EFFECTS OF ROUGHNESS PARAMETERS ON INCLINED SPHERICAL BALL ROUGHENED SOLAR AIR HEATER

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Abstract— An elaborative experimental investigations result in terms of heat transfer and frictional losses for an inclined spherical ball roughened solar air heater has been presented in a very precise way in the present paper with an objective to visualize the effects of roughness parameters on heat transfer and frictional losses . To show the effect of ever changing environmental variables like solar radiation, wind velocity, ambient temperature, etc, on the heat transfer results, the readings were noted for every 15 minutes in the experimental hours 10:00 to 15:00 hours. The present paper deals with the experimental results drafted in the form of rise in Nusselt number (Nu) and friction factor (f) for spherical ball roughened solar air heater (SAH) over those of smooth ones. Flow and roughness geometrical parameters have been varied as relative roughness pitch (p/e) 9-18, relative roughness height (e/Dh) 0.024-0.040, ball„s height to diameter ratio (e/db) 0.5-2, angle of attack (α) 35°-75° and Reynolds no (Re) 2500-18500. Parametric analysis has also been made and the effects of these parameters on Nu and f characteristics have been shown. This article reveals that maximum augmentation in „Nu" & „f" for varying „p/e", „e/Dh" & „e/db" and „α" was respectively found to be of the order of 2.1 to 3.54 times, 1.87 to 3.21 times and 2.89 to 3.27 & 1.74 to 3.56 times for „Nu" and 0.84 to 1.79 times, 1.46 to 1.91 times, 1.67 to 2.34 times & 1.21 to 2.67 times for „f" in compared to non-roughened duct. The optimum roughness parameters found under present investigation is p/e = 15, e/Dh = 0.036, e/db = 1 and α = 55°.

Keywords: Artificially roughened solar air heater, relative roughness pitch, relative roughness height, Nusselt number, friction factor, angle of attack

