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# Thermo-Hydraulic Performance of a Rectangular Duct with Staggered Inclined Discrete Rib Arrangement Using CFD

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**ABSTRACT:**

The use of artificial roughness on the underside of the absorber plate is an effective and economic way to improve the thermal performance of a solar air heater. Several experimental investigations, involving different types of roughness elements, have been carried out to improve the heat transfer from the absorber plate to air flowing in solar air heaters.In this work the CFD analysis on heat transfer and friction in rectangular ducts with roughened with inclined ribs with a gap in staggered arranged at an inclination with respect to the flow direction. The range of parameters for this study has been decided on the basis of practical considerations of the system and operating conditions of solar air heaters. The numerical investigation encompassed the Reynolds number(Re) range from 2000 to 16,000, relative width to height ratio (W/H) of 8.0, relative gap position (dt/W & dl/W) of 0.3 & 0.4, relative gap width (g/e) is varied of 0.5 to 2.5, relative roughness height (e/Dh) of 0.045, relative roughness pitch (P/e) of 8, angle of attack (a) of 40$^{o}$. The effects of relative gap width on Nusselt number, friction factor and thermo-hydraulic performance 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, Pressure drop, Duct

## I. Introduction:

It has been observed that the heat transfer coefficient between the absorber plate and working fluid of solar air heater is generally low. It is attributed to the formation of a very thin boundary layer at the absorber plate surface commonly known as viscous sub-layer. This convective heat transfer coefficient can be increased by providing the artificial roughness on the heat transferring surface. It has been found that the artificial roughness applied on the heat transferring surface breaks the viscous sub-layer, which reduces thermal resistanceand promotes turbulence in a region close to artificiallyroughened surface. Although the applicationof artificial roughness in the duct of a conventionalsolar air heater has been shown to be an efficientmethod of enhancement of thermal efficiencyof solar air heater, however, the use of artificialThe 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,GlicksmanLR,Rohsenow WM[18],Prasad BN,Saini JS{19],TaslimME,LiT,KercherDm[20],Webb RL,EckertErg,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],KukrejaRT,LueSC,McMillin RD[24],Lau SC,McMillinRD,Han JC[25], for different roughness parameters and duct aspect ratios . 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 LanjewarA,BhagoriaJL,Sarviya RM[26],Hans VS,SainiRP,Saini JS[27].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. Computational studies have also been used extensively in studying the flow and heat transfer effects in ribbed ducts. The advantage of being able to study both the flow and heat transfer in the entire flow field is worth the effort required to simulate ribbed duct flows, but the whether the channel roughened with ribs of different shape can improve the heat transfer rate. There have been attempts undertaken to overcome the adverse effect by varying the geometry of ribs. Lockett and Hwang employed the non-invasive optical method of holographic interferometer to investigate the heat transfer in turbulent flow over square and rounded rib-roughness elements. They found that the heat transfer distribution depends on the Reynolds number for the rounded rib, but independent for square rib geometry. In both cases, the minimum heat transfer occurred at the base of the rear facing rib wall.

## 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 arc shaped ribs combined with staggered rib roughness on the absorber plate at the underside of the top of the duct while other sides are considered as smooth surfaces.

