International Journal of Thermal Technologies
E-ISSN 2277 – 4114
Available at http://inpressco.com/category/ijtt/


*Research Article*

# Effect of rib height on heat transfer and friction factor in a square channel roughened by inclined ribs with a gap

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Received 10 Oct, Accepted 15 Dec 2017, Available online 18 Dec 2017, **Vol.7, No.4 (Dec 2017)**

***Abstract***

*This work concentrates on experimental investigation of forced convection heat transfer and friction factor (pressure drop) characteristics of a rib-roughened surface with varying rib height of discrete inclined ribs. The test section of the square duct (AR=1) is roughened on its top and bottom wall with Inclined square ribs having a gap on its length. Reynolds number (Re) based on duct hydraulic diameter varied from 5,000 to 40,000, relative roughness pitch (p/e) is 10, relative gap width (g/e) is 1 and relative gap position (d/W) is taken as 1/3. The rib attack angle (α) is taken as $60^0$ .The effects of five rib height to hydraulic diameter ratios ($e/D_h$) of 0.047, 0.060, 0.074, 0.087 and 0.10 on heat transfer in terms of Nusselt number and friction loss in the form of friction factor are experimentally investigated. The results show that there is significant effect on the Nusselt number and friction factor when ($e/D_h$) has changed. It is observed that the heat transfer augmentation in the channel increase with decrease in the rib height to hydraulic diameter ratio ($e/D_h$) (from 0.10 to 0.060) but only at the cost of the pressure drop across the test section. Maximum heat transfer enhancement is associated with ribs of ($e/D_h$) = 0.060 which also produces the maximum pressure drop penalty in the range of parameters investigated. The thermal hydraulic performance for all ($e/D_h$) ratios is also presented. The thermal hydraulic performance of ribs with ($e/D_h$) = 0.060 has found maximum and is about 2.18.*

***Keywords:*** *Nusselt number, Friction factor, Rib height to hydraulic diameter ratio, Reynold's number, thermal performance*

## 1. Introduction

Generally gas turbine cooling is achieved by bleeding some relatively cool air from the compressor and using it inside the gas turbine blades to remove heat transferred into the blade from the hot mainstream. The cooling air flows through internal cooling passages inside the blade, these passages are specifically designed to maximize the heat transfer. Rib turbulators are the most frequently used method to enhance the heat transfer in the cooling passages. Roughened internal blade passage is one of the popular ways to enhance the heat transfer through the blade surface and effectively used in the design of internal cooling passage of turbine blade. The blade surfaces roughened with the ribs cause extra flow resistances. The performance of the heat transfer surface with ribs depends significantly on the Rib parameters, flow parameters as well as the area of the surface.

Many investigators have investigated fluid flow and heat transfer distributions in rib roughened channels. Various geometrical parameters such as channel aspect ratio (AR), rib height-to-passage hydraulic diameter ratio ($e/D_h$), rib attack angle (α), rib pitch-to-height ratio (p/e), rib shape, discretization of ribs and the manner in which the ribs are positioned relative to one another have considerable effects on heat transfer coefficient and friction factor of the passage [Han *et al*, 2001]. Chandra and Alexander, 2003, presented results of experimental studies on heat transfer and pressure drop in a square channel with continuous ribs on one, two, three and four walls.

Experiments were conducted for a rib to hydraulic diameter ratio of 0.0625, pitch to rib height ratio of 8 and Reynolds number ranging from 12,000 to 72,000. It was observed that with increasing Reynolds number, the heat transfer augmentation decreased and the friction factor augmentation increased. It was also observed that the heat transfer augmentation and the friction factor increased with the increase in the number of ribbed walls. Rau *et al*, 1998, presented local heat transfer distribution in a square channel for various pitch to rib height (p/e) ratios with ribs on one wall. Liquid crystal thermography technique was used for determining local temperature field. Different pitch to rib height (p/e) ratios covered were 6, 8, 9, 10, 12,

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14 and 16 with a rib height to hydraulic diameter ($e/D_h$) ratio of 0.1. It was observed that the heat transfer augmentation was highest for (p/e) ratios of 9 and 12 compared to all other (p/e) ratios studied. Liou and Hwang, 1992, presented both local and average heat transfer distributions along with friction factor variations in rectangular channel with two opposite rib roughened walls. Reynolds number varied from 5000 to 50,000 and the rib to hydraulic diameter ratios ($e/D_h$) of 0.063, 0.081 and 0.106. Laser holographic interferometry technique was used for local heat transfer measurement and thermocouples were used for average heat transfer measurement. They concluded that the average Nusselt number increased by 2.2- to 2.9-folds that of a smooth channel for an ($e/D_h$) variation from 0.063 to 0.106.

