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HEAT TRANSFER ENHANCEMENT OF GAS TURBINE BLADE'S COOLING RECTANGULAR CHANNEL WITH INTERNAL RIBS OF DIFFERENT RIB CROSS SECTIONS USING CFD.

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Abstract - *The present study investigates the three-dimensional CFD simulations to investigate heat transfer and fluid flow characteristics of artificially roughened rectangular channel using Ansys- CFX. Heat transfer characteristics of the rectangular channel are investigated for Reynolds numbers ranging from 8000 to 18000. Model geometry is designed in CATIA V5 R20, and then meshed, analysed, and post-processed using Ansys-CFX software. Fluid flow and heat transfer characteristics of different roughness configurations are simulated and then results compared using turbulent flow model (k- omega model). Rectangular channel has an aspect ratio of 5, while the domain length for numerical analysis is kept 550 mm long the hydrodynamic diameter(Dh) of duct is 66 mm the relative roughness height (e/Dh) is 0.030, relative roughness pitch (p/e) is 10. Total three models of rectangular channel have been created with bottom portion of the channel is provided with aluminium plate and this plate is roughened by three different ribs shape in such a way that the cross-section area of every shape is same, the ribs attack angle is taken as 45^o .The another surface of the aluminium plate is kept at constant heat flux 1000 W/m^2.*

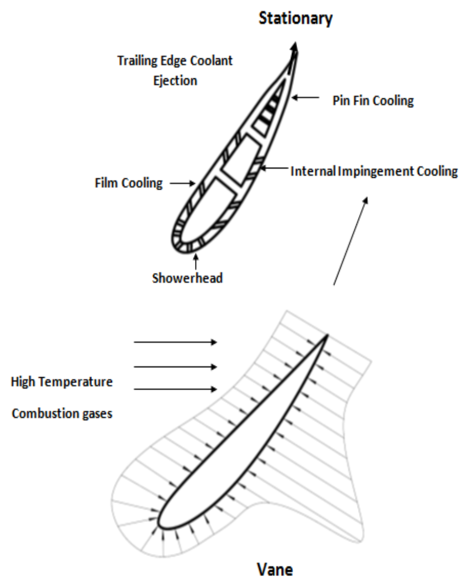
Reasonable difference is found between the heat transfer simulation data for different roughness configurations. From the present study it is found that there is a significant change in heat transfer rate, friction factor, Nusselt Number ratio, friction factor ratio and thermal performance factor, and it can be said that the change in rib shape in rectangular channel can increase the heat transfer rate.

Key Words: **Computatonal Fluid Dynamic (Cfd), Reynolds number, Nusselt Number, friction factor, Rib Attack Angle.**

