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Thermo-Hydraulic Performance of a Rectangular Duct With Staggered Inclined Discrete Rib Arrangement

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Abstract: Artificial roughness in the form of ribs is a beneficial strategy to improve the thermal performance of solar air heaters (SAHs). In the present research work, experimental examinations have been conducted on heat transfer and friction characteristics in the rectangular channel, which is roughened through the inclined discrete ribs. The inclined ribs were discretized by creating gaps at the different positions (not inline) on trailing and leading edges in consecutive ribs The rib roughness has relative roughness pitch as 8.0, rib combination of relative gap position is varied from 0.3 & 0.1 to 0.3 & 0.4, and mass flow rate varies between 3000 -14,000 and rib gap width as 1. The higher improvement in the Nusselt number and factor of friction coefficient is obtained to be 2.92 and 3.33 times respectively, as compared with that of the smooth duct. The higher thermo-hydraulic performance parameter (THPP) is obtained for the combination of relative gap position of 0.3 & 0.3.

Keywords: Combination of relative gap position, Friction factor, Gap width, Nusselt Number, Reynolds number, and Thermo hydraulic performance (THP).

I. INTRODUCTION

The SAHs in light of its direct arrangement and low activity and support cost is comprehensively used as a solar collector. The thermal performance of SAHs is an immediate result of its poor heat transfer boundary between the absorber plate and the working fluid, for example, air. The use of artificial roughness on the absorber surface is an effective technique for improving heat transfer between the absorber plate and the working fluid. The roughness element breaks the thermal boundary layer thereby increasing the heat transfer. However, this also increases friction loss resulting in increased pumping power requirements from blower or fan. To reduce friction loss and pumping power, turbulence must be created in the vicinity of the absorber surface so that the sub-layer of the lamina is broken. Due to the use of artificial roughness in SAH, many researchers [1-4] have been done made to improve the cooling of the path of turbine blade. Han J.C. et al. [1] examined the impact on the shape of the ribs, pitch proportion of the height to the rib coefficient of friction and angles of attack and heat transfer characteristic of rectangular ducts with 2-sides of the rough dividers.

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They saw that the higher estimations of the heat transfers and coefficient of friction and the ribs are arranged at an angle as 45°, and the rib relative roughness on the pitch (P/e) as 10. Lau S.C. et al. [2] it has been seen that due to the interactions of the primary and secondary flows resulting in the exchange of transverse ribs in a continuous manner by the inclined rib square duct, the wall of the ribbed there is greater turbulence. Some of the notable researchers are Lau H.C. et al. [2, 3], Han J.C. et al. [4], Han J.C. et al. [5], Cho H.H. et al. [6] and Cho H.H. et al. [7]. They used inclined rib roughness geometries for heat transfer enhancement. Aharwal K.R. et al. [8] examined the impact of heat transfer characteristics and the coefficient of friction using a discrete integral inclined rib on the square plates of SAHs. They observe the highest values Nusselt number in the rib roughness pitch of 8 for the attack angle as 60°. Aharwal K.R. et al. [9] examined the geometry of roughness as inclined rib along gaps to increase heat transfer from that the absorber plates of SAHs. They optimize the gap positions and gap width in the inclined rib and report that the maximum thermo-hydraulic performance value for the rib gap position was obtained as 0.25 and rib gap width as 1.0. In the previous research work, most of the ribs have been discretized by creating the gap in a straight-line manner. However, no research work has yet been made for inclined ribs in which gaps are created in the conjugative ribs in a zig-zag manner (not in a straight line) as shown in the proposed roughness geometry in previous research work [2, 3, 5, 6, 7, 8 and 9]. This research work was so undertaken up to decide the ideal location of the different gaps arrangements (which are not in line) and the ability of SAH to improve heat transfer from the roughened duct to the working fluid. The present research work will help to determine the position and size of the gap during the discretization of an inclined rib in order to increase the performance in comparison with the non-discretized ribs.

II. TEST SET-UP

The test set-up is shown in Figure 1, according to Duffy J.A., and Beckmann W.A. [10]. It has a rectangular test section, converging section, the circular pipe having an orifice plate to measure flow rate, blower, and electric motor. A variac is used to control the voltage and current, which supplies heat flux to the absorber plate. The ammeter and voltmeter are used to measure the current and voltage to be supplied to the heater. The thermocouple wires are used to measure inlet, outlet and plate temperature. An electronic data logging device is used to determine the temperature in real-time. An inclined U-tube manometer is utilized to measuring the pressure drops in the orifice plate. Pressure drop along the plate is measured with the electronic pressure meter.

