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Experimental Investigations on Thermo-hydraulic Performance due to Flow- Attack- Angle in Multiple V-ribs with Gap in a Rectangular Duct of Solar Air Heaters

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Abstract: An experimental investigation was carried out to study the effect of artificial roughness, in the form of multi v-shaped ribs with gap on one heated wall of a rectangular solar air heater duct, on heat transfer (Nusselt number) and friction loss (friction factor). The artificially roughened duct had a width to height ratio (W/H) of 12, relative roughness width ratio (W/w) of 6, relative roughness pitch (P/e) of 10, relative roughness height (e/D) of 0.0433, relative gap width (g/e) of 1.0, relative gap distance (Gd/Lv) of 0.69, while the angle of attack (α) was varied from 30° to 75°. The heat transfer and friction characteristics of the duct were compared with those of a smooth duct under similar experimental conditions. It was found that there was a significant effect on the Nusselt number and friction factor when the angle of attack was changed.

Keywords: Angle of attack, Friction factor, Gap distance, Gap width, Nusselt number.

1. Introduction

Solar air heaters have been found to have a low thermal efficiency because of the low heat transfer coefficient between the absorber plate and air which leads to a high absorber plate temperature and hence a greater heat loss to the surroundings [1]. It has been found that the main thermal resistance to convective heat transfer is due to the formation of a boundary layer on the heat-transferring surface. Efforts for enhancing heat transfer have been directed towards artificially destroying or disturbing this boundary layer. Artificial roughness in the form of ribs is commonly used in various systems such as turbine blade cooling channels, heat exchangers, nuclear reactors and solar air heaters. These systems play important roles in many industrial applications including chemical processes, power generation, air-conditioning and transportation. The heat transfer enhancement associated with ribs involves flow separation/reattachment and flow turbulence which leads to the disruption of the laminar sub-layer. The effectiveness of the ribs depends strongly on their geometry such as shape, height, pitch and angle of attack. Many experimental investigations have been carried out involving roughness elements of different shapes, sizes and orientations with respect to flow direction. Prasad and Saini [2] studied the effect of roughness and flow parameters such as relative roughness height (e/D) and relative roughness pitch (P/e) on heat transfer and the friction factor. It has been found that transverse ribs enhance the heat transfer rate by about 1.8 times more than that of conventional smooth ducts due to flow separation at the ribs and reattachment of flow between two adjacent ribs.

Later on, it was established that angled ribs enhance heat transfer more than transverse ribs due to the generation of secondary flow in addition to breaking the laminar sub-layer. Gupta et al. [3] experimentally investigated the effect of relative roughness height (e/D), inclination of the rib with respect to flow direction and Reynolds number (Re) on the thermo-hydraulic performance of a roughened solar air heater duct in the transitionally rough flow region ($5 < e+ < 70$). Lau et al. [4-5] also observed that the replacement of continuous transverse ribs by inclined ribs in a square duct resulted in higher turbulence at the ribbed wall due to interaction of the primary and secondary flows.

The v-shaping of angled rib can further increase heat transfer due to the generation of two high heat transfer regions. Momin et al. [6] experimentally investigated the effect of geometrical parameters of v-shaped ribs on heat transfer and fluid flow characteristics of rectangular ducts of a solar air heater. The investigation covered a Re range of 2500-18,000, e/D range of 0.02-0.034 and angle of attack of flow (α) range of 30°-90° for a fixed relative roughness pitch (P/e) value of 10. The rate of increase of the Nusselt number was observed to be lower than the rate of increase of the friction factor with an increase in Re. The maximum enhancement of the Nusselt number and friction factor as a result of providing artificial roughness has been found to be 2.30 and 2.83 times, respectively, that of smooth ducts.

Han & Park [7] investigated the combined effect of rib angle and channel aspect ratio. They reported that the maximum heat transfer and pressure drop is obtained at an angle of attack of 60° and a square channel provides a better heat-transfer performance than a rectangular channel. Taslim et al. [8] investigated the heat transfer and friction characteristics of a channel roughened with angled and V-shaped ribs. They found that V-shaped ribs pointing downward have a much higher heat-transfer coefficient because the warm air being pumped toward the rib-leading region increases the apex region heat-transfer coefficients when compared to that of the leading end region. Gao and Sunden [9] also reported that downward pointing V-shaped ribs perform better than upward pointing ribs.

The overall thermal performance can be further improved by using broken ribs. The secondary flow through the broken rib may interrupt the growth of the boundary layers downstream of the nearby reattachment zone. Aharwal et al. [10] experimentally studied the effect of width and position of the gap in inclined split-ribs with a square cross section on heat transfer and friction characteristics of a rectangular duct. They found that discrete inclined ribs a have much higher heat transfer rate compared to that of the continuous inclined shaped ribs.