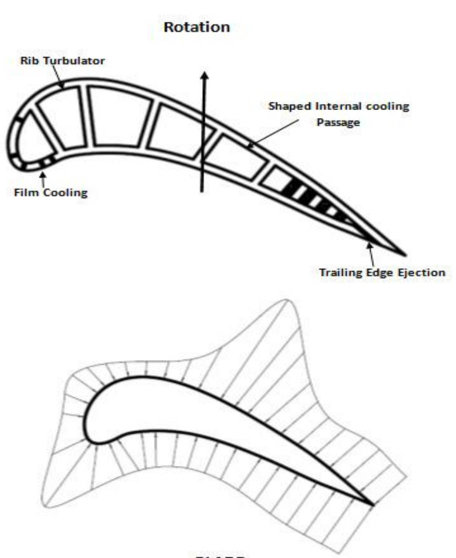
1.INTRODUCTION

Gas turbines play a vital role in today's industrial environment. As the demand for power and energy increases, improvement in power output and thermal efficiency of gas turbine is essential, this can be achieved by efficient cooling methods. The cooling of gas turbine components using internal convective flow of a single phase gas has been used for last 50 years; from simple smooth cooling passage to very complex geometries involving many different surfaces, architectures and fluid-surface interaction. The main goal is to obtain high overall cooling effectiveness with lowest possible penalty on thermodynamic performance cycle. An advanced gas turbine engine operates at a high temperature of 1500^0 C to improve thermal efficiency and power output[9]. This high temperature at rotor blade can exceed the melting temperature of the metal. It is mandatory for the blades and vanes to be cooled so that they withstand these high temperatures. 20% to 30% of the compressed air at 650^0C is extracted from the compressor and passed through the high pressure turbine. With cool compressed air, the blade temperature can be lowered to approximately 1000^0C, which is needed for safe operation of the engine[15]. For these high temperature turbine blades, cooling methods require key and innovative technologies. The metal temperature of the turbine cooled vanes and blades should be predicted in design stages as accurately as possible, to reduce the period of product development cycle and to accurately predict the life of blades and vanes; as these are dependent on the metal temperature. The life of turbine blades is dependent upon accurate mapping of blade surface temperature, local heat transfer coefficients and prevention of local hot spots. Figure 1 shows the cross sectional view of the turbine vane and blade. Complex flow around the vanes and blades makes prediction of metal temperature difficult. The trend of heat flux is similar in both vane and blade, on suction side the flow transition from laminar to turbulent increases the heat transfer coefficient flux. Similar change occurs on the pressure side.

Due to high velocity and complex flow around the gas turbine, it is important to obtain data that will help in designing efficient cooling technologies. Detailed hot gas path heat transfer distribution and film cooling data are needed for airfoil.



(a)



(b)

Figure 1: Cross sectional view and heat flux distribution of (a) vane and (b) blade

A stator vane surface heat transfer is affected by combustor developed high turbulence, laminar to turbulent transition, acceleration, film cooling flow, platform secondary flow and surface roughness. These factors as well as the rotational, centrifugal forces and blade tip clearance and leakage must be considered in the rotating blades. After the hot spots on the turbine and vanes are known, the vane and blade cooling performance can be improved by new and innovative heat transfer data.

It is also essential to understand the flow physics and to improve the current internal cooling design. Many techniques have been developed to enhance the heat transfer in these passages. Near the leading edge of the blade, jet impingement (coupled with film cooling) is one such technique. The cooling passage located in the middle of the airfoil is often used with rib turbulator while pin fins and dimples can be used in the trailing edge portion of the vanes and blades. A number of traditional cooling concepts are used in various combinations to adequately cool the turbine vanes and blades.

2. INTRODUCTION ABOUT RIB TURBULATED COOLING

To enhance the heat transfer in advanced gas turbine blades, repeated rib turbulence promoters are cast on the two opposite walls (pressure and suction sides) of internal cooling passages. To match the external loads, which can be different at pressure and suction sides, the ribs sometimes can be provided only on one side. Due to presence of ribs, the flow separates at top of the rib and reattaches to the flow between the ribs. Figure 2 shows the flow separation and reattachment due to presence of ribs. The boundary layer is disturbed as well as the turbulence of the flow increases due to separation and reattachment[15]. This mixes the fluid elements near the wall with the cooler ones in the middle of flow. The two phenomena results in enhancement of heat transfer. Thermal energy is transferred from the external pressure and suction surfaces of the turbine blades to the inner zones through conduction and that heat is removed by internal cooling.

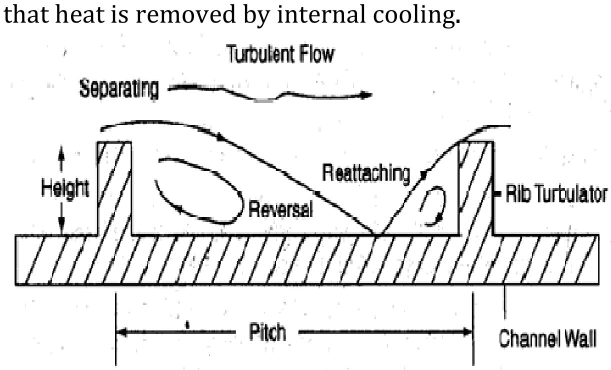


Figure 2: Flow separation and reattachment around ribs

The internal cooling passages are mostly modelled as short rectangular or square channels with different aspect ratios. Many researches had shown that there are certain geometrical parameters that affect the heat transfer coefficient. Such parameters include the passage aspect ratio, blockage ratio, rib angle of attack, reciprocal ribs positioning and rib pitch to height ratio.

