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Experimental Investigation of Packed Bed Solar Thermal Energy System with Cylindrical Elements

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ABSTRACT

The conversion of solar radiations into thermal energy is the easiest way to store solar energy. An experimental study has been conducted on large size cylindrical elements which having different orientation (horizontal and vertical) to see the effect of system and operating parameters on heat transfer and pressure drop characteristics of the packed bed solar energy storage system. Based upon this experimentation, correlations have been developed for Nusselt number and friction factor as a function of Reynolds number and void fraction. These developed correlations are effective to predict the performance of solar thermal energy storage system for large cylindrical elements.

Keywords: *Packed bed, solar, cylindrical, energy*

NOMENCLATURE

A_o	cross-sectional area, m^2
a_e	surface area of material element, m^2
a_s	surface area of a sphere having volume equal to material element, m^2
C_d	coefficient of discharge for orifice meter
C_p	specific heat of air, J/kg K
D_e	equivalent diameter, m
f	friction factor
G	mass velocity of air or mass flow rate of air per unit bed cross-sectional area, kg/s m^2
h_v	volumetric heat transfer coefficient, W/m^3K
h_v^*	apparent volumetric heat transfer coefficient, W/m^3K
K	thermal conductivity of air, W/m K
L	length or height of the bed, m
$\dot{m}$	mass flow rate of air, kg/s
Nu	Nusselt number
∇p	pressure drop across the orifice meter, N/m^2
∇P_b	pressure drop across the bed, N/m^2
R_e	Reynolds number
$\overline{T_i}$	average temperature of air at bed inlet, ºC
$\overline{T_o}$	average temperature of air at bed exit, ºC
$\overline{T_a}$	average temperature of air in the bed, ºC
$\overline{T_s}$	average surface temperature of solids in the bed, ºC
V_b	volume of packed bed, m^3
V_e	volume of material element, m^3
V_s	total volume of storage material packed in the bed, m^3

Greek Symbols

ρ_a	air density, kg/m^3
ε	void fraction
φ	sphericity
μ	dynamic viscosity of air, kg/s m

1. INTRODUCTION

Energy is one of the most important factors in social and economic development of a country. The amount of energy consumption per capita of a country is measure of nation's economic development and it has become an important parameter for sustainable development throughout the world [1]. Conventionally energy is being extracted from petroleum products and fossil fuels like coal, oil and gas etc but the oil crisis in the world in early 80s forced to think about some other alternate sources of energy. The fast depletion rate of petroleum products and their high prices creates a huge impediment in fulfilling the high energy demands of massive population. In addition to the problem of fast depletion and high prices, several environmental impacts like GHG emissions, acid rain are associated with conventional energy sources. The above impediments of conventional energy sources are creating a great need of exploring new alternatives for fulfilling high energy demands.

Renewable energy sources are appropriate solutions of all the problems associated with conventional sources of energy. As compared to the conventional energy sources, renewable energy sources are more promising for sustainable development. Renewable energy resources like solar, wind, tidal energy etc. are renewed by nature and there supply will not be affected by the rate of consumption. The cost of generation of electricity from renewable energy sources comes out to be INR 6.39, 5.04 and 17.60/kWh for biogas, biomass gasification and solar PV systems respectively [2].

Among all renewable energy sources, solar energy is the most promising source due to quantitative abundance and availability of it. Solar energy is intermittent in nature and having low density. The average intensity of solar radiation of world is about 2500 kWh/m^2 and India's average intensity is approximately 2000 kWh/m^2. Solar collectors are commonly used to capture solar radiations and then solar air heaters and solar water heaters are used to transform the radiations into heat energy. Although solar energy is ambiguous yet it is not continuous at all places. It is highly time dependent and varies according to the location of a particular place. In most of the parts of the earth solar radiations are available for only 10-12 hours in a day which limits the continuous solar energy consumption. In addition to this, solar radiations are not available during rainy and winter seasons. Therefore, an energy storage unit is essentially required for storing the energy (solar radiations) that falls on it in the absence of solar radiations.

The direct storage of solar radiations is very difficult therefore an energy conversion has to be carried out first. The storage system which is used to store the available form of energy depends on this conversion. The conversion of solar radiations into thermal energy is the easiest way to store solar energy. Thermal energy storage system is very useful and easier in which energy gain of the fluid from the collector is transferred to the storage medium. An overview of major technique of storage of solar thermal energy is shown in Figure 1.

