CFD Analysis of Solar Air Heater Having Broken Double Arc Rib Roughness in Absorber Plate

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Abstract— In this thesis, results of CFD analysis on heat transfer and friction in rectangular ducts roughened with Broken double arc rib roughness has been presented. The rib roughness has relative gap position of 0.65, relative roughness pitch of 10, arc angle of 30° and relative roughness height of 0.043. The relative gap width was varied from 0.5 to 2.5. The effects of relative gap width on Nusselt number, friction factor and thermo-hydraulic performance parameter have been discussed and results compared with smooth duct and continuous arc rib roughened duct under similar conditions and also compare with previous experimental results. The rough ribs were enough efficient to transfer the desired heat, but they are not economical and are very complex in design and construction. Whereas, the broken double arc ribs with different relative gap width gives more area of contact. So, there is enough time to transfer the heat from the ribs to the passing air which touches the ribs and the heat transfer takes place efficiently. Thus, the broken double arc ribs with different relative gap width, when compared with the smooth and continuous arc ribs with symmetrical gaps, it was concluded that the related Nusselt Number and friction factor for broken double arc ribs with different relative gap width was more efficient as well as economical, than that of smooth and rough ribs with symmetrical gaps for flow Reynolds Number. The smooth ribs could not transfer the desired heat due to absence of friction; so, they are not preferred practically. One of the most important techniques used are passive heat transfer technique. These techniques when adopted in heat transfer surfaces proved that the overall thermal performance improved significantly. Rib roughness on the underside of the top wall of a duct has been found to substantially enhance the heat transfer coefficient. Surface roughness disturbs the laminar sub-layer in the turbulent flow and promotes local wall turbulence that, in turn, increases the heat transfer from the surfaces. The augmentation in heat transfer accompanies a higher pressure drop penalty of the fluid flow. In this work the maximum value is found to be relative gap width 1.0. Solar energy is one of the environmentally compatible sources of renewable energy. It is most recognized as one of the promises that can conserve the Earth to survive in a reasonable shape. Solar energy is virtually unlimited. The Sun is the primary source of renewable energy and it harvest more abundant than any other type of energy. A conventional solar air heater generally consists of an absorber plate with a parallel plate below forming a passage of high aspect ratio through which the air to be heated flows. As in the case of the liquid flat-plate collector, a transparent cover system is provided above the absorber plate, while a sheet metal container filled with insulation is 'provided on the bottom and sides.

Keywords: CFD, Solar Energy, Geometric Modeling

I. INTRODUCTION

Solar energy is one of the environmentally compatible sources of renewable energy. It is most recognized as one of the promises that can conserve the Earth to survive in a reasonable shape. Solar energy is virtually unlimited. The Sun is the primary source of renewable energy and it harvest more abundant than any other type of energy. A conventional solar air heater generally consists of an absorber plate with a parallel plate below forming a passage of high aspect ratio through which the air to be heated flows. As in the case of the liquid flat-plate collector, a transparent cover system is provided above the absorber plate, while a sheet metal container filled with insulation is 'provided on the bottom and sides.