Periodic ribs are frequently employed in various ducts to enhance the heat transfer process for many applications including gas turbine cooling systems and compact heat exchangers. These arrangements of ribs have important influence on the thermal and hydraulic performances of these cooling ducts. Due to favourable longitudinal secondary flow, angled ribs are more favourable than perpendicular ribs when both heat transfer and pressure drop are concerned.

3. OBJECTIVE OF STUDY

In this study a channel has been considered of rectangular section 200x40 mm^2 with length of rectangular channel is 550 mm. The bottom portion of channel is provided with aluminium plate having one side of the plate is roughened by three different ribs shape in such a way that the cross-section area of every shape is same at 45 degree ribs attack angle. There are total three models created with different ribs cross section cases by using CATIA V5 modelling Software. And the bottom surface of plate is kept under constant heat flux of 1000W/m^2. The air has been passed through duct at different Reynolds number range from 8000 to 18000, and then following parameter has been studied in this study.

1. To find out the Friction factor and Nusselt Number for rectangular channel of all the ribs cross section cases
2. To find out the Nusselt Number ratio [Nusselt number with rib (Nur)/ Nusselt number without rib (Nuo)] and Friction factor ratio[Friction factor with rib (fr)/ Friction factor without rib (fo)] for rectangular channel of all the ribs cross section cases
3. To find out the thermo hydraulic performance factor for rectangular channel of all the ribs cross section cases
4. Finally concluded the results and discussed the best combination of model.

4. METHODOLOGY

The model of all the cases has been modelled in 3d modelling software CATIA V5-R20 version and then the model of all the cases has been saved in the format of .stp. These .stp files are than import in the ANSYS CFX module for analysis.ANSYS CFX used the computational fluid dynamics (CFD) approach to analyse system involving fluid flow, heat transfer and phenomena such as chemical reaction a set of mathematical equations is used to construct a numerical model first which describe the flow in order to obtain the flow variables through the flow domain .These equations are then solved using a computer programme.

➢ **Physical models.**

Considered the problem of air flowing through a rectangular duct with length (L) and Hydraulic diameter (Dh) of 550 mm and 66 mm respectively. The bottom of the rectangular duct is provided with a plate having number of ribs. The cross section of rib is square with rib attack angle is 45°. With zig-zag gapping has been provided in the rib.

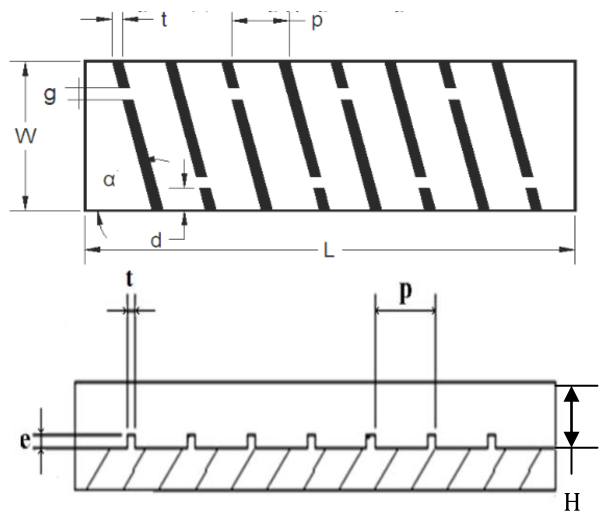


Figure 3: Physical geometry of rectangular duct.

The above figure 3 shows the physical geometry of rectangular duct.

