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EFFECT OF STAGGERED RIB LENGTH ON PERFORMANCE OF SOLAR AIR HEATER USING V-RIB WITH SYMMETRICAL GAP AND STAGGERED RIB

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ABSTRACT

The present paper details an experimental investigation on heat transfer and friction factor characteristics of solar air heater roughened with V rib with symmetrical gap and staggered rib. The roughness has fixed value of relative roughness pitch (P/e) 12, relative staggered rib pitch (P'/P) 0.65, relative gap width (g/e) 4, number of gaps on each side of V rib (Ng) as 3 and angle of attack (α) 60°. The relative staggered rib size (w/g) varied from 0.5 to 2 and the variation in Reynolds number is from 3000 to 14000. The enhancement in Nusselt number and friction factor over smooth surface under similar operating and flow condition has been observed. The highest thermo hydraulic performance of roughened solar air heater having V-rib with symmetrical gap and staggered rib is found for relative staggered rib size (w) is equal to the gap width (g).

Keyword: solar air heater, V-rib with symmetrical gap and staggered rib, thermo-hydraulic performance.

INTRODUCTION

A conventional solar air heater is a device which is used to heat the air by using solar radiations through convective heat transferring surface. A conventional solar air heater mainly consists of an absorber plate to absorb the solar radiations and convert the solar energy into heat energy in form of heated air. The heated air is then used for several purposes like cooking, crop drying, distillation of water, chemical process heat, heating of building etc. Heat transfer coefficient and thermal efficiency of solar air heater is low because of low convective heat transfer between the heated plate and air. This is because of developing the laminar viscous sub layer near the convective surface which acts as an insulating layer for the convection of heat from the surface. In order to decrease the losses artificial roughness is provided to improve the turbulence in the flow of air near the viscous laminar sub layer region. The artificial roughness on the heated plate is in form of grooves, dimples, baffles, wire mesh, ribs etc. and is the best way to increase the thermal efficiency of solar air heater by improving its heat transfer coefficient but it also increases the frictional losses and leads to more power required by blower for fluid flow. The key parameters influences on heat transfer behavior in the duct are rib geometry, height, pitch and rib arrangement. Several investigations have been carried out before by using different types of artificial roughness [1-11]. Singh *et al.* [12] did his investigation with discrete V-down roughness. Thermal performance of solar air heater was investigated by Patil *et al.* [13] using broken V-rib roughness combined with staggered ribs. V-rib having multi gap with the combination of staggered rib was investigated by Deo *et al.* [14]. Maithani *et al.* [15] investigated the performance of roughened solar air heater with V-shaped roughness having symmetrical gap. The value of number of gap and angle of attack ranges from 1 to 5 and 30 to 75 degree respectively. Jain *et al.* [16] investigated the thermal performance of solar air heater using V-Rib with Symmetrical Gap and Staggered Rib and found improved thermal performance of solar air heater as compared to smooth plate. They performed the investigation with relative staggered rib size (w/g) of 2.5, relative roughness pitch (P/e) of 12, number of gaps as 3 and relative gap width (g/e) as 4 with Reynolds number range of 3000 to 14000 and found better performance as compare to smooth plate.

It is seen from the literature that presence of gap and staggered rib significantly enhances heat transfer. Previous work of the author only studied performance of V-Rib with Symmetrical Gap and Staggered Rib roughness and no study was conducted to study the effect of staggered rib length. Till date no investigation has been performed to optimize the length of the staggered rib size for V-Rib with Symmetrical Gap and Staggered Rib roughness. Keeping this in mind a new V rib roughness having symmetrical gap combined with staggered rib element is suggested for investigation for heat transfer and friction factor aspect for different length of staggered rib element in present study. The new roughness geometry is proposed by placing staggered rib element in front of two consecutive symmetrical gaps. The effect of staggered rib element length on Nusselt number, friction factor and Thermo hydraulic performance is examined. The performance of present rib roughness is also compared with the smooth surface in order to examine its influence. The detail of experimental study, range of parameters investigated, roughness geometry, outcomes etc are discussed in detail as below.

EXPERIMENTAL SETUP

In order to analyze the performance of V rib with symmetrical gap and with staggered rib roughness on heat transfer coefficient and friction factor an indoor experimental set up has been fabricated as per ASHRE standard [17]. Schematic diagram is shown in Figure-1.