Wang and Sunden [11] reported that the rectangular duct (AR=8) roughened on two opposite sides with discrete V-up ribs have higher heat transfer and pressure drop when compared to continuous V-up ribs. Wright et al. [12] reported that a rectangular duct (AR=4) roughened on two opposite sides with a discrete V-rib resulted in higher heat transfer and lower pressure drop as compared to a continuous V-rib for $P/e = 10$, $e/D = 0.078$, $\alpha = 60$ degree, and a Reynolds number range of 10000-40000.

Singh et al. [13] investigated the heat transfer and pressure drop in a rectangular duct roughened with a new configuration of “discrete V-downstream ribs” on one broad wall. This type of rib was achieved by creating a small symmetrical gap equal to the rib height in both legs of the V-shape. The rectangular duct has a width-to-height ratio of 12 and the Reynolds number ranged from 3000 to 15,000. They found that discrete V-downstream ribs have a much higher heat transfer rate compared to that of continuous V-downstream shaped ribs.

Further, the use of a Multi V-shaped rib across the width of the absorber plate is found to enhance heat transfer by increasing the number of secondary flow cells several times when compared to simple single V-shaped ribs. Hans *et al*. [14] experimentally investigated the heat transfer and friction characteristics of multiple v-ribs roughened rectangular ducts. The investigation encompassed a Re from 2000 to 20000, a e/D value of 0.019-0.043, a P/e range of 6-12, an angle of attack (α) range of 30°-75° and a W/w range 1-10. Based on experimental results, correlations for the Nusselt number and friction factor were developed. A maximum enhancement of the Nusselt number and friction factor due to the presence of such an artificial roughness was found to be six and five times, respectively, in comparison to the smooth duct for the range of parameters considered.

In view of the above, it can be stated that the angling of the transverse rib enhances the heat transfer on account of the movement of vortices along the rib and the formation of a secondary flow cell near the leading end, which results in higher local wall turbulence. V-shaping of a long angled rib helps in the formation of two secondary flow cells as compared to one in the case of an inclined rib resulting in higher heat transfer rate. Producing a gap in the V-shaped rib is found to enhance the heat transfer by breaking the secondary flow and producing a higher level of turbulence in the fluid downstream of the rib. Furthermore, a Multi v-shaped rib across the width of the absorber plate is found to enhance the heat transfer by increasing the number of secondary flow cells as compared to a single V-shaped rib. It is thought that producing gaps in all the limbs of multi-v geometry will bring about a considerably large enhancement in comparison to that of a simple single V-shaped rib arrangement.

In the current work, experimental investigation has been carried out on the performance of solar air heater ducts which have the absorber plate with artificial roughness in the form of Multi v-shaped ribs with gap. The flow Reynolds number was varied between 2000 and 20,000. The variation of the Nusselt number and friction factor as a function of the angle of attack for a fixed value of the other parameters was evaluated and the thermo-hydraulic performance of the system was also examined.

2. Experimental

2.1 Details of the experimental set up

An experimental test facility was designed and fabricated to study the effect of gap width in multi v-shaped rib geometry on the heat transfer and fluid flow characteristics of a rectangular duct. A schematic diagram of the experimental set up is shown in Fig. 1. The wooden rectangular duct has an internal size of 2400 mm × 300 mm × 25 mm which consists of an entrance section, test section and exit section with lengths 525, 1000 and 875 mm, respectively, in accordance with the recommendations of ASHARAE standard 93-77 [15]. A heated 5 mm thick aluminium plate with artificial roughness was used as the top broad wall of the test section whereas the upper wall of the entry and exit sections of the duct was made of 10 mm thick plywood.

The absorber plate was heated from the top by supplying a uniform heat flux by means of an electrical heater topped by an insulation of 50 mm thick glass wool and 14 mm thick plywood. A calibrated orifice meter connected with a U- tube manometer using kerosene as manometric fluid was used to measure the mass flow rate of air. Calibrated thermo-couples were used for the measurement of heated plate temperature and air temperature. The airflow rate was varied to give a flow Reynolds number in the range of 2,000 to 20,000. Data was been collected under steady-state conditions which were assumed to have been reached when the plate and air temperatures did not show any significant variation for around 30-minutes duration. The steady state for each test run was obtained in about 3 to 4 hours.