There have been huge number of studies are presented over there and carried out different experimental studies in fluid flow and friction factor characteristics and show the effects of rib roughness on solar air heater performance by results. Wang et al presented Numerical predictions on heat transfer and flow characteristics in a straight channel with different geometric parameters wavy ribs. The range of per centage deviation is less than 5%, which is reasonably good. With an aim to further improve the performance of hyperbolic ribs. [1]. R. Karwa et al[2], Anil k patil et al [3], Rahul nadda et al[4], Han et al. [5] Ngpure et al all are analysed for viscous sub layer which increased the heat transfer coefficient between the absorber plate and the air in the solar air heater. Kamali and Binesh Investigated the flow over two-dimensional ribs of different shapes is studied to examine the heat transfer characteristics as well as the friction characteristics. The simulations were performed for four rib shapes, i.e., square, triangular, trapezoidal with decreasing height in the flow direction, and trapezoidal with increasing height in the flow direction. The recirculation zones were clearly identified and the flow is seen to reattach before the following in all cases[6]. Saini and Verma [7] investigated and concluded that heat transfer can be enhanced considerably as a result of providing dimple-shape roughness geometry on the absorber plate of a solar air heater duct. Nusselt number and friction factor are the strong function of the system and operating parameters. The maximum value of Nusselt number has been found corresponds to relative roughness height (e/D) of 0.0379 and relative pitch (p/e) of 10. While minimum value of friction factor has been found correspond to relative roughness height (e/D) of 0.0289 and relative pitch (p/e) of 10[8]. Saini JS et al. carried out of experimental investigation on heat transfer and friction in rectangular ducts roughened with broken arc-rib roughness combined with staggered rib piece has been presented. The rib roughness has relative gap position of 0.65, relative staggered rib position of 0.6, relative staggered rib size of 2.0, relative roughness pitch of 10, arc angle of 30° and relative roughness height of 0.043. The relative gap size was varied from 0.5 to 2.5. The effects of gap size on Nusselt number, friction factor and thermo-hydraulic performance parameter have been discussed and results compared with smooth duct and continuous arc rib roughened duct under similar conditions.

[9].Vrshney et al analysd the Performance prediction for solar air heater having rectangular sectioned tapered rib roughness using CFD[10]. Singh et al. presents thermo-hydraulic performance comparison of rib roughness under investigation, 'V- down ribs with gap' and similar reported rib roughness geometries used in solar air heater duct. Five rib roughened plates having relative roughness pitch of 4, 6, 8, 10 and 12 have been tested[12].

A. Geometric Modeling (Solution Domain):

The 2-dimensional solution domain used for CFD analysis has been generated in ANSYS version 14.5 (workbench mode) as shown in Fig. 1.1.The solution domain is a horizontal duct with broken arc shaped ribs roughness on the absorber plate at the underside of the top of the duct while other sides are considered as smooth surfaces. Complete duct geometry is divided into three sections, namely, entrance section, test section and exit section. A short entrance length is chosen because for a roughened duct, the thermally fully developed flow is established in a short length 2–3 times of hydraulic diameter. The exit section is used after the test section in order to reduce the end effect in the test section. The top wall consists of a 0.5 mm thick absorber plate made up of aluminum. Artificial roughness in the form of small diameter galvanized iron (G.I) wires is considered at the underside of the top of the duct on the absorber plate to have roughened surface, running perpendicular to the flow direction while other sides are considered as smooth surfaces. A uniform heat flux of 1000 w/m2 is considered for computational analysis. The geometrical and operating parameters for artificially roughened solar air heater are listed in Table 1.1