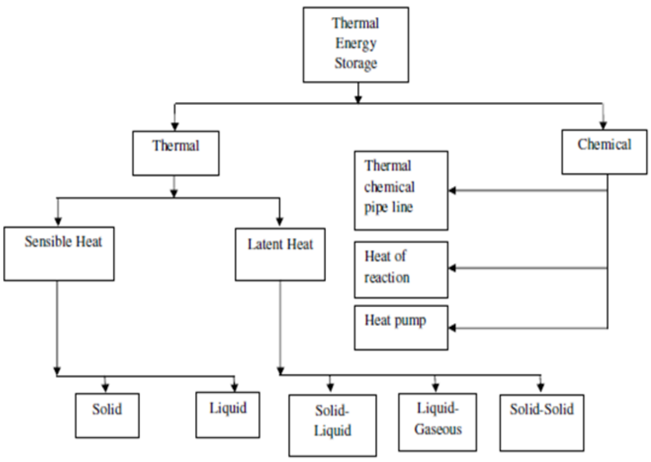


Figure 1: Overview of thermal storage system

Thermal energy can be stored as latent heat, sensible heat or chemical energy. In case of latent heat storage system, heat is stored when the material changes its phase for example phase change materials (PCMs). The latent heat storage is compact heat storage system but the heat exchangers for transferring heat between the working fluid and the storage material is always very complex Sensible heat storage is the most simple and inexpensive way of energy storage system. In sensible heat storage, heat is stored by rising the storage medium temperature. Sensible heat storage is then classified as liquid media storage and solid media storage. Various liquid and solid substances can be used for such systems like heat transfer oils, inorganic molten salts, water, rocks, pebbles etc. As many solar energy utilization systems are based on air, and air having very low density so, it is very inconvenient to store the air system. To overcome the above problem some denser medium (rocks, concrete, and metal) is required for the storage of thermal energy. When rocks or pebbles are packed in large thermal insulated containers then they are called packed beds. The packed beds are used with solar air heaters for thermal energy storage of hot air.

Solid materials such as rocks, metals, concrete, sand and bricks can be used for low as well as high temperature heat storage system. Due to its low cost, pebble beds are generally used for storage, whose size varies from 1-5 cm [3]. Rocks, pebbles are used for energy storage in industrial vessel.

Some studies [4], [5] reported that it has simple design and relatively inexpensive and this system is mainly used for storage up to 100°C. To minimize the cost of heat exchange it is necessary to have direct contact between solid storage medium and heat transfer fluids.

The packed bed is most suitable energy storage unit for air based solar energy storage system. A packed bed does not operate at constant temperature. Different conditions like solar radiations, ambient temperature, collector inlet temperature and load requirement during daytime affects the outlet temperature of the collector [6]. Most of the researchers [5], [7], [8] used small sized bed elements like gravel, rock, pebbles etc. to study the performance of solar packed bed energy storage systems. Large sized material in rock bed has almost the same overall thermal performance as small sized material in a solar heating system with a heat pump. Economical evaluation may then become a decisive factor for the ability to utilize large sized materials.

A lot of research has been done in packed bed energy storage system. It is observed that the two major models of heat transfer, namely, conduction between the particles in the bed and convection between the flowing gas and the particles, interact with each other. This is believed to be the major reason for the difficulty in obtaining a single generalized experimental correlation or theoretical/semi empirical models to evaluate the total heat transfer rates in packed bed gas-solids systems [9].

The heat transfer characteristics of energy storage system depend on several factors viz. airflow rate, diameter of element, void fraction etc. The heat transfer coefficient between air and loose solids is directly dependent upon airflow rate i.e. increase in airflow rate causes increase in heat transfer. However, it is inversely dependent on the diameter of particle (size of element) [5]. Both the pressure drop and the coefficient of volumetric

heat transfer between the air and rock beds depend upon the rock size and air flow rate. In addition, the pressure drop also exhibit dependence on the rock bed porosity [7]. Two parameters viz. size of material elements and pressure drop are very important for designing the storage units [10]. Also variation in void fractions has direct significant influence on both fluid and solid temperature dynamic response [11]. Also, for every small particle including dust and unwashed rocks, substantially increases pressure drop across the bed [12]. The efficiency of the storage bed was limited by dimensions of the storage bed. Efficiency may be lower if flow rate was higher and/or particle dimensions were small [13].

