

Numerical Investigation on Heat Transfer Characteristics of a Mist Cooled Ribbed Channel with Different Rib Angle

Sadhan Mondal*, Khandkar Aftab Hossain

Department of Mechanical Engineering, Khulna University of Engineering & Technology, Khulna-9203, Bangladesh

ABSTRACT

The present work focuses on numerical analysis of a mist cooled rib channel with baffle in an internal cooling of a turbine blade. In this paper, flow and heat transfer characteristics are presented for rib channel with baffle at different angle of ribs that is used as internal cooling passage of turbine blades. ANSYS Workbench software is employed to measure surface heat transfer characteristics and friction factor over the ribbed surfaces in the designed ribbed channel with baffle. Using different boundary conditions, a mist cooled rib channel with baffle is validated for better Heat Transfer Characteristics, Friction factor and pressure profiles. The fundamental goal is to describe the heat transfer performance at different values of Reynolds Number, Prandtl Number with variation of rib angle. Besides this to calculate the friction factors at different values of Reynolds Number, Prandtl Number and rib angle. Increase of Reynolds Number increases the Nusselt Number. Increase of Rib angle increases Nusselt Number. But this is not satisfactory at angle 60°. At angle 60° Nusselt Number is comparatively lower. Because at rib angle 60° the formation of vortex is distributed near all row of rib. Compared with continuous baffle, the low heat transfer behind the rib is enhanced by the designed mist cooled ribbed channel with a slightly reduction of pressure drops. Variation of heat transfer as well as friction factors are respectively 5.6% and 5.4 % compared with continuous baffle. As Rib with baffle can enhance the overall heat transfer performance and create more uniform heat transfer fields, it is used in internal cooling of gas turbine blades.

Keywords: Numerical Simulation, Ribbed Channel, Turbine Blade, Conjugate Heat Transfer, Heat Transfer Enhancement.



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1. Introduction

The power demand is increasing day by day, as a result to mitigate power demand extra power production is increasing rapidly. Power can be generated in different modes. These are water based, land based, air based. Power is produced by using several types of fuel as gas, furnace, oil, diesel, coal etc. Besides this power can be produced by steam turbine and gas turbine. Among them gas turbine is most prominent to produce a large-scale power production. Most of the turbine blade cannot tolerate high temperatures ranges of 1500-2000°C. Because alloys that is used to make turbine blade can withstand temperature near about 1100°C. If turbine blade temperature is more than 1100°C then it will melt. Hence to sustain turbine blade and for higher life time turbine blade cooling is urgent now a days [1].

The efficiency of modern gas turbine is increasing rapidly for its inflow fluid temperature. So, reduction of inflow fluid temperature is a crucial issue for scientist and Engineer's now a days. The metallurgical failure depends on turbine inlet temperature. It can be reduced by turbine blade cooling. The geometrical change is another technique of turbine blade cooling [2]. For this no extra devices are required. As a result, the gas turbine which are used in aircraft as an engine comparatively less weight, taken less floor area and no extra moving parts. So, friction is reduced by using blade cooling technique in turbine. That is why reduction of extra fuel and lube-oil to operate engine. There are different types of rib configuration are invented by different researcher which is used to enhance heat transfer in rib channel. Basically, it will increase turbine blade life time and overall work output. Turbulence generator is technique that is used to turbulation