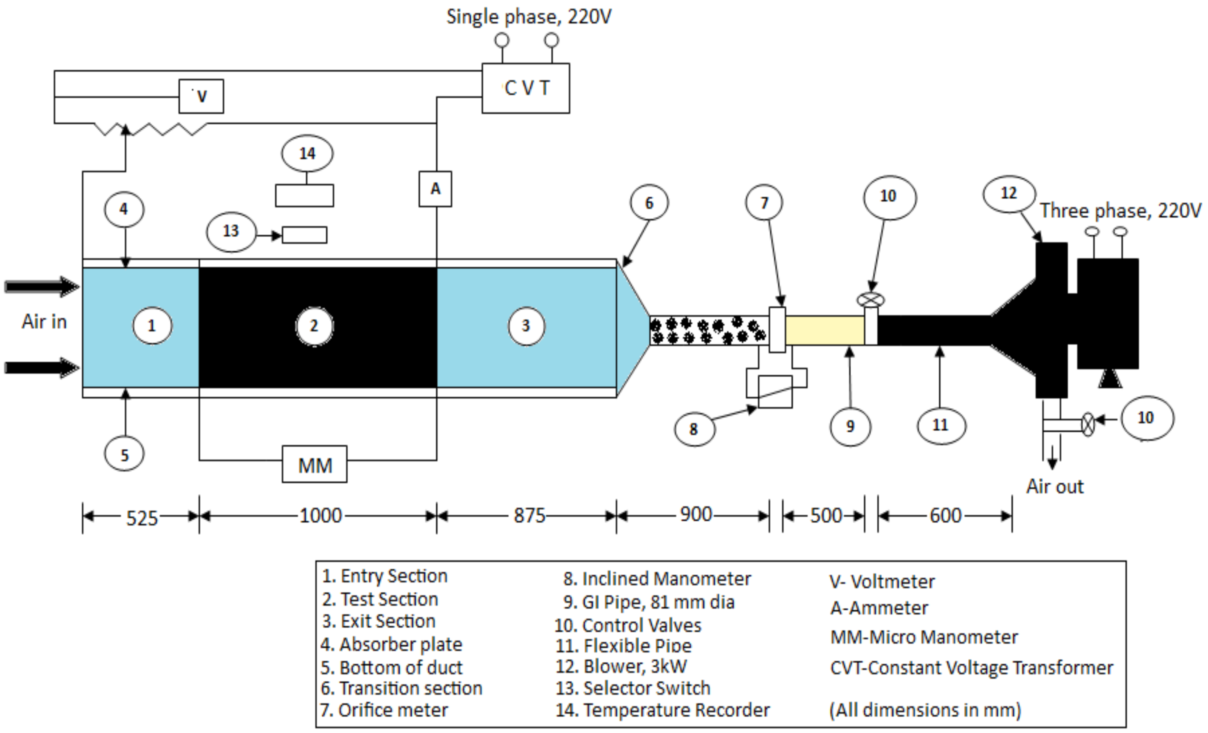

Figure 1. Schematic Diagram of experimental set-up.

2.2 Roughness geometry and roughness parameters

The values of the system and operating parameters of this investigation are listed in Table 1. The W/w, P/e and e/D were selected on the basis of optimum values of these parameters reported in the literature [2-3,6-8,10-14] while the angle of attack was varied between 30° to 75° four values. Fig. 2 shows the general geometry of the Multi v-shaped rib with gap roughness.

Table1. Range of parameters.

Sr. No.	Parameters	Values
1	Relative roughness width (W/w)	6
2	Relative roughness pitch (P/e)	10
3	Relative roughness height (e/D)	0.043
4	Relative gap width (g/e)	1.0
5	Duct aspect ratio (W/H)	12
6	Reynolds number (Re)	2000-20000
7	Relative gap distance (G_d/L_v)	0.69
8	Angle of attack (α)	30°-75°

2.3 Data reduction

The following procedure was employed for the calculation of heat transfer coefficient h; useful heat gain, Q_u; Nusselt number, Nu; Reynolds number, Re; friction factor, f; and thermo-hydraulic performance parameter, η. The heat transfer coefficient, h, for the heated section was calculated from the equation:

$$h = \frac{Q_u}{A_p \cdot (T_p - T_f)} \tag{1}$$

where the rate of heat gain by the air, Q_u is given by:

$$Q_u = m\, C_p\, (T_o - T_i) \tag{2}$$

The heat transfer coefficient was used to determine the Nusselt number, Nu, using the equation:

$$Nu = \frac{h \cdot D}{k} \tag{3}$$

The friction factor, f, was determined from the flow velocity, V, and the pressure drop, $(\Delta P)_d$ measured across the test section length of 1 m using the Darcy- Wiesbach equation:

$$f = \frac{2 \cdot (\Delta P)_d \cdot D}{4 \cdot \rho \cdot L \cdot V^2} \tag{4}$$

Based on the analysis of errors in the experimental measurements (Holman [16]) for different instruments used, the uncertainties in the values of the Reynolds number, Nusselt number, and friction factor, have been estimated to be ±1.25%, ±2.23% and ±5.82%, respectively, for Re = 2000 and those for Re = 20,000 are ±1.14%, ±6.58% and ±1.54%, respectively. The thermo-hydraulic performance parameter (η) was evaluated as:

$$\eta = (St/St_s)/(f/f_s)^{1/3} \tag{5}$$

where St and St_s are Stanton numbers for the roughened and smooth duct, respectively, while f and f_s are corresponding values of friction factors. The Stanton number is obtained from the equation:

$$St = Nu/Re.\ Pr \tag{6}$$

2.4 Validation of experimental data

The values of the Nu and f determined from experimental data for smooth ducts were compared with the values obtained from the Dittus-Boelter equation (7) for the Nusselt number and from the modified Blasius equation (8) for the friction factor.