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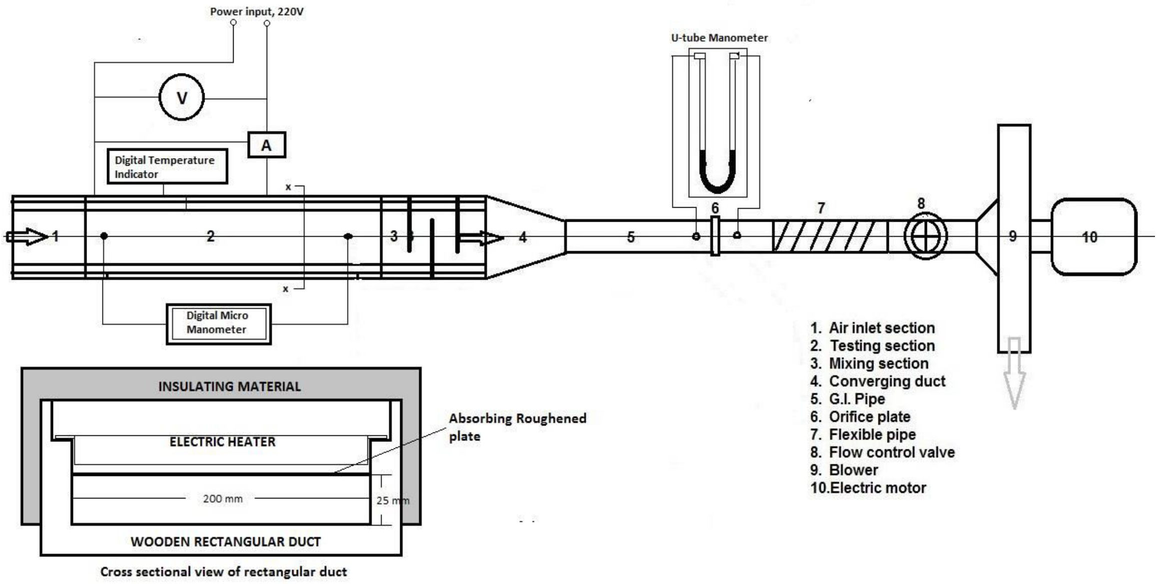
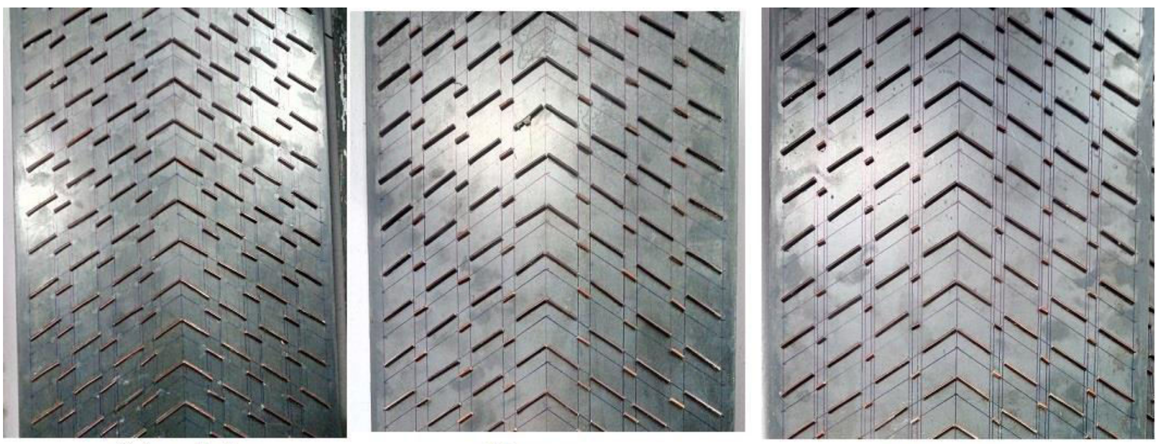


Figure-1. Schematic diagram of test set up.

It consist a rectangular wooden duct having length 2040 mm with cross sectional area of 200mm x 25mm for the flow of air. The flow channel includes four sections namely smooth inlet section, test section, exit section and mixing section as per Duffie and Beckman [18]. An HR sheet of 16 gauge having dimension 1.5 x 0.2 m^2 is used as an absorber plate at the top of the duct. Lower surface of the plate was provided with artificial roughness and the remaining three wall of duct are made smooth. Electric heater of dimension exactly to that of absorber plate is used to generate uniform heat flux of 1000 W/m^2 over the plate. Insulation is provided to reduce the heat loss from the wall as well as from the top of electric heater. Air is sucked through the duct by a blower and gate valve is used to control amount of air flowing in the duct. The other end of the duct is connected to the circular pipe through a transition section. Air flow rate in the duct is measured by flange type orifice meter. Pressure drop in the test section is measured by using Digital micro manometer. Copper-Constantan thermocouples are used to measure to measure inlet air temperature, outlet air temperature and plate temperature. All the data is recorded under study state condition. In order to optimize the staggered rib size, four different dimensions of staggered rib length were investigated. Figure-2 shows photograph of plate with different staggered rib size.



(a) w=1.5g (b) w=g (c) w=0.5g

Figure-2. Photograph of plate with different staggered rib size.

Based on previous specific results obtained by investigations of Maithani *et al.* [15] and Deo *et al.* [14] V-Down orientation is considered for the present study. Before start of test run, all the joints were checked for air leakage and all instruments were tested to ensure the proper functioning. Table-1 shows range of parameters for present study.

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Table-1. Range of parameters for present study.

Parameters	Range of values
Relative roughness height (e/D_h)	0.045
Relative staggered rib position (P'/P)	0.65
Relative roughness pitch (P/e)	12
Number of gaps on each side of V rib (N_g)	3
Staggering ratio (w/g)	0.5, 1.0, 1.5
Angle of attack (α)	60^o

DATA REDUCTION

The mean bulk temperature of air and plate temperature at various locations under steady state condition is evaluated by using following parameters.

