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An experimental investigation of heat transfer and fluid flow in a rectangular duct with inclined discrete ribs

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Abstract
Artificial roughness in the form of repeated ribs is generally used for enhancement of heat transfer heated surface to the working fluid. In the present work experimental investigations has been carried out to study the effect of a gap in the inclined rib on the heat transfer and fluid flow characteristics of heated surface. A rectangular duct of aspect ratio of 5.83 has been used to conduct experiments on one rib roughened surface. Experimental data have been collected to determine Nusselt number (heat transfer coefficient) as a function of roughness and flow parameters in the form of repeated ribs. In order to understand the mechanism of heat transfer through a roughened duct having inclined rib with and without gap, the detailed analysis of the fluid flow structure is required. Therefore the detailed velocity structures of fluid flow inside a similar roughened duct as used for the heat transfer analysis were obtained by 2-Dimensional Particle Image Velocimetry (PIV) system and the heat transfer results were correlated with the flow structure. It was found that inclined rib with a gap (inclined discrete rib) had better heat transfer performance compared to the continuous inclined rib arrangement. Further the inclined discrete rib with relative gap width (g/e) of 1.0 gives the higher heat transfer performance compared to the other relative gap width.

Keywords: Artificial roughness, Relative gap position, Reynolds number, Nusselt number.

1. Introduction
A Large number of studies on heat transfer and flow characteristics have been carried out to investigate the effect of rib design parameters namely rib height, angle of attack, relative roughness pitch, rib arrangement and rib cross-section. However, the artificial roughness results in higher frictional losses leading to excessive power requirement for the fluid to flow through the duct. It is therefore desirable that turbulence must be created only in a region very close to the heat-transferring surface to break the viscous sub-layer for augmenting the heat transfer and the core flow should not be unduly disturbed to limit the increase in friction losses. This can be done by keeping the height of the roughness elements small in comparison to the duct dimensions [1]. Han et al. [2] investigated the effect of angle of attack (α) and relative roughness pitch (P/e) on heat transfer and friction characteristics of rectangular duct with two roughened side walls. They reported that the maximum values of heat transfer coefficient and friction factor occur at relative roughness pitch of 10 at an angle of attack of 45° compared to the other rib arrangements under the requirements of same pumping power. Han et al. [3] reported that the rib configuration with relative roughness pitch of 7.5 gives higher enhancement in heat transfer than that

of the relative roughness pitch of 10 or 5. Webb et al. [4] have reported that the maximum heat transfer occurred at the relative roughness pitch of 6 to 8.

Kiml et al. [5] reported that the rib roughness arrangement with an angle of attack of 60° shows better heat transfer performance compared to that of the 45° rib arrangement. Lau et al. [6, 7] investigated the heat transfer and friction factor characteristics of fully developed flow in a square duct with transverse and inclined discrete ribs. They reported that a five- piece-discrete transverse ribs shows 10-15% higher heat transfer coefficient as compared to continuous transverse ribs, whereas inclined discrete ribs give 10 to 20% higher heat transfer rate than that of the transverse discrete ribs. Hu et al. [8] investigated the effect of inclined discrete rib with and without groove and reported that discrete rib arrangement without groove shows better thermal performance than that of the discrete rib with groove.

Gao and Sunden [9] conducted experiments in rectangular ducts with 90°, 60°, 45° and 30° ribs using PIV system to investigate the effect of rib inclination on the flow field for a constant value of the system parameters such as ratio of rib height to hydraulic diameter (as 0.06), pitch to rib height ratio (as 10) and Reynolds number as 5800. They used three different planes to analyze the flow field using PIV system. They observed that the strength of the secondary flow of 60° rib is higher compared to the other angles of attack. The PIV results obtained for 90° ribs were compared with the data available with Laser Doppler Velocimetry (LDV) system which showed good agreement Bonhoff et al. [10] investigated the flow structure of coolant channel roughened with 45° inclined ribs on two opposite surfaces using PIV system. They validate the results of numerical analysis with observation of PIV system. Gao and Sunden [11] have used PIV system to measure the flow field in a rectangular duct with 60º inclined and V-shaped rib arrangements in three planes and reported that the PIV technique is capable of obtaining the detailed flow structures between two consecutive ribs with reasonable accuracy.