The Nusselt number for a smooth rectangular duct is given by the Dittus-Boelter equation:

$$Nu_s = 0.023 Re^{0.8} Pr^{0.4} \tag{7}$$

The friction factor for a smooth rectangular duct is given by the modified Blasius equation:

$$f_s = 0.085 Re^{-0.25} \tag{8}$$

The comparison of the experimental and estimated values of the Nu and f as a function of the Re is shown in Figs. 3 and 4, respectively. The average deviation of the Nu values is ±2.7% while that of the f is ±2.2%. Thus, a reasonably good agreement between the two sets of values ensures the accuracy of the data being collected using this experimental setup.

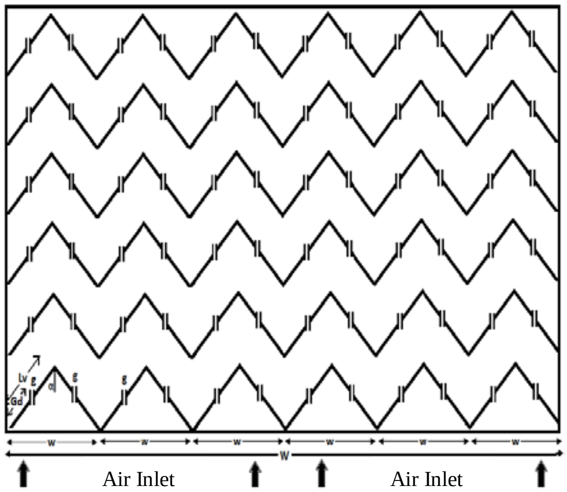

Figure 2. Multi v shaped with gap ribs.

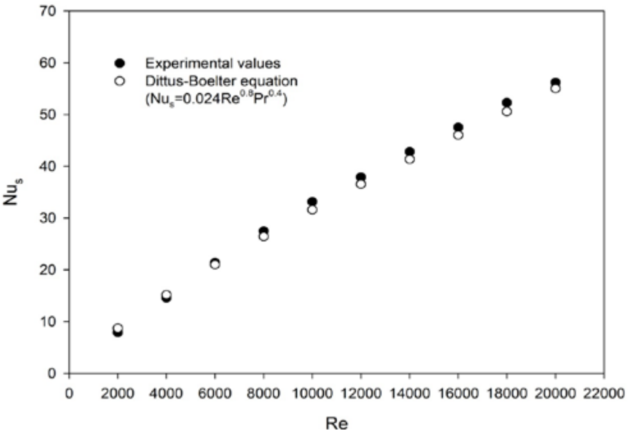

Figure 3. Nusselt number Vs Reynolds number for smooth surface.

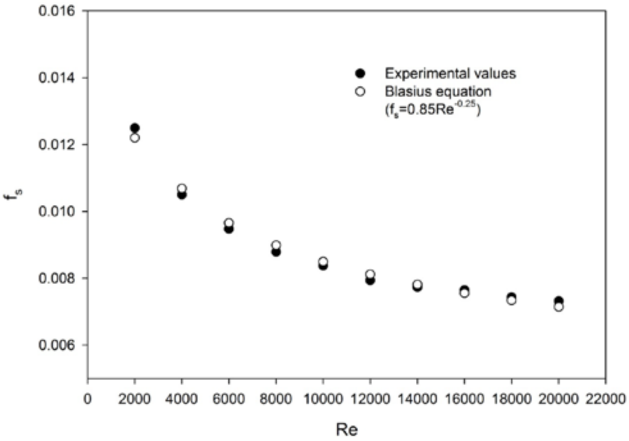

Figure 4. Friction factor Vs Reynolds number for smooth surface.

3. Results and Discussion

The heat transfer and friction factor characteristics of rectangular ducts having one wall heated and roughened with Multi v-shaped rib with gap, computed on the basis of experimental data collected for various flow Reynolds number (Re) and roughness parameters, are discussed below. The results have also been compared with those obtained in using smooth ducts operating under similar experimental conditions to discuss the enhancement in Nusselt number (Nu) and friction factor (f) on account of the use of artificial roughness.