Han *et al,* 1991, presented experimental results on pressure drop and heat transfer in a square channel with ribs on two walls for nine different rib configurations. Regionally averaged heat transfer and friction factor were reported for rib pitch-to-height ratio (p/e) of 10 and the rib height to hydraulic diameter ratio ($e/D_h$) of 0.0625. They concluded that the angled ribs and 'V' ribs provide higher heat transfer augmentation compared to continuous ribs. It was observed that the heat transfer augmentations and the friction factor were highest for the $60^0$ orientation compared to $45^0$ and $90^0$ orientation amongst the angled ribs.

Han and Zhang, 1992, reported results of heat transfer and pressure drop in a square channel with seven different configurations of broken ribs and shows that generally broken ribs give better heat transfer performance than corresponding continuous ribs. Liou *et al*, 1998, investigated the effect of rib height and pitch on the thermal performance of passage with detached solid ribs in a rectangular channel of aspect ratio 4. The rib to duct height ratio was varied from 0.13 to 0.26 and the pitch to rib height ratio (p/e) from 7 to 13. The clearance ratio was fixed at 0.38. Amongst the three rib heights investigated, they found that detached rib with rib to duct height ratio of 0.17 with (p/e) of 10 has highest thermal performance. Also they reported that the vortex shedding was the main controlling mechanism for the observed trend of heat transfer distribution observed in case of detached ribs.

Kiml *et al*, 2001, reported that the thermal performance of rib arrangements with $\alpha = 60^0$ is better than that of $45^0$. Han and Park, 1998, studied heat transfer and pressure losses with 90°, 60°, 45°, and 30° angle ribs in square and rectangular channels. The Reynolds number was from 10000 to 60000. They concluded that the higher thermal performance in the square channel was 30° rib angle and the higher thermal performance in the rectangular channel was 45° rib angle. The higher heat transfer with higher pressure drop in the square channel was 60° rib angle. The square channel in their study showed a larger increase in heat transfer performance than the wide aspect ratio channels.

Lau *et al*, 1991, observed that the replacement of continuous transverse ribs by inclined ribs in a square duct results in higher turbulence at the ribbed wall due to interaction of the primary and secondary flows. Liou and D. Hwang, 1992, studied the heat transfer and flow field in the ribbed channels. They found that the (p/e) of 10 resulted in the best heat transfer; the heat transfer showed a periodic behavior between consecutive ribs; and both heat transfer and friction factor increased with decreasing rib spacing. Liou and J. Hwang, 1993, conducted experiments to measure the local as well as average heat transfer coefficients to compare the performance of square, triangular and semi-circular ribs and found that the square ribs give best heat transfer performance.

Taslim *et al,* 1996, studied the effect of $e/D_h$ on the heat transfer and friction losses with $90^0$, $45^0$ and V-shaped ribs. The Reynolds number was from 5000 to 30000. The ($e/D_h$) was 0.085, 0.125 and 0.167, (p/e) was 10. For ($e/D_h$) = 0.085, the V-shape ribs shows the highest thermal performance and for ($e/D_h$) equal to 0.125 and 0.165, the $45^0$ angled ribs have the highest thermal performance. Taslim *et al*, 1997 and 1998, investigated the effect of (p/e) and ($e/D_h$) on the heat transfer and friction losses with $90^0$ sharp angle ribs and $90^0$ around angle ribs in a square channel. The ($e/D_h$) was 0.133, 0.167 and 0.25 and p/e was 5, 7, 8.5, and 10. The Relative roughness pitch of 8.5 and 10 reported the highest thermal performance. The thermal performance increases as ($e/D_h$) increases.