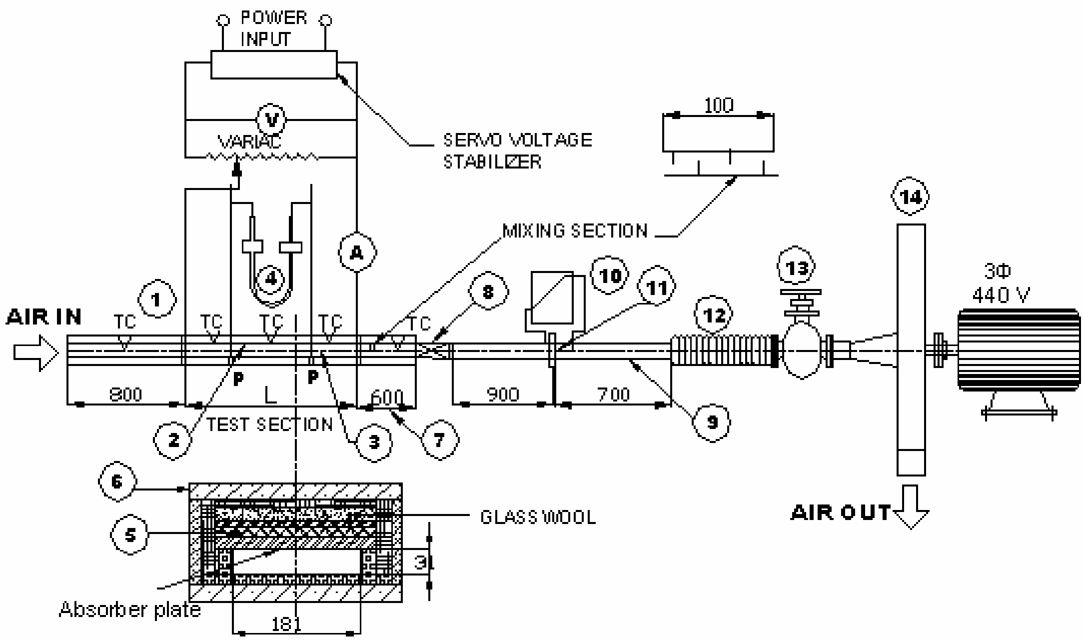
In a recent study, Cho et al. [12] investigated the effect of a gap in the inclined rib on heat transfer in a square duct and reported that a gap in the inclined rib accelerates the flow and enhances the local turbulence which will result in an increase in the heat transfer. They reported that the inclined rib arrangement with a downstream gap position shows higher enhancement in heat transfer compared to that without a gap i.e. of the continuous rib arrangement.

Most of the investigations carried out so far have applied the artificial roughness on two opposite walls with all four walls being heated. However in the case of solar air heaters, the roughness elements have to be considered only on one wall, which is the only heated wall comprises of the absorber plate. These applications make the fluid flow and heat transfer characteristics distinctly different from those found for ducts with two roughened walls and four-heated walls. For simulating the conditions of solar air heater, only one wall of the rectangular duct is to be subjected to uniform heat flux (to substitute insolation) while the remaining three walls are to be kept insulated. Many investigators [13-19] have employed artificial rib roughness in various forms on to improve the thermal performance of solar air heater. They reported that the geometry of the rib namely shapes, height, angle of attack and pitch affects significantly the heat transfer and friction characteristics of the duct.

The literature review reveals that the discrete inclined rib arrangement yields better performance as compared to continuous rib arrangement. However investigations have not been carried out so far to optimize the gap width for discretization of the continuous rib. The present investigation was therefore, taken up to determine the optimum width of a gap in the inclined rib to form discrete rib. This study will help in determining the gap size while descritizing the inclined (non-transverse) ribs for enhancing the performance as compared to continuous ribs. To investigate the effect of gap width on the flow field a Two Dimensional Particle Image velocimetry (2-D PIV) system is used. The PIV results have been compared with the enhancement of heat transfer to correlate the flow field investigation with the mechanism of heat transfer.

2. Experimental setup

Two experimental set-ups, one for heat transfer analysis and other for fluid flow analysis has been designed and fabricated to study the effect of a gap in the inclined rib roughened rectangular duct. A schematic diagram of the experimental set up for heat transfer analysis is shown in Figure 1. The wooden rectangular duct has an internal size of 2600 mm x 181 mm x 31 mm which consists of entrance section, test section and exit section of lengths of 800 mm, 1200 mm and 600 mm respectively according to the guidelines of ASHARAE standard [20]. A 6 mm thick Aluminum plate, roughened artificially at the wetted side, is used as the top broad wall of the test section whereas the upper walls of entry and exit sections of the duct were made of 12 mm thick plywood. The absorber plate is heated from the top by supplying a constant heat flux through an electrical heater, which was insulated by 50 mm thick glass wool and 12 mm thick plywood. A calibrated orifice-meter is used to measure the mass flow rate of air by measuring the pressure drop through a U- tube manometer with kerosene as manometric fluid. A Betz micro-manometer is used to measure the pressure drop across the test section. Calibrated thermocouples have been used for monitoring the temperature variations. The airflow rate has been varied with the help of a control valve to conduct the test in the flow Reynolds number range of 3000 to 18000. Data are collected for study-state condition only, which is assumed to have been reached when the plate and the air temperatures do not show any significant variation for 10-minutes duration.



1. Entrance section, 2. Absorber plate, 3. Air duct (passage), 4. Micro manometer, 5. Electrical heater, 6. Thermal insulation 7. Exit section 8. Transition section 9. G. I. pipe 10. U-Tube manometer 11. Orifice meter 12. Flexible pipe 13. Control valve 14. Blower, P- Pressure tap, TC - Thermocouple

Figure 1. Schematic diagram of experimental setup

For flow structure visualization through a two dimensional PIV system, a similar experimental with the modification in the entrance section and test section of the duct were used. A schematic diagram of flow visualization experimental set-up is shown in Figure 2. In the entrance section, an additional attachment called "plenum" is provided for proper mixing of the seeding particles with the working fluid (i.e. air). In order to visualize the velocities in the test section, its three sides (top and two side walls) were made of transparent acrylic sheet, and the roughened plate is fixed at the bottom side.