1. Introduction

Sun is the ultimate source of most of the sources of energy. The UNDP in its 2000 World Energy Assessment found that annual potential of solar energy was 1,575–49,837 exajoules (EJ), several times larger than total world energy consumption, which was 559.8 EJ in 2012 [1-2]. With about 300 clear and sunny days in a year, the calculated solar energy incidence on India's land area is about 5000 trillion KWh per year. The solar energy available in a single year exceeds the possible energy output of all of the fossil fuel energy reserves in India [3]. Frequent rise in energy prices have motivated many researchers to shift their thrust towards renewable sources of energy. Artificially roughened SAH is an effective method to harness solar heat energy to heat fluids (air & water) used for domestic & industrial applications. A solar collector is a type of heat exchanger which transfers the radiant energy of the incident sunlight to the sensible heat of a working fluid; air or liquid. A solar thermal collector collects heat by absorbing sunlight. The quantity of solar energy striking the Earth's surface (solar constant) averages about 1,000 W/m2 under clear skies. Different types of solar collectors have been designed and developed in the last few years as a result of increased utilization of solar energy [4]. Solar air heating is a renewable energy heating technology used to heat or condition air for buildings or process heat applications. It is typically the most cost-effective out of all the solar technologies, especially in commercial and industrial applications, and it addresses the largest usage of building energy in heating climates, which is space heating and industrial process heating [5]. The value of heat transfer coefficient and heat capacity for air is low which reduces the heat transfer rate and thus increases the heat loss to the surroundings. A large number of researchers have used solar air heaters of different configurations to remove these drawbacks associated with solar air heaters to better serve the purpose of air heating [6]. Using artificial roughness of various shape geometry and orientation has been proven to be the most effective method to harness solar energy. Han et al. [7] investigated the effect of rib pitch to height ratio, and rib height to equivalent hydraulic diameter on friction factor and heat transfer coefficient for Reynolds number range of 7,000 to 90,000, relative roughness pitch range of 10 to 40, and relative roughness height range of 0.021 to 0.063 and found that the maximum values of friction factor and the Stanton number occur at a relative roughness pitch of 10. Saini and Saini [8] experimentally investigated the effect of arc shaped ribs on „Nu & f‟ of rectangular ducts of SAHs. Enhancement of „Nu & f‟ was reported to be of order 3.6 and 1.75 times respectively over smooth. Lau et al. [9] continued their comparison studies on full and staggered discrete ribs arrays and reported that for a constant pumping power, 60˚ and 45˚discrete ribs enhance the ribbed wall heat transfer by about 5 to 19 percent and 11 to 32 percent respectively compared to the corresponding full ribs case. Karwa et al. [10] carried out an experimental investigation on the integral transverse chamfered rib roughened absorber plate and found two-fold increase in the Stanton number and three-fold increase in the friction factor as compare of that of the smooth duct. Mahmood et al. [11] studied 45˚ angled rib turbulators and found that thermal performance is lower in the ribbed channel than in channel with dimples and/or protrusions. Ridouane and Campo [12] investigated computationally the heat transfer and pressure drop of laminar air flow in a parallel-plate channel with transverse hemi-cylindrical cavities and found enhancement in heat transfer by 30 % relative to smooth duct and pressure loss increments by 19 %. Gupta et al. [13-14] investigated 90˚ continuous, 60˚ broken ribs and 90˚ saw tooth profiled & established that the mean heat transfer for square channel with 60˚ V-broken ribs are more eminent than that of 90˚saw tooth profiled rib and 90˚ continuous ribs. Momin et al. [15] investigated the heat transfer and friction characteristics of V-shaped rib roughness with relative roughness height range of 0.02 to 0.034, angle of attack range of 30°-90° and Reynolds number in the range of 2,500 to 18,000. The maximum enhancement in the heat transfer and friction factor was observed as 2.30 and 2.83 times of that of smooth duct for an angle of attack of 60°. Wongcharee et al. [16] investigated the effects of different shaped ribs like cylindrical, rectangular, triangular, concave-concave, convex-concave, on heat transfer and friction factor and found that the cylindrical ribs provided the highest value of thermo-hydraulic performance and minimum enhancement in Nusselt number was for rectangular ribs. Skullong and Promvonge [17] performed experimental study on the heat transfer and friction characteristics in a solar air heater channel fitted with delta-winglet type vortex generators (DWs). The experimental result reveals that in the first case, the 60° DW-E at Rp=1 provides the highest heat transfer and friction factor while the 30° DW-E at Rp=1 performs overall better than the others. Pandey et al. [18] studied heat transfer and friction factor in rectangular channel with multiple-arc shaped with gaps as roughness element. The maximum increment in Nusselt number (Nu) and friction factor (f) was 5.85 and 4.96 times in comparison to the smooth duct. The maximum enhancement for Nu takes place at Reynolds number (Re) = 21,000, g/e=1, d/x= 0.65, W/w=5, e/Dh= 0.044, p/e = 8 and α/60 = 1. Kumar et al. [19-21] has used three sides instead of one side roughened duct & found that augmentation in Nu & f was respectively to be 21-86 % & 11-41 %. They also reported augmentation in thermal efficiency of three sides over one side roughened duct to be 44-56 % for varying p/e and 39-51 % for varying e/Dh. The literature reveals that considerable amount of experimental & analytical work has been done to investigate the effect of turbulence promoters on „Nu & f‟ characteristics of roughened flow passages. Roughness geometries of many shapes in different orientations like transverse rib, angled rib, inclined rib with gap, v-shaped rib, discrete or broken v-shaped rib, discrete v-shaped rib with pieces, w-shaped rib, wedge or chamfered shaped rib, dimpled shaped rib, rib-groove, Multi v-shaped rib, z-shaped rib, etc has already been used. However no study has been reported on SAH roughened with inclined spherical ball of different height and diameter soldered upon collector‟s face. Such roughness geometry has the advantage of inclined pattern as well as discrete roughness that could lead to rise in useful heat gain of air with reduction in propelling power of blower. More improvement can be expected in local heat transfer by using spherical ball roughened SAH, as such geometry can increase the number of secondary flow stream due to variation in angle of attack and geometrical dimension. The present research has been taken up with an objective to conduct experimentation under actual outdoor condition to visualize the effects of roughness parameters on heat transfer and frictional losses.

