameters have been obtained that result in best thermal performance of solar energy collector-storage system.