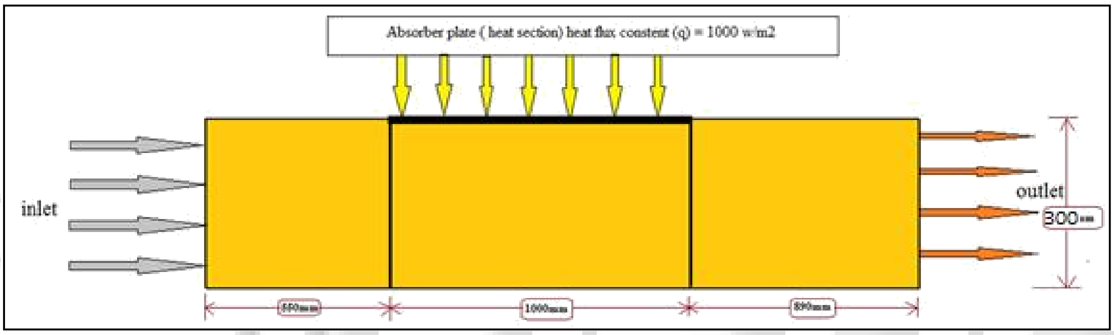


Fig. 1.1: Showing the geometric dimension of the working model

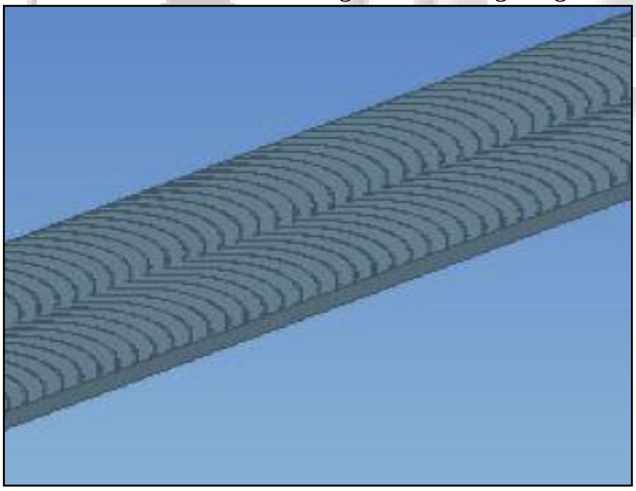


Fig. 1.2: Schematic diagram broken double arc rib

Table 1.1: Range of geometrical and operating parameters for CFD analysis

S. No.	Roughness and flow parameter	Range of parameters
1	Rib Height (e)	2 mm
2	Rib Pitch (P)	20 mm
3	Relative roughness pitch (p/e)	10
4	Relative gap width (g/e)	0.5 - 2.5
5	Angle of arc (α)	30°
6	Relative roughness height (e/D_h)	0.043
7	Reynolds number(Re)	2000-16000

II. MESHING OF GEOMETRY

Type of meshing: - Tetrahedral
No. of element: - 72450
No of face: - 1751098
No of nodes: -91154
Interval Size: - 1

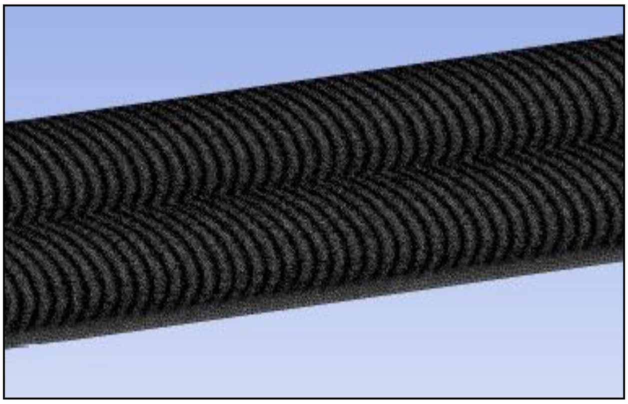


Fig. 1.3: Meshing of duct with roughened absorber plate

III. DATA HANDLING

In order to investigate the effect of relative roughness height on heat transfer and flow friction, following three parameters of interest have been determined:

1) Nusselt number

2) Friction factor, and
3) Thermal enhancement factor.

The procedure of calculation of above mentioned parameters are given below:

A. Hydraulic Diameter (D)

D = 4WH/ 2(W+H)
H = Height of the duct in mW = Width of the duct in m

B. Velocity of air (V)

$$V=Re\ (\nu)/D$$

ν = Kinematic viscosity of air in m²/sec V=Velocity of air

C. Heat Transfer Coefficient

$$Q=h\ A\ \Delta T$$

Average heat transfer coefficient (h) can be obtained directly from FLUENT.

D. Nusselt Number for Roughened Duct:

$$Nu = h\ D\ /k\ k$$

Where k is the thermal conductivity of air andD is the hydraulic diameter.

E. Nusselt Number for Smooth Duct

Nusselt Number for smooth roughened duct can be obtained by Dittus–Boelter correlation

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

F. Friction Factor For Roughened Duct

$$f = \left(\frac{\Delta P}{L}\right)\frac{D}{2\rho V^2}$$

Average pressure drop (ΔP) can be obtained directly from FLUENT.