Where

L: Length of the duct.
W: width of the rectangular duct.
H: Height of the duct.
e: height of rib
t: thickness of rib
P: pitch (distance between to two adjacent ribs)
α: Rib attack angle.
g: gap in rib profile

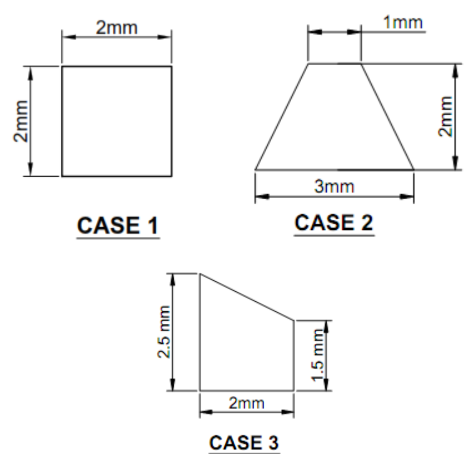


Figure 4: The 3 cross section of rib taken

There are total three model of rectangular channel with three different cross section of ribs has been modelled with rib attack angle of 45° .figure 4 above shows the three cross-section cases.

- **Material properties**

This section of the input contains the options for the materials to be chosen. Here two domains have been created one is fluid and other is solid domain, fluid domain is considered of air and solid domain is considered of aluminium. Air is passing in the rectangular duct under constant wall Heat Flux of 1000 W/m² in the outer face of aluminium plate. The properties of air and aluminium is taken as follows.

Table.1 Properties of air and aluminium plate

Sr. No.	PROPERTIES	AIR	ALUMINIUM PLATE
1	viscosity (μ) kg/ms	$1.7894*10^{-5}$	
2	Specific heat capacity (Cp) j/kg k	1006.43	871
3	Density (ρ) kg/m³	1.225	2719
4	Thermal conductivity (k) W/mk	0.0242	202

- **Boundary condition**

Boundary conditions are a set of properties or conditions on surfaces of domains, and are required to fully define the flow simulation.

The outer wall of the bottom plate was assumed to be perfectly smooth with zero roughness height. A constant wall heat flux of 1000 W/m² was used at the wall boundary.

Velocity at inlet section of air is taken in the range of 1.771 to 3.98 m/s. One face of the air domain along the length of domain, an interface between air and aluminium plate with surface roughened by ribs is considered and other three faces of air domain (along length of domain) is considered as adiabatic.

Table. 2 Boundary condition

1	Inlet condition	Velocity inlet (varies from 1.771 m/s to 3.98 m/s) Reynolds number (8000 to 18000)
2	outlet condition for inlet fluid	pressure outlet
3	Inlet temperature (Tin)	300K
4	Initial gauge pressure	Zero Pascal
5	Constant wall heat flux (qw) W/m²	1000

5. THE PARAMETERS TO BE DISCUSSED IN THIS STUDY

- **Nusselt Number (Nu):** The Nusselt Number is a measure of the convective heat transfer occurring at the surface and is defined as

$$\mathbf{Nu = h\, D_h/k} \qquad \text{EQ (1)}$$

Where h is the convective heat transfer coefficient (W/m²xK), D_h is the diameter of the tube and k is the thermal conductivity of fluid.

- **Friction Factor (f):** Friction factor is the frictional energy loss in a pipe or duct based on the velocity of the fluid and the resistance due to friction.

$$f = \frac{2}{(L/D)}\frac{\Delta P}{\rho U^2} \qquad \text{EQ (2)}$$

Where D is Hydraulic Diameter
U is mean air velocity at inlet

- **Thermo hydraulic Performance factor (η):** This is defined by equation as follows and is Similar to enhancement of heat transfer at constant pumping power

$$\boldsymbol{\eta = (Nu_r/Nu_o)/\{f_r/f_o\text{\^{}}(1/3)\}} \qquad \text{EQ (3)}$$

Where Nur, fr, Nuo and fo are the Nusselt Numbers and friction factors for a duct configuration with and without ribs respectively.