2D-PIV system consists of Laser source, Laser optics, Camera, Synchronizer, Seed generators and Software. The laser source is equipped with two separate ND-YAG lasers, so that the laser can be pulsed one after another and emits light at a wave length of 532 nm with a power output of each laser as 50 mJ per pulse. The light sheet dimensions can be modified by using the laser sheet optics containing spherical and cylindrical lenses.

A high performance (CCD) camera is used to record the motion of the particles moving in the plane of the laser sheet. In the present system, 2-mega pixel camera with internal and external triggering arrangement is used. A Nikon AF Micro- Nikkor 60 mm f/2.8 lens was used with the CCD camera for flow visualization. The operation of the laser and the camera is controlled through the synchronizer. Trigger signal output from the synchronizer controls Nd: YAG laser pulsing sequence so that the laser pulses are located in the appropriate frames in the camera. The entire system is controlled and operated by a computer using INSIGHT 6.11 data analysis software. A six jets atomizer (TSI Model 9306) is used to seed the liquid droplets inside the duct. The atomizer works well under input pressures between 1.4 to 3.5 bar.

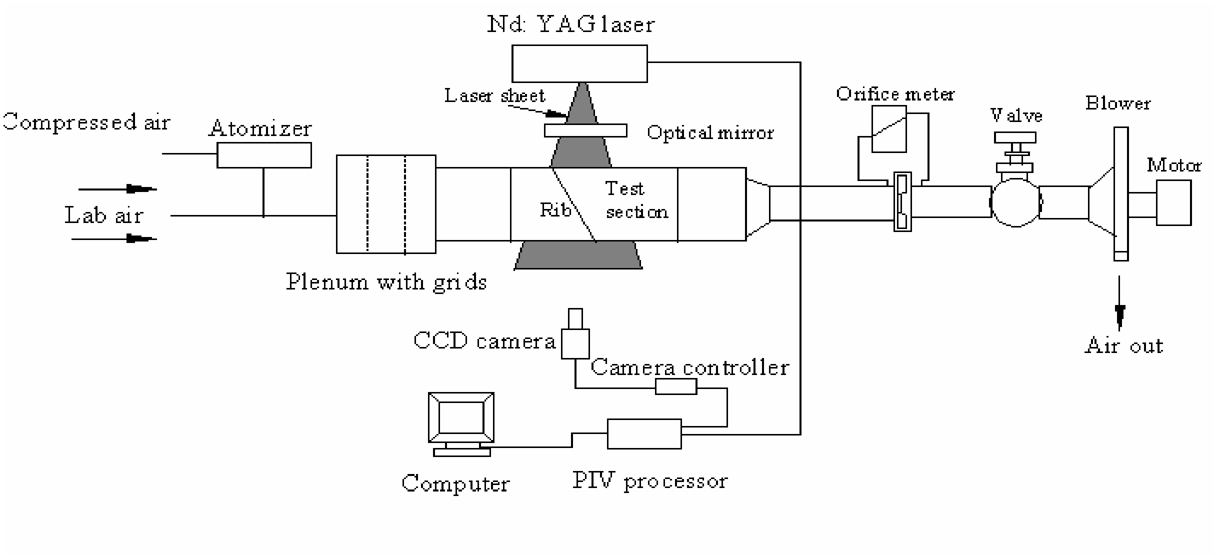


Figure 2. Schematic diagram of experimental set up for PIV measurement

3. Roughness geometry

Figure 3 shows the roughness geometries employed for heat transfer analysis and flow analysis. The absorber plates were machined to develop integral ribs on the surface of an Aluminum plate. The height and width of the ribs were kept equals to 2 mm. A gap in the continuous rib has been made at a distance of 0.25 times of the duct width, measured from the trailing edge portion (see Figure 3). The relative roughness pitch (P/e) defined as the ratio of pitch to rib height and the relative roughness height (e/D), defined as the ratio of rib height to hydraulic diameter are kept as 8 and 0.037 respectively. The relative gap width (g/e), defined as the ratio of gap width to rib height, is varied from 0.5 to 2.0 for the rib inclined at 60º from the flow direction as shown in Figure 3. In our previous study [21], it was observed that inclined rib with relative gap position of 0.25 and relative roughness pitch of 8.0, with an angle of attack of 60º and with relative roughness height of 0.037 performers better then the other relative gap position. Therefore in the present study these parameters were kept constant and only the relative gap width was varied to see the effect of this parameter on enhancement of heat transfer.

For the flow visualization inside a rectangular roughened duct the test facility should be designed in such a way that it will allow to take the measurement in different planes in order to measure the different velocity components. Since the flow through the multi-ribs could not be visualized therefore it is planed to prepare a roughened surface of single rib inclined at an angle of 60º to investigate the flow through this rib under condition of with and without a gap in the rib. The relative gap position is kept as 0.25 and the relative gap width (g/e), defined as the ratio of gap width to rib height, is varied from 0.5 to 2.0. The flow is in two planes namely, plane A and B (see Figure 3) has been visualized through 2D PIV system. In plane A, the laser sheet was adjusted parallel to the direction of main flow while, the camera was kept perpendicular to the main flow direction. In plane B the laser sheet was kept perpendicular to the orientation of the rib and the camera was put along the rib direction (Figure 4). The rib and susequent surface was painted black to decrease the noise signals due to the light scattered by the rib, which would then create invalid velocity vectors.