Correlation for Nusselt number and friction factor are investigated for the data on masonry bricks which are different in dimensions from commonly used masonry bricks [14]. A study has been carried out on heat transfer in packed beds. In this study particle to fluid heat transfer coefficients in packed beds have been measured mostly for air, although a few other gases have also been used. Correlations exist for beds of randomly oriented spheres, or beds of spheres oriented in cubic or rhombohedral arrays for cubes, cylinders, granular materials, and commercial packings. In addition, the data for the ordered arrays were obtained using models with large ratios of wall to wall areas [15]. Experimental measurements were obtained for of the forced convection gas-particle heat transfer coefficient in a packed bed, high-temperature, thermal energy storage system. Experimental results shows that the temperature range up to 1000°C and Reynolds number between 50-120 and the uncertainties associated in Nusselt number was reported to be 10-30% [16].

In the present paper the experimental study on large size cylindrical elements with different orientation (horizontal and vertical) has been conducted. This experiment has been conducted to see the effect of system and operating parameters on heat transfer and pressure drop characteristics of the packed bed solar energy storage system. Based upon experimentation the correlations have been developed for Nusselt number and friction factor as a function of Reynolds number and void fraction. These developed correlations can be effective to predict the performance of solar thermal energy storage system for large cylindrical elements.

2. EXPERIMENTAL SETUP AND PROCEDURE

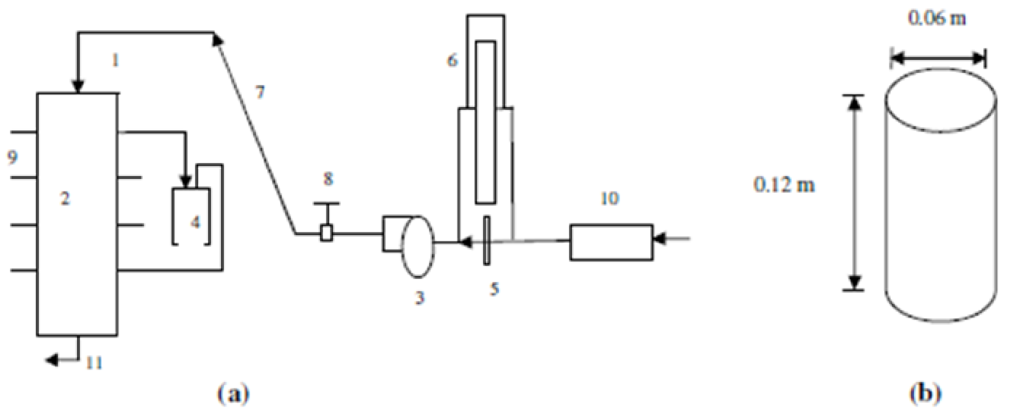
The schematic diagram of experimental set up is shown in Figure 2 (a). For indoor experimentation, an air duct of size 3 × 0.5 × 0.0254 m was used with an electric heater. The entry and exit lengths were 0.65 m and 0.96 m respectively, including the plenum length of 0.61 m at the exit. The heating section was of 2 × 0.5 × 0.0254 m out of which electric heater of 2 × 0.5 m was fabricated by combining series and parallel loops of heating elements. The heater was well insulated with glass wool in order to minimize the heat losses. Air duct was also well insulated from outside. Variable transformer (Variac) is used to control the electric supply to the heater. Fan is used to flow hot air from the duct to the storage tank. Storage tank is made up of MS (mild steel) sheets having thickness of 3 mm. The diameter of the storage tank is 0.60 m and the height of the tank is 1.25 m including lower and upper plenums of height 0.25 m each, which gives the packed bed of height 0.75 m, tank was insulated by polyethylene foam to minimize heat losses from surrounding. It was mounted in hanging condition on a rigid stand, with the tilting provision to make it trouble free. To make air supply from air duct to storage tank, GI pipe of 0.082 m diameter is used and it is properly insulated with polyethylene foam. An arrangement was provided in order to ensure uniform distribution of air into the bed. Thermocouples were used to measure the temperature of different cross section in the bed.

An orifice meter along with U-tube manometer was insulated in the pipeline for measuring the mass flow rate of air. A control valve was provided in the pipeline for controlling the flow rate of the air. Micro-manometer was attached with the taps at the top and bottom of the bed for measuring the pressure drop at different points.

