International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 1 Issue 4, June - 2012

Development and thermal analysis of new class of storage elements

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Abstract

Developing efficient and inexpensive energy storage devices is an important as developing new sources of energy. The material element was designed for storing high charging and low discharging efficiency. The size of the element was taken such that exposed contact surface area could be high. The thermal energy storage (TES) can be defined as the temporary storage of thermal energy at high or low temperatures. . Energy storage can reduce the time or rate mismatch between energy supply and energy demand, and it plays an important role in energy conservation. Energy storage improves performance of energy systems by smoothing supply and increasing reliability. For example, storage would improve the performance of a power generating plant by load leveling. The higher efficiency would lead to energy conservation and improve cost effectiveness. The demand for energy, on the other hand, is also unsteady following yearly and diurnal cycles for both industrial and personal needs. The thermal properties are strongly influenced by the deposit physical structure, i.e. the particle size distribution, the porosity and the degree of sintering. Thermal storage can utilize sensible or latent heat mechanisms or heat from chemical reactions. Sensible heat is the means of storing energy by increasing the temperature of a solid or liquid. Latent heat, on the other hand, is the means of storing energy via the heat of transition from a solid to liquid state.

Keywords: Thermal properties, Reynolds's number, Friction factor, Nusselt number.

1. Introduction

Energy densities for a concrete-based thermal storage system have been estimated at 22 kWh/m^3, resulting in 50 000 m^3 sized storage for a 50 MW parabolic trough power plant with 1100 MWh$_{th}$ storage capacity [1]. As it will be shown in the analysis that follows, efficient thermal storage is accomplished through stratification [2] and effective heat transfer. Porous structures which maximize heat transfer between fluid and storage media and minimize heat transport inside the storage media fulfill both requirements. Stratification is also enhanced by a minimized cross-sectional area normal to the fluid flow direction. A wide body of publications describes numerical models for sensible heat storage in packed beds, but only a few include experimental validation, noteworthy among these are Coutier and Farber [3], Beasley and Clark [4], and Adebiyi et al. [5]. Early literature focused on describing the transient behavior and expanding the range of operating conditions beyond those applicable to the analytical solution of the Schumann model [6] and the various numeric modeling approaches were compared by Ismail and Stuginsky [7]. Multiple studies have evaluated the second law efficiencies, thus accounting for the energy lost due to the effects of viscosity and other irreversibilities [8-11]. An aspect rather neglected so far is the behavior of a thermal storage over multiple charge and discharge cycles. For repetitive consecutive cycles, a cyclic steady state will manifest itself. This important effect was studied in detail in only one recent publication [12], albeit for a generic application and using a model that had not been experimentally validated.

2. Thermal properties of a deposit

The deposit thermal properties, i.e. the thermal conductivity and the surface emissivity, are of great importance for an accurate heat transfer model. The thermal properties are strongly influenced by the deposit physical structure, i.e. the particle size distribution, the porosity and the degree of sintering. The radiative properties depend solely on the surface conditions, while the conductive properties depend on physical data throughout the deposit. The effective thermal conductivity of a two-phase gas–solid system depends on: (1) the thermal conductivity of solid phase k_s, (2) the thermal conductivity of gas phase k_g, (3) the porosity, (4) the size distribution of pores or particles, and (5) the deposit sintering state. The properties k_s and k_g are dependent on the temperature and the chemical composition of the respective phases. Since the thermal conductivity of a solid phase is two to three orders of magnitude greater than the one of a gas phase, heat conduction through a deposit, will primarily occur through the solid phase [13].