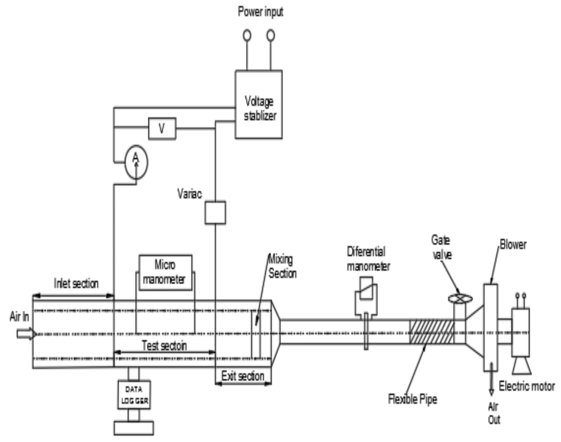

Figure 1: Experimental Test Program.

III. RANGE OF PARAMETERS AND ROUGHNESS RIB GEOMETRY

The value of the system and working parameters of this experimental study are recorded in Table 1. The relative roughness pitch (P/e) value and angle of attack are chosen as 8.0 and 45° respectively, in light of the ideal value of this parameter announced in the literature [8, 9]. The ranges of the Reynolds numbers and rib roughness height have been selected due to the requirements of SAHs (11). The heated plate is 1.5 mm × 0.2 meters (length 1.5 meters and width 0.2 meters) of 5 mm thick aluminum plate, it has been used in the form of roughened duct and bottom surface of the roughened plate was rendered artificially roughness as a staggered inclined discrete rib of an aluminum plate by the CNC machining process and a gap on rib was created by a milling machining. The schematic outline of the roughened plate is appeared in Figure 2 (a-e).

Table 1: The values of the parameter used in this roughness geometry

Sr.no.	Parameters	Values
1.	Reynolds Number (Re)	3000 -14,000
2.	Rib pitch (P/e)	8.0
3.	Rib height (e/D_h)	0.045
4.	Attack angle (α)	45°
5.	Hydraulic diameter (D_h)	44.44
6.	Heat flux	900 W/m^2
7.	Duct aspect ratio (W/H)	8.0
8.	Rib width (g/e)	1.0
9.	Combination of relative gap position (dt/W & dl/W)	0.3 & 0.1 - 0.3 & 0.4

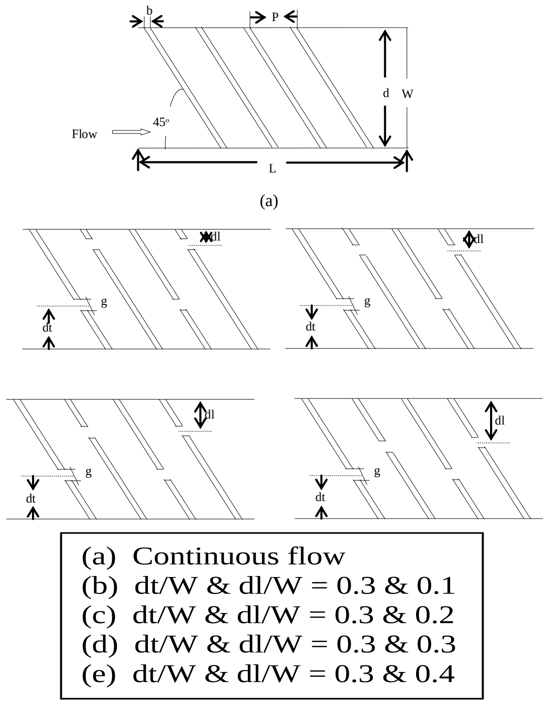

Figure 2 (a-e): Shows the discretization of ribs by creating gaps at different gap position of 45° inclined ribs.

IV. DATA REDUCTION

The values of air and plate temperature are measured for constant mass flow rate and heat flux in a steady state. The heat transfer, Nusselt number and friction factor have been calculated from the data received. It helps in finding the impact of the different parameters on Nusselt number and friction factor utilizing the following formulae.