3. METHODOLOGY

In order to estimate Nusselt number and friction factor, data required was bed and air temperature, air flow rate and pressure drop through the packed bed. The above setup was operated at six different flow rate of air for each set of cylindrical geometry arrangement as shown in Figure 2 (b). The cylindrical elements were packed in different orientations viz. horizontal and vertical. Data was collected for different void fractions for the tightly packed, loosely packed and very loosely packed cylindrical elements. Before packing of storage element, thermocouples were fixed in small sized grooves in material. During packing these were placed at different points at different cross sections of the bed along with thermocouples.

Number of cylindrical elements packed was counted during packing for the calculation of void fraction. The bed was packed with great care for each set, to keep uniform voids along a cross section. After packing, the thermocouple wires were connected to the selector switches through the cold junction. Before putting top cover of the tank, continuity of all thermocouples was checked properly. The measuring instruments i.e. U-tube manometer, micro-manometer were properly checked. Temperature of air was raised above the initial bed temperature with an electric supply to heater mounted in the air duct, for particular flow rate. Pressure drop in the orifice meter and in bed were noted down from U-tube manometer and micro manometer respectively. Data were recorded for cylindrical elements and air temperature after attaining quasi-steady flow. Around 1 hour was required to attain this quasi-steady flow for a particular flow rate.



Description
1- Hot air inlet to packed bed
2- Storage tank
3- Fan
4- Micro manometer
5- Orifice tube
6- U-tube manometer
7- Pipe line
8- Flow control valve
9- Taps for thermocouple
10- Air duct with electric heater
11- Air Outlet

De = 0.865 m
ψ = 0.83

Figure 2: (a) Schematic diagram of experimental set-up (b) Geometry of cylindrical element

4. DATA REDUCTION

As described earlier, the objective of the present study is to investigate the heat transfer and friction characteristics of cylindrical elements used as thermal energy storage system. Fig 2(b) shows the dimensions, equivalent diameter (D_e) and sphericity (ψ) of cylindrical element. The range of these parameters selected for the experimental investigation is given in Table 1. Mass flow rate of air (m) was calculated by using the following equations.

$$m = C_d A_o \left[\frac{2\rho_a \Delta p Sin\theta}{1-\beta^4} \right]^{\frac{1}{2}} \tag{1}$$

The Volumetric heat transfer coefficient (h_v) was calculated using the following equations of net heat transfer rate between air and solids.

$$mc_p\left(\overline{T_i} - \overline{T_o}\right) = h_v . V_b \left(\overline{T_a} - \overline{T_s}\right) \tag{2}$$

In order to take into account the effects of temperature gradients in large size material, apparent volumetric heat transfer coefficient (h_v^*) has been calculated from volumetric heat transfer coefficient (h_v).

$$h_v = \frac{m.c_p\left(\overline{T_i} - \overline{T_o}\right)}{V_b\left(\overline{T_a} - \overline{T_s}\right)} \tag{3}$$

$$h_v^* = \frac{3.h_v}{B+3} \tag{4}$$

where,

$$B = \frac{h_v \cdot R_e^2}{3k_s(1-\varepsilon)} \tag{5}$$

The equivalent diameter (D_e), bed void fraction (ε) and sphericity (Ψ) of the element were calculated from the following equations by [16]

$$D_e = \left(\frac{6.V_e}{\pi} \right)^{\frac{1}{3}} \tag{6}$$

$$\varepsilon = \frac{V_b - V_s}{V_b} \tag{7}$$

$$\psi = \frac{a_s}{a_e} \qquad (8)$$

These data are converted into dimensionless parameters i.e; Reynolds number (Re), Nusselt number (Nu) and friction factor (f) for flow, heat transfer and pressure drop respectively and they are represented below:

$$R_e = \frac{GD_e}{\mu_a} \qquad (9)$$

$$Nu = \frac{h_v^* D_e}{K} \qquad (10)$$

$$f = \frac{\Delta P_b \rho_a D_e}{L.G^2} \qquad (11)$$

The errors cannot be avoided while taking observations from the instruments during the experimental work [17]. When only one parameter is being obtained from an experiment, crude methods of calculation are used to obtain an estimate the error of the result. However, in many research problems, numbers of parameters are obtained simultaneously from an equal or greater number of experimental results. In these cases more formal methods are required to obtain correct estimates of the uncertainties in the parameters. For this experimental study, a maximum error of about 2.25% and 3.97% is possible for the Nusselt number and friction factor respectively.

