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Investigation on Performance of a Packed Bed Solar Energy Storage System Having Large Sized Cylindrical Elements with Perforation

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INTRODUCTION

The solar energy is available freely but its nature is intermittent and unpredictable. So, for utilization of solar energy at constant rate it is important to store solar energy when it is available and use it later when solar is not available. To store solar energy we use packed beds. Packed bed receive hot fluid from solar collectors during charging i.e. storing solar energy top to bottom. When packed bed is discharged cold air is circulated in reverse direction. Hasnain (1998) mentioned that there should be no boiling and freezing of storage material during charging or discharging. Since Schumanns's work (1929) various theoretical and experimental investigations have been carried out on working fluid to transfer heat. The governing parameters for performance of the system are: the temperature difference of fluid and solid, mass flow rate of the fluid, the geometric characteristics of the packed bed and bed porosity. Packing of storage material is also important role but to obtain definite porosity element can be arranged in any manner (Singh, 2006).

The major disadvantage of packed bed storage system is energy consumption to propel the air. To overcome this disadvantage large size storage material can be used which reduce the thermal performance of packed bed. Kulakowski and Schmidt (1982) reported that in a design of packed bed vary due to different diameter of storage bed and energy consumption by fan. According to Gauvin and Katta (1973) operating cost of storage bed effects due to pressure drop in the bed.

Rocks, pebbles and gravels have been mostly used for the study of packed bed. The rocks used in packed beds have a size is between 0.01 and 0.03 m (Sagara and Nakahara, 1991). Duffie and Beckman (1991) stated that large size storage elements reduce the pressure drop but thermal performance also decreases. Standish and Drinkwater (1970) reported that element shape is a major parameter for liquid or gas as a fluid medium.

The system performance is therefore affected considerably by the two major parameters i.e. shape and void fraction of the elements. Singh et al. (2006) investigated different shapes of storage materials of large size. Although this experimental investigation was quite large sized elements, however, a critical appraisal reveals the following limitations:

i. Bed to element size ratio is low (bed diameter of 750 mm and diameters of elements is 150 mm yielding the size ratio range of 3.2-4.8) to ensure the homogeneity of the flow parameters.
ii. Void fraction values have been varied only for one shape of the element (w=0.72).
iii. Reynolds number ranges are different for different shapes of the elements considered.

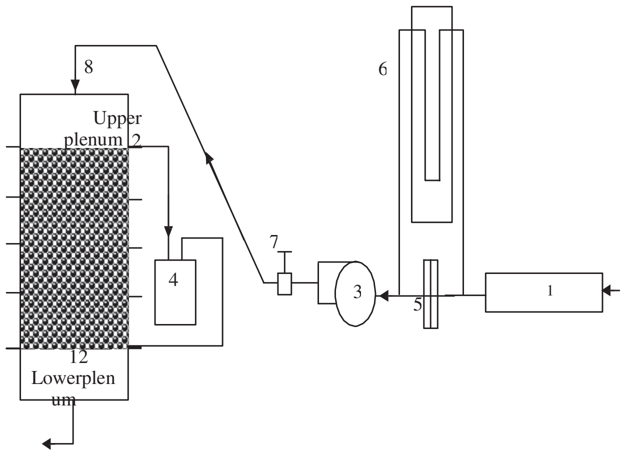
OBJECTIVE OF THE STUDY

Temperature distribution in the packed bed solar storage system determines the overall performance of solar air heating system (Phillips, 1981). Thermal efficiency of system performance is affected by the temperature stratification (Haller, 2009). The stratification is known to improve with decrease of void fraction of the bed, hence rhombohedral packing of the bed is done. Decreasing void fraction increase heat transfer area, thermal storage capacity and mass of storing material.