- **Reynolds Number (Re):** The Reynolds number is a dimensionless number that can be defined as the ratio of the inertia force (ρ u L) and the viscous or friction force (μ) and can be expressed as

$$\mathbf{Re = \rho\, V\, D_h / \mu} \qquad \text{EQ (4)}$$

Where ρ is the density (kg/m3), μ is dynamic viscosity (Ns/m2), ν is the kinematic viscosity, V is the mean velocity of the fluid, and Dh is the hydraulic Diameter of the geometry. As the values of Reynolds number increases, the more turbulent flow will occur.

6. RESULTS AND DISCUSSION

In this section the comparisons have been made for three different rectangular channel each having different rib cross section shape the ribs attack angle against the flow is 45 degree as discussed earlier. Reynolds number is the fixed parameter in every graph and variations of other parameter such as Nusselt Number, Friction Factor, Nusselt Ratio, Friction Ratio and Thermo Hydro Performance Factor, is discussed. Reynolds number ranges from 8000-18000.

6.1 Reynolds number (Re) Vs Nusselt Number (Nur):

Nusselt Number is the measure of the convective heat transfer therefore, it is important to consider this parameter to evaluate the rate of heat transfer.

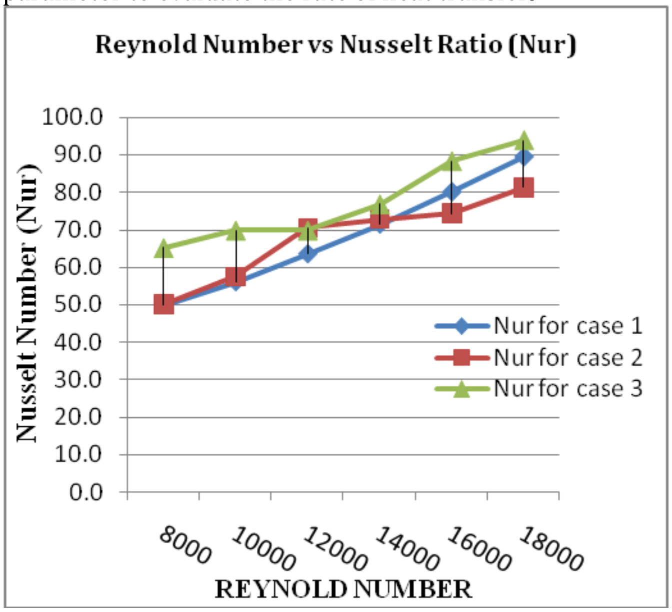


Figure 5: Reynolds number Vs Nusselt Number

Figure 5 show the variation of heat transfer in terms of Nusselt Number with Reynolds number for the channels of different rib cross section case. It is seen that Nusselt Number increase with the increase of Reynolds number. Reynolds number was calculated based on hydraulic diameter (D_h) of the rectangular channel. from the figure 5 it is seen the Nusselt Number for case3 is considerable high as compared to case 1 and case 2. It is also seen that for case 2 Nusselt Number is higher than case 1 for Reynolds numbers range from 8000 to 14000, and for 16000 to 18000 Reynolds numbers ,Nusselt Number of case 1 is higher than case 2.

6.2 Reynolds number (Re) Vs Friction factor (fr):

Friction factor is a measure of the pressure losses in a system to the kinetic energy of the fluid. Generally, the friction factor decreases conventionally with the increasing Reynolds number. It has been noticed through many researches that the friction factor for the ribbed channel is higher than the friction factor obtained from the smooth rectangular channel. This is a result of additional blockage and hindrance to the flowing stream generated by ribs.