Mean bulk air temperature (T_{fav})

Simple arithmetic mean of measured inlet and exit value of air under testing section

$$T_{fav} = (T_i + T_o) /2 \quad (1)$$

Where,
T_i = Inlet temperature of air in ˚C
T_o = outlet temperature of air in ˚C

Mean plate temperature (T_{pav})

Thermocouple wires are arranged at equidistance on the entire length of plate therefore it is the average reading of six points located on the plate.

$$T_{pav} = (T_{p1} + T_{p2} +T_{p3} +T_{p4}+ T_{p5} +T_{p6}) / 6 \quad (2)$$

Where,
T_{p1-6} = Temperature of plate at six different locations of plate.

Pressure drop across the orifice plate (ΔP_o)

$$\Delta P_o = \Delta h \times 9.81 \times \rho_m \quad (3)$$

Where,
Δh = Difference of water level in U-tube manometer
ρ_m = Density of water

Mass flow rate measurement (m)

$$m = C_d \times A_o \times [2\rho(\Delta P_o)/1-\beta^4]^{0.5} \quad (4)$$

Where,
β = Ratio of orifice diameter to pipe diameter, d_2/d_1
C_d = Coefficient of discharge of orifice i.e. 0.62
A_o = Area of orifice plate, m^2
ρ = Air density at mean bulk air temperature

Reynolds number

$$Re= VD_h/\nu \quad (5)$$

Where,
ν = Kinematics viscosity of air at T_{fav} in m^2/sec
D_h = Hydraulic diameter, 4WH/2(W+H)

Heat transfer rate

$$Q_u= mC_p(T_o-T_i) \quad (6)$$

Where,
C_p = Specific heat of air at constant pressure in kJ/kgK

Convective heat transfer coefficient

$$h= Q_u/A_p(T_{pav}-T_{fav}) \quad (7)$$

Nusselt number

$$Nu= hD_h/k \quad (8)$$

Where,
k= thermal conductivity

Friction factor

$$f= 2(\Delta P_d)D_h/4\rho L_f V^2 \quad (9)$$

Where,
ΔP_d = Pressure drop in N/m^2

VALIDITY OF EXPERIMENTAL SETUP

The value of friction factor and Nusselt number obtained from the experiments were compared with the values obtained from correlation of the Modified Dittus-Boelter equation for the Nusselt number given by equation (10) and modified Blasius equation for the friction factor given by equation (11).

Modified Dittus-Boelter equation for Nusselt number

$$Nu_s = 0.024 Re^{0.8} Pr^{0.4} (2R_{av}/D_e)^{-0.2} \quad (10)$$

Where,

$2R_{av}/D_e$ = [(1.156+H/W-1)/ (H/W)]

Modified Blasius equation

$$f_s = 0.085 (Re)^{-0.25} \quad (11)$$

The experimental set up is validated by comparing the experimental data for smooth plate with the theoretical results of smooth plate. The change in the value of Nusselt number with respect to Reynolds number for smooth duct is shown in Figure-3 and small deviation in the experimental and theoretical value is observed. Similar results have been found for the variation in friction factor with respect to the Reynolds number as shown in Figure-4 and shows better compliance between theoretical and experimental results.

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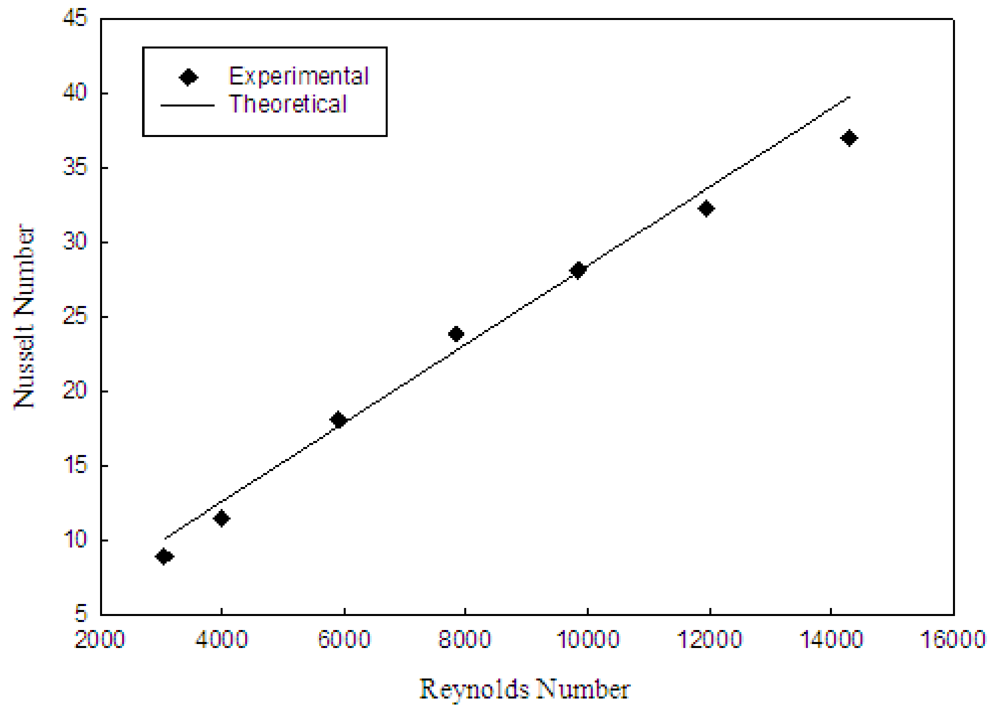

Figure-3. Comparison of experimental and theoretical value of Nusselt number against Reynolds number for smooth plate.