5. CORRELATIONS DEVELOPMENT FOR NUSSELT NUMBER AND FRICTION FACTOR

Nusselt number (Nu) and friction factor (f) are found to be function of Reynolds number and void fraction. Therefore, an attempt has been carried out to develop functional relationship for Nusselt number and friction factor by using first order regression analysis.

$$Nu = f_1(\mathrm{Re}, \varepsilon) \quad \text{and}$$
$$Nu = f_2(\mathrm{Re}, \varepsilon)$$

Correlations are developed for Nusselt number and friction factor by following the procedure given by [18]. Data from Fig 3 is used to develop correlation for Nusselt number from 1st order regression of the data. It has been found that the average slope of all lines is 1.198. Variation of function $\frac{Nu}{\mathrm{Re}^{1.198}}$ with the void fraction 1for bed of cylindrical particles is shown by the following relation:

$$\frac{Nu}{\mathrm{Re}^{1.198}} = (-0.023\varepsilon + 0.069) \qquad (12)$$

$$Nu = \mathrm{Re}^{1.198}(-0.023\varepsilon + 0.069) \qquad (13)$$

which is the developed correlation for Nusselt number.

Data from Fig 4 is used to develop correlation for friction factor from 1st order regression of the data. It has been found that the average slope of all lines is -0.63. Variation of function $\frac{f}{\mathrm{Re}^{-0.63}}$ with the void fraction for bed of cylindrical particles was plotted and the following relation has been obtained.

$$\frac{f}{\mathrm{Re}^{-0.63}} = (-3378\varepsilon + 6190) \qquad (14)$$

$$f = \mathrm{Re}^{-0.63}(-3378\varepsilon + 6190) \qquad (15)$$

which is the developed correlation for friction factor.

6. RESULTS AND DISCUSSION

After obtaining the Nusselt number and the friction factor values from the above stated experimentation and discussion have been plotted against Reynolds number and Figure 3 shows the variation of Nusselt number as the function of Reynolds number for cylindrical elements with constant sphericity of 0.83 for the void fraction ranges from 0.2512 to 0.4816 for different packing of cylindrical elements. It has been observed that at a given values of Reynolds number, Nusselt number increases with decrease in void fraction. As increase in voids may reduces the tortuous nature of fluid flow through the bed and area of contact is also reduces. It has also been observed that the results of the vertical packing with different void fraction were much better than that of horizontal packing of the storage material due to increase in the surface contact area.

Figure 4 shows the variation of friction factor as function of Reynolds number for cylindrical particles at constant sphericity of 0.83 for different void fractions of the bed. It is found that at a given value of Reynolds number, friction factor decreases with an increase in void fraction. An increase in voids may reduce the tortuous nature of fluid flow through the bed and area of contact of flowing fluid with the material particle also reduces. Both these conditions may reduce friction loss. Figures 5 and 6 show the comparison of experiment data of Nusselt number and friction factor and that predicted by the correlation for Nusselt number and friction factor respectively. A good agreement has been achieved. The average absolute percentage deviation between the experiment and predicted data for Nusselt number and friction factor have been found to be 8.2% and 7.1% respectively.

7. CONCLUSION

An experimental study has been carried out to investigate the heat transfer and pressure drop characteristics of the packed bed solar thermal energy storage system having cylindrical elements with vertical and horizontal arrangement. The effects of system and operating parameters on heat transfer and pressure drop characteristics of the packed bed solar energy storage system has been studied. Besides the study, correlations have also been developed for Nusselt umber and friction factor as function of Reynolds number, void fraction of the bed. These developed correlations can be effective to predict the performance of solar thermal energy storage system for large cylindrical elements. A heat transfer and friction factor result shows that inverse in void fraction.

