CFD ANALYSIS OF HEAT TRANSFER AND FRICTION CHARACTERISTICS OF SOLAR AIR HEATER DUCT USING BROKEN DOUBLE ‘S’ SHAPED RIBS ROUGHNESS

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Abstract

CFD analysis on heat transfer and friction in rectangular ducts with double ‘S’ shape with gap roughness has been presented. The rib roughness has 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 under similar conditions. The rough ribs were efficient enough to transfer the desired heat, but they are not economical and are very complex in design and construction. Whereas, roughness 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 double ‘S’ shaped rib with different relative gap width, when compared with the smooth plate, it was concluded that the related Nusselt Number and friction factor for double ‘S’ shaped rib with different relative gap width was more efficient. The smooth plate 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 at a Reynolds number of 16000.

Keyword: *Reynolds number, Heat transfer, Friction factor, Pressure drop, Duct*

Introduction: Solar air heater is one of the basic equipment through which solar energy is converted into thermal energy .The main application of solar air heater are space heating ,seasoning of timber ,curing of industrial products and these can also be effectively used for curing/drying of concrete/clay building components .A solar air heater is simple in design and required little maintenance . However the value of the heat transfer coefficient between the absorber plate and air is low and this results in a lower efficiency .Low value of heat transfer coefficient is due to presence of laminar sub layer that can be broken by providing artificial roughness on heat transferring surface[1].Several methods including the use of fins , artificial roughness and packed beds in the ducts ,have been proposed for the enhancement of thermal performance .Artificial roughness in form of ribs and in various configuration has been used to create turbulence near wall or to break laminar sub-layer . Artificial roughness results in high friction losses leading to more power requirement for fluid flow. Hence turbulence has to be created in region very close to heat – transferring surface for breaking viscous sub-layer .The use of artificial roughness in solar air heaters owes its origin to several investigations carried out in connection with the enhancement of heat transfer in nuclear reactors and turbine blades .Several investigations have been carried out to study effect of artificial roughness on heat transfer and friction factor for two opposite roughened surface by Han[2,3].Han et al.[4-5],Wrieght et al.[7],Lue et al,[8-10],Taslim et al. and Hwang[12],Han and Park[14],Park et al.[15] developed by different investigators .The orthogonal ribs i.e. ribs arranged normal to the flow were first used in solar air heater and resulted in better heat transfer in comparison to that in conventional solar air heater by Prasad k, Mullick S.C. et al [16].Many investigators Gao x sunden B[17],Han J.C,Glicksman LR,Rohsenow WM[18],Prasad BN,Saini JS{19],Taslim ME,Li T,Kercher Dm[20],Webb RL,Eckert Erg,Goldstein RJ[21] have reported in detail the Nu and f for orthogonal and inclined rib-roughened ducts. The concept of V-shaped ribs evolved from the fact that the inclined ribs produce longitudinal vortex and hence higher heat transfer .In principal ,high heat transfer coefficient region can be increased two folds with V-shape ribs and hence result in even higher heat transfer et al. [20].The beneficial effect on Nu and f caused by V-shaping of ribs in comparison to angled ribs has been experimentally endorsed by several investigators Geo X,Sunden B{22],Karwa R.[23],Kukreja RT,Lue SC,McMillin RD[24],Lau SC,McMillin RD,Han JC[25], for different roughness parameters and duct aspect ratios .For V-shape ribs,the inter-rib local heat transfer coefficient reduces from leading edge(s) to trailing edge(s) in transvers direction[19,21,22],However in the flow direction ,the inter- rib local heat transfer coefficience varies like saw tooth [20,22,23].In addition ,multiple V-ribs have also been investigated with the anticipation that the more number of secondary flow cells may result in still higher heat transfer et at Lanjewar A,Bhagoria JL,Sarviya RM[26],Hans VS,Saini RP,Saini JS[27]. Based on the experimental studies carried out by various investigators, correlations for heat transfer and friction were developed. Chao et al.[28]examined the effect of an of angle of attack and number of discrete ribs, and reported that the gap region between the discrete ribs accelerates the flow, which increases the local heat-transfer coefficient. In a recent study ,Chao et al.[29] investigated the effect of a gap in the inclined ribs 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 of the continuous inclined rib arrangement. Aharwal et al. [30] carried out experimental investigation of heat transfer and friction factor characteristics of a rectangular duct roughened with repeated square cross-section split-rib with a gap, on one broad wall arranged at an inclination with respect to the flow direction. A gap in the inclined rib arrangement enhances the heat transfer and friction factor of the roughened ducts. The increase in Nusselt number and friction factor is in the range of 1.48–2.59 times and 2.26–2.9 times of the smooth duct, respectively, for the range of Reynolds numbers from 3000 to 18,000. The maximum values of Nusselt number and friction factor are observed for a gap in the inclined repeated ribs with a relative gap position of 0.25 and a relative gap width of 1.0.Table 2 summarizes the various arrangements of discreatizing the ribs employed by these investigators. The studies of Han et al.[5],Lau et al.[8] and Taslim et al.[11] not covered the wide range of roughness and operating parameters as would be required for detailed analysis for detailed optimal design or selection of roughness parameter to be used in conventional solar air heaters .Most of the investigations carried out so far have applied artificial roughness on two opposite wall with all four walls being heated .However in case of solar air heater ,roughness elements are applied to heated wall while remaining three walls are insulated .Heated wall consists of absorber plate and is subjected to uniform heat flux(insulation).This makes fluid flow and heat-transfer characteristics distinctly different from those found in case of two roughened walls and four heated wall duct Producing a gap in the inclined rib is found to enhance the heat transfer by breaking the secondary flow and producing higher level of turbulence in the fluid downstream of the rib .A similar gap in both the limbs of v-rib further enhances the heat transfer by introducing similar effects in both the limbs. Further the use of multi v-rib across the width of the plate is found to enhance the heat transfer by increasing the number of secondary flow cells several times. It is thought that producing gaps in all the limbs of multi-v geometry will bring about considerably large enhancement in comparison to that of simple single v-rib arrangement. It will therefore be pertinent to investigate the effect of various geometrical and flow parameters on the heat transfer and friction characteristics of rectangular duct having its absorber plate roughened with multi v-rib with gap in the limbs of V.