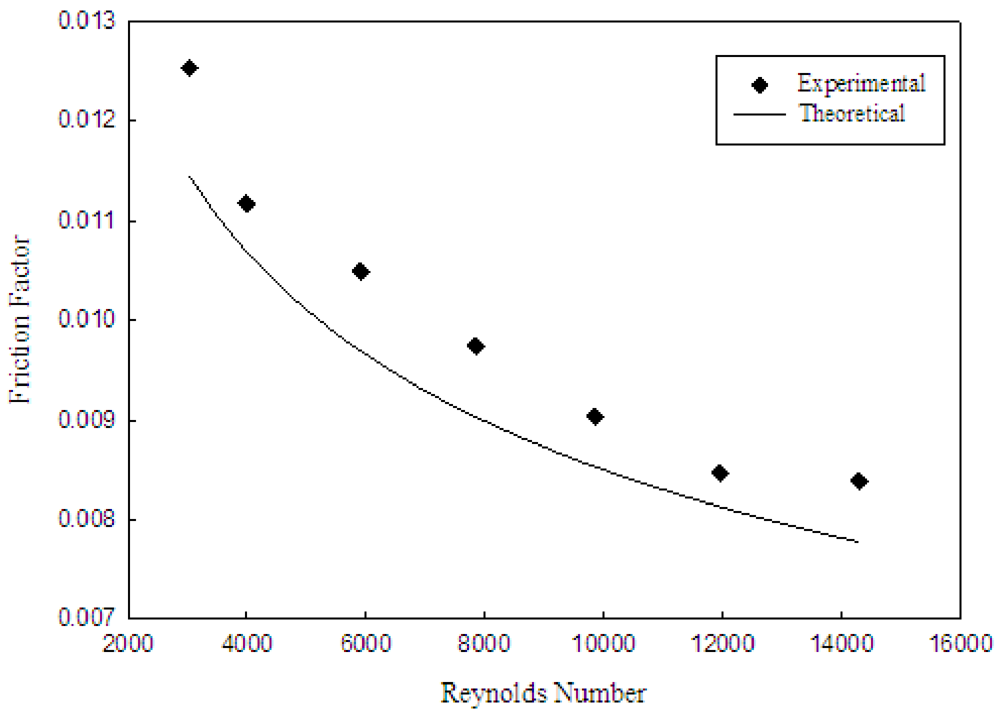

Figure-4. Comparison of experimental and theoretical value of friction factor against Reynolds number for smooth plate.

RESULTS AND DISCUSSIONS

Present experimental study investigated the effect of staggered rib length between the two consecutive gaps of rectangular solar air heater duct having V rib with symmetrical gap and with staggered rib roughness geometry. The variation of Nusselt number, friction factor and Thermo hydraulic performance with respect to Reynolds number were investigated for different relative staggered rib size (w/g). Figure-5 shows the variation of Nusselt number for different relative staggered rib sizes against Reynolds number. From the Figure it is observed that the Nusselt number increase by increasing the value of

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Reynolds number. Higher value of Reynolds number increases the intensity of turbulence which tends to increase the convective heat transfer from the absorbing plate. Figure-6 shows the variation of friction factor with Reynolds number and it is observed that the friction factor decrease with increase in Reynolds number for all the values of relative staggered rib sizes.