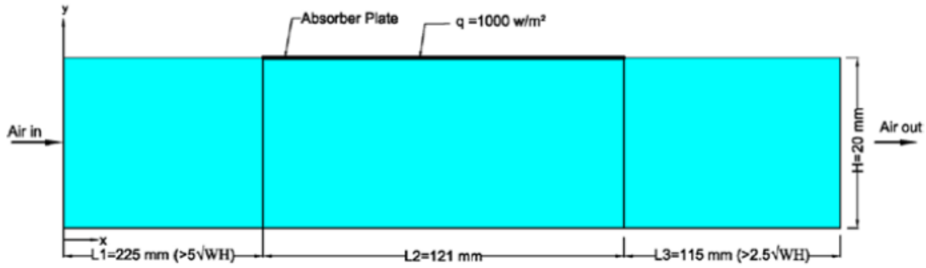



Fig.1. showing the geometric dimension of the working model

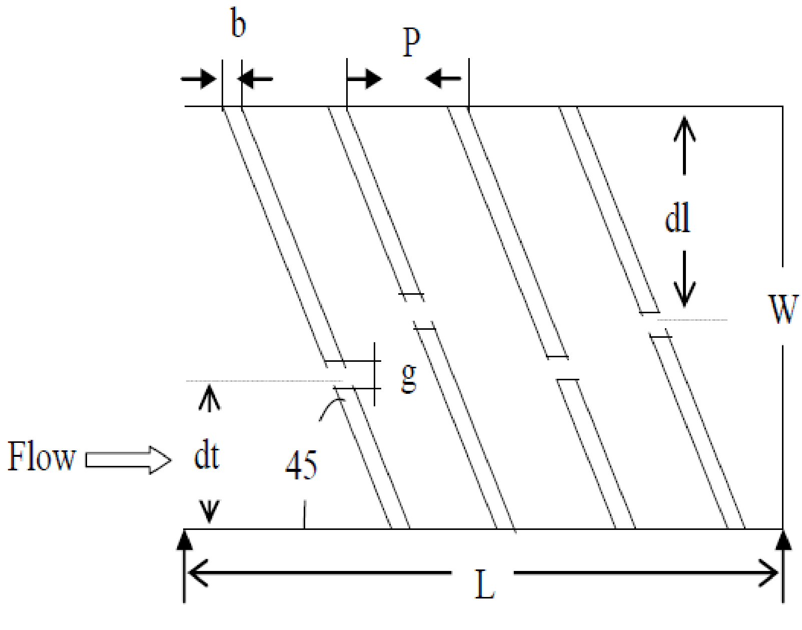



**Fig. 2 Geometry of inclination rib with a gap in staggered arrangement**

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/m$^2$ is considered for computational analysis.

Fig no 2 Schematic diagram arc 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 inclination rib with a gap in staggered arrangementon the absorber plate at the underside of the top of the duct while other sides are considered as smooth surfaces.

