ABSTRACT

In view of the growing energy needs and increasing environmental concern, alternatives to the use of non-renewable and polluting fossil fuels have to be investigated. One such alternative is the use of renewable energy sources. These are considered to be capable of overcoming the energy crisis and environmental threat, which are the results of continuous use of fossil fuels. Solar energy is most important among renewable energy resources due to its quantitative abundance. Although the solar energy is available everywhere but its availability is intermittent. It is therefore, necessary to provide a storage system with solar collectors to store energy and to meet the demand in the absence of solar radiation. Packed bed is generally recommended for thermal energy storage in solar air heaters.

Packed bed sensible heat energy storage consists of solid material of good heat capacity packed in a storage tank through which the heat transport fluid is circulated. Solar air heater supplies hot air, which flows through the bed to transfer the thermal energy to the solid particles. The stored thermal energy can be recovered by making cold ambient air flow through the bed. A packed bed has been of interest in view of its several important applications. The heat transfer and pressure drop in the bed have been the subject of several theoretical and experimental investigations. Generally small size storage materials in the size range of 1 to 3 cm have been used to store thermal energy. Small size storage material having large effective surface area can provide high rates of heat transfer, however, it is also accompanied by large pressure drop in the bed. High pressure drop results in substantially large energy consumption to propel air through the bed. This reduces the overall benefit of the solar energy utilization system. Pressure drop in the bed could be reduced with the use of large sized material elements. Reduction in the heat transfer rate to large size material elements due to smaller surface area per unit volume of storage is compensated by substantial reduction in the amount of energy consumption by fan due to low pressure drop in the packed bed. It can therefore be concluded that the large size material could be more beneficial for use as the storage material.

It is well known that the heat transfer coefficient and friction factor relationships/correlations are required to predict the performance of the packed bed system. Most of the relationships reported in the literature are for small size materials, which can not be utilized for the design of packed bed systems using large sized elements because fluid flow and heat transfer characteristics of such systems are substantially different from those with small size materials. The fluid flow through such packed beds follow a very tortuous path, continuously turning through the flow channels formed by the large sized packing material that are highly non-spherical and usually have large number of sharp corners. The shape of the packing material and void fraction of the bed determine the size and distribution of the channels. The effect of these parameters is required to be taken into account along with the operating parameters for accurate prediction of heat transfer and pressure drop in the bed. Since the generalized heat transfer coefficient and friction factor correlations are not available in the literature which could predict the thermal and hydrodynamic performance of the system for different shapes of the large size material elements at different void fractions of the bed, it was planned to investigate the heat transfer and pressure drop characteristics of the packed bed with the following objectives:

i) To investigate the effect of system parameters on heat transfer and pressure drop characteristics of packed bed as function of the operating conditions.

ii) To develop the correlations for heat transfer coefficient (Nusselt number) and friction factor as function of the system (shape of material elements and void fraction of the bed) and operating parameters (Reynolds number).

iii) To investigate thermal and hydrodynamic performance of the packed bed solar energy storage system.

iv) To determine the optimum values of system parameters that yields the best thermohydraulic performance of the packed bed solar energy storage system.

In order to meet the above-mentioned objectives, an extensive experimental investigation has been planned. An experimental set up comprising of sensible heat storage tank containing bed elements, a heating system, a fan, temperature and fluid flow measuring system 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 data on air temperature and material temperature at different locations inside the packed bed and pressure drop across the bed were collected for six different mass velocities of air ranging from 0.155 to 0.266 kg/s m^2 for each set of different material shapes and void fraction of the bed. In order to take into account the effect of temperature gradients inside the material elements on heat transfer coefficient, values of a new parameter called apparent volumetric heat transfer coefficient have been determined.

To investigate the effect of material shape on heat transfer coefficient and pressure drop in the packed bed, material elements of five different shapes i.e. concrete cubes, standard masonry bricks, concrete spheres, standard masonry tile bricks and T-joint masonry tile bricks have been used. Sphericity parameter (ψ) is used to represent the shape of material elements. Table 1 gives the range of system and operating parameters used in the present investigation.