The values of the Nusselt number (Nu) and Nusselt number ratio (Nu/Nu_s) for fixed values of the relative gap distance (Gd/Lv) of 0.69, relative gap width (g/e) of 1.0, relative roughness width ratio (W/w) of 6, relative roughness height (e/D) of 0.043, relative roughness pitch (P/e) of 10 and different values of angle of attack (α) are presented in Figs. 5 and 6, respectively. These figures show that the Nusselt number and Nusselt number ratio increase with an increase in the angle of attack up to about 60°, beyond which they decrease with increase in the angle of attack. The Nusselt number and Nusselt number ratio was highest for an angle of attack of 60° and lowest for an angle of attack of 30° (Fig. 7).

This variation may be caused by the interaction of secondary flow and the boundary layer at the front side of the multi v-rib. The boundary layer is inlet flow with the roughened surface and originates from flow reattachment point between the ribs up to the succeeding downstream rib. The strength of the secondary flow along the rib changes with a change in angle of attack.

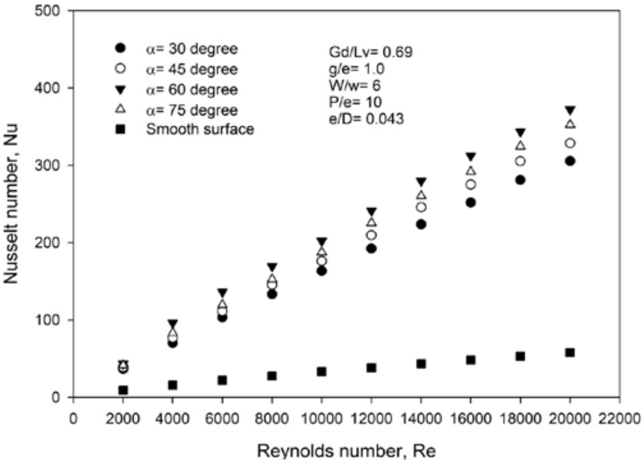

Figure 5. Variation of Nusselt number with Reynolds number at different angle of attack.

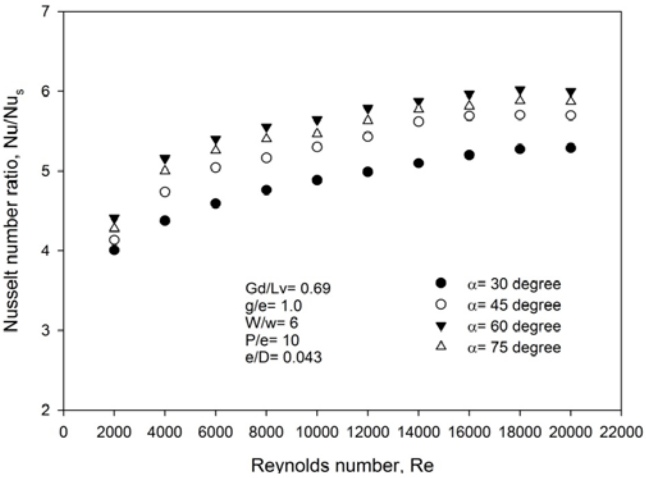

Figure 6. Variation of Nusselt number ratios with Reynolds number at different angle of attack.

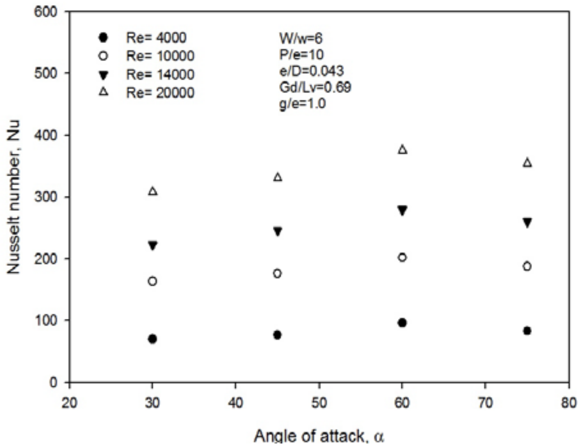

Figure 7. Variation of Nusselt number with angle of attack at selected Reynolds number.

These two factors determine the Nusselt number and Nusselt number ratio at different angles of attack. The results agree with earlier studies on V-down ribs Momin et al. [6], Singh et al. [13].