of inflow fluid by blockage over stream wise flow direction [3]. The inflow fluid through passage for Gas Turbine blades flows with high heat. So, to reduce the turbine rotor and stator blades temperatures, different methods have been used. These are improvement of the alloy composition of the gas turbine airfoils, spraying thermal barrier coatings, growing of single crystal blades, and improvement of the airfoil cooling techniques [4]. Present study focuses about improving the cooling technique. The squared-rib increases heat transfer performance which is used as a turbulence generator. In this technique ribs are placed in the cooling channel of turbine blade that creates a serpentine passage inside the cooling channel of turbine. By this method a low heat transfer zone creates near rear rib region due to formation of vortex. In this research a new rib arrangement called baffle with rib will be imposed to eliminate disadvantages of the square rib. The arrangement of the baffle with rib creates a surplus tiny coolant passage zone. Igor. et al. [5] in their research described that the friction factor increases with increases of aspect ratio of the channel. They concluded that pressure drop reduces with reduction of aspect ratio of the channel. Krishnaswamy K et al. [6] described highest heat transfer characteristics of v and w shape ribs of a gas turbine blade. X. Lei et al. [7] investigated a ribbed channel which is steam cooled to determine the best heat transfer performance. They used neural networks and genetic algorithms for their numerical research. The aims of their work for the optimization of the ribbed channel to gain a suitable heat transfer performance. Z. Lihao et al. [8] analyzed cat-ear-shaped film-cooling holes on turbine blades numerically. They proved that the inclination angle α

*Corresponding Author Email Address: msadhan687@gmail.com

considerably impact the heat transfer phenomena of the film hole. Aditi Neekhara et al. [9] studied a ribbed channel with inclined rib arrangement in a certain gap between two ribs. They found that, Nusselt number increases and friction factor decreases with an increase of Reynolds number. K.K.s Siva et al. [10] investigated heat transfer performance of convergent/divergent square duct in turbulent flow region. They showed the vortex field creates near baffle, which enhances the turbulence mixing of the flow field and enhancement of heat transfer.

2. Methodology

2.1 Physical Model

The complete geometry of the moisturized air-cooled ribbed channel in this study is described in Fig.1. The mist cooled ribbed channel is taken from a cooling channel of a gas turbine blade, The dimension of mist cooled ribbed channel are length 1,000 mm, height of channel is 40 mm, width of the channel is 80 mm and thickness of wall is 3mm, and material is selected here stainless steel. The diameter is taken compared with smooth tube 52.33 mm. The ribs are placed inside the upper and lower wall of the geometry. The value of Re , α , h and P are used to increase or decrease the heat transfer characteristics of the mist cooled ribbed channel. In detail $30^\circ \leq \alpha \leq 90^\circ$, $0.05 \leq h/D \leq 0.15$, $0.5 \leq P/D \leq 1.5$, $Re = 10 \times 10^3 - 10 \times 10^4$ and $Pr = 0.7$ to 1.0. Two domains are created by ANSYS fluent. One is called solid domain and another is called fluid domain. Then solid domain is suppressed from geometry due to contact zone creating between two layers of the geometry.

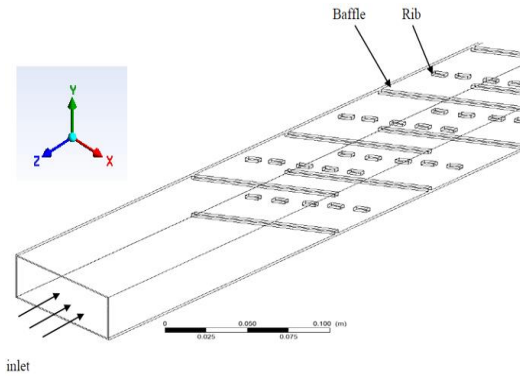


Fig.1 Mist Cooled Ribbed Channel

2.2 Conjugate Heat Transfer Approach

The conjugate heat transfer method is taken for the simulation of ANSYS fluent. For the purpose of fluid domain computation, the moisturized air flow is assumed as turbulent flow. Finite volume method is used here. Three set of equation mass, momentum and energy conservation equation are adopted for computation of numerical calculation. The Reynolds Averaged Navier–Stoke's equations are used as governing equation. The Energy equation is considered for the computation of heat transfer characteristics. The bounded central difference scheme is selected to discretize the governing equations. The SST $k - \omega$ turbulence model is used in this numerical simulation, where $k - \varepsilon$ model is used in the mainstream region and $k - \omega$ model is used in the near-wall region which will moderate flow separation near ribbed wall.

The Nusselt Number can be illustrated from the equation below [11]

$$Nu = \frac{qD}{(T_w - T_f)\lambda} \quad (1)$$

Where, q is called wall heat flux; T_w is called the local temperature of the channel inner surface; T_f is called the reference temperature; λ is called as the local thermal conductivity of moisturized air.