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

$$h = \frac{Q_u}{A_p} \times \left[T_{pav} - T_{fav}\right] \quad (2)$$

$$Re = \frac{V \times D_h}{\upsilon} \quad (3)$$

$$Nu_r = \frac{(h \times D_h)}{\kappa} \quad (4)$$

$$f_r = \frac{2 \times [(\Delta P)_d] D_h}{4\rho L f V^2} \quad (5)$$

$$\eta = (St_r/St_s)/(f_r/f_s)^{1/3} \quad (6)$$

V. RESULTS AND DISCUSSION

A. Validity Test Set-Up

Validation of test program depends on empirical values and theoretical values. Empirical values of smooth duct are obtained from the test. From the literature correlations work, the performance of theoretical values evaluated. Theoretical values of Nu_s evaluated from correlations of Dittus-Boelter condition (7) and theoretical values f_s evaluated from the correlation of modified Blasius condition (8). These theoretical equations are given below:

Correlation of Dittus-Boelter condition used in dimensionless number (Nu) for smoothness [12]

$$Nu_s = 0.085 \times Re^{-0.25} \quad (7)$$

Correlation of Modified Blasius condition used in dimensionless number (fs) for smoothness [13]

$$f_s = 0.023 \times Re^{0.8} \times Pr^{0.4} \quad (8)$$

Figure 3 indicates dimensionless Nusselt number (Nu_s) versus dimensionless Reynolds number (Re) of the smooth surface. The friction factor (f_s) versus dimensional number (Re) of the smooth surface is given in Figure 4. Empirical values of dimensionless number (Nu_s) and the factor of friction coefficient closely match with theoretical values, the validity of the test is guaranteed.

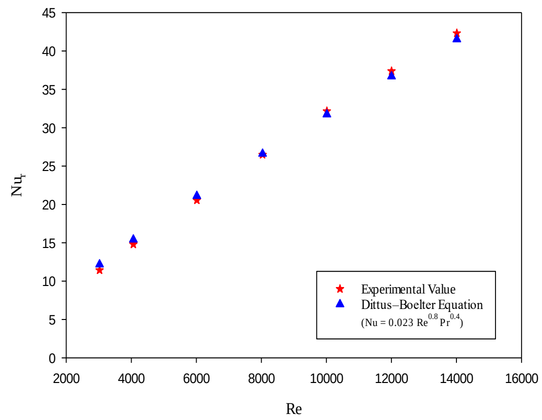

Figure 3: shows the dimensionless Nusselt number (Nu_s) versus dimensionless Reynolds number (Re) of the smooth surface.

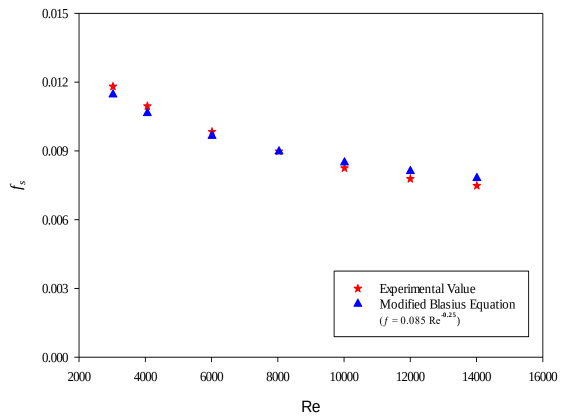

Figure 4: shows the dimensionless friction factor (fs) versus dimensionless Reynolds number (Re) of the smooth surface.

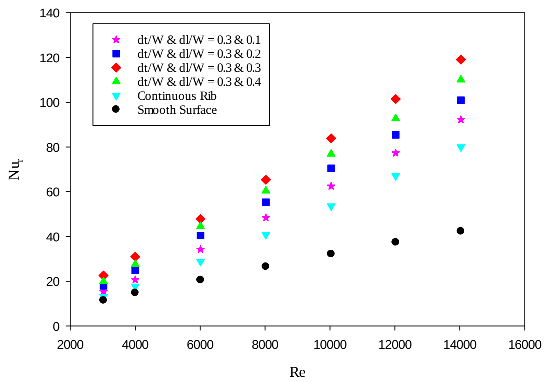

Figure 5: shows variations of Nusselt number with Reynolds numbers for various gap positions.

