PERFORMANCE OF A PACKED BED SOLAR ENERGY STORAGE SYSTEM HAVING RECTANGULAR ELEMENTS AS STORAGE MATERIAL

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Abstract— A storage system constitutes an important component of the solar energy utilization system. Packed bed generally represents the most suitable energy storage unit for air based solar energy systems. A packed bed is a volume of porous media obtained by packing particles of selected material into a container. An experimental study on a packed bed solar energy storage system has been conducted and reported in this paper. Packing of small sized particles requires a large pressure drop for uniform flow of hot air through the bed, which causes a large amount of energy consumption to propel hot air through the bed. Four different types of rectangular concrete elements of relatively large size have been used as the storage material in order to reduce the energy consumption. The storage elements are arranged differently and uniformly to obtain four void fraction values and the range of Reynolds number is taken from 500 to 866.The effect of system and operating parameters on the heat transfer and pressure drop characteristics has been investigated.

I. INTRODUCTION

The energy from sun has intermittent nature, often unpredictable and diffused; this makes the energy storage critically important. The storage of energy of a solar process is necessary in order to have uninterrupted supply of energy in absence of availability of solar energy. Thermal energy storage is of particular interest and significance in using this technique for solar thermal applications. Packed beds represent the most suitable storage units for air-based solar system. Heated fluid flows from solar collectors into a bed of graded particles from top to bottom in which thermal energy is transferred during the charging phase as shown in Fig.1. Recovery of this stored energy is usually achieved in discharging mode by circulating air from bottom to top. The high heat transfer coefficient between the air and solid causes quick heat transfer from air to the solid. The optimum size of the storage system depends on the particular application concerned and is a function of several parameters such as storage temperature, material, storage heat losses, weather data such as insolation, ambient temperature, collector area, efficiency etc.

Hasnain [1] suggested that with packed beds the energy could be stored at low as well as high temperatures, since these solid materials used for storage do not freeze or boil.

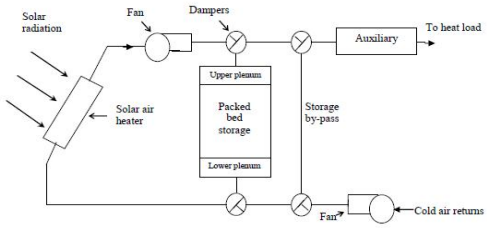


Figure 1 Schematic Diagram of a Packed Bed Solar Energy Storage System

II. NOMENCLATURE

A_o	[m^2]	Cross sectional area of orifice meter
C_d		Coefficient of discharge of orifice meter
c_p	[J/kg-K]	Specific heat of air
D_s	[m]	Sphere diameter
f		Friction factor
G	[kg/s-m^2]	Mass velocity (mass flow rate of air / bed cross-sectional area),
h_v	[W/m^3-K]	Volumetric heat transfer coefficient
$h_v{}^*$	[W/m^3-K]	Apparent volumetric heat transfer coefficient
K	[W/m-K]	Thermal conductivity of air
$\dot{m}$	[kg/s]	Mass flow rate of air
Nu		Nusselt number
ΔP	[Pa]	Pressure drop across the orifice meter
ΔP_b	[Pa m^{-1}]	Pressure drop/ bed length
Re		Reynolds number
$\overline{T}_i$	[°C]	Average temperature of air at bed inlet
$\overline{T}_o$	[°C]	Average temperature of air at bed exit
$\overline{T}_a$	[°C]	Average temperature of air in the bed
$\overline{T}_s$	[°C]	Average surface temperature of elements in the bed
V_b	[m^3]	Volume of packed bed
V_s	[m^3]	Total volume of spheres packed in the bed
θ		Tilt angle of U tube manometer
β		Ratio of orifice and pipeline diameter
μ_a	[kg/s-m]	Dynamic viscosity of air
ρ_a	[kg/m^3]	Dynamic viscosity of air
ε		Void fraction

The heat transfer to and from a flowing fluid to a packed bed has been the subject of many theoretical and experimental investigations since Schumann's [2] work. The rate of heat transfer to or from the solid in a packed bed is a function of the physical and thermal properties of the fluid and solid, the temperature difference between the fluid and the solid, mass flow rate of the fluid and the geometric characteristics of the packed bed material which depends upon the shape and orientation of the packing material and on the bed porosity. The packing is usually random, where particles of apparently the same size and shape are packed in an arbitrary manner into the container. However the material elements may also be arranged in a definite manner in the bed so as to obtain the desired bed porosity. Singh et al. [3] reported that the effects of particle shape and bed porosity are required to be taken into account while investigating the heat transfer and pressure drop characteristics of packed bed energy system.