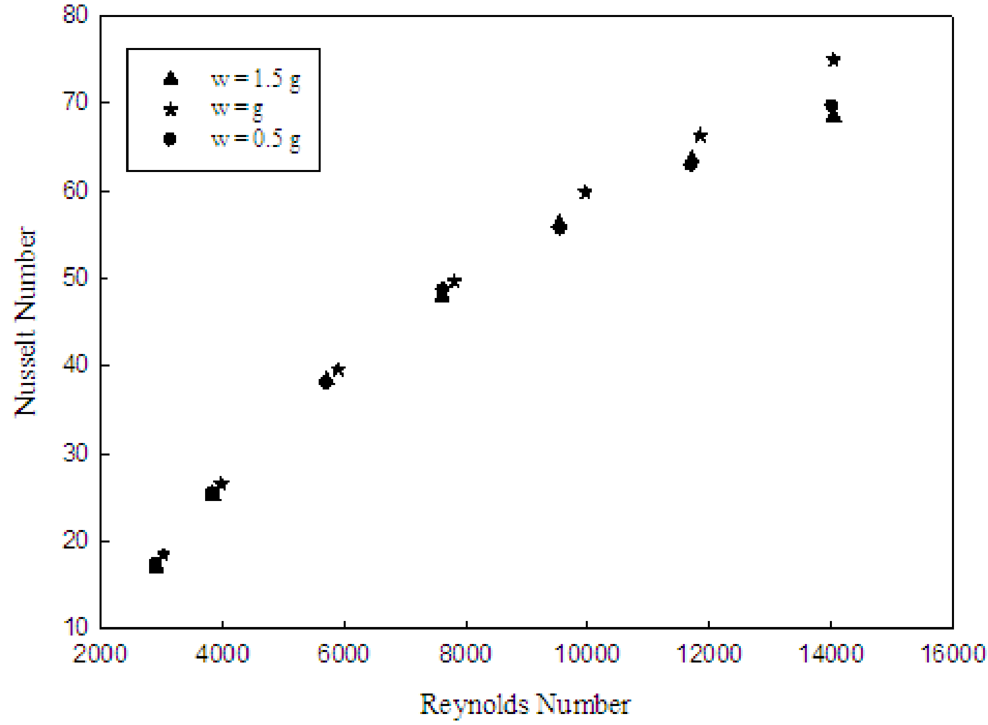

Figure-5. Variation of Nusselt number with Reynolds number for V-rib with symmetrical gap and staggered rib.

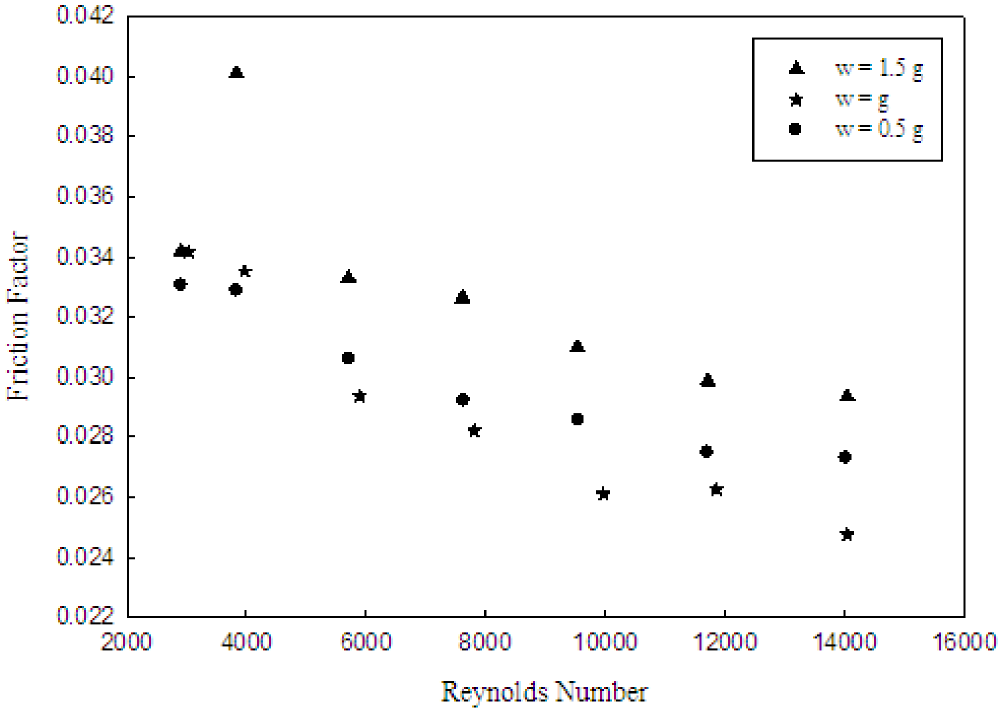

Figure-6. Variation in friction factor with Reynolds number for V-rib with symmetrical gap and staggered rib.

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To study the effect of staggered rib size on Nusselt number, the results are presented in Figure-7 and effect of friction factor is presented in Figure-8.

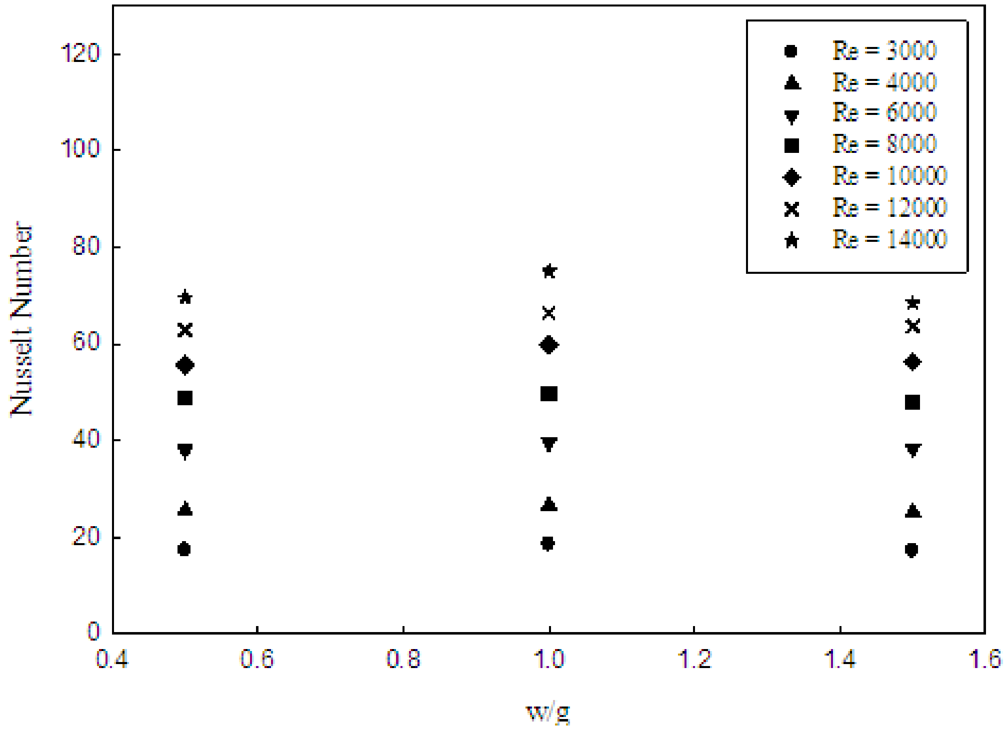

Figure-7. Variation of Nusselt number with relative staggered rib size.