2. Experimentations

Investigation is conducted to obtain the experimental values of „Nur & fr‟ in the spherical ball roughened collectors. The test rig was fabricated and calibrated properly before taking data for roughened and non-roughened ducts. The test rig had two ducts capable of accommodating roughened and non-roughened ducts simultaneously. The various sets of data recorded from the test rig included: inlet and outlet air temperatures, plate temperatures, pressure drop across the duct and the orifice and solar insolation.

2.1 Test rig

The experimental set-up has been designed and fabricated as per the ASHRAE standards [22]. Fig. 1 & 2 respectively shows the schematic and actual photograph of experimental set-up. A 5 HP Centrifugal blower with a 3.5 kW Electric motor has been provided in the set-up to suck air from atmosphere through the test sections. The rectangular duct is having dimensions of 2150 mm × 330 mm × 30 mm in which the length of test section is 1200 mm and lengths of entry and exit sections are 650 mm and 300 mm respectively. The aspect ratio (W/H) of the duct is 11. The entry section is made a bell-mouthed shape at the inlet side to avoid loses at the entry. Each test section contains a glass cover of 4 mm thickness at the top and a back plate of 3 mm thick G.I sheet in the bottom. A Control valve was provided to control the flow in both the ducts. Calibrated orifice meter was installed to measure the flow rate of air through the roughened ducts. A copper constantan thermocouple has been provided at various locations to measure the plate temperatures. A digital pyranometer system was used to measure solar radiation, wind velocity, ambient temperatures. Fig. 3 & 4 shows the actual and schematic diagram of the spherical ball roughened plate used under present study. Fig.5 shows the schematic diagram of roughened and non-roughened ducts. Fig. 6 shows the positioning of thermocouples on the absorber plates. A photograph of digital pyranometer system has been shown in Fig 7 & 8.

2.2 Roughness parameters range

SAH roughened passage has an L = 1200 mm, H = 30 mm and W = 300mm, the hydraulic diameter, Dh = 54.54 mm. The spherical ball roughness geometry has been provided under various sets of dimensionless parameters under varying relative roughness pitch (p/e) 9-18, relative roughness height (e/Dh) 0.024-0.040, ball height to diameter ratio (e/db) 0.5-2 and relative angle of attack (α/55) 35˚-75˚. The flow Reynolds number has been varied from 2500-18500 to generate the best result in terms of „Nur & fr‟. Table 1 shows the range of experimental set-up and operating roughness parameters.

Fig. 1 Schematics of test rig

Fig. 2 Photograph of test-rig

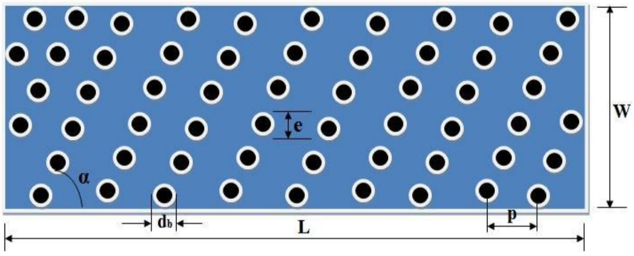


Fig. 3 Schematics of spherical ball roughened absorber

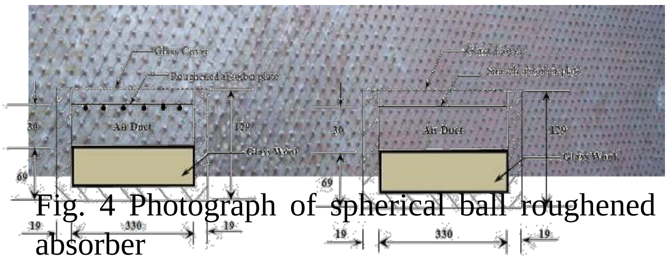


Fig. 4 Photograph of spherical ball roughened absorber

Fig. 6 Positioning of thermocouples on absorber

Fig. 7 Photograph of Pyranometer

Fig. 8 Photograph of digital pyranometer system

The values/range of geometrical parameters of solar air heater duct, roughness parameters and experimental conditions e.g. mass flow rate, wind velocity, insolation etc used during experimentation have been given in Table 1