Major disadvantage of the packed bed storage system is considered to be the pressure drop in the bed i.e. energy consumption by fan to propel the air through the bed. This reduces the overall benefit of the solar energy storage system. Packing the large sized elements of storage material could reduce pressure drop in the bed. The thermal performance of the system may decrease due to lesser area available for heat transfer. Kulakowski and Schimdt [4] emphasized that diameter of the storage elements and pressure drop through the bed are considered to be two parameters of primary importance in the design of the storage unit. Gauvin & kutta [5] mentioned that the major operating cost in packed bed system is directly related to the pressure drop in the bed, which cannot be predicted with reliability when the elements in the bed depart from the spherical shape.

Singh et al. [6] presented a detailed list of various types of experimental and theoretical investigations done on the performance of the packed beds.

Most of the investigators used small sized bed elements like gravel, rocks and pebbles to study the performance of the packed bed system. Sagara and Nakahara [7] investigated the heat transfer and pressure drop characteristics of the system with large sized material particles and reported that packing of large sized elements of storage material could be used to reduce the pressure drop and the thermal performance decreases. Duffie and Beckman [8] reported that the size of the rocks used is between 0.01-0.03 m.

Standish and Drinkwater [9] reported that the element shape is a significant variable in gas/liquid flowing in packed columns. Scmidt & Willmott [10] mentioned that the shape of packing element and the porosity determine the size and distribution of the flow channels formed by packing of the storage elements and hence the shape and porosity are the important factors to be taken into account.

Singh et al. [3] investigated different shapes of storage materials in large size and have developed correlations for Nusselt Number and Friction Factor. Lof and Hawley [11] reported that large variations of heat transfer might be expected with change of bed voids and shape of the material element. The shape of the material elements and void fraction of the bed are two major system parameters, which could affect the system performance considerably.

An experimental study has been conducted and reported in the present paper for investigating heat transfer and friction characteristics of the system with four different rectangular elements of concrete having the same volume as storage material shown in Figure 2.

The volume has been kept to be same to have same equivalent diameter. The storage elements are arranged uniformly with care and uniformly to obtain four different void fraction values ranging from 0.28 to 0.48. In order to get different void fraction, 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 numbers of elements to be put in each layer are calculated. During packing this arrangement of the elements has been repeated i.e. the third layer is the replica of the first layer and fourth layer is the replica of the second layer and so on.

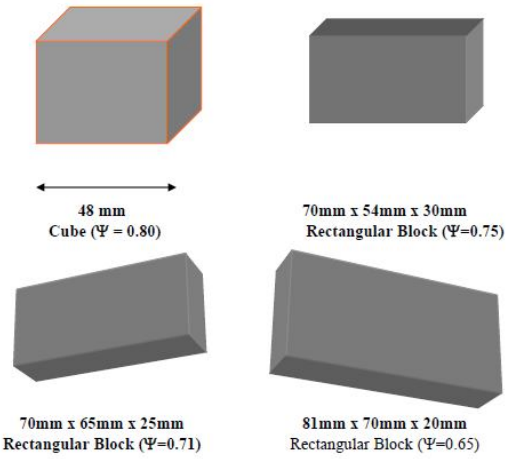


Figure 2 List of Elements Used in Present Study

The mass velocity of air was varied with the help of a control valve and the range was 0.155 - 0.266 kg/s m^2 and Reynolds Number was taken from 500 to 866 during the experimentation.

EXPERIMENTAL STUDY

The details of the experimental setup, instrumentation, range of parameters, material used and methodology have been discussed in detail.

An experimental setup has been designed and fabricated and a schematic of the same is shown in Figure 3. A storage tank was made of MS sheet of 3

mm thickness. In order to have diameter ratio to be equal to 10, the diameter of the bed has been fixed to be equal to 0.60 m. The height of the bed was taken to be equal to 0.75m. Length of upper and lower plenums in the storage tank has been fixed as 0.25 m each. Therefore the height of the tank is 1.25 m for a bed height of 0.75 m. The storage tank was provided with number of taps to take the thermocouple wires out of the tank for measurement of the temperature.