The effect of the angle of attack on the friction factor and friction factor ratio of roughened ducts is presented in the Figs. 8 and 9. It can be seen that the friction factor and friction factor ratio increase with increases in the angle of attack up to 60° and decreases with further increase in the angle of attack. The value of the friction factor and friction factor ratio is highest for an angle of attack of 60° and lowest for an angle of attack of 30° (Fig. 10). Figs. 11 and 12 show the effect of Reynolds number on

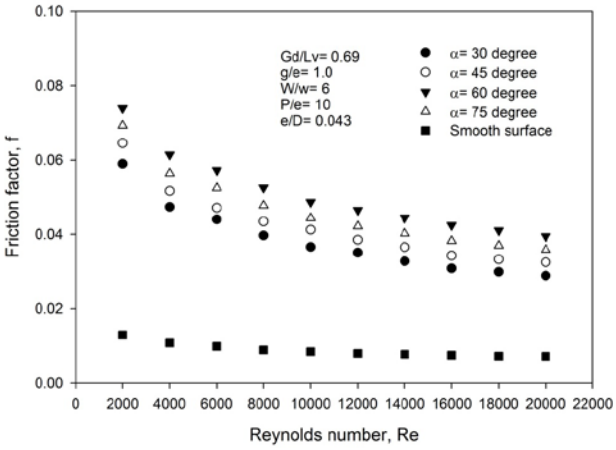

Figure 8. Variation of friction factor with Reynolds number at different angle of attack.

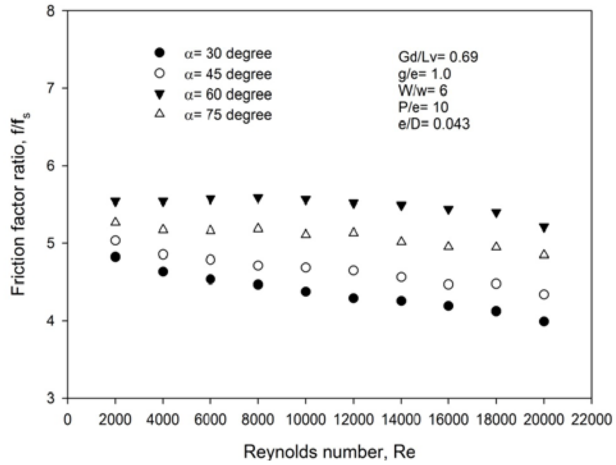

Figure 9. Variation of friction factor ratios with Reynolds number at different angle of attack.

the Nusselt number and friction factor for Multi v-shaped ribs with gap roughness with Gd/Lv = 0.69, g/e = 1.0, W/w = 6, P/e = 10, e/D = 0.043, α = 60°, multi v-shaped rib roughness with W/w = 6, P/e = 10, e/D = 0.043, α = 60° and the smooth solar air heater. The values of the Nusselt number were found to increase with increasing Reynolds number in all cases as expected. The Multi v-shaped ribs with gap roughness can be seen to yield higher a Nusselt number and friction factor when compared to that of the continuous Multi v-shaped rib with smooth solar air heater surface.

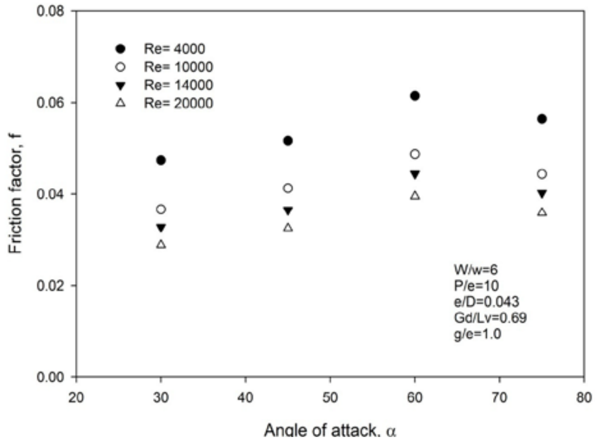

Figure 10. Variation of friction factor with angle of attack at selected Reynolds number.

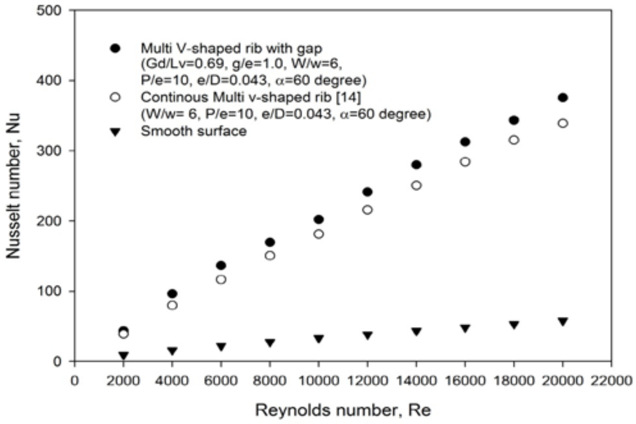

Figure 11. Variation of Nusselt number with Reynolds number for Multi v-shaped rib with gap, Multi v-shaped rib and smooth duct.