2.3 Data reduction

The mean temperatures, Tpm & Tfm are simply the arithmetic mean of the noted values of temperatures at different locations in between the inlet & exit of the test section. Thus:

Table 1 Details of Experimental Set-up and Operating conditions

Entry length	650	mm
Test section length (L)	1200	mm
Exit length	300	mm
Width (W)	330	mm
Height (H)	30	mm
Duct aspect ratio (W/H)	11	mm
Hydraulic diameter (D_h)	54.54	mm
Glass cover thickness (t_g)	4	mm
Distance between top glass cover and absorber plate (L_1)	30	mm
Relative roughness pitch (p/e)	9-18	-
Relative roughness height (e/D_h)	0.024-0.040	-
Ball height to diameter ratio (e/d_b)	0.5-2	-

Angle of attack (α)	35˚-75˚	degree
mass flow rate (ṁ)	0.0104-0.05126	Kg/s
Reynolds number (Re)	2500-18500	-
Ambient temperature (T_a)	21-41	˚C
Solar radiation	674-986	W/m^2
Wind velocity (W_v)	0.7-3.1	m/s

2.3.1 Mass flow rate measurement

Using the pressure drop measurement across the orifice, the flow rate of air under roughened plate is calculated as:

□ 2□□p □0.5
m □ Cd Ao □ o □ (3)
1□ □ 4
□ □

2.3.2 Friction Factor

The „f" value is calculated using pressure drop □□p□d , across test section length, L of 1200 mm and the mass flow rate, m as:

f □□ p □d Dh (4)
2□Lv 2
d

where, Dh: hydraulic diameter for the duct and is evaluated as:

Dh □ 4WH (5)

□2(W □ H)□

and, vd is the flow velocity of air flowing inside the roughened duct.

2.3.3 Reynolds Number

The „Re" is calculated using:

Re □ vd Dh (6)
□

2.3.4 Heat Transfer Coefficient

Useful heat gain of air is given by:

Qu □ mC p □T6 □T1 □ (7)

The heat transfer coefficient for the heated test section has been calculated from:

h □ Qu (8)
Ap □T pm □Tfm □

where, Ap is the heat transfer area, assumed corresponding one side roughened plate area.

2.3.5 Nusselt Number

The heat transfer coefficient is used to determine the „Nu" and is determined as:

Nu □hDh (9)
k

where, „k": thermal conductivity of the air

S.No.	Name of parameter	Uncertainty range (%)
1.	Area of absorber plate (A_p)	0.08
2.	Cross sectional area of air flow duct (A_c)	0.16
3.	Area of orifice meter (A_o)	0.26
4.	Hydraulic diameter	0.37
5.	Density	0.106
6.	Mass flow rate	0.84
7.	Velocity of air through test section	0.76
8.	Reynolds Number (Re)	0.8
9.	Heat transfer co-efficient	3.724
10.	Nusselt number (Nu)	4.357
11.	Friction factor (f)	4.871
12.	Useful heat gain	3.753

2.4 Validation of experimental data

Alongside roughened ducts, data were also recorded for non-roughened duct for validating the experimental set-up. The data of „Nus & fs" obtained from experimentation have been compared with those of data obtained from the correlation of „Nus & fs" as per Dittus-Boelter equation and modified Blasius equation respectively.

Nus for non-roughened surface as per Dittus-Boelter equation is given by:

Nu □ 0.023Re 0.8 Pr0.4 (10)
s

fs for non-roughened surface as per modified Blasius equation is given by:

f s □ 0.085 Re□0.25 (11)

The data for „Nus & fs" of non-roughened ducts so obtained from experimentation and the correlations suggested above compared well with a mean deviation in experimental & estimated values of „Nus & fs‟ as ± 3.5 % for „Nus‟ & ± 4.4 % for „fs‟.

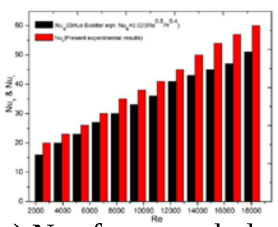
Fig. 9 (a & b) indicates the comparison of experimental values „Nus & fs‟ with „Nus‟ & „fs‟ obtained from the correlations above.