EXPERIMENTAL SETUP

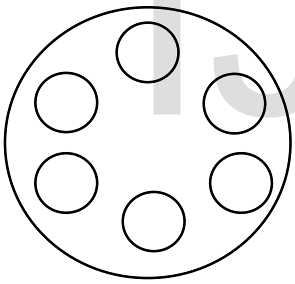
An experimental setup was planned and made up to achieve the desired objectives. Fig.1 represents the schematic of the fabricated setup. A tank made of mild steel (MS) sheet was used for storage. A value of 10 for the ratio of diameter of the bed to element size has been used in order to have a homogeneous system. The bed was 0.75 m high with 0.18 m long upper and lower plenums, which accounted to the total height of 1.10 m. the thermocouple wires were put in the tank with taps on the bed for measurement of temperature at different location. For the flow of air into or out of the storage the pipes were fitted on the tank. The top cover of the tank could be lifted with the help of handles and rubber packing was provided below the cover for tight fitting with nuts and bolts .To reduce the heat losses the polyethylene foam was used. An air duct of rectangular cross section having its topside as electric heater has been provided for supplying the hot air to bed. The heater was capable of supplying a heat flux of

1000W/m^2. To suck the air through the duct and to supply the hot air to the bed, a blower with a control valve is used. The blower was a centrifugal fan driven by a 2 kW, single phase, 230-v and 2880-rpm motor.



INSTRUMENTATION

An orifice meter having a U-tube manometer with water as manometric fluid measured the rate of flow of air. A control valve was used to vary flow rate. A micro-manometer was used to determine the bed pressure drop. J-type thermocouples were used to find the temperatures in the bed.



Top view of 6-Hole Perforated Cylinder

The thirty eight thermocouples were fixed on the surface of elements by boring shallow grooves before packing. These elements were put at desired pre-determined locations in the bed, for the measurement of air temperature near these locations in the voids.

METHODOLOGY

Through rhombohedral arrangement, the lowest value of void fraction be obtained.To obtain the required void fraction the number of elements, number of layers and number of elements in each layer were calculated and filled in the bed.The packing of the elements was done in staggered manner. The elements have been packed with great care in order to have approximate uniform distribution of voids and minimum possible surface contact in the bed.

The top cover of the tank was filled tightly and the tank was connected to the air supply. The measuring instruments were checked and the U tube and the micro manometer leveled and marked. The liquid level in the micro manometer was precisely marked before the start of air supply. The blower was started by fully opening the control valve and then the heater was given electric supply. The air flow rate was controlled with control valve and the input to heater was adjusted with the variac. For each set of experimentation the system was run continuously for 8hrs.For each run of experimentation the following parameters were calculated:

i. Differential heat (D_{h1}) in the orifice meter from U tube manometer.
ii. Head loss in the bed (D_{h2}) from micro-manometer.
iii. Air temperature at different locations.
iv. Surface temperature of material elements at different locations.

DATA REDUCTION

The flow rate of air (m_a) (Saini and Saini, 1997) and volumetric heat transfer coefficient (h_v) were determined as:

$$m_a = C_d A_o \left[\frac{2\rho_a \Delta P_1 \sin\theta}{(1-\beta^4)} \right]^{\frac{1}{2}} \quad (1)$$

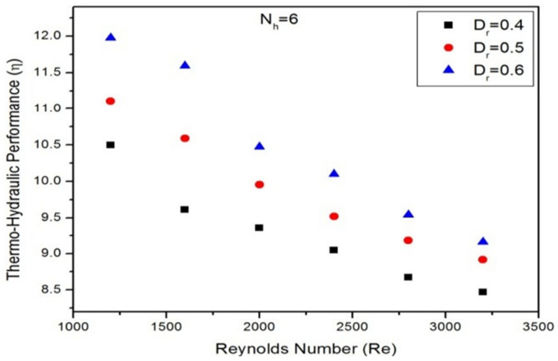
$$h_v = \frac{m_a c_p (T_i - T_0)}{V_b (T_a - T_s)} \quad (2)$$

Values of apparent volumetric heat transfer coefficient (h_v^*) have been determined as reported by Gauvin and Katta (1973).