A pipe was fitted on the top of the tank for supply of the air. A similar arrangement was provided at the bottom to allow air to the atmosphere. 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. Tank was properly insulated with polyethylene foam to minimize the heat losses.

In order to supply hot air to the bed, an air duct of rectangular cross section was designed. For indoor experimentation, an electric heater was fabricated by combining series and parallel loops of heating wire on asbestos sheet. Five series loops were connected in parallel to give a heat flux of 1000 W/m^2. The heater was fixed on the top of the duct. The backside of the heater is insulated with glass wool. Electric supply to heater was controlled by variac. GI pipeline was used to make air supply from air duct to storage tank. Fan was used to make flow of hot air from air duct to storage tank**.** A control valve was provided with the fan to control the flow of air.

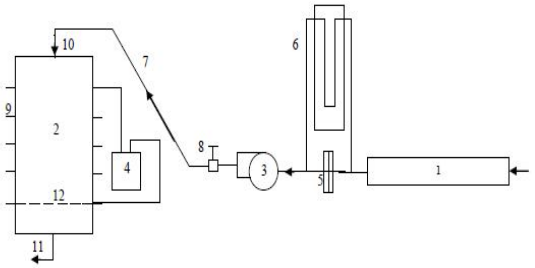


Figure 3 Schematic Diagram of the Experimental Set-up

For measuring flow rate of air an orifice meter connected with U-tube manometer was installed in the pipeline. The control valve provided in the pipeline controlled the flow of air. A micro manometer was fitted with the taps in storage tank for measuring pressure drop in the bed. Temperatures at different locations along different cross sections in the bed for air and solid were measured with copper-constantan thermocouples.

Before packing of the elements, 24 thermocouples were fixed on the surface of elements in small sized grooves. During packing these were placed at different points in different cross sections of the bed along with 24 thermocouples for measurement of air temperature near the same points in the voids. The thermocouple wires were connected to the selector switches through cold junction.

The continuity of all the thermocouples was checked at the time of filling them. The measuring instruments i.e. U-tube manometer, temperature indicator and micro manometer were properly checked after filling the elements.

Range of Parameters

In order to keep the equivalent diameter of the elements same, the volume of elements used was kept to be equal. The equivalent diameter of the elements was taken equal to 60 mm. The mass velocity of air was varied from 0.155 - 0.266 kg/s m^2 and the range for Reynolds Number was from 503 to 866.Four different Sphericity values were considered and the range varied from 0.65 - 0.80.Futher in order to know the effect of void fraction the range of void fraction was 0.28 - 0.48.

III. METHODOLOGY

In order to collect the experimental data at different parameters the following methodology was adopted:

Number of elements packed was counted before the packing for calculating void fraction of the bed. With the height of the bed and the element to be known the number of elements to be packed in each layer was counted and the elements were filled in the tank with care to obtain the required void fraction.

The top cover of the tank was fitted tightly with the help of nuts and bolts and the tank was connected with the air supply. The joints were properly sealed and checked.

Airflow was made with six different mass velocities of air for operating the system. The measuring instruments were properly checked and the U – tube manometer and the micro manometer were properly leveled and marked. The liquid level in the micro – manometer was precisely marked before the start of air supply.

The fan was started by fully opening the control valve and then the electric supply to the heater was switched on. The flow of air was controlled with the help of the control valve and the input to the heater was adjusted with the variac.

The system was run continuously for each set of experimentation at different mass velocities of air. The hot air was allowed to flow in the bed for two hours on every start. 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. The following observations were then taken:

1. Head loss (Δh_1) in the orifice meter from U tube manometer.

2. Head loss in the bed (Δh_2) from micro-manometer.

3. Air temperature at different locations along different cross sections of bed.

4. Surface temperature of material elements at different locations along different cross sections of bed.

For the next mass velocity of air, the flow rate was changed and adjusted to the required value with the help of control valve. After operating the system for one hour the above-mentioned data was collected for that mass velocity of air. This step was repeated for rest of the mass velocities of air.