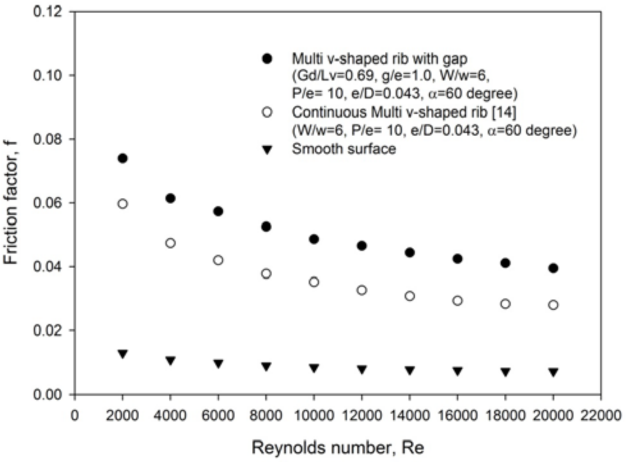

Figure 12. Variation of friction factor with Reynolds number for Multi v-shaped rib with gap, Multi v-shaped rib and smooth duct.

Fig. 13 shows the perceived secondary flow pattern for a V-shaped rib. As pointed out by earlier investigators, V-shaping of the rib helps in the formation of two leading ends (where heat transfer rate is high) and a single trailing end (where heat transfer rate is low) as well as two secondary flow cells which promote turbulent mixing and hence increased heat transfer [8]. The introduction of a gap in the V-shaped rib allows the release of the secondary flow that mixes with the main flow through the gap as shown in Fig.14. This results in its acceleration, which energizes the retarded boundary layer flow along the surface, resulting in the increase of heat transfer through the gap width area behind the ribs [10]. The secondary flow exerts a measurable effect in disturbing the axial flow profile, which increases the friction factor. These results broadly agree with previous studies on discrete rib roughened ducts [6,8,10-14].

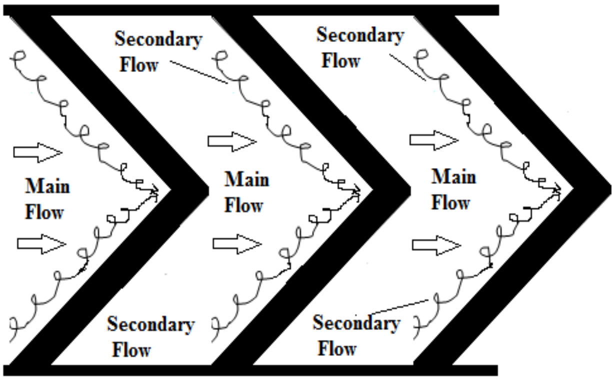

Figure 13. Secondary flow pattern for Continuous V-shaped rib.

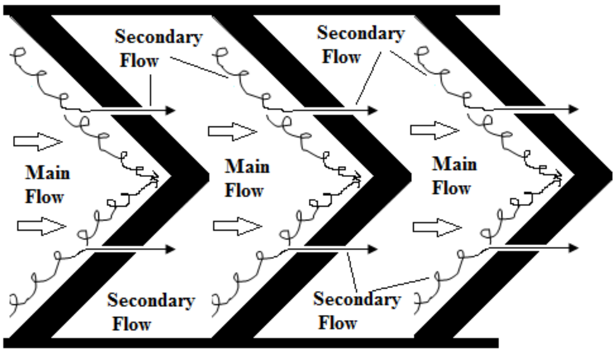

Figure 14. Secondary flow pattern for Continuous V-shaped rib with gap.

3.1 Thermo-hydraulic performance

Study of heat transfer and friction characteristics shows that an enhancement in heat transfer is, in general, accompanied with a friction power penalty due to a corresponding increase in the friction factor. Therefore it is essential to determine the geometry that will result in a maximum enhancement of heat transfer with a minimum friction power penalty. In order to achieve this simultaneous objective of thermal as well as hydraulic performance, Lewis [17] proposed a thermo-hydraulic parameter known as the efficiency parameter 'η' which evaluates the enhancement in heat transfer of a roughened duct compared to that of a smooth duct for the same pumping power requirement and is defined as :

$$(St/St_s)/(f/f_s)^{1/3}$$

A heat transfer enhancement device having a value of thermal as well as hydraulic parameter (η) higher than unity ensures the fruitfulness of using an enhancement device and therefore, this parameter is generally used to compare the performance of different roughness arrangements to decide the best roughness arrangement among all the possible combinations. Fig. 15 shows the effect of the angle of attack on thermo-hydraulic performance parameters and it can be seen that the maximum value of the performance parameter corresponds to an angle of attack of 60° for all values of Reynolds number.