Table 1 : Range of system and operating parameters

Parameter	**Range**
Sphericity (ψ)	0.55 - 1.00
Void fraction (ε)	0.306 - 0.630
Mass velocity of air (G)	0.155 - 0.266 kg/s m^2

Nusselt number (Nu), friction factor (f) and Reynolds number (Re) have been used to represent the heat transfer coefficient, pressure drop and operating conditions respectively in non-dimensional form. It has been observed that Nusselt number and friction factor are strong functions of sphericity of material elements, void fraction of the bed and Reynolds number. Nusselt number has increased monotonously with increase of Reynolds number; however, friction factor has decreased with increase of Reynolds number for a given value of sphericity and void fraction. In the beds of non-spherical elements presence of sharp corners results in enhanced level of turbulence, which enhances the heat transfer as well as friction losses. However the surface contacts in the case of non-spherical elements reduce the solid-fluid contact area as compared to the bed of spheres. Nusselt number and friction factor have been found to vary considerably with change of sphericity of material elements under the given operating conditions. A minima is observed correspond to a sphericity of 0.80 for both the heat transfer coefficient and friction factor. It is observed that Nusselt number and friction factor decrease with increase of sphericity from 0.55 to 0.80 and then increase with further increase of sphericity.

The changes in the values of heat transfer and friction parameters with sphericity and void fraction are substantial which call for a judicious selection of these parameters to result in maximum heat transfer gain for a minimum friction penalty. Using the experimental data following correlations for Nusselt number and friction factor have been developed as function of Reynolds number, sphericity and void fraction.

Correlation for Nusselt number:

$$Nu = 0.437(\mathrm{Re})^{0.75}\,(\psi)^{3.35}\,(\varepsilon)^{-1.62}\left\{\exp\left[29.03(\log\psi)^{2}\right]\right\} \qquad (1)$$

Correlation for friction factor:

$$f = 4.466(\mathrm{Re})^{-0.2}\,(\psi)^{0.696}\,(\varepsilon)^{-2.945}\left\{\exp\left[11.85(\log\psi)^{2}\right]\right\} \qquad (2)$$

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. Validity of the correlations has been checked by comparing the values generated from the correlations developed by previous investigators reported in the literature and those generated from the these correlations for the given values of the sphericity and void fraction of the bed. A good agreement has been observed.

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

It has been observed that heat transfer coefficient has considerable effect on the stratification of the bed. The bed having spherical elements (sphericity of 1.00) found to be the most stratified and the least stratified bed was with elements having sphericity of 0.80. Thermal and available energy stored in the bed has been found to be maximum for elements with a sphericity of 1.00 while the bed with the elements of sphericity of 0.80 had minimum values. 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. This rise in availability of energy has been seen to be brought about by the relatively higher grade of energy stored when void fraction is increased even when the amount of thermal energy stored is relatively smaller. This is an important conclusion, which may help the designer in deciding the storage geometry for optimal conditions.

Major expenditure to operate the packed bed energy storage system is the energy consumption by the fan to propel the air through the bed. The stratification of the bed has considerable effect on the energy consumption by fan and thermal performance of the collectors. Since the objective of the system designer is to have minimum energy consumption by fan per unit energy stored, the design of the system should be based on thermohydraulic performance rather than the thermal performance alone. For this purpose optimization of the system parameters has been carried out to make an optimal combination of the available energy stored in the bed and the energy consumption by fan to propel the air through the bed. Considering available energy stored in the bed (Q_{at}) and the energy consumption by fan (W_t) for pumping air through the bed, thermohydraulic optimization of the packed bed solar energy storage system has been carried out on the basis of maximizing the optimization parameter 'Q_{at}/W_t'.

Design plots have been prepared that can yield the optimum value of system parameters namely sphericity and void fraction of bed for given values of operating parameters i.e. temperature rise parameter '$\Delta T/I$' and average insolation (I).

Summarizing, it can be stated that data on heat transfer and flow characteristics of an energy storage system consisting of large sized material elements has been collected as a result of extensive experimentation. The experimental results have been utilized to develop heat transfer and friction correlations that have been employed to prepare design plots on the basis of thermohydraulic optimization of energy storage system. These plots can be used by the designer for the selection of optimum values of the set of sphericity and void fraction of the system that will yield best thermohydraulic performance of the packed bed solar energy storage system under the given operating conditions.