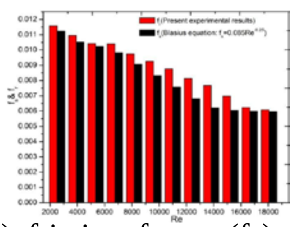
2.5 Uncertainty Analysis

Based on the method of Kline and McClinLock [23] of the uncertainties associated with various parameters, the uncertainties have been discussed and the elaborated form is given in Appendix-A. Uncertainties values of various parameters are given in Table 2:

3. Results and Discussions

The present investigation is aimed at examining how the „Nur‟ & „fr‟ is affected by spherical ball roughness element and their varying roughness parameters. The literature of artificially roughened SAH reveals that introducing roughness on the surface of absorber enhances the heat transfer coefficient but the matter of concern is that it is also increases frictional losses; consequently the pumping power required to ensure the continuous flow inside roughened duct also increases which results in higher power consumption, consequently reducing the net energy gain. Thus, the roughness parameters should be selected in such a way that maximum heat transfer can be obtained at the cost of minimum rise in pressure drop





(a) Nus for smooth duct (b) friction factor (fs) for smooth duct

Fig. 9 Comparison of experimental and calculated values of „Nus‟ & „fs‟

Under present experimental studies, effects of spherical ball roughness element parameters such as „p/e‟, „e/Dh‟, „e/db‟ & „α‟ on „Nur‟ & „fr‟ has been studied exhaustively and presented as rise in „Nur‟ & „fr‟ with mass flow rate of air (Reynolds number).

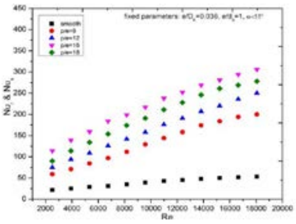
3.1 Heat transfer results

This section deals with the effects of spherical ball roughness element parameters as „p/e‟, „e/Dh‟, „e/db‟ & „α‟ on „Nur‟ has been studied exhaustively and presented as rise in „Nur‟ with mass flow rate of air (Reynolds number).

Fig. 10 shows the variation of „Nur‟ as a function of „p/e‟ & „Re‟ for fixed „e/Dh‟=0.036, „e/db‟=1 & „α‟=55˚. The maximum & minimum value for „Nur‟ is obtained at „p/e‟ of 15 & 9 respectively for the entire values of „Re‟ investigated. Likewise, Fig. 12

8

shows the variation of „Nur‟ as a function of „e/Dh‟ & „Re‟ for fixed „p/e‟=12, „e/db‟=1 & „α‟=55˚. The maximum & minimum value for „Nur‟ is obtained at „e/Dh‟ of 0.036 & 0.024 respectively for the entire values of „Re‟ investigated. Fig 14 shows the variation of „Nur‟ as a function of „e/db‟ & „Re‟ for fixed „e/Dh‟=0.036, „p/e‟=12 & „α‟=55˚. The maximum & minimum value for „Nur‟ is obtained at „e/db‟ of 1 & 2 respectively for the entire values of „Re‟ investigated. Likewise, Fig. 16 shows the variation of „Nur‟ as a function of „α‟ & „Re‟ for fixed „p/e‟=12, „e/db‟=1 & „e/Dh‟=0.036. The maximum & minimum value for „Nur‟ is obtained at „α‟ of 55˚ & 35˚ respectively for the entire values of „Re‟ investigated. Maximum augmentation in „Nur‟ for varying „p/e‟, „e/Dh‟ & „e/db‟ and „α‟ was respectively 2.1 to 3.54 times, 1.87 to 3.21 times, 2.89 to 3.27 & 1.74 to 3.56 times compared to non-roughened duct. The presence of maximum Nusselt number at some particular roughness parameter signifies the presence of maximum shear layer and number of re-attachment point at that particular geometrical value. Air under roughened duct is heated because of heat absorbed by collector‟ surface and the roughness provided on its surface. Primary flow (flow of air in contact with absorber) and secondary flow (flow of air in contact of roughness) has the maximum opportunity t o meet each other at relative roughness pitch of 15, relative roughness height of 0.036, spherical ball height to diameter ratio of 1 and angle of attack of 55˚, causing maximum heat rise of air at such values.