II. Computational Fluid Dynamics

Computational fluid dynamics or CFD is the analysis of systems involving fluid flow, heat transfer and associated phenomena such as chemical reactions by means of computer-based simulation. The technique is very powerful and spans a wide range of industrial and non-industrial application areas. The 2-dimensional solution domain used for CFD analysis has been generated in ANSYS version 14.5 (workbench mode) as shown in Fig.1.The solution domain is a horizontal duct with broken double ‘S’ shaped ribs roughness on the absorber plate at the underside of the top of the duct while other sides are considered as smooth surfaces.

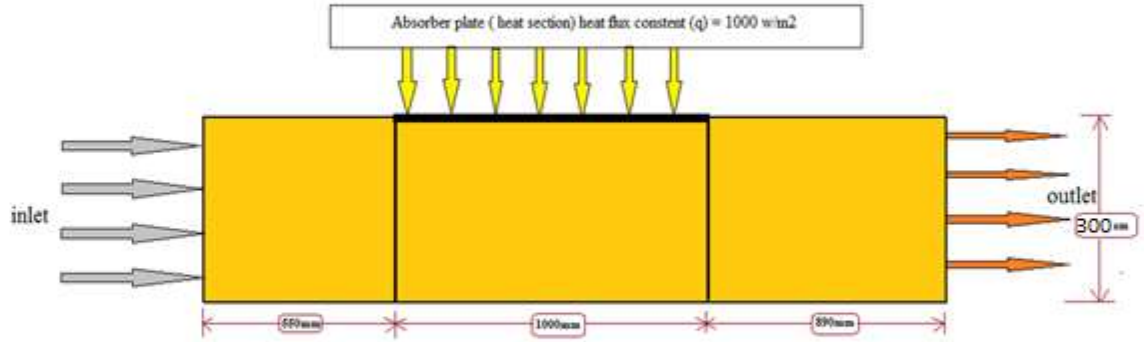

Fig.1. showing the geometric dimension of the working model

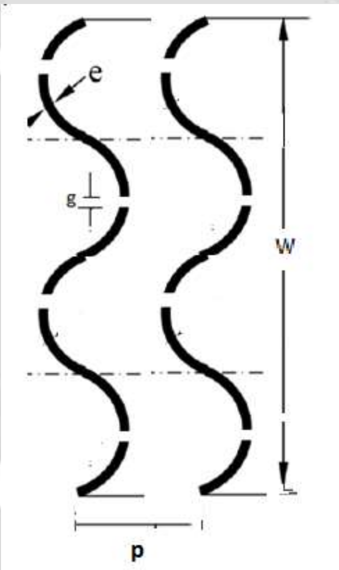

Fig. 2 Schematic diagram broken double 'S' shaped rib

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 1.0 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/m^2 is considered for computational analysis.