G. Friction Factor for Smooth Duct

Friction factor for smooth roughened duct can be obtained by Blasius correlation

$$f_s = 0.079\ R_e^{-0.25}$$

H. Thermal Enhancement Factor

$$TEF = \frac{Nu/_{Nu_s}}{\left(f/_{f_s}\right)^{\frac{1}{3}}}$$

IV. RESULTS AND DISCUSSION

A. Heat Transfer and Friction Factor Characteristics:

Effect of the relative gap width (g/e) on heat transfer is also shown typically in Fig. 7.1. It can be seen that the enhancement in heat transfer of the roughened duct with respect to the smooth duct also increases with an increase in Reynolds number. It can also be seen that broken double arc rib the Nusselt number values increases with the increase in relative gap width (g/e) of up to 1 and than decrease for a fixed value of roughness pitch (*P*). The roughened duct having gap in double arc shaped ribs with relative gap width (g/e) of 1 provides the highest Nusselt number at a Reynolds number of 16000. For rectangular rib the maximum enhancement of average Nusselt number is found to be 2.65 times that of smooth duct for relative gap width (g/e) of 1 at a Reynolds number of 16000.The heat transfer phenomenon can be observed and described by the contour plot of turbulence intensity. The contour plot of turbulence intensity for broken double arc shaped ribs is shown in Fig. 7.2 (a, b and c).The intensities of turbulence are reduced at the flow field near the rib and wall and a high turbulence intensity region is found between the adjacent ribs close to the main flow which yields the strong influence of turbulence intensity on heat transfer enhancement.

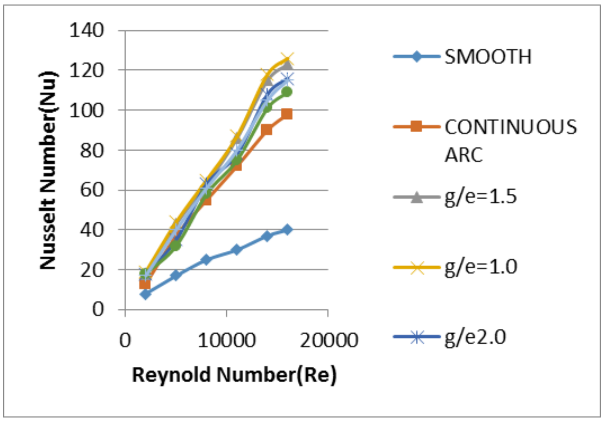


Fig. 7.1: Variation of Nusselt number with Reynolds number for different Values of relative gap width (g/e).

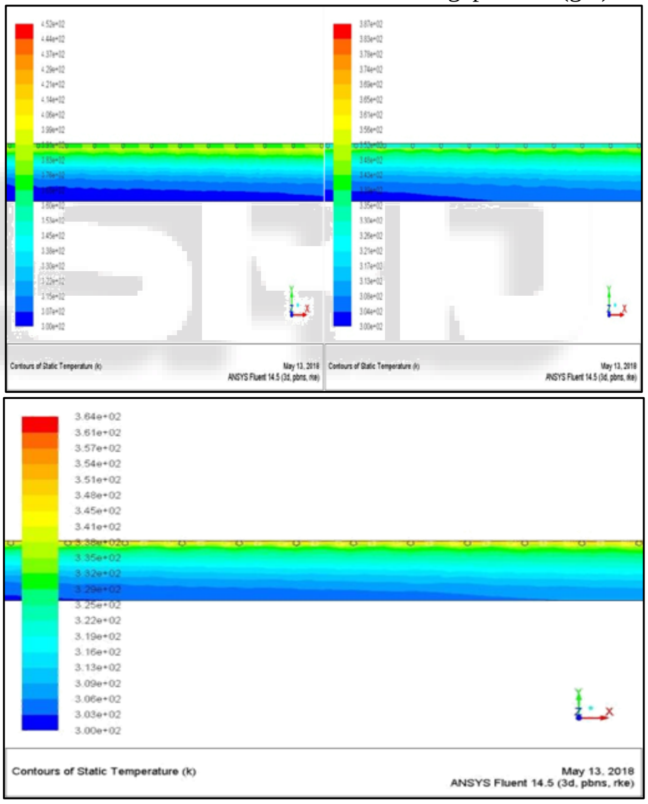
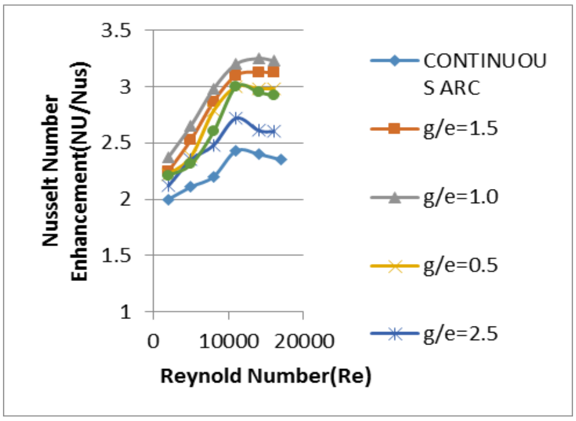