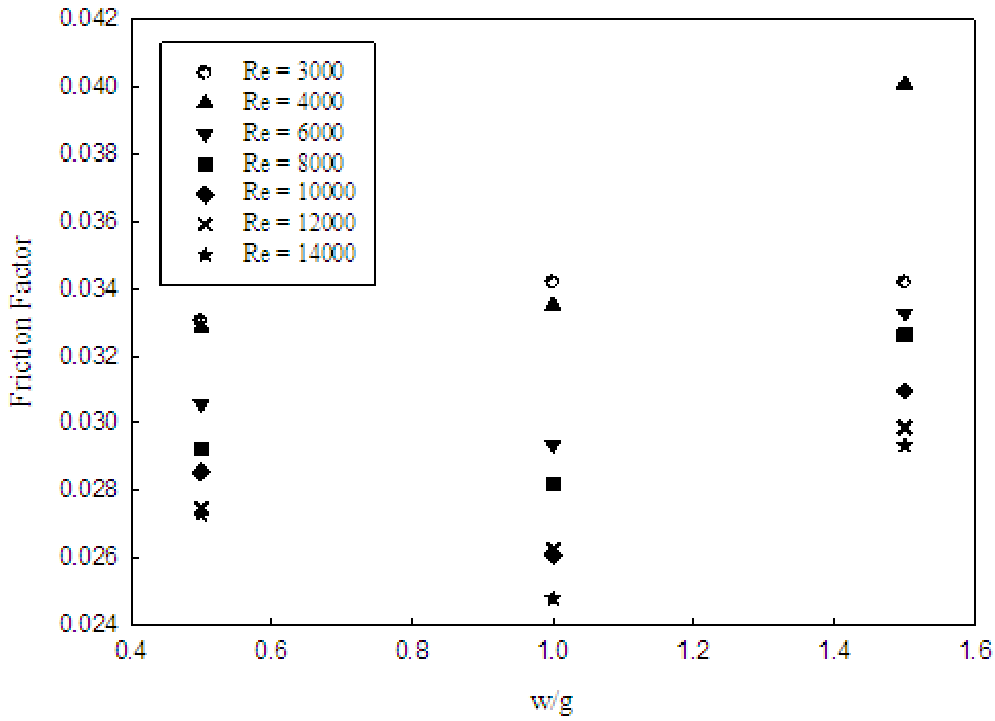

Figure-8. Variation of friction factor with relative staggered rib size.

From the Figure-7 and Figure-8 it can be seen that maximum Nusselt number is obtained for the relative staggered rib size equal to gap width and minimum friction factor is obtained with the staggered rib size equal to gap width. From the figures is clear that for relative staggered rib size (w/g) more than the gap width scatters the flow along span wise direction but at the same time it interferences with the reattachment points obtained in the

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main flow at downstream of the V rib this lowering heat transfer. Now if we lower the relative staggered rib size than gap width, Nusselt number decreases because of lesser scattering of flow along the span which in turn reduces the turbulence near the staggered rib region. Hence from Figure-5 and Figure-7 the optimum value of relative staggered rib size is obtained as equal to gap width which gives the best comparative results.

Artificial roughness in rectangular duct results in increase in heat transfer because of increase in turbulence near the laminar sub layer region but at the same time it also increases the friction factor which negatively affects the overall performance of solar air heater. Therefore in order to obtain the optimum value of staggered rib size that will maximize the heat transfer coefficient with minimum frictional losses, it is required to examine the thermo hydraulic performance of rib geometry.

THERMO-HYDRAULIC PERFORMANCE

In order to consider the performance of roughness geometry on both heat transfer enhancement as well as friction factor Webb and Eckert [19] suggested a parameter called thermo-hydraulic performance parameter (η) is given as:

$$\eta = (Nu/Nu_s)/(f/f_s)^{1/3} \quad (12)$$

The value of above parameters more than unity assures the benefit of using roughness geometry. The variation in the value of thermo-hydraulic performance with Reynolds number for different length of staggered rib is shown in Figure-9. It can be seen from the Figure-9 that the performance of relative staggered rib size equal to the gap width give higher value of thermo-hydraulic performance as compare to the other relative staggered rib sizes. Hence it is preferable to use V rib with symmetrical gap and staggered rib geometry with length of staggered rib as equal to gap width as compare to other lengths of staggered rib.