Fig no 2 Schematic diagram double 'S' shaped rib in different gap and continuous rib.
The 3-dimensional solution domain used for CFD analysis has been generated in ANSYS version 14.5 as shown in Fig.3.The solution domain is a horizontal duct with broken double 'S' shaped rib on the absorber plate at the underside of the top of the duct while other sides are considered as smooth surfaces.

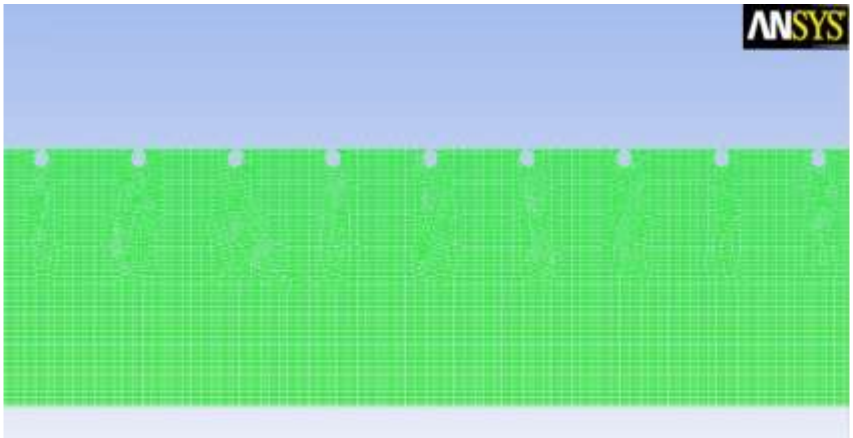

Figure 3. Meshing of duct with roughened absorber plate

In the present simulation governing equations of continuity, momentum and energy are solved by the finite volume method in the steady-state regime. The numerical method used in this study is a segregated solution algorithm with a finite volume-based technique. The governing equations are solved using the commercial CFD code, ANSYS Fluent 14.5. A second-order upwind scheme is chosen for energy and momentum equations. The SIMPLE algorithm (semi-implicit method for pressure linked equations) is chosen as scheme to couple pressure and velocity. The convergence criteria of $10^{-3}$for the residuals of the continuity equation, 10^{-6} for the residuals of the velocity components and 10^{-6} for the residuals of the energy are assumed. A uniform air velocity is introduced at the inlet while a pressure outlet condition is applied at the outlet. Adiabatic boundary condition has been implemented over the bottom duct wall while constant heat flux condition is applied to the upper duct wall of test section.

III. RESULTS AND DISCUSSION

A. Heat Transfer Characteristics and Friction Factor Characteristics

Fig.4 shows the effect of Reynolds number on average Nusselt number for different values of relative gap width (g/e) and fixed value of roughness pitch (*P*). The average Nusselt number is observed to increase with increase of Reynolds number due to the increase in turbulence intensity caused by increase in turbulence kinetic energy and turbulence dissipation rate.

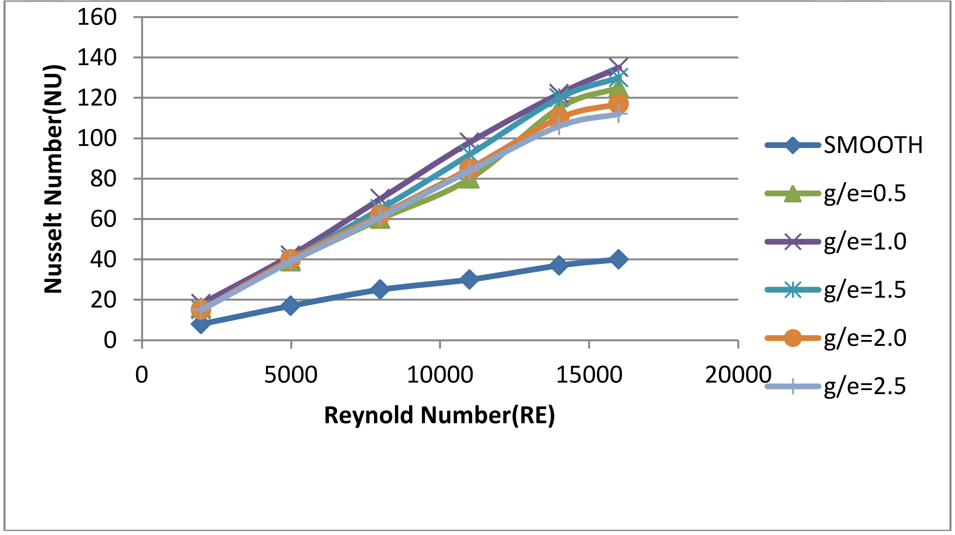

Fig. 4.Variation of Nusselt number with Reynolds number for different Values of relative gap width

Effect of the relative gap width (g/e) on heat transfer is also shown typically in Fig. 4. 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 Nusselt number values increases with the increase in relative gap width (g/e) of up to 1.0 and than decrease for a fixed value of roughness pitch (*P*). The roughened duct having broken double ‘S’ shaped rib with relative gap width (g/e) of 1.0 provides the highest Nusselt number at a Reynolds number of 16000. For rectangular rib the maximum enhancement of average Nussel tnumber is found to be 2.84 times that of smooth duct for relative gap width (g/e) of 1.0 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 ‘S’ shaped rib arrangements shown in Fig.5 .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.