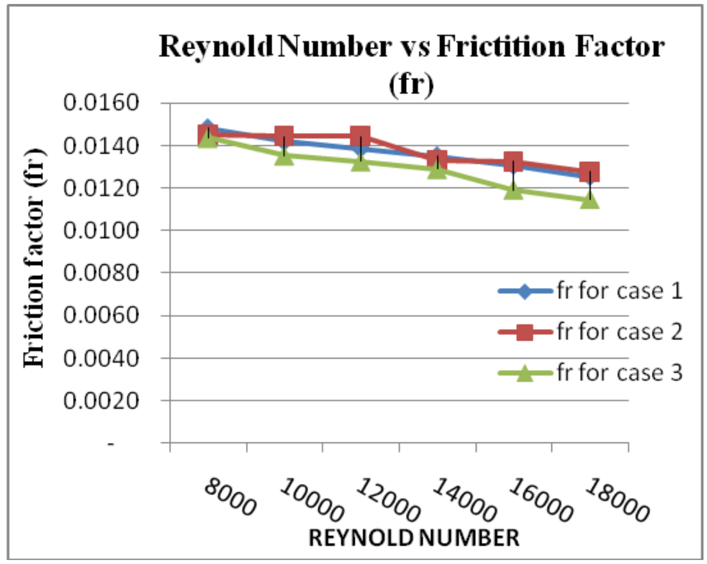


Figure 6: Reynolds number Vs Friction factor

From figure 6 later it is clearly seen that the friction factor decreases as the Reynolds number increases. and if compare the results of friction factor for different rib cross section cases it is also found that the friction factor is lowest for case 3 as compare to case 1 and 2. If comparison is being made between case 1 and 2 at many values of Reynolds number the friction factor for both cases is almost same, only between Reynolds number 10000 to 12000 the Friction factor for case 2 is higher than case 1.

6.3 Ratio of Nusselt Number with ribbed channel to Nusselt Number with smooth channel (Nur/Nuo) vs Reynolds number:

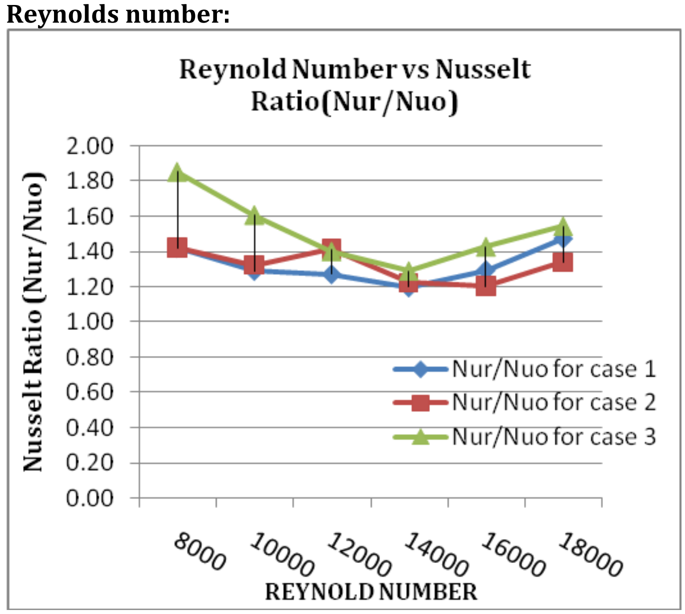


Figure 7: Reynolds number Vs Nusselt number Ratio

The ratio Nur/Nuo obtained in the figure.7 is more desirable as far as the thermo hydraulic performance factor is concerned.

Figure7 shows the variation of Nusselt number Ratio for different rib cross-section cases, here it has been noticed that the Nusselt Ratio for case 3 is highest as compare to case 1 and 2. And if comparison is being made between case 1 and case 2 Nusselt Ratio for case 2 is higher than case 1 for Reynolds number ranges from 8000-14000.