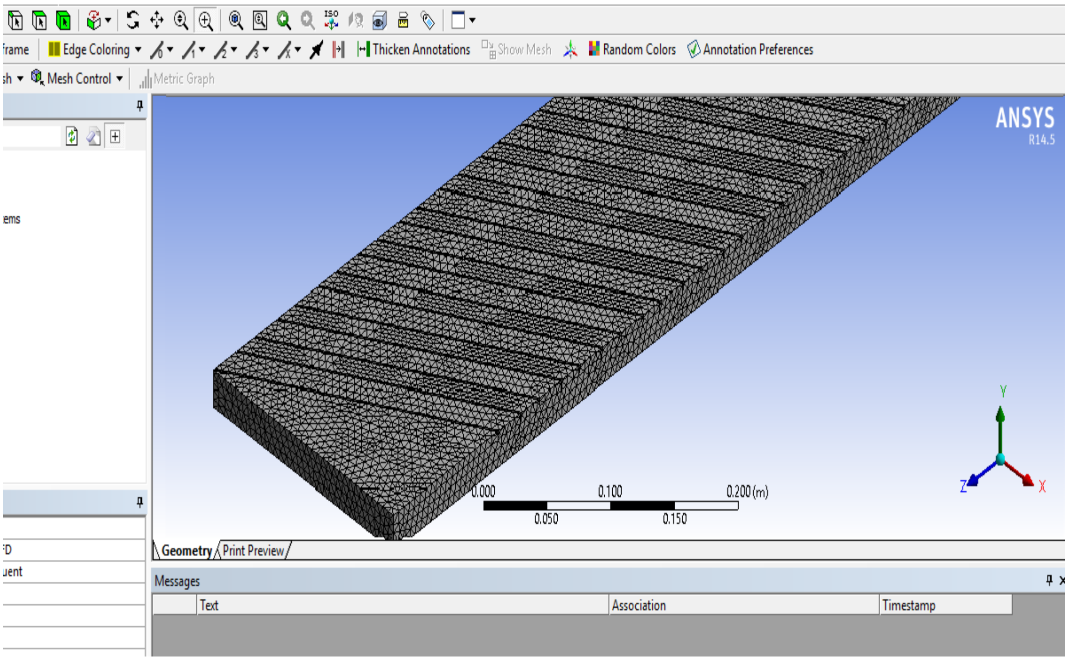



Figure 3. Meshing of duct with roughened absorber plate

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.

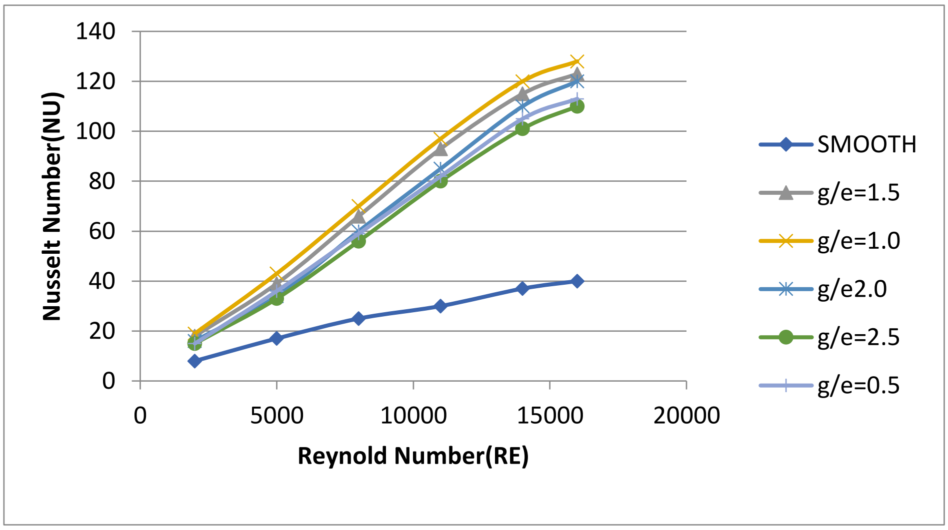
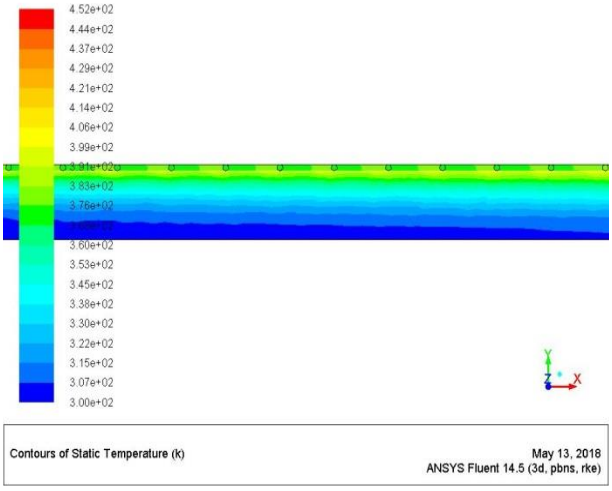
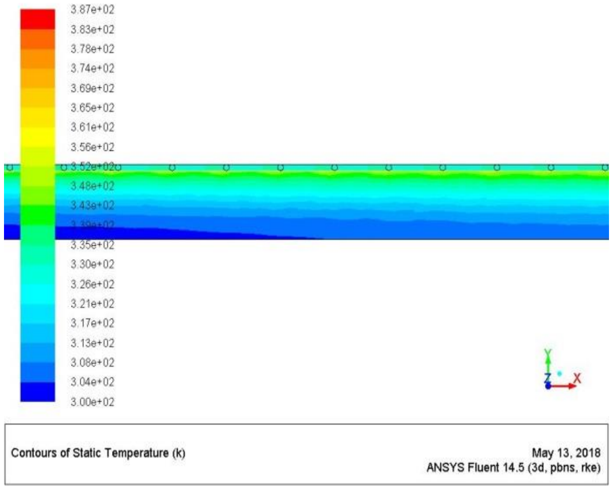