Sriharsha *et al*, 2009, studied the effect of ($e/D_h$) on the local heat transfer distributions in a double wall ribbed square channel with $90^0$ continuous and $60^0$ V-broken ribs. It was observed that the enhancement caused by $60^0$ V-broken ribs are higher than those of $90^0$ continuous attached ribs and also results in lower pressure drop. But, with increase in ($e/D_h$), the enhancements are found to decrease in the channel with broken ribs.

Saha, 2010, concluded that Nusselt number and friction factor increase by increasing flow turbulator height and Reynolds number in square, rectangular and circular channels with ribs inserted in opposite walls. Thianpong *et al*, 2009, reported the heat transfer and friction loss behaviors of different heights of triangular ribs with three e/H ratios (e/H =0.13, 0.2 and 0.26) and aspect ratio 10 using data acquisition system (fluke 2650B). They observed that the uniform rib height performs better than the corresponding non-uniform one. Casarsa *et al*, 2002, showed that in their square channel with ($e/D_h$) = 0.30 a strong acceleration of the flow over ribs occurred due to the reduced cross-section. Bailey and Bunker, 2003, considered an aspect ratio of 1:2.5 with three blockage ratios of 0.193, 0.263, and 0.333. They showed that heat transfer enhancement and friction increases with the blockage ratio.

It is evident from the literature that there is scant data available on effect of rib height on heat transfer distributions at higher ($e/D_h$) ratios, particularly in broken rib configurations. Thus the role of rib's height seems to need more investigations. Hence, the present work focuses on the effect of the rib's height in the two opposite side's roughened square channel having discrete inclined ribs. The optimum value of ($e/D_h$) have been obtained and discussed.

## 2. Experimental set-up and Roughness Geometry

A schematic diagram of the experimental set-up including the test section is shown in Fig.1, which was previously used by Gupta *et al*, 2013 and Chaube *et al*, 2014.

The flow duct consists of an entrance section, a test section and an exit section of length 1500 mm (20Dh), 1500 mm ($20D_h$) and 750 mm ($10D_h$) respectively.

The dimension of wooden duct was 3750 mm x 75 mm x 75 mm (L x W x H) (inner dimensions of duct). G. I. pipe having internal diameter of 81 mm was connected to the exit end of the duct with a calibrated orifice plate (to measure flow rate) through a square to circular transition piece. The outside of entire set-up from inlet to the orifice plate, were covered with 25 mm thick thermocole sheet, to minimize the heat losses from the test section.