3. Packed bed energy storage system

A packed bed is a volume of porus media obtained by packing particles of selected material into a container. A number of studies carried out on packed beds for their performance analysis were reported in the literature. These studies included the design of packed beds, materials used for storage, heat transfer enhancement, flow phenomenon and pressure drop through packed beds. Schematic of a packed bed energy storage system is shown in Figure 1. A packed bed in a solar heating system does not operate normally with constant temperature. During daytime different conditions like solar radiations, ambient temperature, collector inlet temperature and load requirements result in a variable collector outlet temperature. The optimum size of the storage system is a function of several system parameters such as storage temperature, material, storage heat losses, costs of the storage medium container, heat exchanger, cost of auxiliary energy and operating conditions such as insulation, ambient temperature, wind speed and solar fraction of the total heat load. Energy can be stored in rocks or pebbles packed in insulated vessels. This type of storage system is used very often for temperatures up to 100 ^{0}C in conjunction with solar air heaters. It is reported to be simple in design and relatively inexpensive. Direct contact between the solid storage media and a heat transfer fluid is necessary to minimize the cost of heat exchange in a solid storage medium. The use of rocks for thermal storage provides advantages such as (i) rocks are non-toxic and non-flammable, (ii) rocks are inexpensive and (iii) rocks act both as heat transfer surface and storage medium. The heat transfer between air and a rock bed is good, due to large heat transfer area, low effective heat conductance of the rock pile and small area of contact between the rocks. Theses factors contribute the advantage of low heat losses from the pile.