6.4 Friction Ratio (ribbed channel to smooth channel (fr/fo).

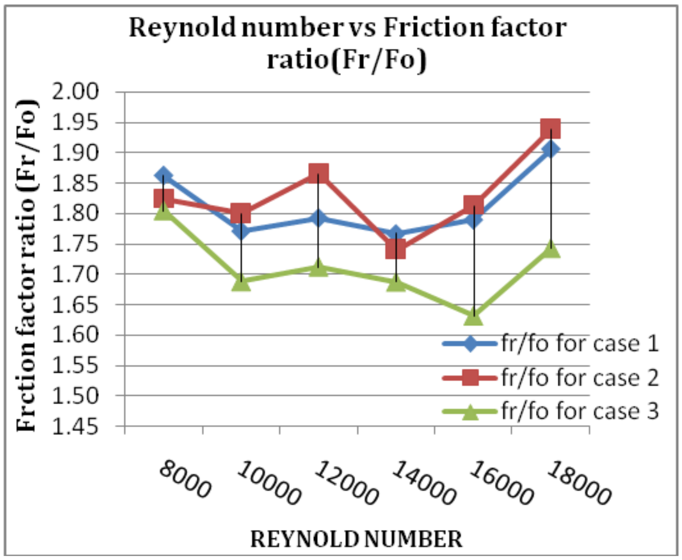


Figure 8: Reynolds number Vs Friction Ratio

The friction ratio fr/fo obtained is also important as this ratio is also desirable as for as the thermal performance factor is concerned. From figure 8 it is clearly seen that friction ratio for case 3 is lower than other two cases.

As far the variation between case 1 and case 2 is concerned the value of friction ratio for case 2 is higher in most of the values of Reynolds Number.

6.5 Thermo hydraulic Performance Factor (η) for different rib cross section cases.

As discussed before Thermo hydraulic Performance factor is depend upon the Nusselt ratio and friction ratio.

From figure 9 before it is seen that the Thermo hydraulic Performance factor for case 3 is highest as compare to case 1 and 2. And comparison between case 1 and 2 shows that the Thermo hydraulic Performance factor of case 2 is slightly higher than the case 1 from Reynolds number ranges 8000-14000, and from Reynolds number 16000-18000 the Thermo hydraulic Performance factor for case 1 is higher than case 2.

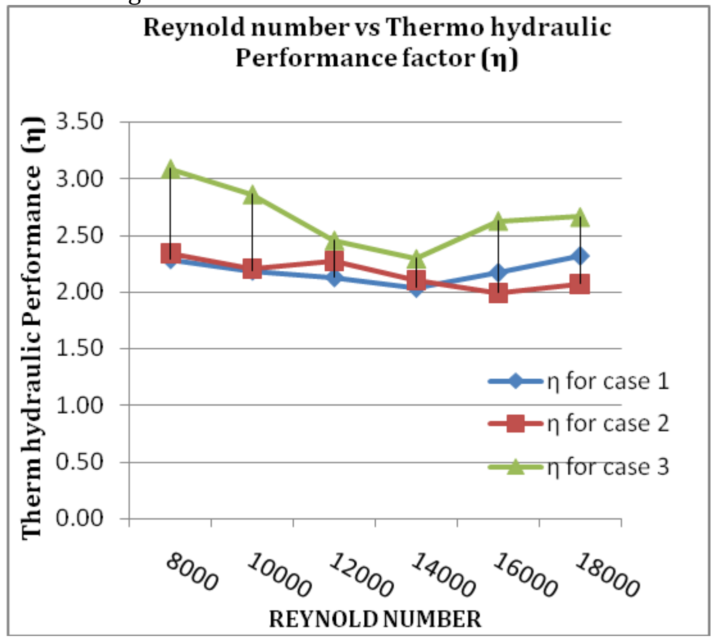


Figure 9: Reynolds number Vs thermo hydraulic performance factor

7. CONCLUSIONS

As figures of different parameters has been discussed in the last section, here in this section final conclusion of overall study is mentioned. Following are the conclusion of whole study.

- The Nusselt number increases as the Reynolds Number of the flow increases in every case. Case 3 shows the best increment compare to case 1 and 2
- The Friction factor decreases as the Reynolds number increases, for this parameter also the case 3 show better results than case 1 and case 2, because friction factor of case 3 is lowest in all range of Reynolds Number and this results in increase of thermo hydraulic performance factor.
- As discussed above as the friction factor decreases the friction ratio also decreases here also case 3 shows better results.
- The Thermo hydraulic Performance factor of case 3 show the best results in all the range of Reynolds Number.
- Overall In comparisons to all the rib cross section cases, case 3 shows the best shows results in all parameters considered in this study.

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