The Reynold equation can be derived for Mist is taken as

$$Re = \frac{u_{in}D}{\nu} \quad (2)$$

Where u_{in} and ν are the inlet velocity and kinematic viscosity of moisturized air respectively.

A temperature-dependent function is derived using equation, considering the influence of temperature on the thermal conductivity of the stainless steel which is given below

$$\lambda_s = 0.009471T + 14.0614 \quad (3)$$

The friction factor f can be expressed as follows

$$f = \frac{\Delta p D}{2\rho L u_{in}^2} \quad (4)$$

Where Δp is called the pressure drop of the mist cooled channel, ρ is called the density of moisturized air.

The Nu_0 and f_0 of the smooth tube are written as follows

$$Nu_0 = 0.023 Re^{0.8} Pr^{0.4} \quad (5)$$

$$f_0 = \frac{1}{(1.58 \ln Re - 3.28)^2} \quad (6)$$

$$F = \frac{\left(\frac{Nu}{Nu_0}\right)}{\left(\frac{f}{f_0}\right)^{1/3}} \quad (7)$$

F is called the thermal performance factor.

Table 1 Geometrical parameters & Boundary Conditions

Geometrical parameters	
Hydraulic Diameter (D)	53.33 mm
Channel Height (H)	40 mm
Channel Width (W)	80 mm
Rib Height (h)	2-3.5 mm
Rib width	2 mm
Boundary Conditions	
Total Temperature	430 K
Total Pressure	0.5 MPa
Heat Flux	5 kW/m ²
Turbulence Intensity	5%
Reynolds Number	10000-100000

2.3 Grid independency test and validation

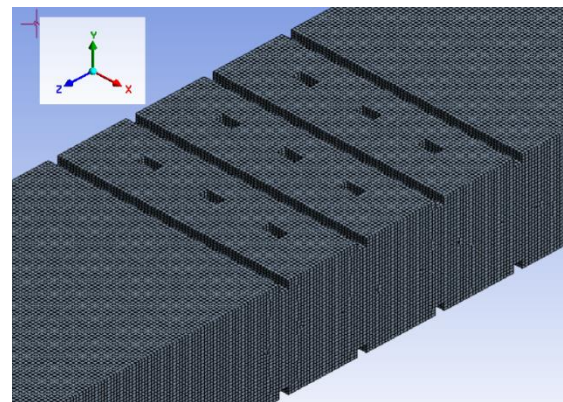


Fig.2 Mesh structure of Fluid Domain of Ribbed Channel

Fig.2 shows mesh structure of fluid domain of ribbed channel. It is clearly shown that the mesh structure is fine

both upper and lower wall and also left and right side of the geometry.

Table 2: Computational grid densities and Corresponding variation in Nusselt Number

Sl No	Number of cells	Nu
Mesh 1	178220	63.256
Mesh 2	187827	58.26
Mesh 3	198336	54.50
Mesh 4	211746	53.254
Mesh 5	210985	53.032
Mesh 6	223896	53.030

3. Result and Discussion

3.1 Discussion of various contours

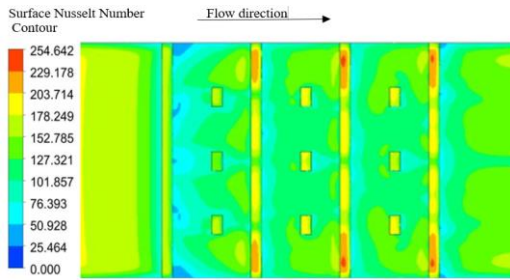


Fig.3 Surface Nusselt number contour on upper wall with angle 90°

Fig.3 describes surface Nusselt number contour on upper wall of geometry with angle 90°. Augmentation of heat transfer in the mid-point of the geometry. This is because of small ribs are arranged in the mid-point of the geometry. On the other hand, heat transfer at outlet of the channel both upper and lower cases are higher than inlet.