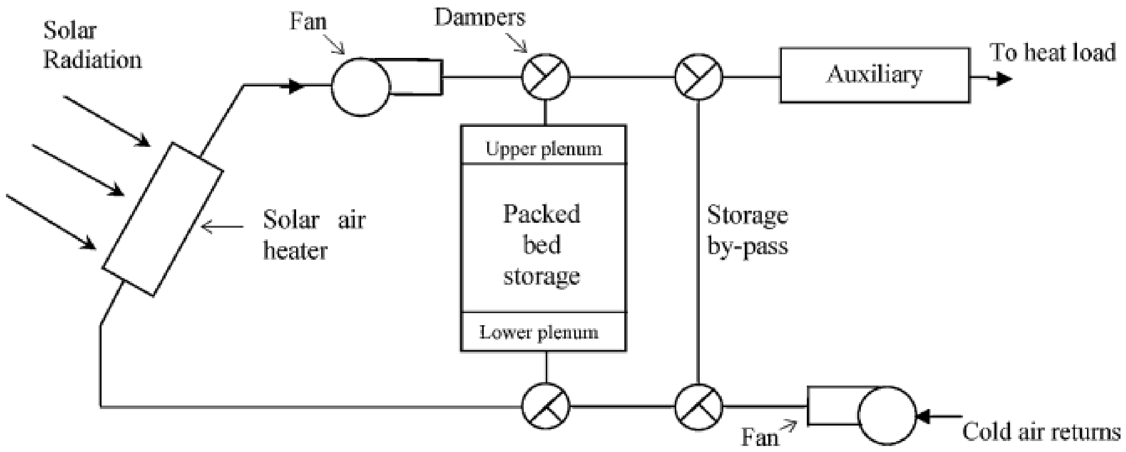


Figure 1 Schematic of a packed bed energy storage system

4. Experimental analysis of packed bed energy storage system

Furnas [14] probably conducted the first experimental study for heat transfer from a fluid stream to a bed of broken solids. He concluded that the coefficient of heat transfer varies along a straight line with gas velocity. The temperature of gas was reported to have a little effect on heat transfer coefficient and the degree of packing in a bed having a very large influence on resistance to fluid flow. A considerable variation in heat transfer for different materials was observed and the value of heat transfer coefficient decreased with an increase in particle diameter. There was no significant difference between the different iron ores studied when they were put on a common void basis. Colburn [15] used granular materials, pebbles, porcelain balls and zinc balls of different sizes in the experimental study on heat transfer between air flowing through a filled tube with granular materials. The particles with smaller diameter, i.e. with higher values of inter phase surface area per unit volume cause a large degree of stratification in the bed. On contrary particles with large diameter degrade stratification. Audi [16] tested small sized rocks for the stability analysis and their possible use as storage materials. Some of tested rocks such as Tarsand and Zeolite disintegrated under the operational environment. However, Jordian Basalt and Limestone demonstrated excellent stability during the tests and their storage properties were acceptable. Sagara and Nakahara [17] suggested that the improvement of thermal performance and the reduction of friction in the packed beds are a trade-off in designing air based solar heating systems. The energy performance of solar heating systems using various kinds of storage materials were suggested to be investigated in order to prepare data with which designers can select the optimum storage material for their purpose. In case of large sized materials temperature gradient inside the solid cannot be ignored. It was found that thermal performance for a large size material like brick and concrete blocks was poor but they required less power supply to run the fans. They reported that the large size materials had almost the same thermal performance as small size materials in a solar heating system with a heat pump. If the bed is longer, the difference of fan energy between large and small materials becomes greater and then in that case, large size materials may be more favorable as storage materials. They mentioned that economic evaluation might become a decisive factor for the ability to utilize large size materials. El-Kassaby and Ghoneim[18] analyzed natural soil for air based system and water for water based system in the sensible heat storage systems to study the variations in the amount of energy stored with time. They reported that the use of soil as storage material is possible instead of water, but additional collector area must be provided. Using a stratified air tank, the system efficiency can be increased by 5% and amount of heat stored by 25% over a day. The use of water system was found superior from the heat capacity point of view, but there were problems in maintaining the system.

5. Design of storage material particles (Elements)

Thermal storage can utilize sensible or latent heat mechanisms or heat from chemical reactions. Sensible heat is the means of storing energy by increasing the temperature of a solid or liquid. Latent heat, on the other hand, is the means of storing energy via the heat of transition from a solid to liquid state. For each material, the low and high temperature limits are given. These limits, combined with the average mass density and heat capacity, lead to a volume-specific heat capacity in kWht per cubic meter. The selection of the type of storage material has been based on the recommended energy storage material in the literature for packed bed system. This material should be such type that we can formed easily in any shape according requirement.

Our cylindrical particles are made of cement and sand. The dimensions of particle are