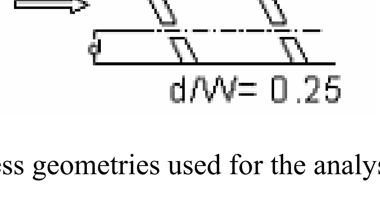


Figure 3. Roughness geometries used for the analysis of heat transfer

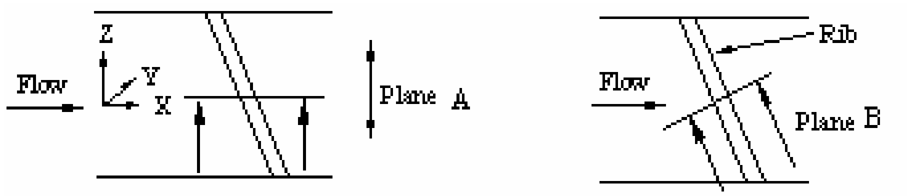


Figure 4. Laser sheet arrangement for PIV measurement of single rib

4. Results and discussion

The results of experimental investigation of heat transfer and flow characteristics of the roughened ducts are presented as a roughness parameters. The variation of the Nusselt number with Reynolds number as a function of relative gap width is shown in Figure 5. It is seen that the value of Nusselt number increases with increase in relative gap width up to 1.0 and then decrease with further increase in the relative gap width at all Reynolds numbers. The lowest value of Nusselt number is observed at the relative gap width of 2.0. To bring out the effect of relative gap width clearly, variation of Nusselt number, shown in Figure 5 is re-plotted in Figure 6 with the relative gap width at few selected values of Reynolds numbers. It shows that at all the values of Reynolds number, the Nusselt number increases with increase in the relative gap width up to 1.0, beyond which it decreases with further increase in relative gap width. The possible explanation for increase in the heat transfer due to a gap is that the gap in the inclined rib releases the air partly belonging to the secondary flow and partly belonging to the main flow through the gap. As a result of the presence of gap, the secondary flow along the rib joins the main flow to accelerate it which energizes the retarded boundary layer flow along the surface leading to an increase in the heat transfer through the gap width area behind the rib. It seems that increase in the gap width reduces the flow velocities through the gap and hence the local turbulence. At the same time a very small gap will also not allow sufficient amount of the secondary flow fluid to pass through it and thus the main flow could not be energized well. This may have resulted in the observation of the maximum value of the Nusselt number at a certain value of gap width namely relative gap width of 1.0 only.

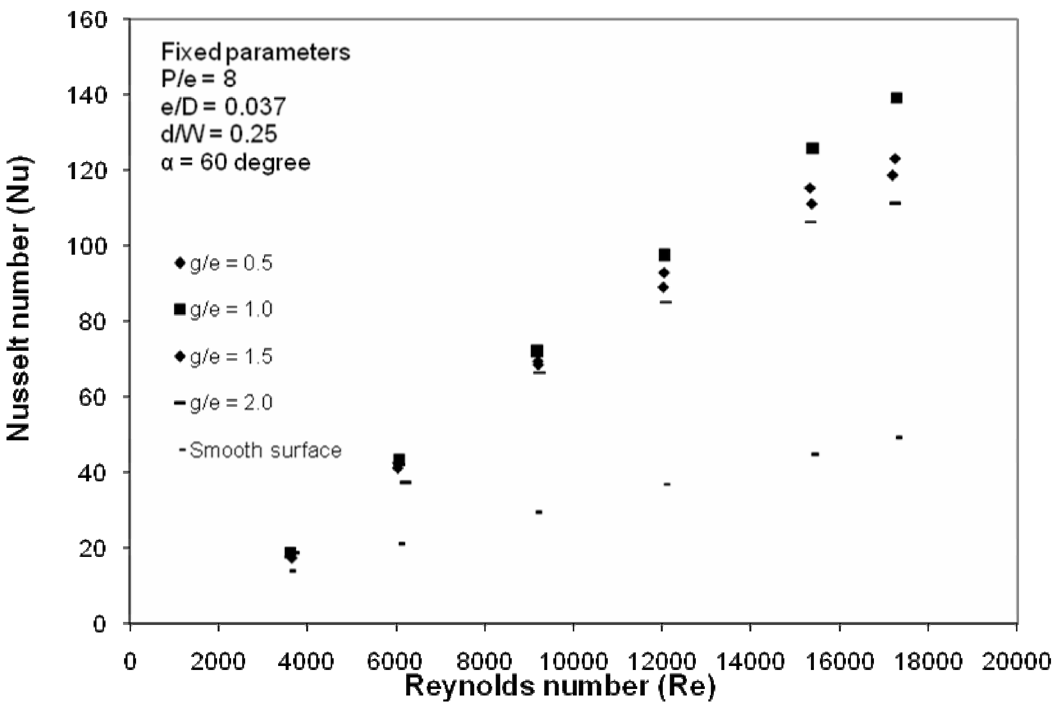


Figure 5. Variation of Nusselt number with Reynolds number as a function of relative gap width for P/e = 8.0, d/W = 0.25, α = 60 and e/D = 0.037