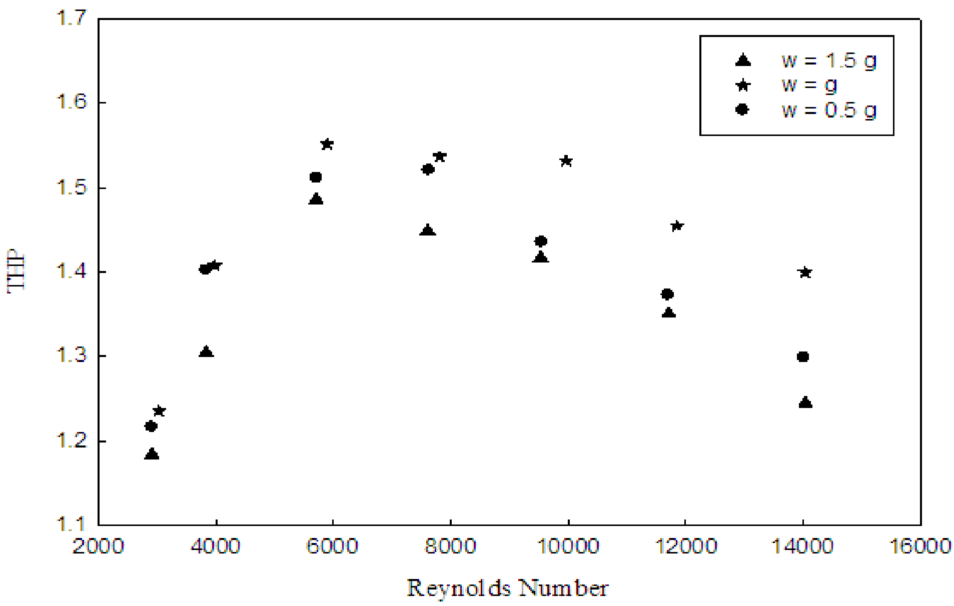

Figure-9. Variation in thermo-hydraulic performance with Reynolds number.

DEVELOPMENT OF CORRELATION

Many researchers have developed the empirical correlations of heat transfer and friction factor for solar air heater having roughened duct. Nakuradse [20] employed the friction empirical correlation based on law of wall similarity for grain roughness in pipes. The results presented by Nakuradse [20] in terms of roughness function (R) and Reynolds number (e^+) are defined as

$$R = \sqrt{\frac{2}{f}} + 2.5\ln\left(\frac{2e}{D_h}\right) + 3.75 \quad (13)$$

and

$$e^+ = \sqrt{\frac{2}{f}} \times Re \times \left(\frac{e}{D_h}\right) \quad (14)$$

The heat transfer similarity law for correlation heat transfer data for tubes with grain roughness developed by Dipprey and Sabersky [21] for heat transfer function (g) is defined as

$$g = \left[\left(\frac{f}{2St}\right) - 1\right]\sqrt{\frac{2}{f}} + R \quad (15)$$

The variation of roughness function (R) against Roughness Reynolds number (e^+) for V-rib with symmetrical gap and staggered rib roughness geometry is shown in Figure-10 and Figure-11 shows the variation of heat transfer function (g) against the Roughness Reynolds number (e^+) for V-rib with symmetrical gap and staggered rib roughness geometry.

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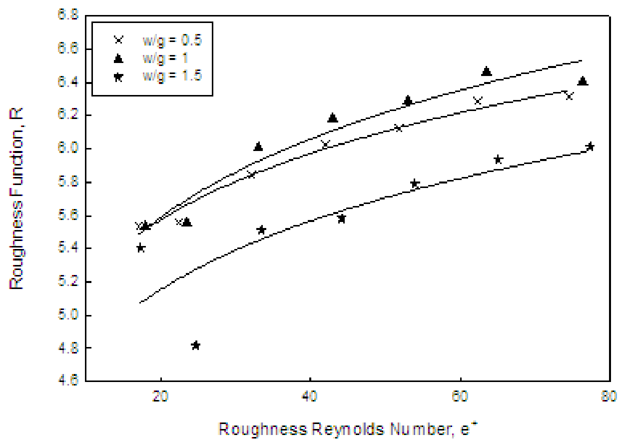

Figure-10. Effect of roughness Reynolds number on roughness function.

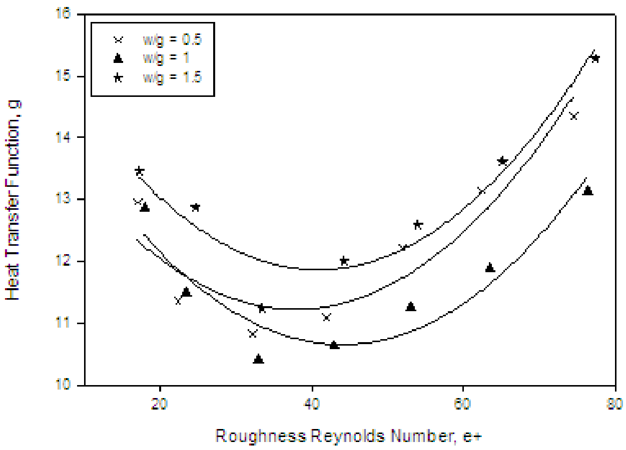

Figure-11. Effect of roughness Reynolds number on heat transfer function.

The experimental data is compared with the data calculated by using correlations for the roughness function and heat transfer function and the comparison is shown in Figure-12 and Figure-13 for R ang g respectively.