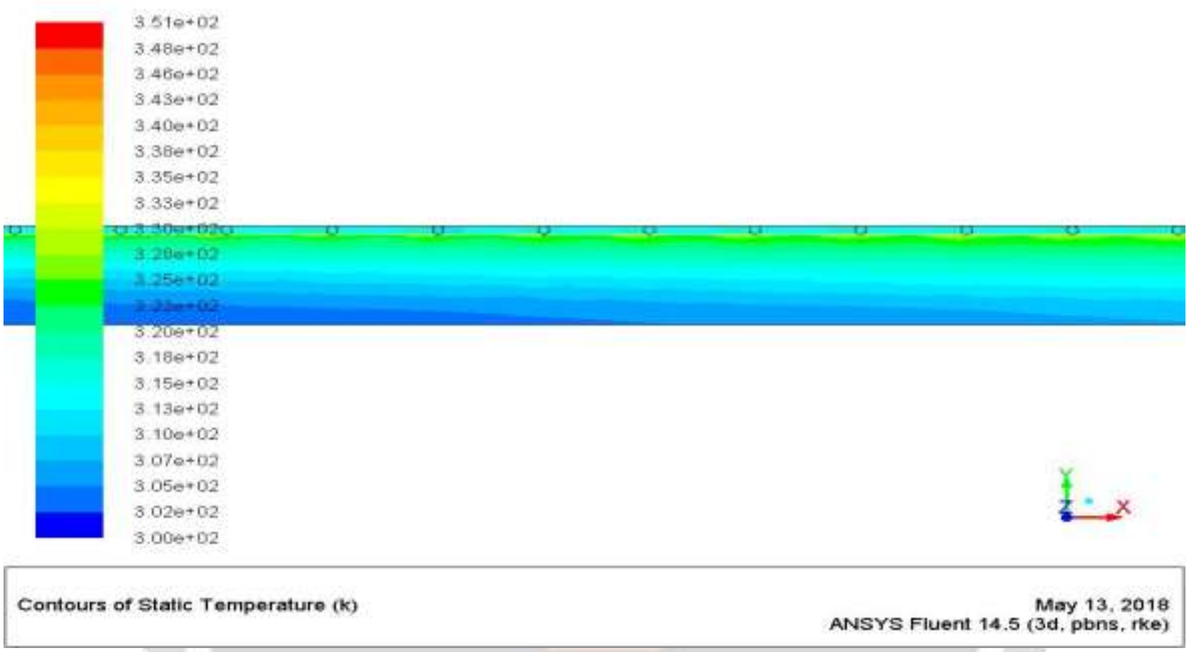

Fig. 5 Contour plot of turbulent intensity for circular

Fig.6 shows the effect of Reynolds number on average friction factor for different values of relative gap width and fixed value of roughness pitch. It is observed that the friction factor decreases with increase in Reynolds number because of the suppression of viscous sub-layer.

Fig 6 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 1.0 and than decrease for fixed value of roughness pitch, attributed to more interruptions in the flow path.