Data Reduction

The mass flow rate of air ($\dot{m}$) [12], volumetric heat transfer coefficient (h_v) and void fraction (ε) were calculated from the equations (1), (2) and (3) respectively.

$$\dot{m}=C_d A_o \left[\frac{2\rho_a \Delta P \mathrm{Sin}\theta}{1-\beta^4}\right]^{1/2} \quad (1)$$

$$\dot{m}c_p\left(\bar{T}_i-\bar{T}_o\right)=h_v V_b\left(\bar{T}_a-\bar{T}_s\right) \quad (2)$$

$$\varepsilon=\frac{V_b-V_s}{V_b} \quad (3)$$

To take into account the effect of temperature gradients in large size material, values of apparent volumetric heat transfer coefficient (h_v^*) have been evaluated by using the model given by Sagara and Nakahara [7] as is given below:

$$hv^* = 3hv \div (B+3) \quad (4)$$

$$\text{Where, } B=\frac{h_v R^2}{3K_s(1-\varepsilon)}$$

The data were transformed into dimensionless groups *viz.* Reynolds number (Re) proposed by Chandra and Willits [13], Nusselt number (Nu) proposed by Kulakowski and Schimdt [4] and friction factor (f) proposed by Hollands and Sullivan [14] with the following equations:

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

$$\mathrm{Re}=\frac{GD_s}{\mu_a} \quad (6)$$

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

IV. RESULTS AND DISCUSSION

An experimental study has been conducted on four different rectangular shaped elements at four void fractions in a packed bed. The data have been collected in the form of heat transfer coefficient and pressure drop and transformed into dimensionless form as Nusselt number and friction factor. The results for Nusselt number and Friction Factor have been discussed separately here.

Nusselt Number

The variation in Nusselt number has been observed due to Reynolds Number, Sphericity and void fraction. These have been separately discussed for Sphericity and void fraction in combination with the Reynolds number.

Effect of Sphericity

The Nusselt number has been plotted against the Reynolds number in Fig. 4 for a fixed void fraction value of 0.48 at different Sphericity values. The Nusselt Number increases with an increase in the Reynolds Number and is almost linear for all the cases. The Reynolds number increases with an increase in the mass velocity of air and hence with an increase in the Reynolds number the turbulence in the airflow increase. Therefore, increase in heat transfer coefficient and also an increase in Nusselt number can be expected as has been observed in the present investigation.

For all void fraction values, the Nusselt number is maximum for the element having a Sphericity of 0.65 and is minimum for the cubical element i.e. having Sphericity equal to 0.80.It has been observed that the value of Nusselt number is decreasing with an increase in Sphericity.

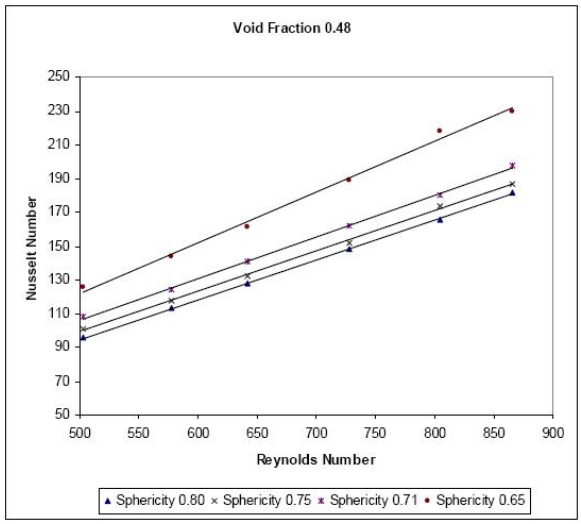


Figure 4 Effect of Reynolds number on Nusselt number at a fixed void fraction of 0.48

The Nusselt number is plotted against the Sphericity for a fixed value of void fraction and at a fixed value

of Reynolds Number in Fig 5. It is clearly indicated that the Nusselt number decreases with an increase in the Sphericity at all Reynolds Numbers and for all sets of void fraction. The Nusselt number has the maximum value corresponding to highest Reynolds number and the minimum Sphericity and it decreases as the Sphericity increases and attains the lowest value corresponding to the maximum Sphericity equal to 0.80.Further, the lowest values have been obtained for the minimum Reynolds Number. Similar trends have been observed for all void fraction values.

A perceptible change of flow patterns and area of contact available for heat transfer are supposed to be responsible for such a change in Nusselt number. Flow patterns are function of number of sharp corners of material elements in the bed, shape of the voids, flow channeling, etc. Therefore, the flow patterns get changed with change of shape of the material elements. Area of contact of flowing air with the solid depends upon the size and shape of the material elements.