Fig. 7.2: Contour plot of turbulent intensity for broken double arc rib (a) Re=4000 (b) Re=8000 (c)Re=12000

B. Enhancement of Heat Transfer:

The enhancement in Nusselt number as a result of providing artificial roughness in the form of rib with a gap can be represented in terms of Nusselt number ratio defined as ratio of Nusselt number of an artificially roughened duct to that of the smooth duct under similar operating conditions. From Fig. 7.4, it is seen that the highest values of Nusselt number ratio is observed at relative gap width of 1.0 and its lowest value is observed at relative gap width of 2.5

C. Enhancement of Nusselt number with Reynolds number for various relative gap width (g/e)



D. Characteristics:

Fig. 7.5 shows the effect of Reynolds number on average friction factor for different values of relative gap width (g/e) and other parameter are fixed. It is observed that the friction factor decreases with increase in Reynolds number because of the suppression of viscous sub-layer.Fig 7.5 also shows that the friction factor decreases with the increasing values of the Reynolds number in all cases as expected because of the suppression of laminar sub-layer for fully developed turbulent flow in the duct. It can also be seen that friction factor values increase with the increase in relative gap width (g/e) up to 1 and than decrease for fixed value of other parameter, attributed to more interruptions in the flow path.

As the considerable rise has been observed in the value of Nusselt number and friction factor due to the presence of roughness in comparison to the smooth surface for all the values of relative gap width(g/e). So there is need to quantify the enhancement in Nusselt number and friction factor as a result of roughness over smooth surface. In order to do so the values of the Nusselt number enhancement (Nu/Nus) and friction factor enhancement (f/fs) are presented in Figs. 7.4 and7. 7. It is clear from these Figures the relative gap width considerably affects the Nusselt number enhancement and friction factor enhancement. The maximum enhancement in Nusselt number and friction factor corresponds to relative gap width (g/e) value of 1.0 than at other values of relative gap width. Nusselt number enhancement increases with increase in Reynolds number up to 11000 and then decreases with further increase in Reynolds number. On the other hand, friction

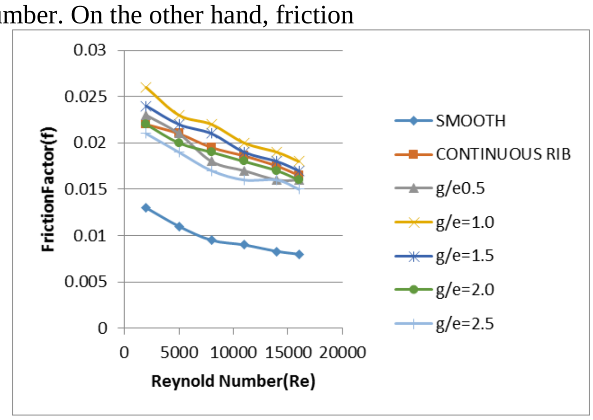
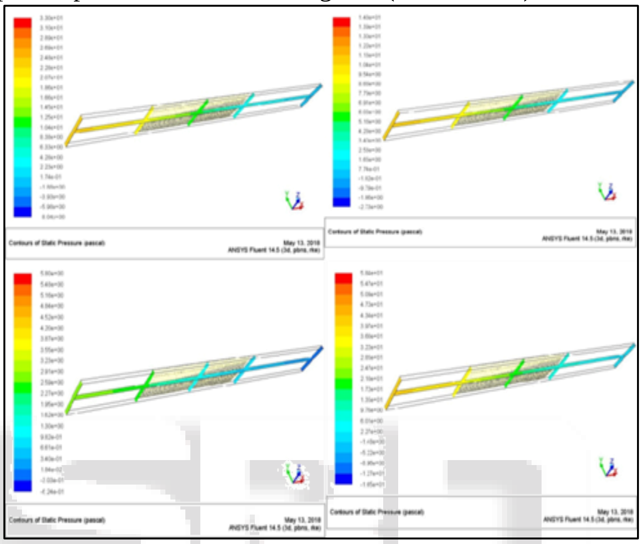