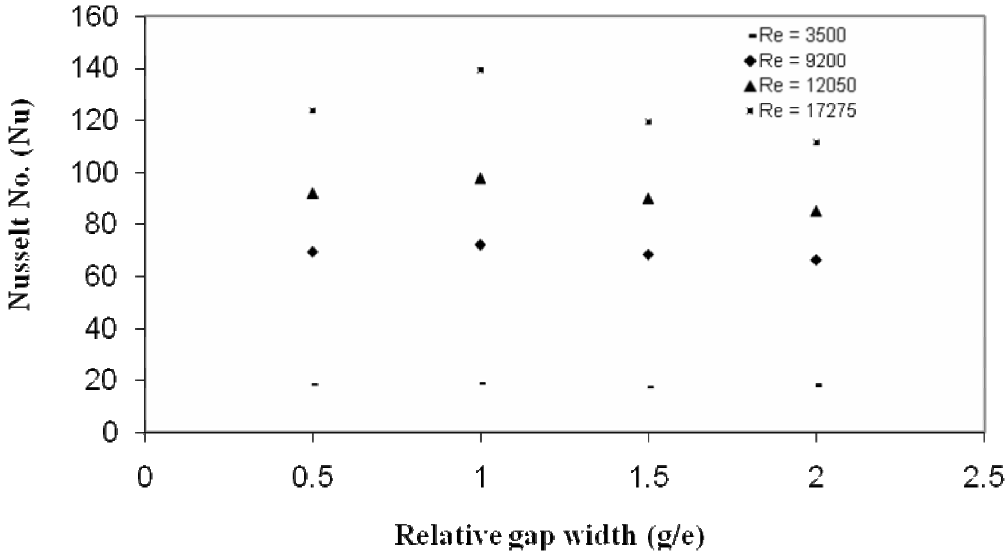


Figure 6. Variation of Nusselt number with relative gap width at few Reynolds number for P/e = 8.0, d/W = 0.25, α = 60 and e/D = 0.037

To investigate the effect of a gap and its gap width on the flow field of the inclined rib, a 2-D PIV system is used. The flow field visualized through plane 'A' inside a rectangular duct roughened with an inclined continuous rib is shown in Figure 7. The flow upstream of the rib could not be visualized as the inclined portion of the rib has blocked this area. However, the flow field downstream of the rib could be visualized for a distance up to 10 times of the rib height. The flow is seen to be separated at the rib which generates re-circulating eddies behind the rib. The flow separated at the rib appears to be reattached with the surface at around 5 times of the rib height. It is seen that the separated boundary layer behind the rib results in a dead zone as marked "A", which reduces the heat transfer through this area. The presence of gap in the inclined rib allows the fluid to pass through it and also the release of secondary flow through this gap alters the velocity profiles. The flow field for a gap in the inclined rib, visualized through plane 'A' passing through the middle of the gap is presented in Figure 8 for similar flow conditions as applied to continuous rib (see Figure 7). Figure 8 shows that the dead zone "A" shown in Figure 7 gets disappeared which may be attributed to the release of main and secondary flow through the gap. Further presence of some of the high velocity vectors just behind the rib confirm the enerzization of retarded main flow due to release of secondary flow through the gap. This is in line with the assumption of the Cho et al. [12] that a gap in the inclined rib accelerates the flow through the gap which enhances the heat transfer performance. Tariq et al. [22] also reported that a slit in a rib modifies the flow field which reduces the reattachment length after the rib and thus increases the heat transfer coefficient.

Further to investigate the flow phenomenon through the gap of an inclined rib, the turbulence intensity which is a measure of level of turbulence in the flow field is measured at different gap widths using the 2-D PIV system. The variation of the total turbulence intensity for flow over the rib for the relative gap width of 0.5, 1.0, 1.5 and 2.0 at different distances downstream of the rib namely 1.0 mm, 2.5 mm, 7 mm and 12 mm are shown in Figures 9-12. The range of turbulence intensity varies from 11.2 to 41.8, 12. 8 to 65.1, 12.1 to 52.3 and 10.8 to 40.0 percent for relative gap width of 0.5, 1.0, 1.5 and 2.0 respectively. It is seen that the maximum and minimum value of total turbulence intensity at all locations behind the rib is observed at the relative gap width of 1.0 and 2.0 respectively. The variation of turbulent intensity with distance from the wall of the rib shows that it is the maximum always at a distance of rib height and decreases as one move away from the rib. It is also noted that this effect is predominant up to 3-4 times of the rib height from the surface and thus the main flow remained undisturbed due to the ribs. This is desirable to limit the increase in friction factor due to artificial roughness. Zhang et al. [23] have also reported that the maximum turbulence intensity at the location of rib height from the wall for rib-groove roughened surface.