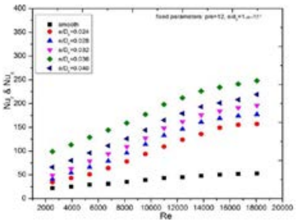
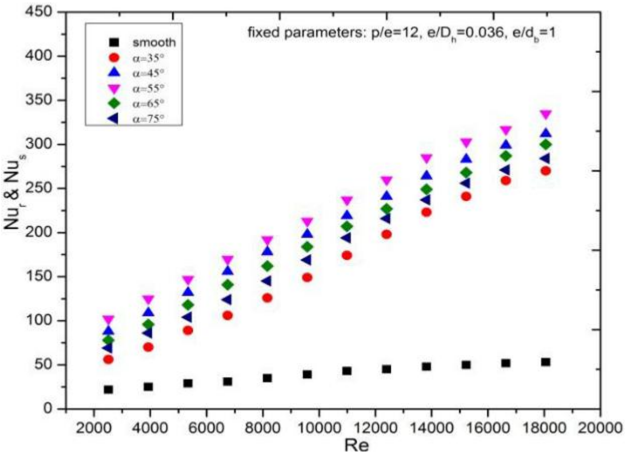


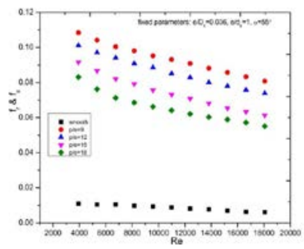
Fig. 10 Variation in „Nu‟ with „Re‟ for different „p/e‟ & fixed „e/Dh‟=0.036, „e/db‟=1 & „α‟=55˚

Fig. 11 Variation in „Nu‟ with „Re‟ for different „e/Dh‟ & fixed „p/e‟=12, „e/db‟=1 & „α‟=55˚



3.2 Friction factor results

Providing artificial roughness on the collector surface results in rise in useful heat gain of air but that rise is obtained at slight increase in frictional losses compared to smooth duct. The roughness element helps in increasing heat transfer characteristics but these also offer resistance to flow that increases power requirement to propel air through roughened ducts. Geometrical dimensions of roughness is selected such that maximum Nu rise is obtained at minimum frictional losses. This section presents the effect of roughness geometrical parameter on rise in frictional losses of roughened duct compared to smooth ones. Fig. 14 shows variation of „fr‟ as a function of „p/e‟ & „Re‟ for fixed „e/Dh‟=0.036, „e/db‟=1 & „α‟=55˚. The maximum & minimum value for „fr‟ is obtained at „p/e‟ of 9 & 18 respectively for the entire values of „Re‟ investigated. The occurrence of maximum friction factor at „p/e‟ of 9 signifies that this geometrical parameter offers maximum resistance to the flow causing maximum propelling power requirement. Likewise, Fig. 15 shows the variation of „fr‟ as a function of „e/Dh‟ & „Re‟ for fixed „p/e‟=12, „e/db‟=1 & „α‟=55˚. The maximum & minimum value for „Nur‟ is obtained at „e/Dh‟ of 0.040 & 0.024 respectively for the entire values of „Re‟ investigated. At „e/Dh‟ of 0.040, maximum friction is obtained because of maximum height of spherical ball under constant hydraulic diameter. Air need more power to overcome the resistance offered by each spherical ball and move forward. Fig 16 shows the variation of „fr‟ as a function of „e/db‟ & „Re‟ for fixed „e/Dh‟=0.036, „p/e‟=12 & „α‟=55˚. The maximum & minimum value for „fr‟ is obtained at „e/db‟ of 1 & 2 respectively for the entire values of „Re‟ investigated. The presence of maximum and minimum value of friction factor at particular „e/db‟ value signifies that at „e/db‟ of 1, i.e. when the diameter of ball is equivalent to its height, more resistance is offered by roughness element. For minimum rise in friction, the favorable condition is ball ‟s height should be twice its diameter. Likewise, Fig. 17 shows the variation of „fr‟ as a function of „α‟ & „Re‟ for fixed „p/e‟=12, „e/db‟=1 & „e/Dh‟=0.036. Angle of attack is key parameter deciding rise in frictional losses value. If the arrays of spherical ball are oriented at such angle relative to flow which can result in tremendous rise in resistance offered by roughness element, such orientation should be discarded. In the present investigation, it was found that maximum frictional losses are obtained at an angle of attack 55˚. The maximum & minimum value for „fr‟ is obtained at „α‟ of 55˚ & 35˚ respectively for the entire values of „Re‟ investigated. It was found that the maximum augmentation in „fr‟ for varying „p/e‟, „e/Dh‟, „e/db‟ and „α‟ was respectively found as of 0.84 to 1.79 times, 1.46 to 1.91 times, 1.67 to 2.34 times & 1.21 to 2.67 times compared to non-roughened duct.