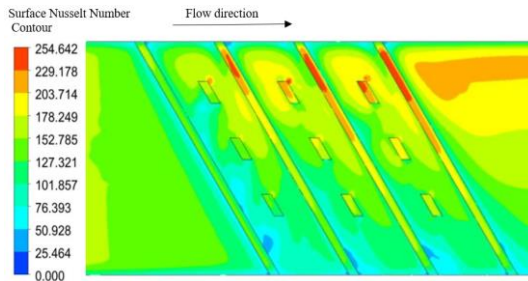


Fig.4 Surface Nusselt number contour on upper wall with angle 60°

Fig.4 describes the contours of Nusselt number on upper wall of geometry of mist cooled rib channel with angle 60°. The heat transfer augmentation at outlet than inlet both upper and lower wall. Heat transfer is higher at the right side of the geometry than left side because a secondary flow generates along the length of the rib which have a lower velocity.

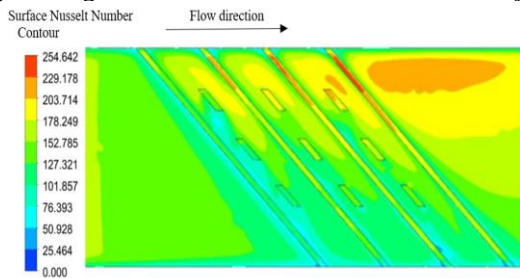


Fig.5 Surface Nusselt number contour on upper wall with angle 45°

Fig.5 illustrates the contours of Nusselt number for rib with baffle on upper wall with angle 45°. The heat transfer augmentation at outlet than inlet both upper and lower wall. Heat transfer is higher at the right side of the geometry than left side because a secondary flow generates along the length of the rib which have a lower velocity.

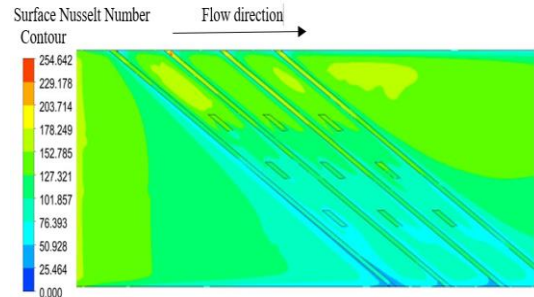


Fig.6 Surface Nusselt number contour on upper wall with angle 30°

Fig.6 shows the contours of Nusselt number on upper wall of mist cooled rib channel with angle 30°. On the contrary, heat transfer difference between inlet and outlet decreases with increasing rib angle. Heat transfer increases right side of geometry than left side both upper and lower wall. Because at right side of the wall velocity is lower.

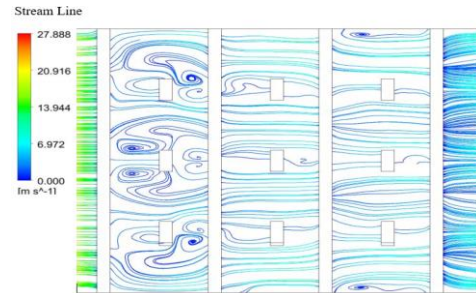


Fig.7 Stream line along x-z plane with angle 90°

Fig.7 describes Stream line along x-z plane with angle 90°. The effect of stream line can be observed x-z plane of ribbed channel. It is apparent that vortex creates near first row of rib and vortex formation reduces gradually near second and third row of rib. So cooling rate is higher near first row of rib than second row of rib.

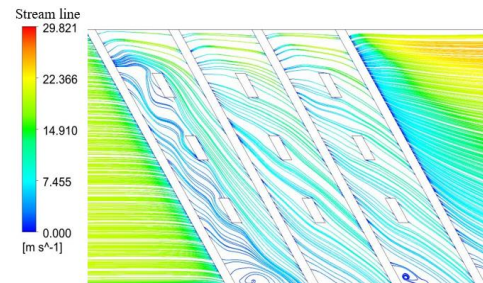


Fig.8 Stream line along x-z plane with angle 60°

Fig.8 describes Stream line along x-z plane with angle 60°. The effect of stream line can be observed x-z plane of ribbed channel. There is small vortex formation near first row of rib. Formation of vortex near rib is lower with decreasing angle of rib. The flow direction is along the length of the rib.