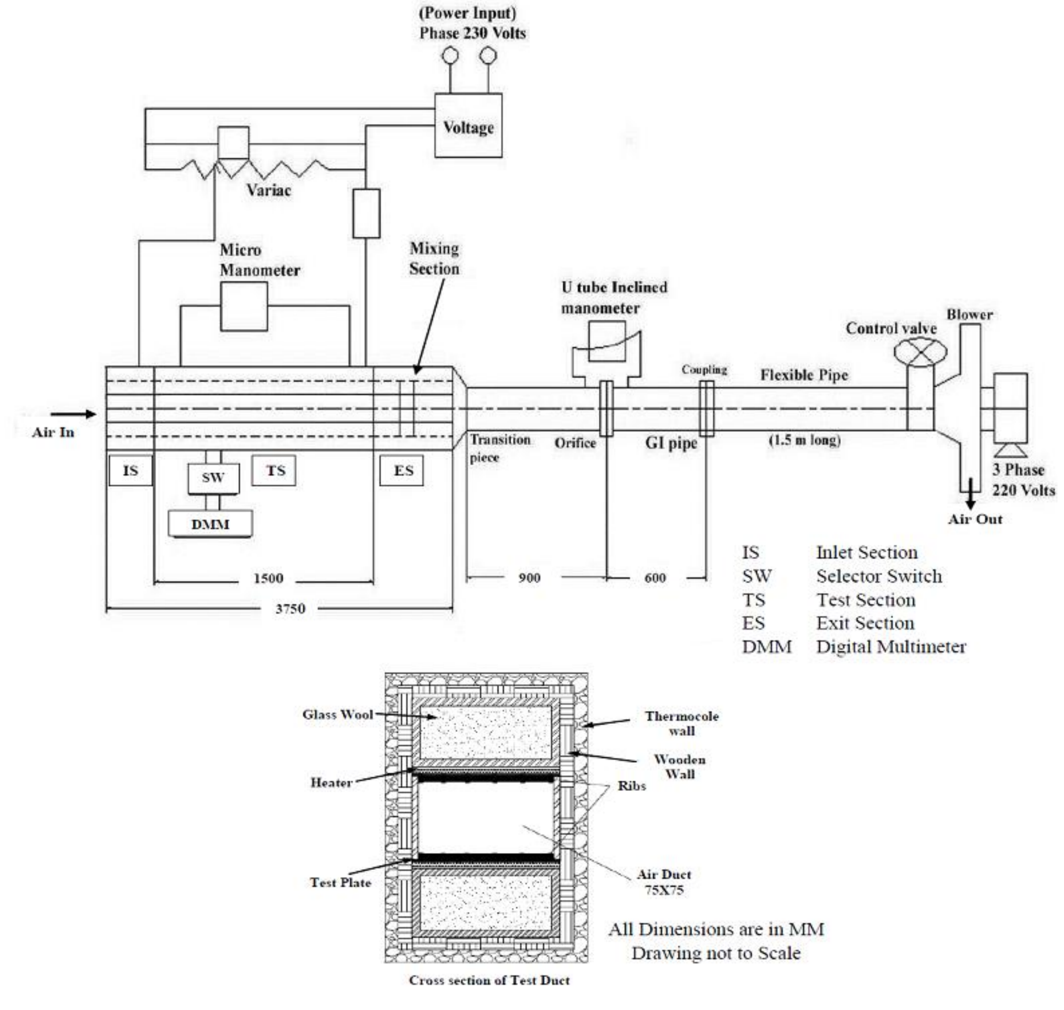


**Fig.1** Schematic diagram of experimental set-up

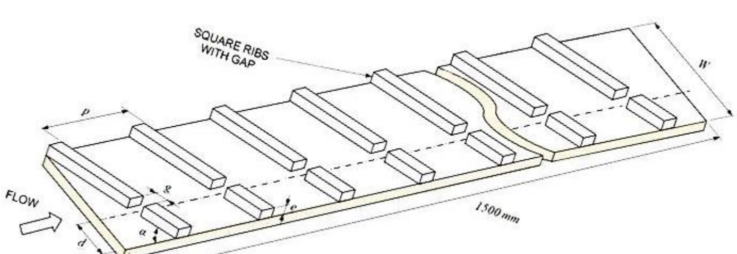


**Fig.2** Schematic of roughness geometry

## 3. Data Reduction

The values of useful parameters were calculated as follows:

The Reynolds number based on the channel hydraulic diameter, $D_h$, is given by

$$Re = \frac{\rho_a V D_h}{\mu_a} \quad (1)$$

The mass flow rate, $m$, of air through the duct has been calculated from pressure drop measurement across the orifice plate.

$$m = C_d . A_o . \left[ \frac{2.\rho_a.(\Delta P)_o}{1-\beta^4} \right]^{0.5} \quad (2)$$

The average heat transfer coefficient, $h$, is evaluated from the measured temperatures and heat inputs as below:

$$Q_u = m\, C_p\, (T_o - T_i) \quad (3)$$

$$h = \frac{Q_u}{A_p (T_p - T_f)} \quad (4)$$

The average value of plate temperature ($T_p$) is calculated as a weighted mean of the plate temperature measured at different locations and mean bulk air temperature ($T_f$) is calculated from the following equations.

$$T_f = \frac{T_i + T_o}{2} \quad (5)$$

$$T_p = \sum_{n=1}^{20} \frac{T_n}{20} \quad (6)$$

Then, average Nusselt number, Nu, is written as

$$Nu = \frac{h D_h}{k_a} \quad (7)$$

The friction factor is determined from the measured values of pressure drop, $(\Delta P)_d$ across the test section length, between the two points located 1.2 m apart.

$$f = \frac{2 (\Delta P)_d\, D_h}{4\, \rho_a\, L_f V^2} \quad (8)$$

The thermo-hydraulic performance can be calculated by

$$\eta = [(Nu_r/Nu_o)/(f_r/f_o)^{1/3}] \quad (9)$$

From the analysis of the uncertainties in the measurement by various instruments [Holman, 2004, Bhatti and Shah, 1987], the maximum uncertainties in the calculated values of various parameters are within ±10%.

