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

Mukesh Kumar Solanki, K. R. Aharwal

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 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 laminar 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. 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] have 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.

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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 have been 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).

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/Dₜ)           | 0.045                |
| 4.     | Attack angle (α)            | 45°                  |
| 5.     | Hydraulic diameter (Dₜ)     | 44.44                |
| 6.     | Heat flux                   | 900 W/m²             |
| 7.     | Duct aspect ratio (W/H)     | 8.0                  |
| 8.     | Rib width (g/e)             | 1.0                  |
| 9.     | Combination of relative gap position | 0.3 & 0.1 - 0.3 (dt/W & dl/W) & 0.4 |

Figure 1: Experimental Test Program.

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.

\[ m = C_d \times A_o \times \left( \frac{2 \rho \Delta P_o^{0.5}}{1 - \theta^2} \right) \]  
\[ h = \frac{Q}{A \times T_{av}} \times [T_{avg} - T_{far}] \]  
\[ Re = \frac{V \times D_h}{\nu} \]  
\[ Nu_e = \frac{(h \times D_h)}{k} \]  
\[ f_e = \frac{2 \times ([\Delta P_e]_d) D_h}{4 \rho L f V^2} \]  
\[ \eta = (St_r/ St_s)/(f_r/f_s)^{1/3} \]

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 Nuₜ evaluated from correlations of Dittus-Boelter condition (7) and theoretical values fₑ 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]

\[ Nu_e = 0.085 \times Re^{-0.25} \]  

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

\[
f_s = 0.023 \times Re^{0.8} \times Pr^{0.4}
\]  

(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.](image)

![Figure 4: shows the dimensionless friction factor \((fs)\) versus dimensionless Reynolds number \((Re)\) of the smooth surface.](image)

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 \((Nu_s/Nu_u)\) 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 conjugal 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 5: shows variations of Nusselt number with Reynolds numbers for various gap positions.](image)

![Figure 6: shows variations of Nusselt number ratio with Reynolds numbers for various gap positions.](image)
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\[ \eta = \frac{(St_r/Str_x)}{(f_r/fg)}^{1/3} \]  

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 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.
NOMENCLATURE

Dimensional Parameters

- $C_p$: Air specific heat (J/kg$^{-1}$K$^{-1}$)
- $D_h$: Equivalent depth of duct (m)
- $d_l$: Leading edge
- $d_t$: 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$^2$K$^{-1}$)
- $k$: 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
- $f_r$: factor of friction coefficient for smoothness
- $f_r$: factor of friction coefficient for smoothness
- $g/e$: Rib gap width
- $N_u_r$: Roughness Nusselt number for Roughened plate
- $N_u_s$: Smoothness Nusselt number for smooth plate
- $P/e$: Roughness for rib pitch
- $Re$: Reynolds Number

Greek Symbols

- $\alpha$: Attack angle (Degree)
- $\rho$: Density for air (kg/m$^3$)
- $\eta_{THP}$: THP efficiency

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