Fig. 7.4: Comparison between Friction factor and Reynolds number at different gap width(g/e)

Factor enhancement goes on increasing with increase in Reynolds number and attained maximum value corresponding to Reynolds number value of 14000. The maximum enhancement in Nusselt number has been found to be 175% at Reynolds number value of 11000 with simultaneous enhancement in friction factor of 130%. The roughened duct having gap in double arc shaped with relative gap width of 1.0 provides the highest friction factor. For gap in double arc-rib roughness the maximum enhancement of average friction factor is found to be 3.67 times that of smooth duct for relative gap width of 1.0

The fluid friction phenomenon can be observed and described by the contour of pressure for rectangular rib. The contour plot of pressure is shown in Fig. 7.6 (a, b, c and d).



E. Enhancement of Friction Factor (f/fs):

The enhancement in friction factor as a result of providing artificial roughness in the form of double arc ribs with a gap can be expressed in terms of friction factor ratio defined as the ratio of friction factor of an artificially roughened duct to that of the smooth duct under similar operating conditions. Fig. 7.7. It is seen that the friction factor ratio increases with increase in relative gap width from 1.0 to 1.5 and then decreases with further increase in the value of relative gap width. The highest value of friction factor ratio is observed for the relative gap width of 1.0 and its lowest value is observed at a relative gap width of 2.5.The present CFD investigation shows that the roughened duct with relative gap width (g/e) of 1.0 yields the maximum value of average friction factor whereas similar roughened duct with similar operating condition. Therefore, it is essential to determine the optimal rib dimension and arrangement that will result in maximum enhancement in heat transfer with minimum friction power penalty.

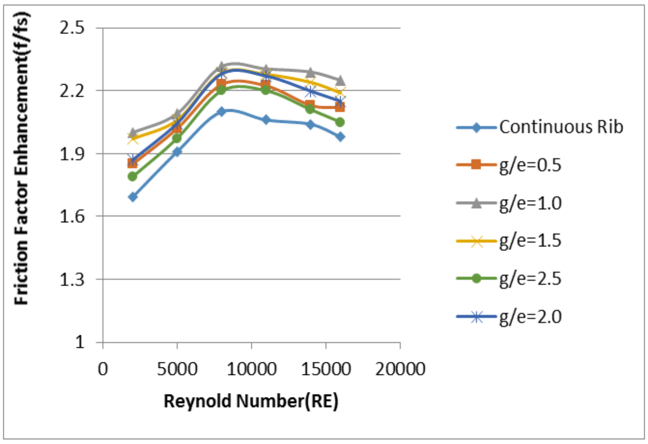


Fig. 7.6: Variation of friction factor ratio with Reynolds number as a function of relative gap width (g/e)