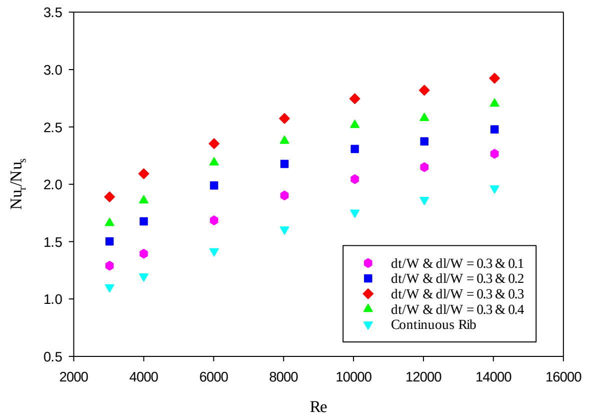

Figure 6: shows variations of Nusselt number ratio with Reynolds numbers for various gap positions.

B. Effect of Reynolds Number

Figure 5 shows variations of Nusselt number with Reynolds number that different combinations of relative gap position (dt/W & dl/W) for a fixed value of rib gap width, angle of attack and rib pitch. It is observed that the value of the Nusselt number is increasing as the Reynolds number increases for all roughness arrangements. The higher value of Nusselt number is observed that the combination of relative gap position of 0.3 & 0.3 and it's lowest for a combination of relative gap position of 0.3 & 0.1. To observe that the impact of rib artificial roughness on the improvement of heat transfers when compared with that of without artificial roughness arrangements (smooth surfaces), the ratio between the Nusselt number of artificially rough surfaces and the Nusselt number of smooth surfaces (Nu_r/Nu_s) as different values of Reynolds number is displayed in Figure 6. From this figure, it can be observed for any Reynolds number, that the value of the Nusselt number ratio is highest for the arrangement of the artificially roughened as a gap in a scattered manner in conjugative inclined ribs than those ribs without any gaps. There is a large gap between smooth and staggered inclined discrete roughened plate test data due to turbulence caused by rib roughness. The rib roughness breaks the laminar sub-layer causing turbulence that promotes heat transfer. At minimum Reynolds number, the gap between the smooth and rough plate is less, but it is very significant for the highest value of the Reynolds numbers. It very well may be seen for the Nusselt number ratios varied from 1.10 to 2.92 times for the proposed ranges of Reynolds numbers. The highest value of Nusselt number ratio is observed that the combination of relative gap position of 0.3 & 0.3 whereas its minimum values are achieved for the combination of relative gap position of 0.3 & 0.1. This may be because of the way that the combination of gap positions of 0.3 & 0.3 is creating more local turbulence as compared with the other combination of relative gap position.

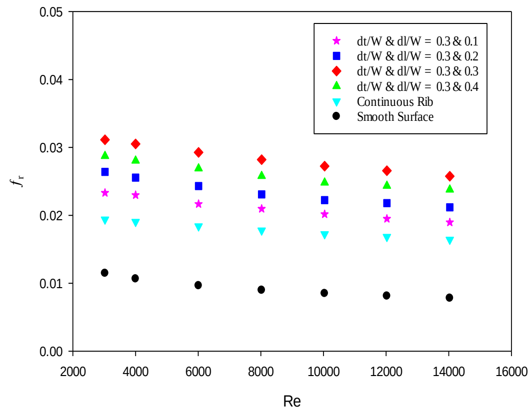

Figure 7: shows variations of friction factor with Reynolds numbers for various gap positions.

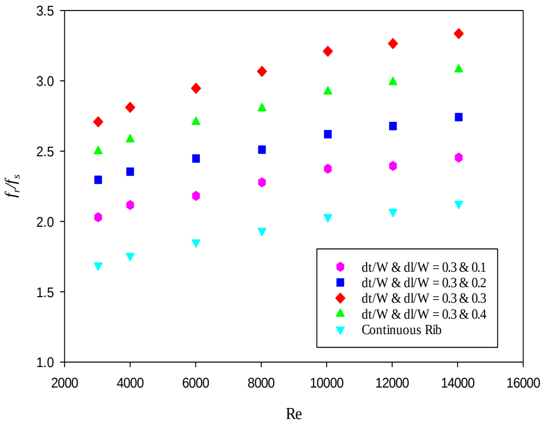

Figure 8: shows variations of friction factor ratio with Reynolds numbers for various gap positions.