## 5. Results and Discussion

Figure 3 and Fig. 4 shows the values of Nusselt number, and Nusselt number ratio for discrete inclined ribs respectively. It is shown in the figures that the Nusselt number increases as Reynolds number increases and maximum heat transfer enhancement is about 4.1 times that of smooth duct. The increased turbulence at higher Reynolds numbers produces much more increase in heat transfer for ribbed duct as compared to increase in heat transfer for smooth duct. It is expected that the flow travels along the ribs from side wall and generate secondary flows and the swirling motion created by the secondary flow helped to generate a high overall average heat transfer coefficient.

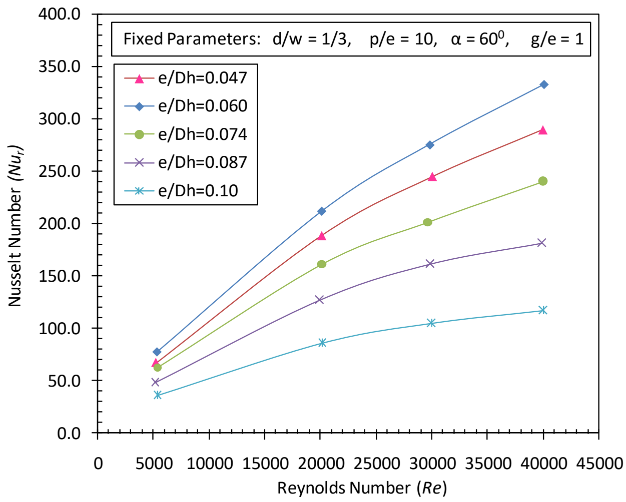


**Fig. 3.** Nusselt number as a function of Reynolds number for different values of $e/D_h$

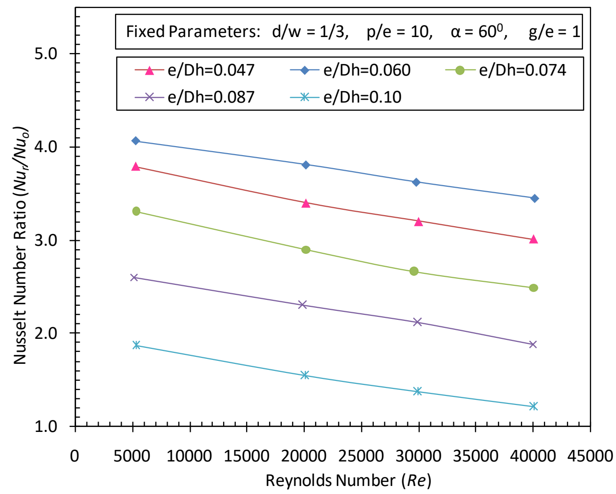


**Fig 4.** Variation of Nusselt number ratio with Reynolds for different values of $e/D_h$

The effect of relative roughness height $e/D_h$ on Nusselt number is depicted in Figures 3 and 5. It can be observed that the increase in relative roughness height results in a decrease in heat transfer coefficient for the range of parameters investigated in the study. The augmentations are found to decrease with increase in the rib height. This may be due to the reason that with an increase in the rib height, the effect of inclination of the rib is not distinctly observed. Hence, it acts as a discrete transverse rib resulting in lower augmentations. The maximum enhancement in Nusselt number is observed for $e/D_h$= 0.060 which is about 4.1 times that of smooth duct.

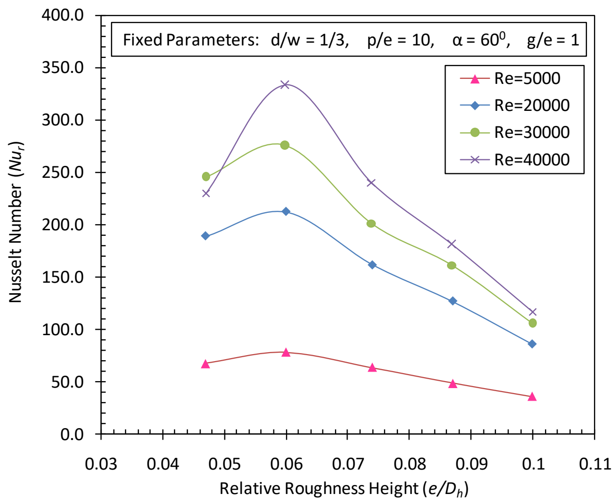


**Fig.5** Nusselt number as a function of $e/D_h$ Ratio for different Reynolds number

Figure 6 and Fig. 7 shows the effect of Reynold number on friction factor and friction factor ratio for Inclined ribs with a gap respectively. In general, friction factor decreases with an increase of Reynolds number as expected. However, the values of friction factor are distinctly different as compared to those obtained for smooth plate due to distinct change in the fluid flow characteristics as a result of roughness that causes flow separation, reattachment and the generation of secondary flows.