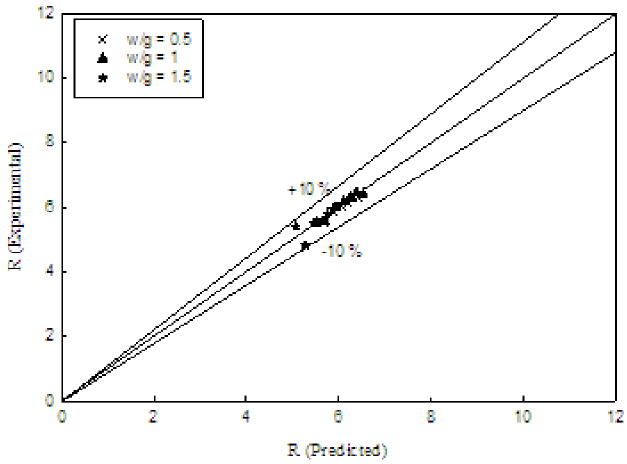

Figure-12. Comparison of experimental and calculated data for roughness function.

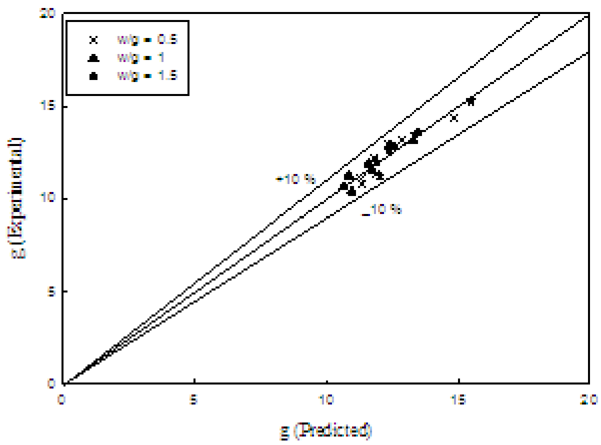

Figure-13. Comparison of experimental and calculated data for heat transfer function.

It is seen that the variation of roughness function and heat transfer function data lies within ± 10% for the correlations for roughness function and heat transfer function having coefficients and exponents as indicated in Table-2.

Table-2. Coefficients and exponents for roughness and heat transfer functions.

$R = a(e^+)^b$			$g = a_1 + b_1(e^+) + c_1(e^+)^2$		
	a	b	a_1	b_1	c_1
w/g = 0.5	4.1410	0.1021	14.9113	-0.1950	0.0026
w/g = 1	3.9425	0.1165	15.7022	-0.2298	0.0026
w/g = 1.5	3.6990	0.1108	16.3548	-0.2201	0.0027

In order to design the solar air heater having enhanced performance we can utilize the correlation which has been developed during investigation.

CONCLUSIONS

As per the experimental investigation on heat transfer and friction in the flow of air in solar air heater duct having V shaped symmetrical gap with staggered element, following conclusions are drawn:

a) The staggered rib element in between two consecutive symmetrical gaps of V rib has strong impact on the value of Nusselt number and friction factor. The present study of V rib symmetrical gap with staggered rib element enhanced the Nusselt number and friction factor upto 2.06 and 2.61 times respectively as compare to the smooth duct for staggered rib length equal to gap width.

b) The maximum value of Nusselt number is obtained with relative staggered rib size of 1.
c) The thermo-hydraulic performance parameter for V rib with symmetrical gap and staggered rib element is higher than that of other staggered rib length for the range of Reynolds number examined. The maximum value of thermo-hydraulic performance parameter with present study is obtained as 1.55.
d) The correlation has been developed for friction factor and heat transfer coefficient correlations. Maximum variance reported between calculated and experimental results for roughness function and heat transfer function is found to be ±10%, for both the parameters.

Nomenclature

A_o	Throat area of orifice plate (m^2)
A_p	Area of absorber plate (m^2)
C_d	Coefficient of discharge
C_p	Specific heat of air (KJ/kg K)
D_h	Hydraulic Diameter
e	Roughness height (mm)
e/D_h	Relative Roughness height
g/e	Relative gap width
H	Height of air channel (m)
h	Convective heat transfer coefficient (W/m^2 ℃)
k	Thermal conductivity of air (W/mK)
L	Length of duct (m)
L_f	Length of plate for pressure drop
m	Mass flow rate (kg/s)
Ng	Number of gaps
P	Roughness pitch
P’	Distance of staggered rib
P/e	Relative roughness pitch
ΔP_o	Pressure drop
ΔP_d	Pressure drop in duct
Q_u	Heat transfer rate
T_{fav}	Average temperature of air
T_i	Initial temperature of air
T_o	Outlet temperature of air
T_{pav}	Average plate temperature
V	Velocity of air
W	Width of air duct
W/H	Aspect ratio
w/g	Staggering ratio

Dimensionless parameters

f	friction factor of rough plate
f_s	friction factor for smooth plate
Nu	Nusselt number
Nu_s	Nusselt number for smooth plate
P_r	Prandtle number
Re	Reynolds number

Greek symbols

β	Ratio of orifice diameter to pipe diameter
ρ	Density of air
ρ_m	Density of manometer fluid
μ	Dynamic viscosity

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