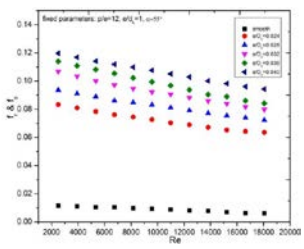


Fig. 14 Variation in „fr‟ with „Re‟ for different „p/e‟ & for fixed „e/Dh‟=0.036, „e/db‟=1 & „α‟=55˚

Fig. 20 Variation in „f‟ with „Re‟ for different „e/Dh‟ & for fixed „p/e‟=12, „e/db‟=1 & „α‟=55˚

It is clearly evident from this study that heat transfer is a very strong function of flow and geometrical parameters of roughness geometry. Varying the distances between spherical balls exhibited heat transfer augmentation only up to certain value beyond which any further increament in pitch resulted in heat transfer decrement. The inclination of spherical ball arrangement also shows that maximum heat transfer occur at an angle of attack of 55˚.

4. CONCLUSIONS

Exhaustive experimentation under actual outdoor conditions was conducted to generate experimental data for heat transfer and frictional losses. To increase the experimentation accuracy, data for absorber and air temperature, pressure drop across test section and orifice, wind velocity, solar radiation, etc, were recorded at every 15 minutes interval during experimentation from 1000 hours to1500 hours. The results have been shown in the form of rise in „Nur‟ & „fr‟ for roughened duct over those of non-roughened ones.

Nusselt number and friction factor for roughened duct varied as „p/e‟, „e/Dh‟, „e/db‟ & „α/55‟ were varied under the given operating range. In the entire range of „Re‟ studied, „Nur‟ increased as „p/e‟ was increased from 9 to 15. On further increasing the value of „p/e‟, „Nur‟ decreased. Nusselt number for roughened duct increased as the „e/Dh‟ was increased from 0.024 to 0.036, beyond this, Nusselt number started decreasing with increase in e/Dh value. An increase in ball height to diameter ratio „e/db‟ resulted in an increase in Nur from 0.5 to 1. Upon increasing e/db from 1 to 2, it was found „Nur‟ decreased. „Nur‟ increased as angle of attack was increased from 35˚ to 55˚. On further increament, „Nur‟ started decreasing. Maximum augmentation in „Nur‟ for varying „p/e‟, „e/Dh‟, „e/db‟ and „α/55‟ was respectively found as 2.1 to 3.54 times, 1.87 to 3.21 times, 2.89 to 3.27 & 1.74 to 3.56 times compared to non-roughened duct. The optimum roughness parameters yielding best result is „p/e‟ = 15, „e/Dh‟ = 0.036, „e/db‟ = 1 and α = 55˚. Friction factor decreased monotonously as the „p/e‟ increased from 9-18. With the variation of „e/Dh‟ from 0.024 to 0.04, the values of „fr‟ increased monotonously. As „e/db‟ varied from 0.5 to 1, friction factor increased and as „e/db‟ varied from 1 to 2, friction factor decreased for the entire „Re‟ range investigated. The „fr‟ increased as the angle of attack „α‟ was increased from 35˚ to 55˚. For further increament in angle of attack from 55˚ to 75˚, „fr‟ decreased. The maximum augmentation in „fr‟ for varying „p/e‟, „e/Dh‟, „e/db‟ and „α‟ was respectively found as 0.84 to 1.79 times, 1.46 to 1.91 times, 1.67 to 2.34 times & 1.21 to 2.67 times compared to non-roughened duct.

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