Figure 7 shows variations of friction factor with Reynolds number that different combinations of relative gap position (dt/W & dl/W) for a fixed value of rib gap width, angle of attack and rib pitch. It is observed that the value of the friction factor is decreasing as the Reynolds number increases for all roughness arrangements. The friction factor is higher for the combination of relative gap position of 0.3 & 0.3 and it's lowest for the combination of relative gap position of 0.3 & 0.1. A higher friction factor due to flow acceleration and scattering whereas proposed geometry namely staggered inclined discrete rib has the highest friction factor due to the greater scattering of flow and flow acceleration. Figure 8 shows variations of the friction factor ratios (f_r/f_s) along with the Reynolds number as the combination of relative gap position. It tends to be observed that the range of the friction factor ratios varies from 1.68 to 3.33 times that the proposed ranges of Reynolds numbers. The highest value of friction factor ratio is observed for the combination of relative gap position of 0.3 & 0.3 whereas its minimum values are achieved for the combination of relative gap position of 0.3 & 0.1.

C. Thermo-Hydraulic Performance

The thermo-hydraulic performance (THP), Lewis [14] offered THPP known's as the efficiency parameters "η", the need for same pumping power prerequisite, which assesses the improvement, when compared along with the smooth duct in the heat transfer of a roughened duct and is characterized as:

$$\eta = (St_r/St_s)/(f_r/f_s)^{1/3} \qquad (9)$$

More than solidarity, a value of this parameter guarantees the productivity of using the upgrade gadget and can be used to see the performance of the number of activity arrangement of action to pick the best. The value of this parameter for the roughness geometries explored in this work has appeared in Figure 9. It is observed that the values of parameters are by and large higher for staggered inclined discrete ribs than those with and without ribs under similar test conditions. It tends to be seen as the THP parameters varied from 0.92 to 1.96 times that the proposed ranges of the Reynolds numbers. The highest values for this parameter are observed that the combination of relative gap position of 0.3 & 0.3 in all Reynolds number values.

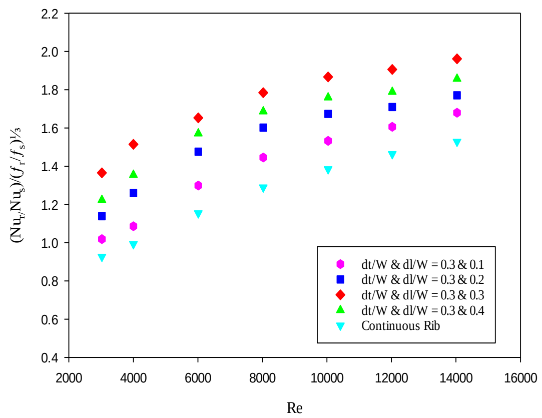

Figure 9: shows variations of thermo-hydraulic performance with Reynolds numbers for various gap positions.

VI. CONCLUSIONS

In the present research work, the heat transfer and friction factor have been analyzed experimentally by the SAH duct, whose absorber surface has been made to be roughened with the staggered inclined discrete ribs. The main conclusions shown by this study are given below:

(i) The Nusselt number shows increasing trends with increasing Reynolds number. The higher value of Nusselt number is observed for the combination of relative gap position (dt/W & dl/W) of 0.3 & 0.3 compared to the other combination of relative gap position

(ii) The friction factor shows decreasing trends with increasing Reynolds number. The higher value of friction factor is observed for the combination of relative gap position (dt/W & dl/W) of 0.3 & 0.3 compared to the other combination of relative gap position.

(iii) The value of thermo-hydraulic performance parameter for the proposed roughness geometry has also been estimated and the highest value of this parameter is observed for the combination of relative gap position of 0.3 & 0.3 compared with the other combination of relative gap position.

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NOMENCLATURE

Dimensional Parameters

C_p Air specific heat ($J/kg^{-1}K^{-1}$)
D_h Equivalent depth of duct (m)
dl Leading edge
dt Trailing edge
d/W Gap position
e Height of rib element (m)
g Width for gap (m)
H Duct for Depth (m)
h Coefficient of heat transfer convective (W/m^2K^{-1})
k Air for thermal conductivity (W/m^{-1} K^{-1})
L Length for plate (m)
m Quantity of air rate Passing through duct (kg/s^{-1})

Non-Dimensional Parameters

e/D_h Rib roughness height
f_s factor of friction coefficient for smoothness
f_r factor of friction coefficient for smoothness
g/e Rib gap width
Nu_r Roughness Nusselt number for Roughened plate
Nu_s Smoothness Nusselt number for smooth plate
P/e Roughness for rib pitch
Re Reynolds Number

Greek Symbols

α Attack angle (Degree)
ρ Density for air (kg/m^3)
η_{th} THP efficiency

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