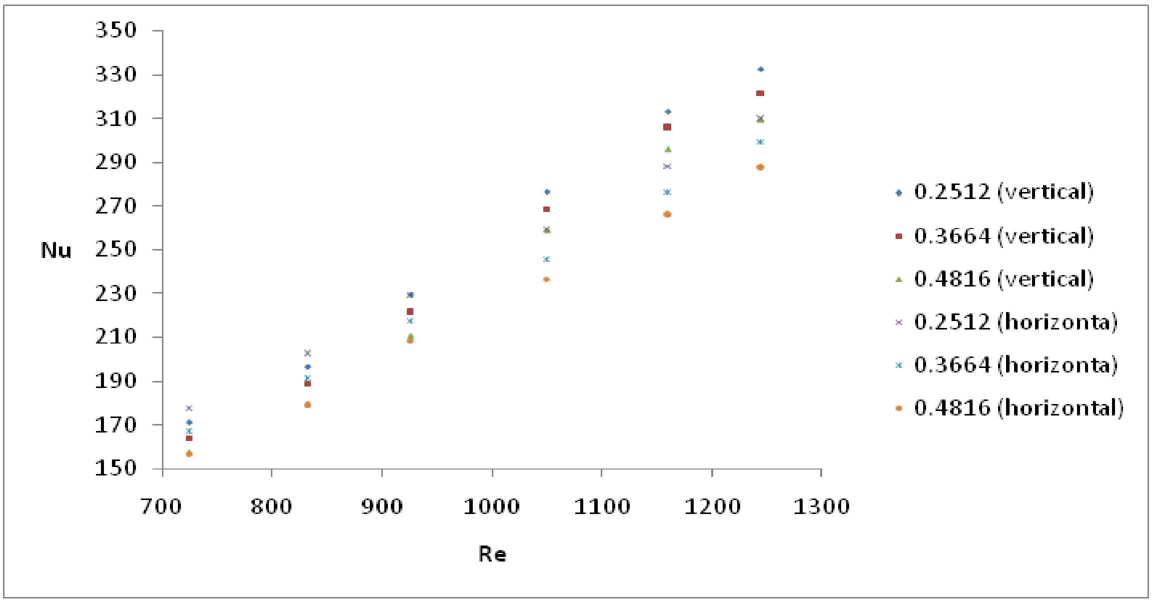


Figure 3: Effect of Reynolds number on Nusselt number

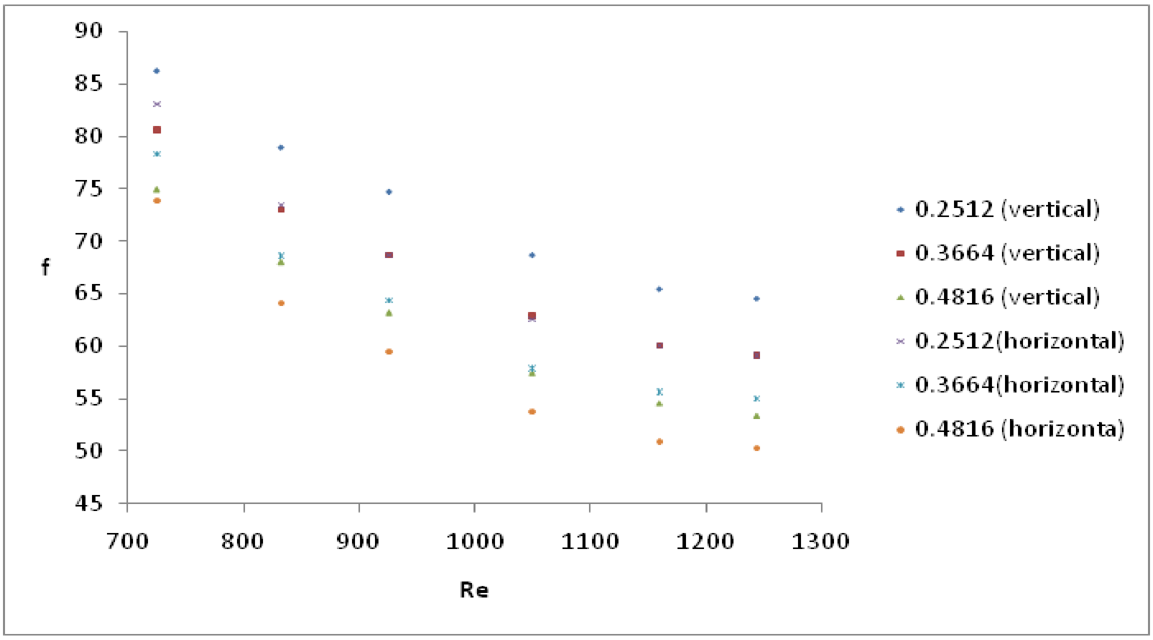


Figure 4: Effect of Reynolds number on friction factor

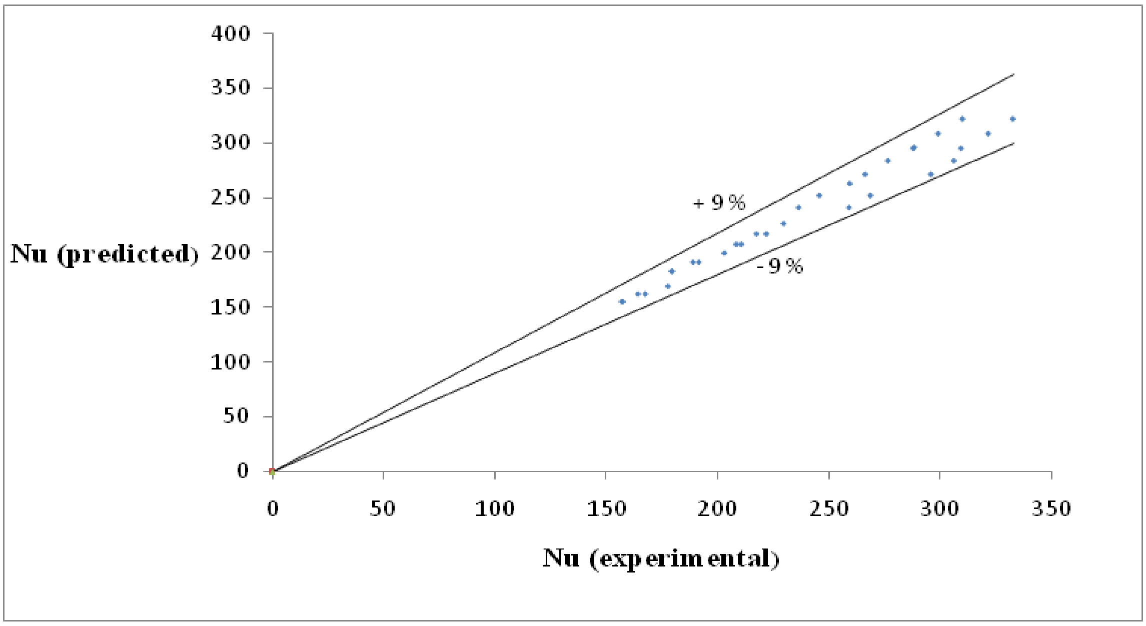


Figure 5: Comparison of experimental and predicted values of Nusselt number

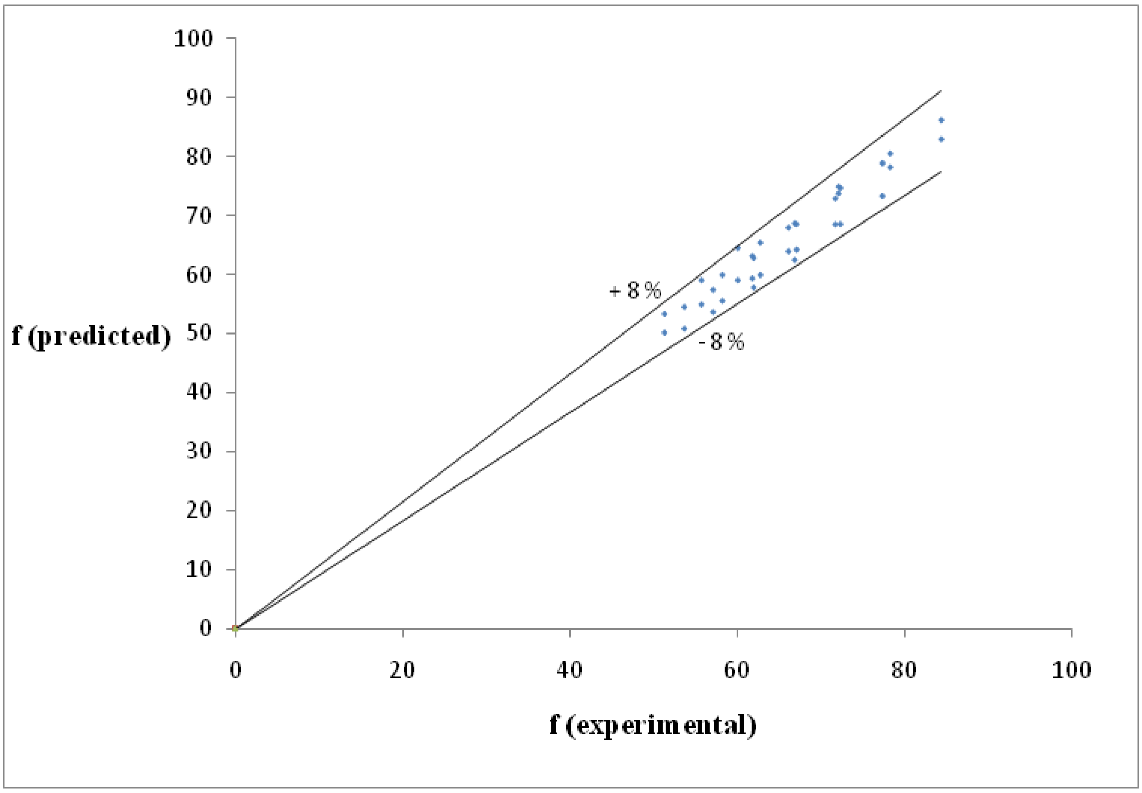


Figure 6: Comparison of experimental and predicted values of friction factor

REFERENCES

[1] Varun, Singal SK. Review of augmentation of energy needs using renewable energy resources in India. Renewable and Sustainable Energy Reviews 2007; 11:1607-15.

[2] Singal SK, Varun, Singh RP. Rural electrification of a remote island by renewable energy sources. Renewable Energy 2007; 32:2491-2501.

[3] Hasnain SM. Review on sustainable thermal energy storage technologies. Part 1. Heat storage material and techniques. Energy Convers Manage J 1998; 39(11):1127-38.

[4] Lof, GOG, Hawley RW. Unsteady state heat transfer between air and loose solids. Ind. Eng. Chem. 1948; 40(6):1061-70.