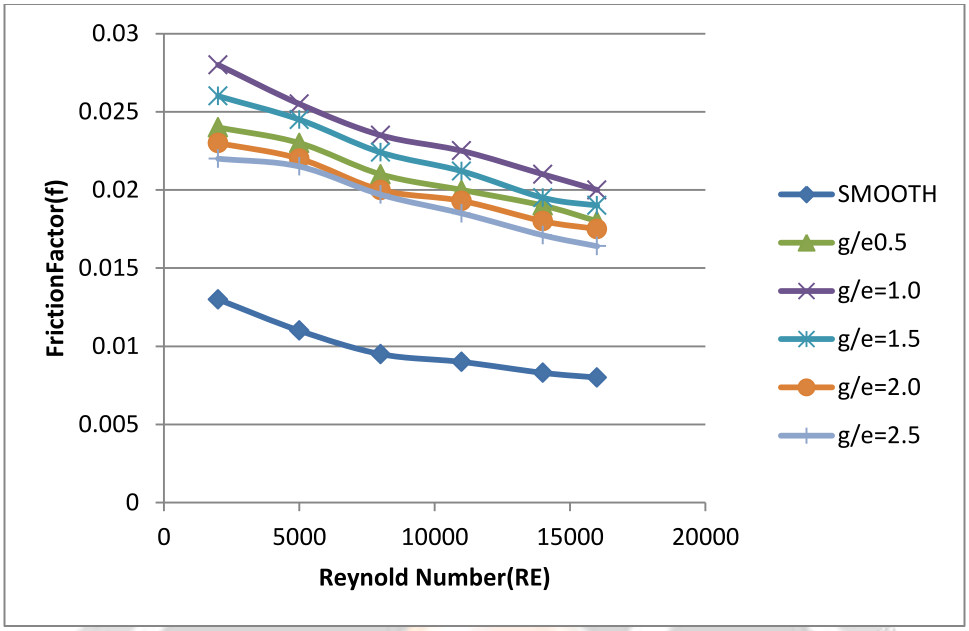

Fig. 6 Comparison between Friction factor and Reynolds number at different gap width

B. Thermo-Hydraulic Performance

It has also been observed from Figures 4 and 6 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 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,

$$\text{Thermal enhancement factor} = \frac{{}^{\text{Nu}}/_{\text{Nu}_\text{s}}}{\left({}^{\text{f}}/_{\text{f}_\text{s}}\right)^{\frac{1}{3}}}$$

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. 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 ‘S’ shaped rib is better as compared to smooth duct.

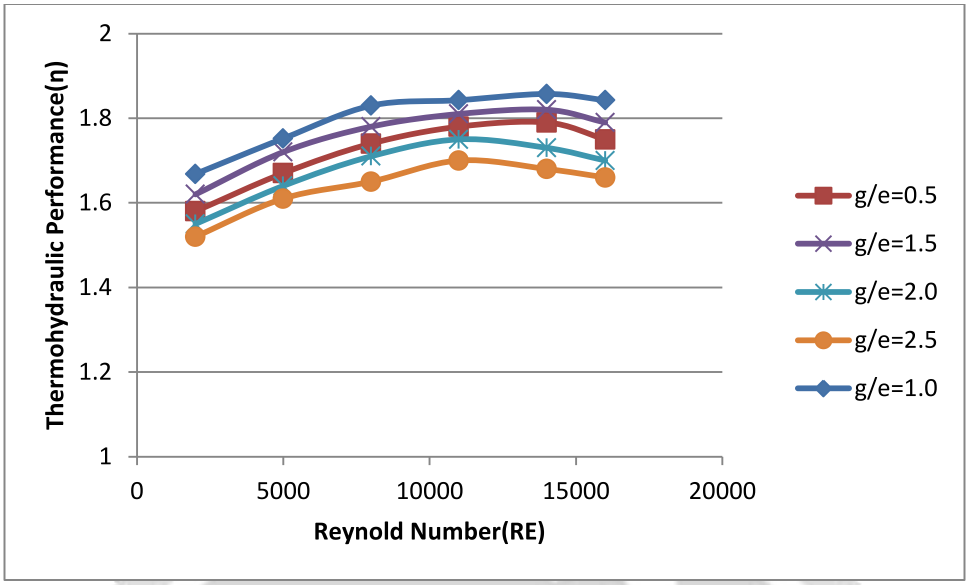

Fig.5 Thermo-hydraulic performance parameter as a function of Reynolds Number for different relative gap width

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 broken double 'S' rib having gap width equaled to 1.0 is best as compared to other values of relative gap widths. The highest value of thermo-hydraulic performance parameter obtained is 2.67 at Reynolds number of 11000.

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Conclusion:

The Numerical investigations were conducted on solar air heater duct roughened with broken double arc rib. The following conclusions are drawn from the present study:

1. The roughened duct having gap in double 'S' shaped rib with relative gap width of 1.0 provides the highest Nusselt number at a Reynolds number of 16000.
2. For gap in double 'S' shaped rib roughness is enhancement of average Nusselt number is found to be 2.75 times that of smooth duct for relative gap width of 1.0 at a Reynolds number of 16000.
3. The roughened duct having gap in double 'S' shaped rib with relative gap width of 1.0 provides the highest friction factor at a Reynolds number of 3500.
4. For gap in 'S' shaped rib roughness is the enhancement of average friction factor is found to be 2.63 times that of smooth duct for relative gap width of 1.0 at a Reynolds number of 3800.
5. It is found that the thermal hydraulic performance of relative gap width of 1.0 is maximum.

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