(a) Diameter of particle (D_p) =12 cm, Length of particle (L_p) =10.5 cm

(b) Diameter of particle (D_p) =10.5 cm, Length of particle (L_p) =10.5 cm

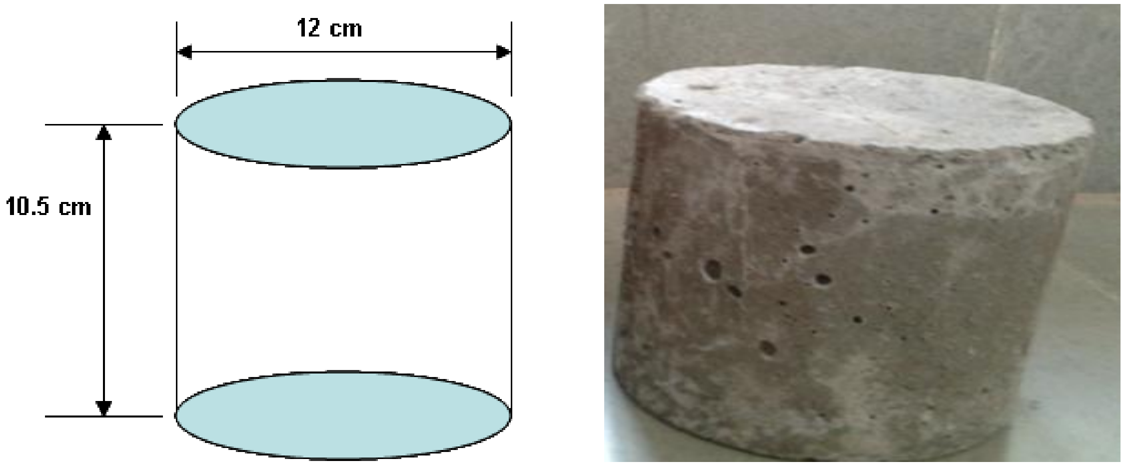


Figure 2 Schematic diagram and prepared material element for 12 cm diameter

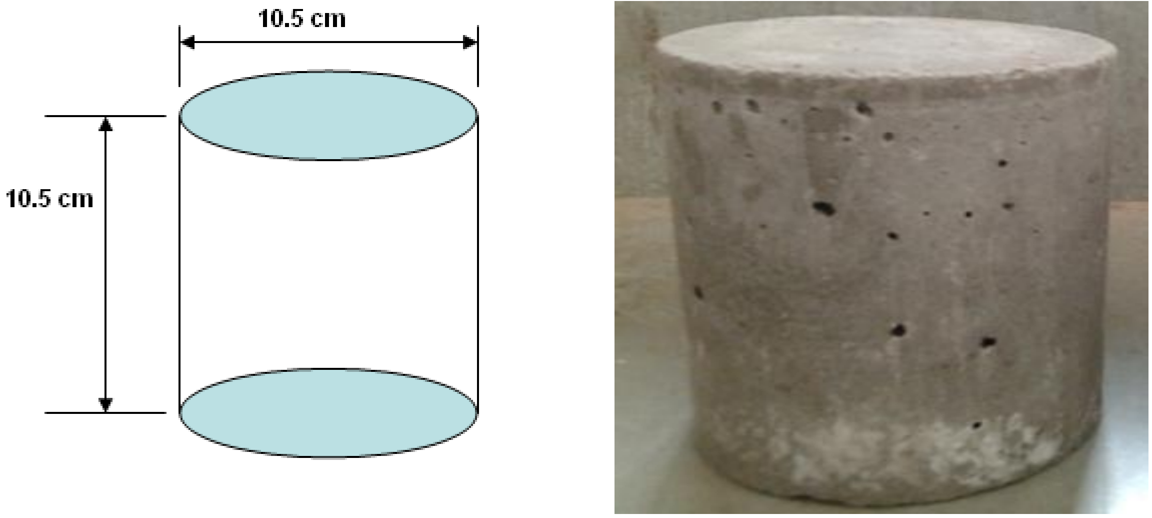


Figure 3 Schematic diagram and prepared material element for 10.5 cm diameter

6. Experimental apparatus

The schematic diagram of the channel flow loop and the test section is shown in Figure 3.4. The flow system consists of an entry section, the test section, the exit section, a flow meter and centrifugal blower. The duct comprised 25 mm thick wooden panels and the size of the duct was 2650 x 405 x 35 mm. The test section was 405 mm in width, 35 mm in height and 1000 mm in length. The entry and exit lengths were 1100 and 900 mm, respectively, including the length of plenum on the exit side of the duct. An electric heater having a size of 2100 x 405 mm was fabricated by combining series and parallel loops of heating wire on a mica sheet to get uniform heat flux. The backside of the heater was insulated with glass wool, to minimize the heat losses. The heater was used on the top of the duct and controlled by a variac. The absorber plate of the duct being a 20 SWG MS sheet of 2100 x 425 mm size was painted black and artificial roughness was produced on its underside by fixing expanded metal. The mass flow rate of the air was measured by means of an orifice meter connected with an inclined manometer, and the flow was controlled by the control valves provided in the lines.