These results shows good agreement with the heat transfer studies in which the maximum enhancement of heat transfer coefficient (Nusselt number) is observed at relative gap width of 1.0 whereas the minimum enhancement is observe at relative gap width of 2.0.

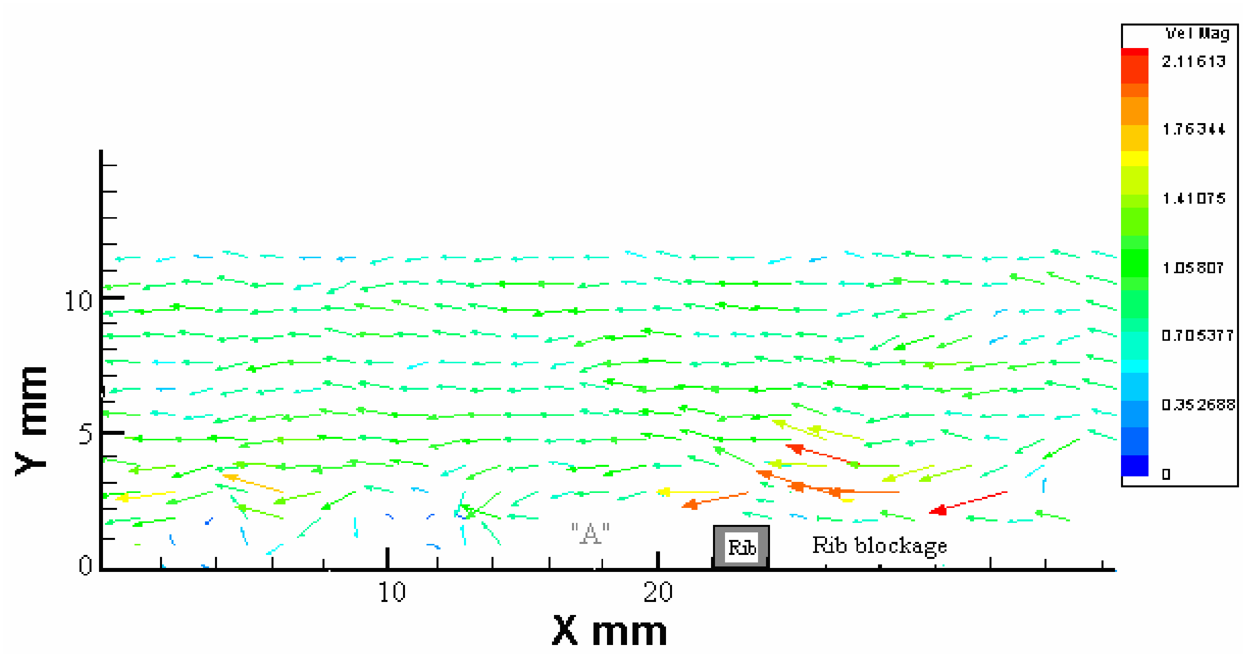


Figure 7. Velocity profile for flow over an inclined continuous rib

Here X is the distance from the reference point “0”along the direction of main fluid flow and Y is the distance from the ribbed surface perpendicular to the direction of main fluid flow.