V. THERMO-HYDRAULIC PERFORMANCE

It has also been observed from Figures 7.3 and 7.4 that the maximum values of Nusselt number and friction factor correspond to relative gap width of 1.0, thereby, meaning that an enhancement in heat transfer is accompanied by friction power penalty due to a corresponding increase in the friction factor. Therefore, it is essential to determine the effectiveness and usefulness of the roughness geometry in context of heat transfer enhancement and accompanied increased pumping losses. In order to achieve this objective, Webb and Eckert [23] proposed a thermo-hydraulic performance parameter 'η', which evaluates the enhancement in heat transfer of a roughened duct compared to that of the smooth duct for the same pumping power requirement and is defined as, The value of this parameter higher than unity ensures that it is advantageous to use the roughened duct in comparison to smooth duct. The thermo-hydraulic parameter is also used to compare the performance of number of roughness arrangements to decide the best among these. The variation of thermo-hydraulic parameter as a function of Reynolds number for different values of relative gap width (g/e) and investigated in this work has been shown in Fig. 7.8. For all values of relative gap widths, value of performance parameter is more than unity. Hence the performance of solar air heater roughened with broken double arc shaped ribs is better as compared to smooth duct.

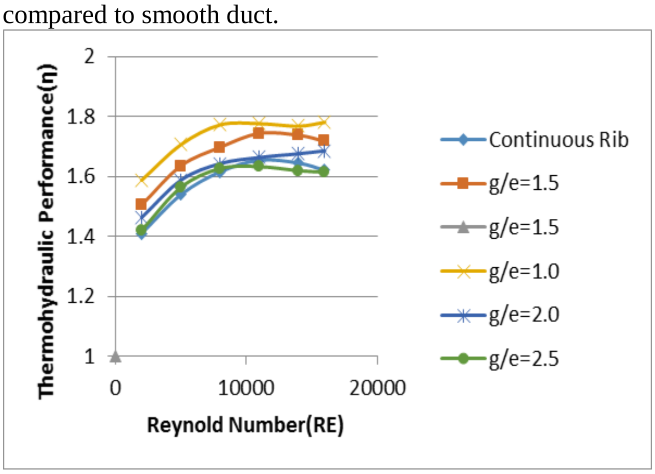


Fig. 7.7: Thermo-hydraulic performance parameter as a function of Reynolds Number for different relative gap width (g/e)

It is also observed that the value of this parameter is maximum corresponding to relative gap width of 1.0 and it decreases on both sides of this gap width for all values of Reynolds number investigated. This result indicates that it is advantageous to use gap in double arc ribs having gap width equaled to 1.0 as compared to other values of relative gap widths. The highest value of thermo-hydraulic performance parameter obtained is 2.14 at Reynolds number of 11000.

VI. CONCLUSION

The Numerical investigations were conducted on solar air heater duct roughened with broken double arc shaped ribs. The staggered rib piece was fixed at a distance of 0.6 of the main arc rib pitch on the downstream side of gap. The following conclusions are drawn from the present study:

A 2-dimensional CFD analysis has been carried out to study heat transfer and fluid flow behavior in a rectangular duct of a solar air heater with one roughened wall having rectangular and broken double arc-rib roughness. The effect of Reynolds number and relative gap width(g/e) on the heat transfer coefficient and friction factor have been studied. In order to validate the present numerical model, results have been compared with available experimental results under similar flow conditions. CFD Investigation has been carried out in medium Reynolds number flow (Re = 2000–16,000). The following conclusions are drawn from present analysis:

1) The Renormalization-group (RNG) k-ε turbulence model predicted very close results to the experimental results, which yields confidence in the predictions done by CFD analysis in the present study.
2) RNG k-ε turbulence model has been validated for smooth duct and grid independence test has also been conducted to check the variation with increasing number of cells.
3) The roughened duct having broken double arc shaped rib with relative gap width of 1.0 provides the highest Nusselt number at a Reynolds number of 16000.
4) For broken double arc rib the maximum enhancement of average Nusselt number is found to be 2.78 times that of smooth duct for relative gap width (g/e) of 1.0 at a Reynolds number of 11000.
5) The roughened duct having broken double arc- rib with relative gap width of 1.0 provides the highest friction factor at a Reynolds number of 3500.
6) 6. For broken double arc-rib the maximum enhancement of average friction factor is found to be 3.67 times that of smooth duct for relative gap width of 1.0 at a Reynolds number of 3800.
7) It is found that the thermal hydraulic performance of relative gap width of 1.0 is maximum.

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