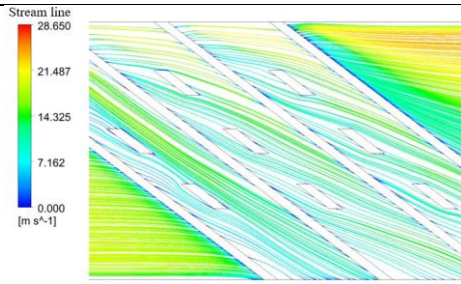


Fig.9 Stream line along x-z plane with angle 45°

Fig.9 describes the Stream line along x-z plane with angle 45°. The effect of stream line can be observed x-z plane of ribbed channel. Formation of vortex near rib with angle 45° is lower than angle 60°. The flow direction is along the length of the rib.

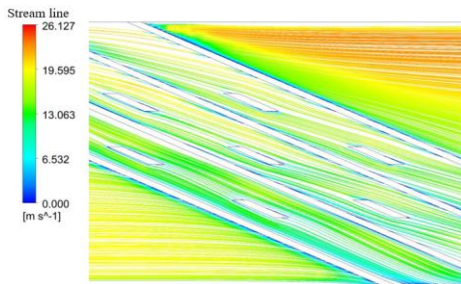


Fig.10 Stream line along x-z plane with angle 30°

The streamlines at x-z plane with angle 30° are discussed in Fig.10. The effect of stream line can be observed x-z plane of ribbed channel. In Fig.7 describes vortex formed near small rib with x-z plane. But with decreasing rib angle in Fig.10 rotation of fluid about x-z plane is decreasing. The flow direction is along the length of the rib.

3.2 Graphic Representation of obtained result

In this section different graphs are plotted by obtaining result numerically by ANSYS FLUENT of this mist cooled ribbed channel which are shown below.

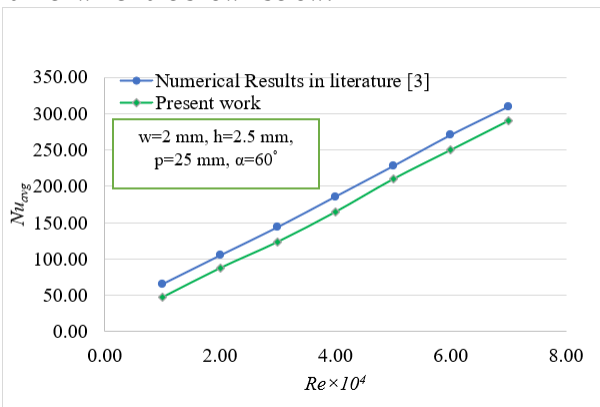


Fig.11 Comparison of present work with published result.

Fig.11 shows comparison of present work with published results of average Nusselt number distribution of entire wall with different Reynolds number. Heat transfer gradually increases with increasing Reynolds number. In present work due to rib with baffle augmentation of heat transfer performance. This is because of velocity drop and pressure rise in the midpoint of the geometry. Pressure reduces at the outlet of the geometry.