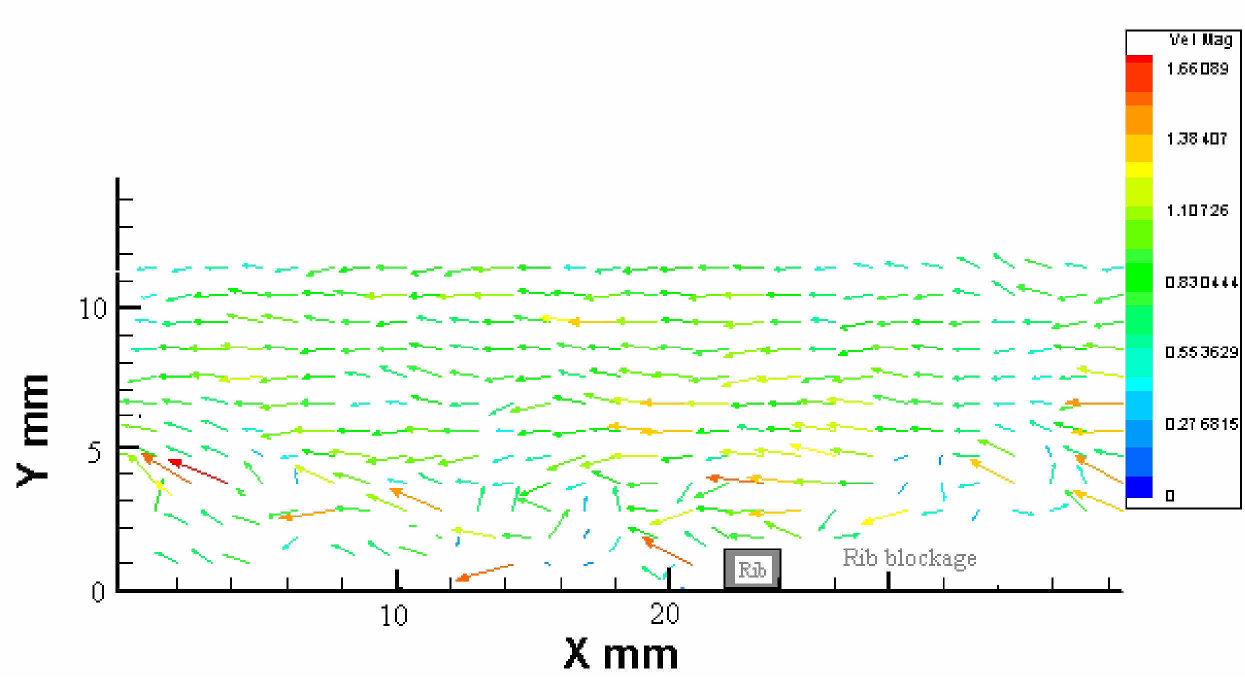


Figure 8. Velocity profile for flow over an inclined rib with a gap

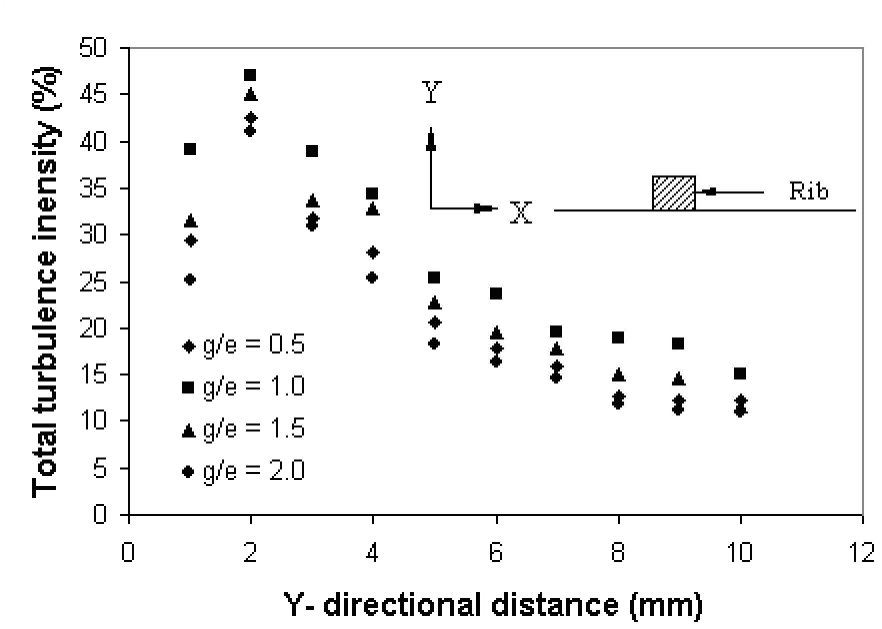


Figure 9. Distribution of total turbulence intensity at a distance of 0.5 mm from downstream face of the rib

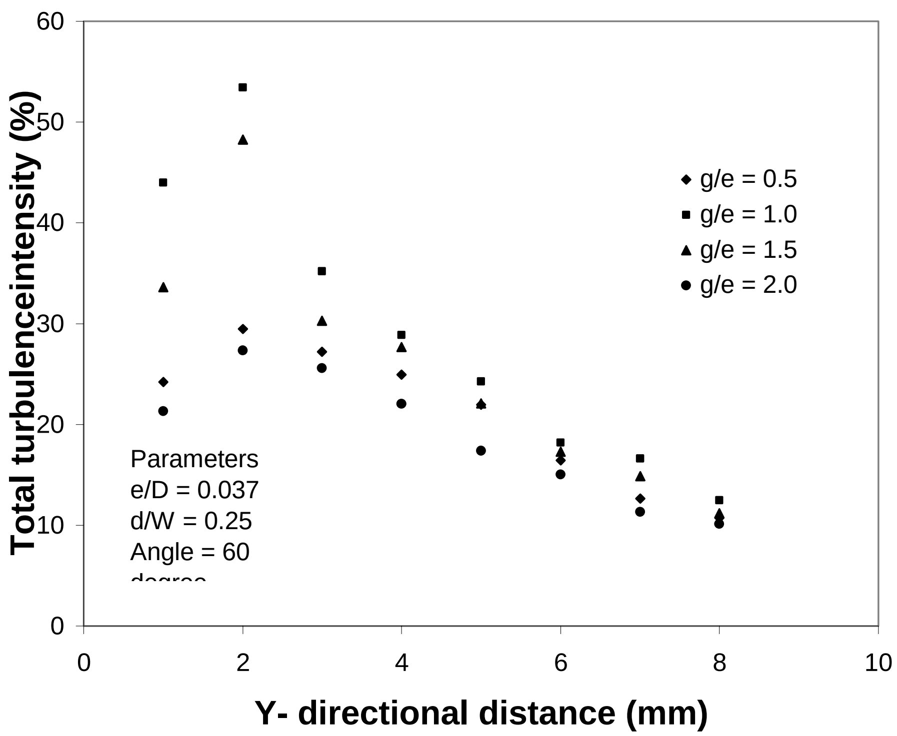


Figure 10. Distribution of total turbulence intensity at a distance of 2.5 mm from downstream face of the rib