[5] Singh H, Saini RP, Saini JS. A review on packed bed solar energy storage system. Renewable and Sustainable Energy Reviews 2010; 14:1059-1069.

[6] Cautier JP, Farber EA. Two applications of a numerical approach of heat transfer process within rock bed. Sol. Energy 1982; 27(6):451-62.

[7] Chandra P, Willits DH. Pressure drop and heat transfer characteristics of air rock bed thermal storage systems. Sol. Energy 1981; 27(6):547-53.

[8] Colburn AP. Heat transfer and pressure drop in empty baffled and packed tubes. Ind. Eng. Chem J 1931; 23(8):910-3.

[9] Balakrishnan A, Pei R, David CT. Heat transfer in packed bed systems-a critical review. Ind. Eng. Chem. Process Des. Dev.1979; 18(1):30-40.

[10] ulakowaski BT, Schmidt FW. Design of a packed bed thermal storage unit for a solar system. Sol. Energy Engg. 1982; 104:223-28.

[11] Beasley DE, Clark JA. Transient response of packed bed thermal energy storage. Int J Heat Mass Transfer 1984; 27(9):1659-69.

[12] Hollands KGT, Sullivan HF. Pressure drop across rock bed thermal storage systems. Solar Energy 1984; 33(2):221-5.

[13] Sorour MM. Performance of small sensible heat energy storage unit. Energy Convers Manage J 1988; 28(3):221-5.

[14] Singh R, Saini RP, Saini JS. Nusselt number and friction factor correlation for packed bed solar energy system having large sized elements of different shapes. Solar Energy 2006; 80:760-71.

[15] Barker JJ. Heat transfer in packed beds. Ind. Eng. Chem.1965; 57:43-51.

[16] Nsofor EC, Adebiyi Geroge A. Measurements of the gas particle convective heat transfer coefficient in a packed bed for high temperature energy storage. Exp Thermal Fluid Sci 2001; 24:1-9.

[17] Kline SJ and Mcclintock FA. Describing Uncertainties in Single Sample Experimental, Mechanical Engineering 1953; 75: 3-8.

[18] Saini RP and Saini JS. Heat transfer and friction factor correlations for artificially roughened ducts with expanded metal mesh as roughness element. Int Journal of Heat and Mass Transfer 1997; 40(4):973-986.