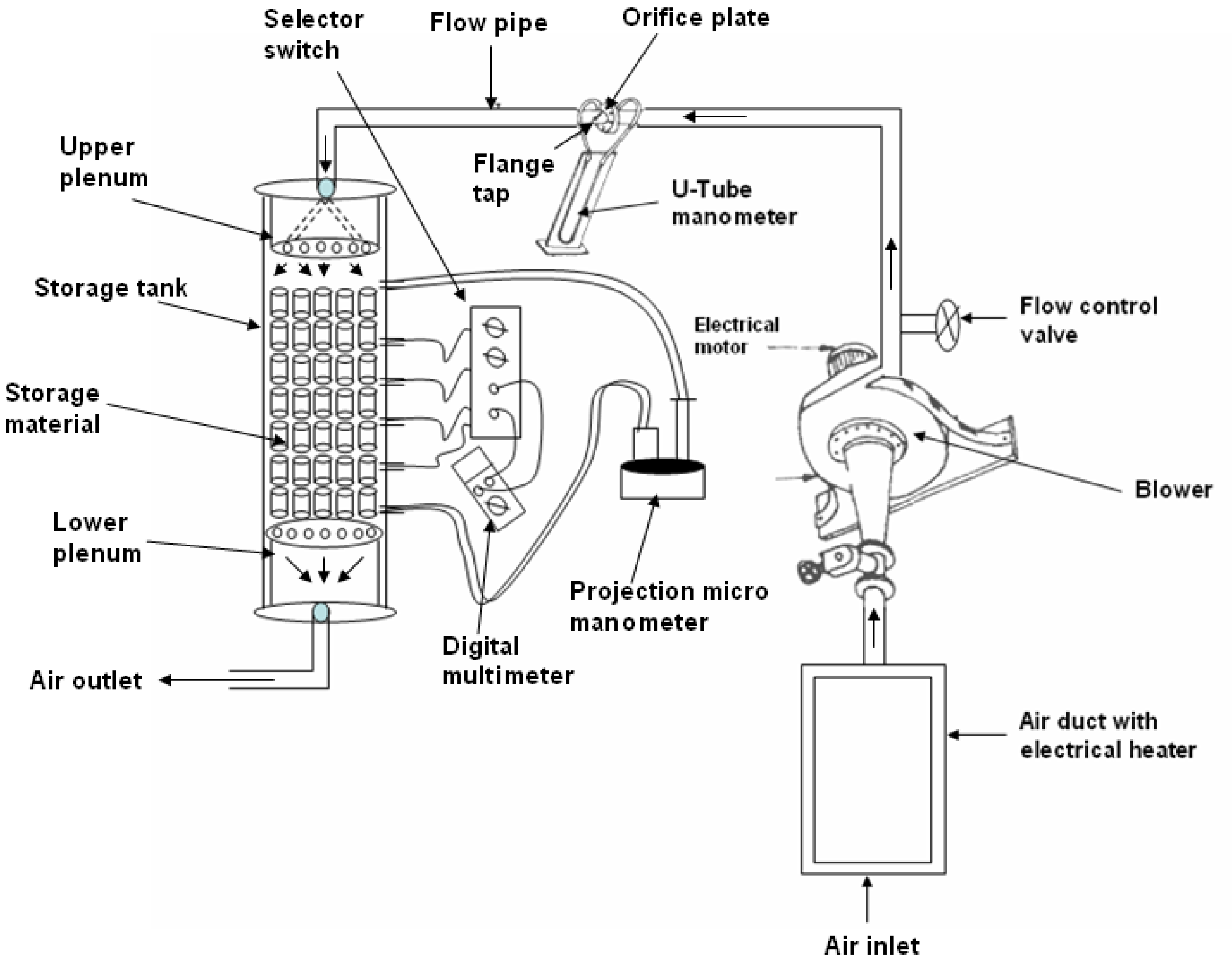


Figure 4 Schematic diagram of experimental set-up

7. Results and discussion

7.1 Effect of void fraction on Nusselt number and friction factor

Figures 5 and Figure 6 have been drawn to represent the Nusselt number against Reynolds number for loose and tight packing derived from the test results as a function of the system and operating parameters. It can be seen from the figures that for given values of roughness parameters, the Nusselt number monotonously increases with increasing Reynolds number. It can also be seen from these figures that the enhancement in heat transfer also increases with an increase in Reynolds number. Figure 5 and Figure 6 depicts the average Nusselt number as a function of Reynolds number for a aspect ratio of (L/D) values of 1.75, 1 and 0.875 . It is seen that for all Reynolds number values, Nusselt number increases with decrease in void fraction in relative from 0.3901 to 0.2941. The occurrence of maxima in the heat transfer coefficient with variation of the parameter of relative void fraction appears to be in line with the observation of Han et al. [19], who reported that the heat transfer coefficient is a function of the angle of attack of the flow with the roughness elements and that an angle of about 60 corresponds to the maximum heat transfer coefficient.