The values of the thermo-hydraulic parameter determined for this geometry of multi v-rib with gap have been compared with the corresponding values for Transverse ribs [2], Angled ribs [5], Broken v-ribs [8], V-rib with gap [13] and Multi v-rib [14] (see Fig. 16). It can be seen that the multi v-rib geometry with gap results is best the thermo-hydraulic performance.

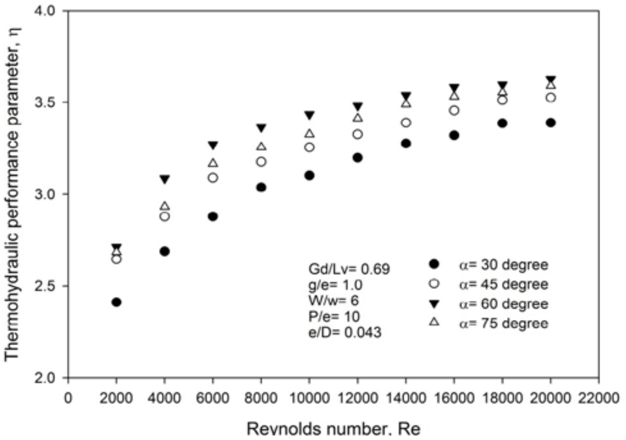

Figure 15. Variation of thermo-hydraulic performance parameters with Reynolds number at different angle of attack.

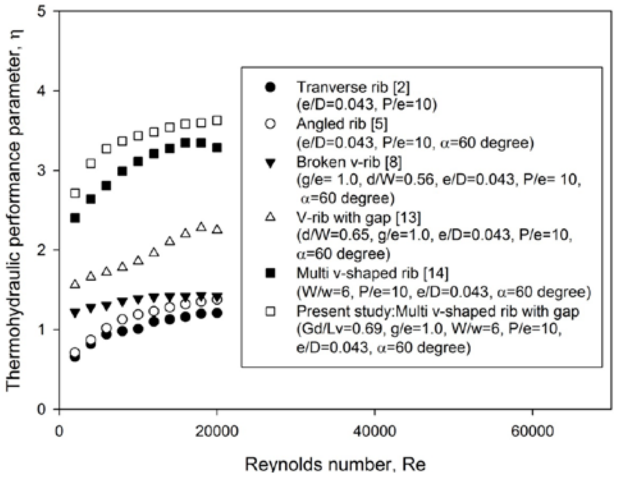

Figure 16. Comparison of thermo-hydraulic performance with previous investigations.

4. Conclusions

On the basis of the experimental investigation of solar air heater ducts with Multi v-shaped ribs with gap roughness geometry, the following conclusions can be drawn:

1. The Nusselt number and friction factor of the roughened duct are a strong function of the angle of attack.
2. The value of Nusselt number and friction factor increase with an increase of angle of attack and are maximum at an angle of attack of 60°.
3. A symmetrical gap equal to the rib height in both legs of a Multi v-shaped rib results in a substantial improvement in the thermo-hydraulic performance.
4. An angle of attack of 60° represents the thermo-hydraulically best geometry of multi v-shaped ribs with gap.

Nomenclature

A_p	area of absorber plate, m^2
A_o	cross section area of orifice, m^2
C_d	coefficient of discharge of orifice
C_p	specific heat of air at constant pressure, J/kg K
D	hydraulic diameter of duct, m
e	rib height, m
e/D	relative roughness height
f_s	friction factor of smooth duct
f	friction factor of roughened duct
G_d	gap distance, m
G_d/L_v	relative gap distance
g	gap width, m
g/e	relative gap width
H	depth of duct, m
h	convective heat transfer coefficient, W/m^2 K
k	thermal conductivity of air, W/m K
L_v	length of single v shaped rib, m
L	test section length for pressure drop measurement, m
m	mass flow rate, kg/s
Nu	Nusselt number of roughened duct
Nu_s	Nusselt number of smooth duct
$(\Delta P)_o$	difference of manometric fluid level in U-tube manometer, m
$(\Delta P)_d$	difference of water column level in micro-manometer, m
P	pitch of the rib, m
P/e	relative roughness pitch
Q_u	useful heat gain rate, W
Re	Reynolds number
T_f	mean temperature of air, K
T_i	inlet temperature of air, K
T_o	outlet temperature of air, K
T_p	average plate temperature, K
V	velocity of air, m/s
W	width of duct, m
w	width of single v-shaped rib, m
W/w	relative roughness width ratio

Greek symbols

α	rib angle of attack, degree
β	ratio of orifice diameter to pipe diameter
η	thermo-hydraulic performance parameter
ρ	density of air, kg/m^3
ρ_m	density of manometric fluid, kg/m^3

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