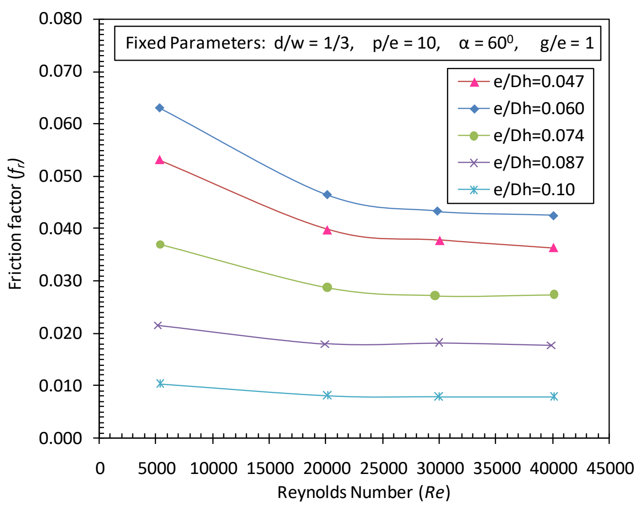


**Fig.6** Nusselt number as a function of Reynolds number for different values of $e/D_h$

The maximum enhancement in friction factor was found to be 7.4 times that of smooth duct for $e/D_h$= 0.060. Fig. 8 shows that by increasing the relative roughness height friction factor decreases. It is also seen that the rate of decrease of Nusselt number is lower than that of the friction factor.

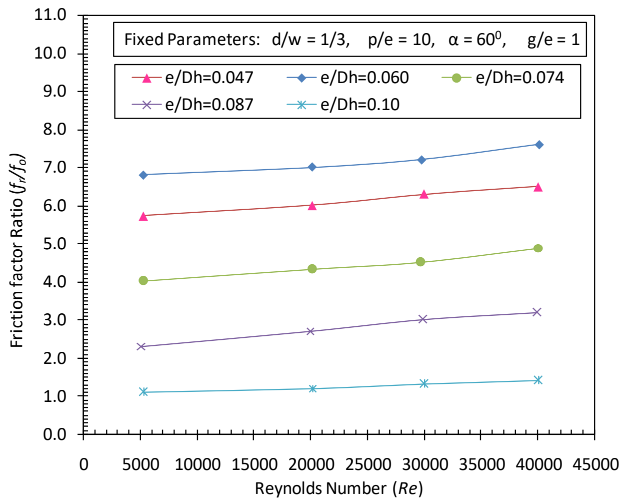


**Fig.7** Variation of Nusselt number ratio with Reynolds for different values of $e/D_h$

It has been found that artificial roughness results in considerable enhancement of heat transfer which is accompanied by a substantial increase in friction factor. Therefore, to select the best rib geometry, the heat transfer and friction characteristics should be considered simultaneously. A parameter that facilitates the simultaneous consideration of thermal and hydraulic performance known as thermo-hydraulic performance [Lewis, 1975] is evaluated for both the cases and plotted as in Figure 9 and 10.