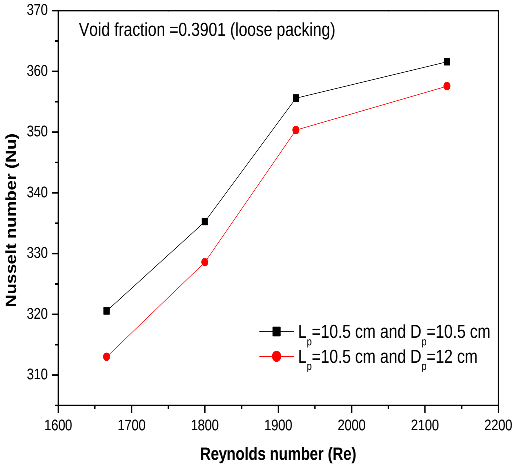


Figure 5 Variation of Nusselt number against Reynolds number for loose packing

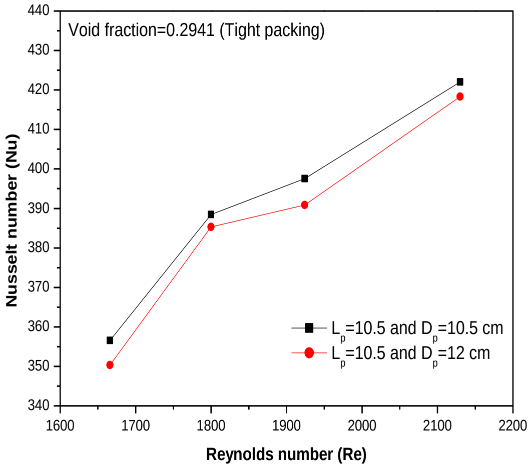
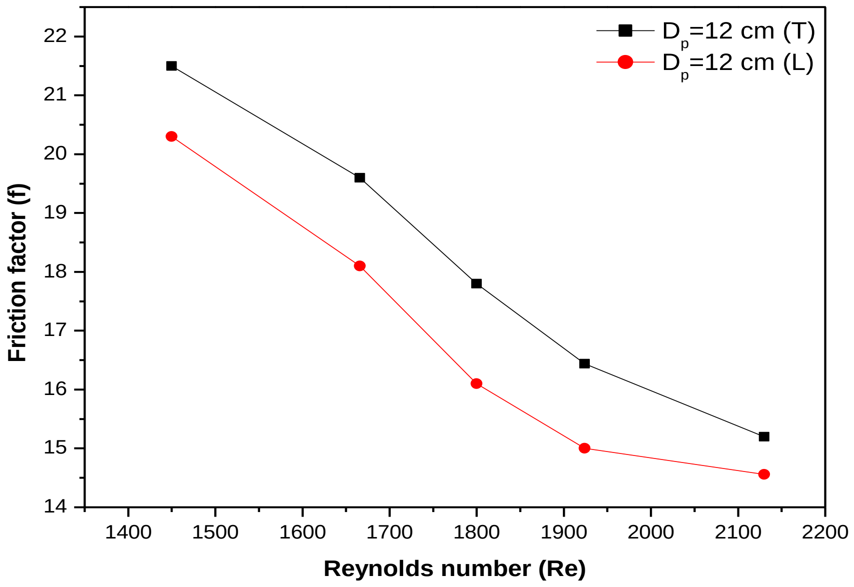