$$h_v = \frac{3h_v}{(B+3)} \quad (3)$$

$$B = \frac{h_v R^2}{3K_s(1-\varepsilon)} \quad (4)$$

The data were changed to dimensionless parameters as Reynolds Number (Re) proposed by Chandra and Willits (1981), Nusselt Number (Nu) proposed by Kulakowski and Schmidt (1982) and friction factor (f) proposed by Hollands and Sullivan (1984). These are expressed as:



$$Nu = \frac{h_v^* D_s^2}{K} \qquad (5)$$

$$\mathrm{Re} = \frac{G D_s}{\mu_a} \qquad (6)$$

$$f = \frac{\Delta P_b \rho_a D_s}{G^2} \qquad (7)$$

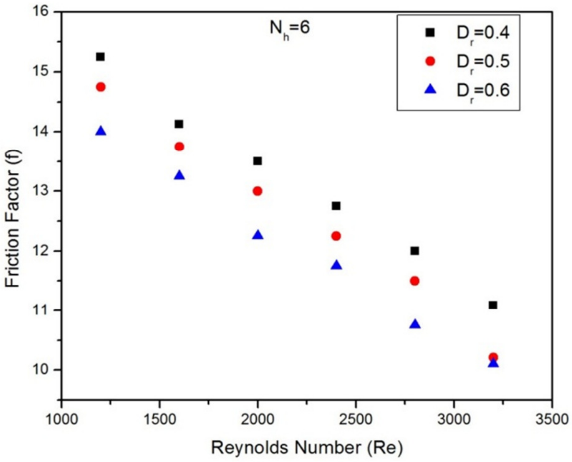
UNCERTAINITY ANALYSIS

An error analysis was done to determine the uncertainties as suggested by Kline and McClintock (1953). To have maximum possible uncertainty in measurements, the uncertainties have been calculated at maximum value of mass velocity employed in the experimental investigation. The values of maximum uncertainties were 6.33% and 4% respectively for Nusselt Number and Friction factor.

RESULTS AND DISCUSSIONS

NUSSELT NUMBER

The effect of number of perforation on the Nusselt Number is given in fig. for perforation ratio of 0.6. There is an increase in Nusselt Number with increase in the number of perforation. Maximum value of Nusselt Number has been observed corresponding to the highest number of perforation and at maximum Reynolds Number.



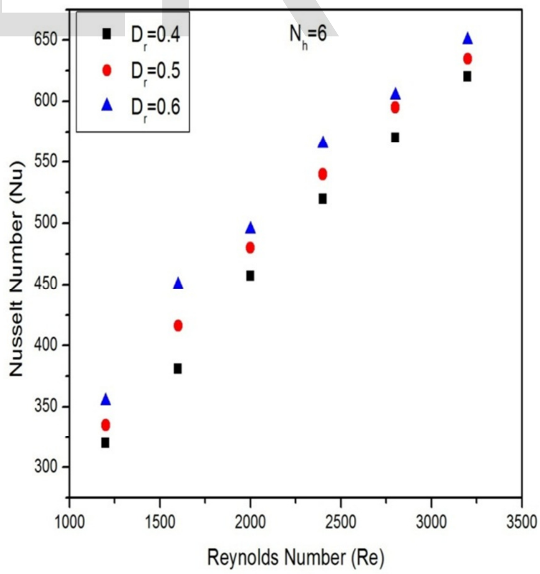
The Nusselt Number then gradually increases as the number of perforation increases.A change of patterns of flow and contact area for heat transfer may be responsible for this type of change in Nusslet Number. It seems that with air flow in the bed, there is more surface contact of the air film.

FRICTION FACTOR

Fig shows the variation of friction factor with Reynolds nuber corresponding to different perforation ratio. It is observed that friction factor decreases when the Reynolds number increases at all values. The maximum value obtained for 0.4 perforation diameter.

THERMO-HYDRAULIC PERFORMANCE

It has been seen from the study that with an increase in heat transfer, there is also an increase in the friction factor. Thus to have utmost improvement in heat transfer with minimum friction factor. Therefore to have simultaneous considerations of thermal along with hydraulic performance, a thermo-hydraulic parameter as recommended by Webb (1979) has been used.



$$\eta = \frac{St}{f^{\frac{1}{3}}}$$

The variation of this parameter with perforation ratio is shown in fig . The thermo-hydraulic parameter increases gradually as number of holes increases. The maximum value at corresponds to 6 hole and 0.6 perforation ratio.

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