**Fig. 4.Variation of Nusselt number with Reynolds number for different Values of relative gap width (g/e)**

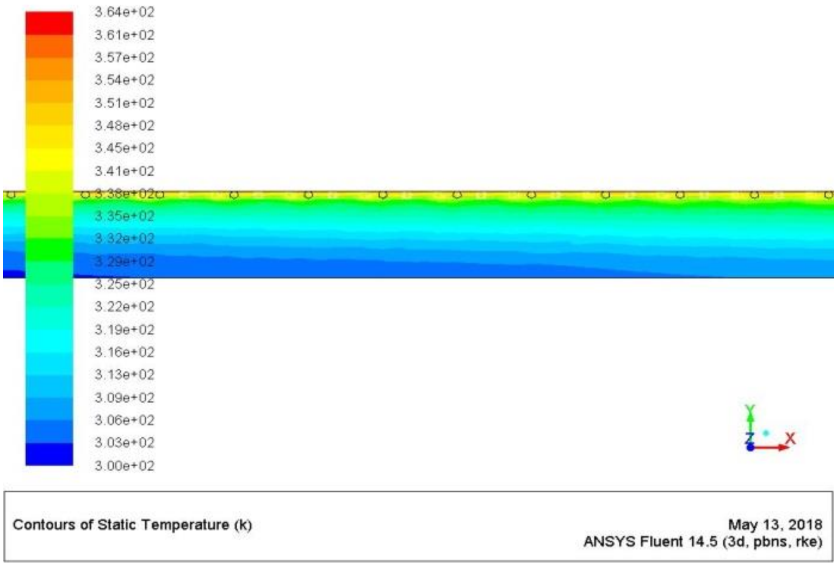
Effect of the relative gap width (g/e) on heat transfer is also shown typically in Fig. 4It can be seen that the enhancement in heat transfer of the roughened duct with respect to the smooth duct also increases with an increase in Reynolds number. It can also be seen that Nusselt number values increases with the increase in relative gap width (g/e) of up to 1 and than decrease for a fixed value of roughness pitch (*P*). The roughened duct having inclination rib with a gap in staggered arrangementwith 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 Nusseltnumber is found to be 2.78 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 inclination rib with a gap in staggered arrangementis shown in Fig.5 (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.




**(a)**




**(b)**




**(c)**

**Fig. 5 Contour plot of turbulent intensity for circular rib (a) Re=4000 (b) Re=8000 (c) Re=12000**

Fig.6 shows the effect of Reynolds number on average friction factor for different values of relative gap width (g/e) 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 and than decrease for fixed value of roughness pitch, attributed to more interruptions in the flow path.