Figure 6 Variation of Nusselt number against Reynolds number for tight packing

7.2 Effect of mass flow rate on Nusselt number and friction factor

Increasing flow rates increases the centrifugal forces. The effect of increasing centrifugal force is significant at the outer region, where it is dominant at the outer part and symmetry is established at this zone. Figure 5 and 6 shows developing of Nusselt number, while the curves for all situations show an initial decrease in the Nusselt number. Initially, the secondary flow causes a few increasing on the boundary layer temperature. After reaching to a minimum, the Nusselt number beings to increase. This is a sign that the secondary flow resulting from the centrifugal and buoyancy force starts to influence the temperature boundary layer. In a given flow rate an increase in particles concentration causes a increase in Nusselt number. It is acceptable for low as well as high flow rate that are shown in Figure 5 and 6.



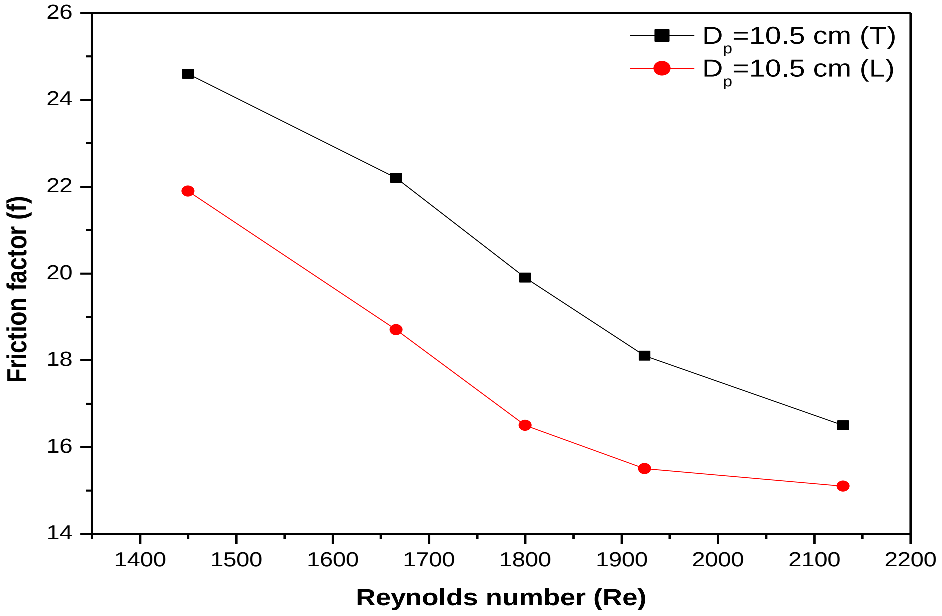


Figure 7 Effect of mass flow rate on friction factor

Conclusions

This experimental investigation on packed bed heat storage system has lead to the following specific conclusions.

- The design of storage material element kept the active surface area per unit volume material high.
- The Pressure drop through bed matrix was low.
- Solid cylinder gave at least 14.5% more surface area then sphere of equivalent volume.
- When particle aspect ratio (l_p/d_p) decreases, heat transfer rate decreases.
- In case of packed bed, the most significant parameter is the tube (bed) to particle diameter ratio d_t/d_p. it is found that where $d_t/d_p < 10$, the total pressure drop ΔP is very sensitive to the bed voidage, (ε).
- The storage tank of internal diameter of 45 cm is made of MS sheet of 3mm thickness. Tank height is 110 cm including upper and lower plenums of height

22.2 cm each. Thus the actual packed bed height is 65 cm. These plenums with distribution vanes are provided for proper distribution of air in the bed. The length of upper and lower plenum is decided as 22.2 cm as per the recommendation of Holland. The lower and upper part of storage tank each are made by two circular plates diameter of 43 cm and 55 cm which are weld on a box of MS channels. That 43cm diameter plate is provides support to storage material in the storage tank and plate of 55 cm diameter is used as a cover plate. This tank is mounted on a stand which is made of MS channels.

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