In the present range of the Sphericity values, there is an increase in the flatness of the surface as the Sphericity increases. The greater flatness of the surfaces causes high turbulence of the fluid flow. This results in an increase in the value of Nusselt number. Therefore, it can be observed that as the value of Sphericity increase from 0.65 to 0.80, the flatness of the surface decrease and hence the turbulence in the flow decreases and hence a decrease in Nusselt number has been obtained. Although solid-fluid contact area decreases but the effect of enhanced turbulence due to flatness of surface is much more visible as compared to the effect of decreased fluid contact area.

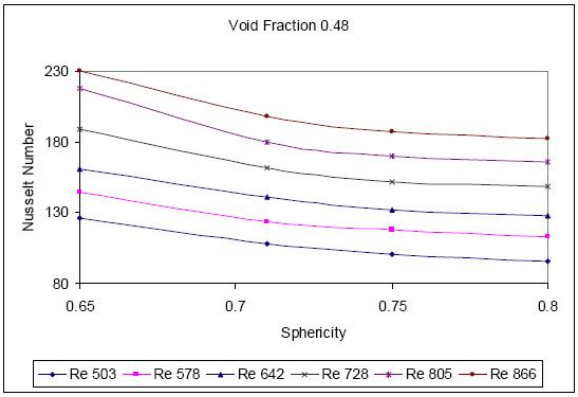


Figure 5 Effect of Sphericity on Nusselt number at a fixed void fraction of 0.48

Effect of Void Fraction

The variation of Nusselt number has been plotted against void fraction for a fixed value of Sphericity in Fig.6. It has been observed that the Nusselt number decrease with an increase in the void fraction similar behavior has been obtained at all values of Sphericity i.e. for all the shapes. Highest value of Nusselt number has been observed corresponding to the lowest void fraction and at maximum Reynolds number. The Nusselt number then gradually decreases as the void fraction increases and it also decreases as the Reynolds number is decreased.

An increase in void fraction decreases the volume/amount of material packed in the bed, which results in an increase in the volume of voids for flow of air in the bed. Increase in void fraction gives rise to flow channeling i.e. reduction in tortuousness of the airflow through the bed. The number of sharp corners in the bed also decreases with increase of void fraction. These conditions result in a decrease in heat transfer coefficient between flowing air and material elements. Hence a reduction is Nusselt number is expected and has been observed in the study.

Friction Factor

The effect of Reynolds number on friction factor at a fixed value of void fraction has been shown in Fig. 7. It is clearly indicated that the friction factor decreases almost linearly with an increase in the Reynolds number for all void fraction. Friction factor has the maximum value corresponding to the minimum Reynolds number and then it starts decreasing to a minimum value at the highest Reynolds number. The same trend has been observed for all the void fraction. The increase in mass velocity of air increases the frictional losses and hence large pressures drop in the bed. Hence the friction factor decreases with an increase in the Reynolds number.

The variation of friction factor with Sphericity for a fixed void fraction is shown in Fig. 8.The friction factor has the maximum value for the least Sphericity and it decreases as the Sphericity increases. It has the maximum value corresponding to the Sphericity equal to 0.65 for minimum value of Reynolds number. The friction factor is lowest for the highest Sphericity 0.80 and minimum Reynolds number. The same trend is observed for all the void fraction values. 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 a value of 0.80 to 0.65.

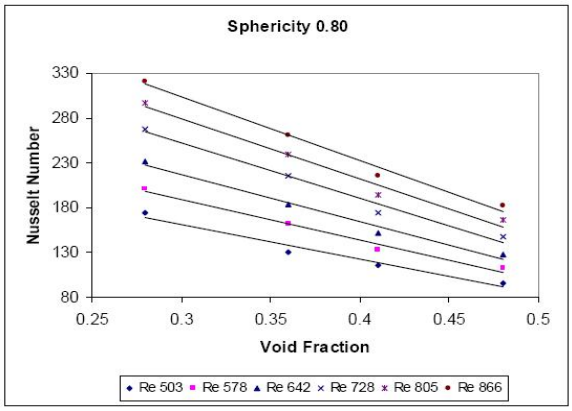


Figure 6 Effect of Void Fraction on Nusselt number for a fixed Sphericity of 0.80