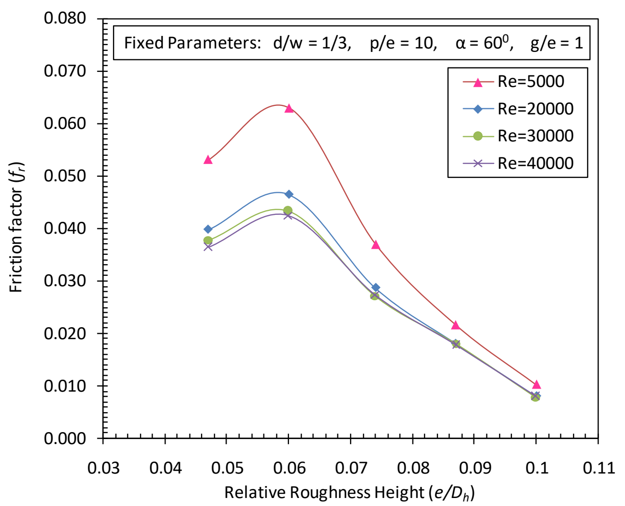


**Fig.8** Friction factor as a function of $e/D_h$ Ratio for different Reynolds number

It is observed from the figures that, in general, the thermo hydraulic performance improves with decreasing values of relative roughness height and absolute maxima occurs with relative roughness height of 0.060 which is about 1.9 times that of smooth duct, in the range of values investigated in the present study.

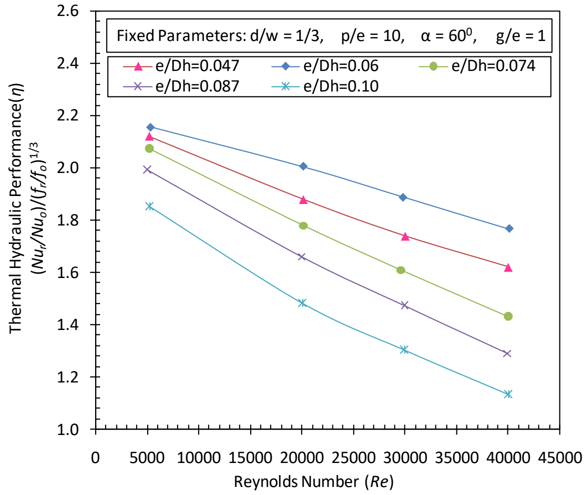


**Fig.9** Variation of Thermo hydraulic performance with Reynolds number Reynolds for different values of $e/D_h$

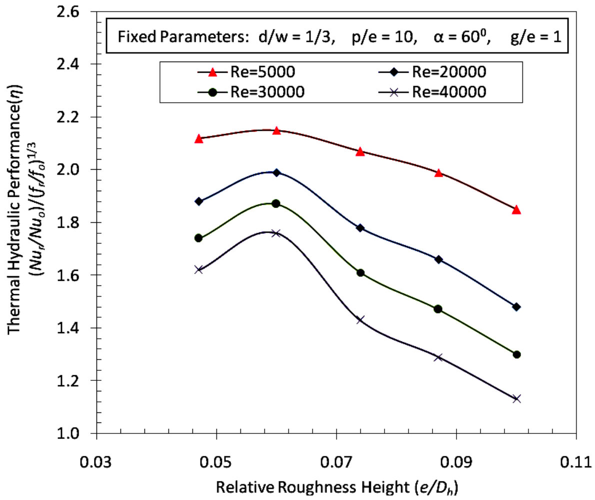


**Fig.10** Variation of Thermo hydraulic performance with $e/D_h$ for different values of Reynolds number

## Conclusions

The following conclusions can be drawn from the present work:

(1) In general, Nusselt number increases and friction factor decreases with an increase of Reynolds number. Nusselt number and friction factor are significantly higher as compared to those obtained for smooth duct. This is due to the distinct change in the fluid flow characteristics as a result of discrete inclined ribs that causes flow separations, reattachments and the generation of secondary flows.

(2) The Nusselt number enhancement decreases when the Reynolds number increases. The friction factor ratio is found to increases as Reynolds number increases and becomes constant at high Reynolds numbers.

(3) It was observed that the rate of increase of Nusselt number with an increase in Reynolds number is lower than the rate of increase of friction factor.

(4) The relative roughness height plays an important role for desirable fluid flow characteristics. The maximum value of Nusselt number is obtained for relative roughness height of 0.060. Nusselt number ratio at this relative roughness height was 4.1 times that of smooth duct for the range of parameters investigated due to stronger and optimum secondary flow.

(5) The maximum enhancement in Nusselt number and friction factor values compared to smooth duct are of the order of 4.1 and 7.4 respectively.

(6) The thermal performance decreases when the Reynolds number increases. The discrete inclined rib with relative roughness height of 0.060 gives the highest thermal hydraulic performance.

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