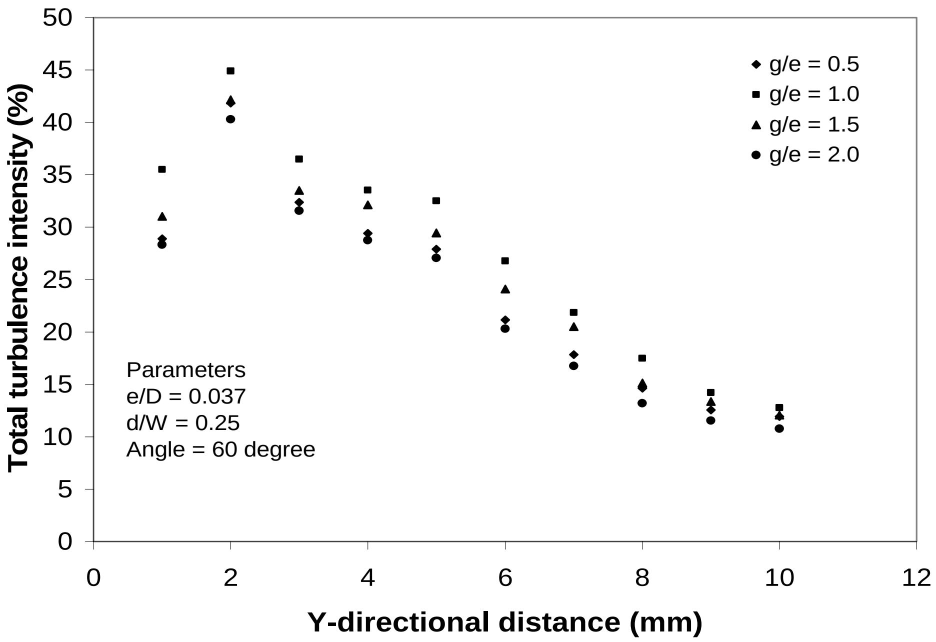


Figure 11. Distribution of total turbulence intensity at a distance of 7.0 mm from downstream face of the rib

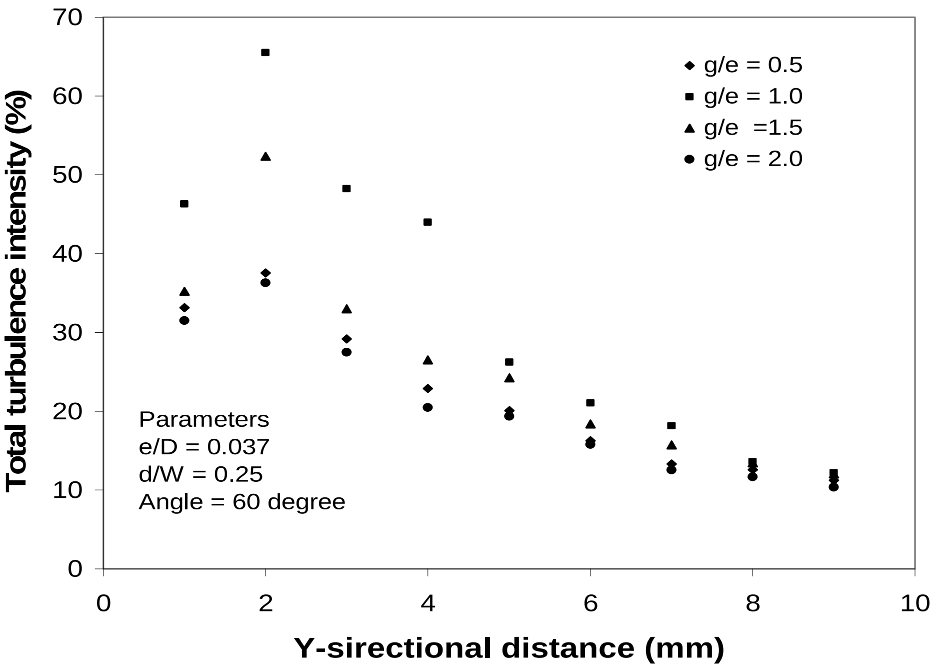


Figure 12. Distribution of total turbulence intensity at a distance of 12.0 mm from downstream face of the rib

5. Conclusion

In the present investigation study the effect of gap width on the heat transfer coefficient has been investigated and attempt has also been made to determine the optimum width of a gap in the inclined rib to form discrete rib for the better heat transfer performance. Investigations have been carried out for the relative gap width of 0.5 to 2.0 and the Reynolds number range of 3000-18000 at relative roughness height of 0.037. It was found that inclined rib with relative gap width (g/e) of 1.0 gives the highest value of heat transfer coefficient compared to the other relative gap width. To investigate the effect of gap width on the flow field, a Two Dimensional Particle Image velocimetry (2-D PIV) system is used. The level turbulence intensity at different relative gap width has been measured. It is observed that the highest value of turbulent intensity is observed at the relative gap width of 1.0 which is in the line of heat transfer measurements. These results of PIV showed good agreement between the heat transfer results and the flow analysis results.

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