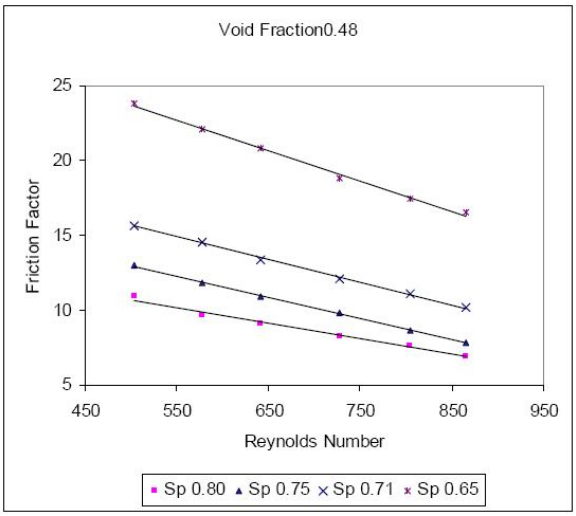


Figure 7 Effect of Reynolds number on Friction Factor at a fixed void fraction of 0.48

Further it has been observed from Fig. 9 that friction factor has decreased with increase in void fraction at a typical value of Reynolds number. An increase in void fraction give rise to the channeling of fluid flow i.e. the reduction in tortuousness of the flow through the bed and also a reduction in contact area occur. The number of sharp corners per unit volume also reduces with increase in void fraction of the bed. These conditions reduce the frictional losses between fluid and solid and consequently the friction factor decreases as has been observed in these results.

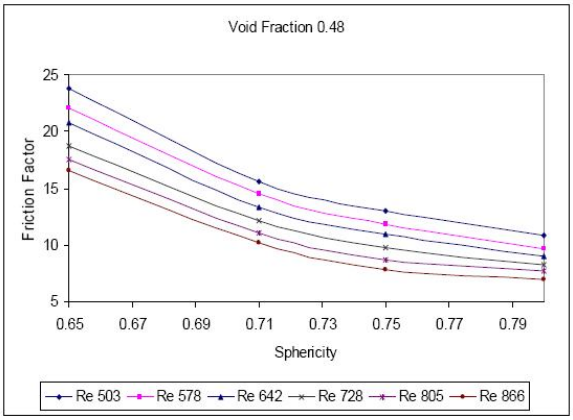


Figure 8 Effect of Sphericity on Friction Factor at a fixed void fraction of 0.48

CONCLUSIONS

An experimental study has been reported on four different rectangular shaped storage elements in this paper in order to investigate the effect of Sphericity and void fraction on heat transfer and friction characteristics in a packed bed. It is concluded that the Nusselt number and friction factor are dependent on Reynolds number, Sphericity and void fraction.

The Nusselt number increases with an increase in the Reynolds number and is maximum at the highest value of Reynolds number in the range. The Nusselt number then decreases as the Reynolds number decreases. Nusselt number has the highest value for the minimum Sphericity i.e. for the rectangular element with Sphericity equal to 0.65.With an increase in Sphericity the Nusselt number decreases and is minimum for the bed of cubes with Sphericity equal to 0.80.An increase in void fraction reduces the Nusselt number and it has a maximum value corresponding to the minimum void fraction equal to 0.28 and is minimum at the maximum void fraction of 0.48.

Further the friction factor reduces with increase in Reynolds number and is maximum at highest Reynolds number in the range. The friction factor is maximum at the minimum value of Sphericity i.e. for the bed of rectangular elements with Sphericity equal to 0.65.The bed of cubes is having the minimum value of friction factor. The friction factor increases with a decrease in the void fraction and a maximum value is obtained at void fraction equal to 0.28 and a minimum at void fraction equal to 0.48.

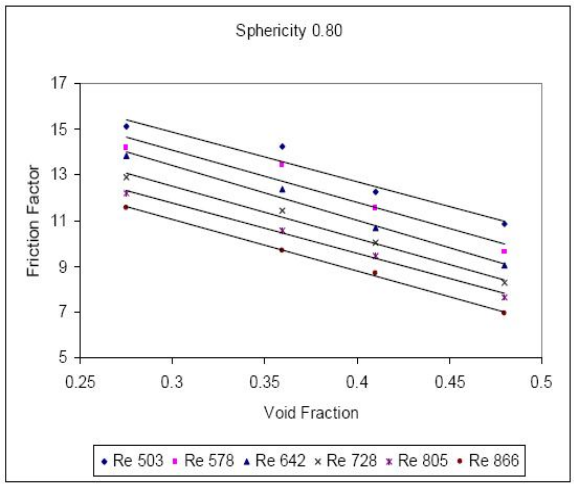


Figure 9 Effect of Void Fraction on Friction Factor at a fixed Sphericity of 0.80

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