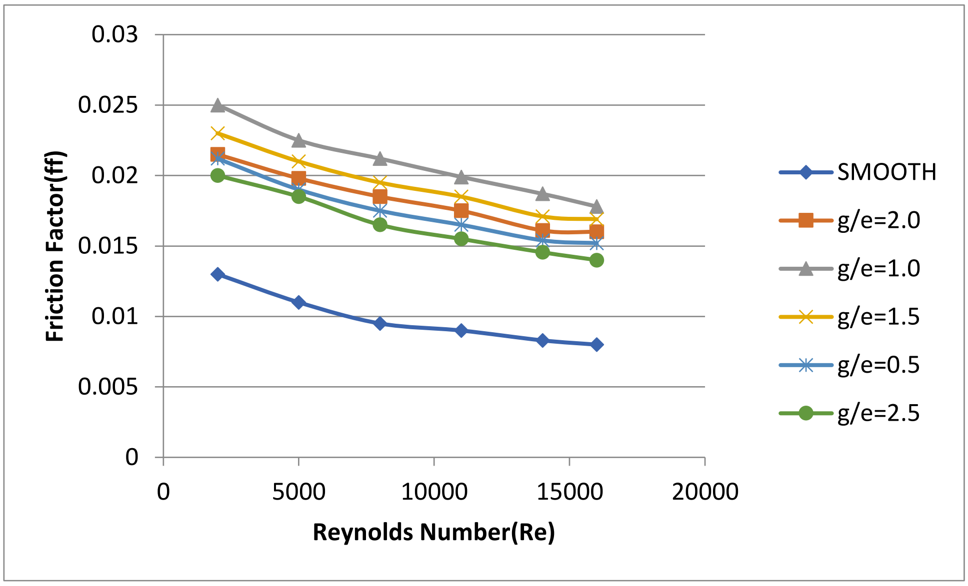



**Fig. 6 Comparison between Friction factor and Reynolds number at different gap width**

**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,

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

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 inclination rib with a gap in staggered arrangement is better as compared to smooth duct.

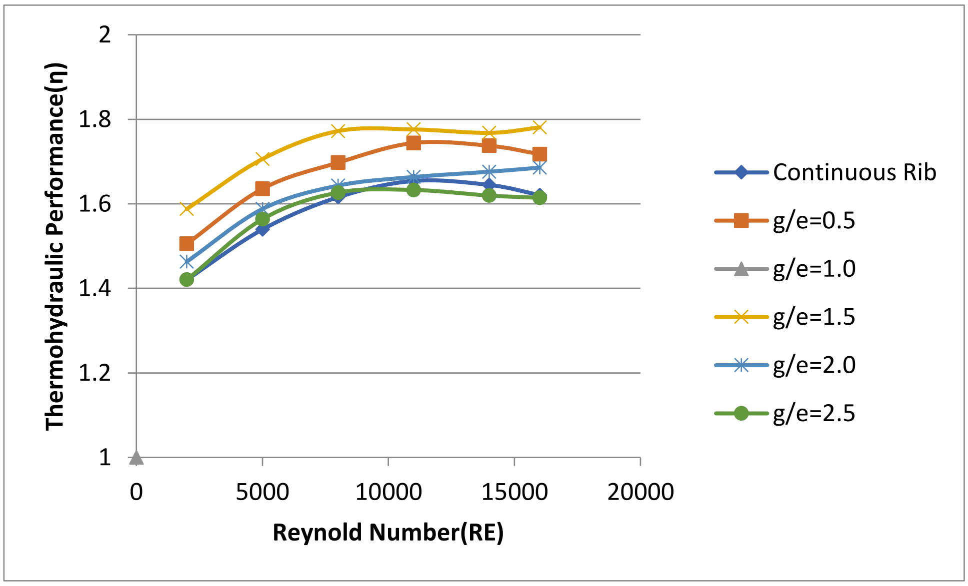



**Fig.5 Thermo-hydraulic performance parameter as a function of Reynolds Number for different relative gap width (g/e)**

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 inclination rib with a gap in staggered arrangement piece 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 2.09 at Reynolds number of 11000.

## Conclusion:

The Numerical investigations were conducted on solar air heater duct roughened with inclination rib with a gap in staggered. The following conclusions are drawn from the present study:

1. The roughened duct having inclination rib with a gap in staggered with relative gap width of 1.0 provides the highest Nusselt number at a Reynolds number of 16000.
2. For rectangular rib the maximum enhancement of average Nusselt number is found to be 2.72 times that of smooth duct for relative gap width of 1.0 at a Reynolds number of 11000.
3. The roughened duct having inclination rib with a gap in staggered with relative gap width of 1.0 provides the highest friction factor at a Reynolds number of 3500.
4. For inclination rib with a gap in staggered the maximum enhancement of average friction factor is found to be 3.14 times that of smooth duct for relative gap width of 1.0.
5. It is found that the thermal hydraulic performance of relative gap width of 1.0 is maximum..

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