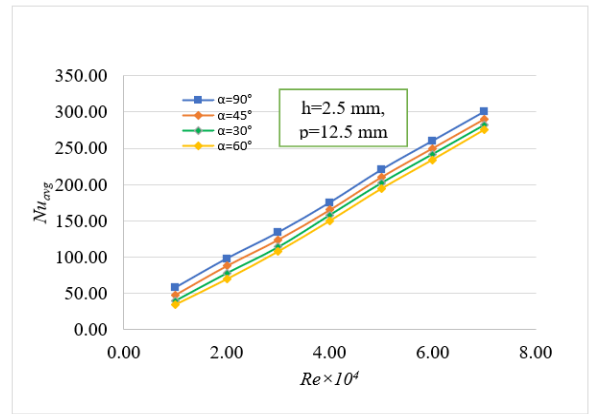


Fig.12 Average Nu verses Re with angle

Fig.12 shows average Nusselt number verses Reynolds number with different Rib angle. Heat transfer phenomena is dependent on rib angle. For lower rib angle heat transfer increases but at higher rib angle heat transfer decreases. Because decreasing rib angle surface area increase in channel. On the other hand, for higher rib angle surface area decreases. In Fig.12 heat transfer increase gradually with increasing Reynolds number. This is because of increasing Reynolds number velocity increases and decreases fluid retention time in the channel. So it is clear that heat transfer is decreasing. On the other hand for low Reynolds number velocity is lower. Fluid retention time in the channel increases. So heat transfer is increases here and cooling rate increases. But 60° is a satisfactory angle where Nusselt Number is lower. Because at rib angle 60° the flow blockage is distributed equally near first, second and third row of rib. On the contrary at rib angle 90° the major flow blockage creates near first row of rib.

Another reason due to arise of flow blockage, velocity is lower. So, heat transfer performance is increases and cooling rate is increases. So, we can say improvement of co-efficient of heat transfer.

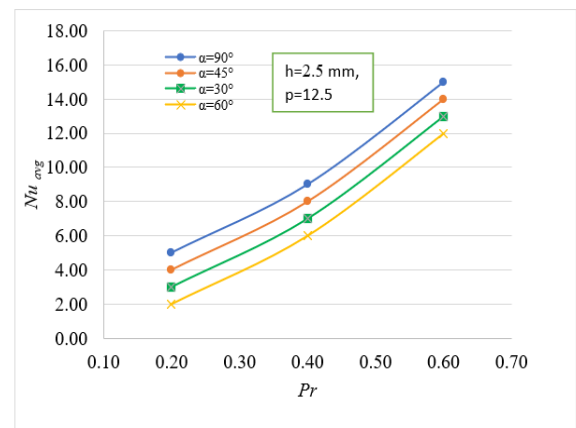


Fig.13 Average Nu Number verses Pr number with angle

Fig.13 describes variation of average Nusselt number for different Pr number with angle where average Nusselt number increases with increase of Prandtl number. From Fig.13 it is shown that heat transfer increases with increase of Prandtl Number. This is due to flow blockage for small rib arranged in the midpoint of the geometry. As a result, velocity reduces in the midpoint of the geometry. So cooling increases in the midpoint of the geometry.

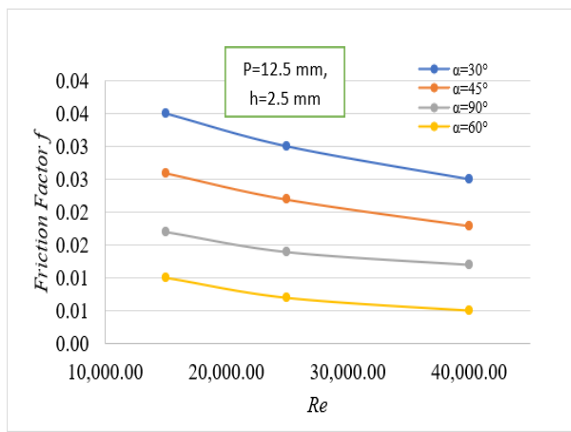


Fig.14 Friction factor f verses Re

Fig.14 demonstrates friction factor f verses Re with values of α where rib pitch and rib height are constant. It is apparent that friction factor is higher at low Reynolds number. On the contrary, friction is lower at higher Reynolds number. This is due to at lower Reynolds number, working coolant retention time is higher both upper and lower wall of the geometry for lower coolant velocity. On the contrary if Reynolds number is higher working coolant retention time is lower due to higher velocity of coolant.

On the other hand, friction factor increases gradually with decreasing rib angle. Because decreasing angle increases of co-efficient of friction. At angle 60° co-efficient of friction is lower due to lower contact surface of fluid with ribbed channel.

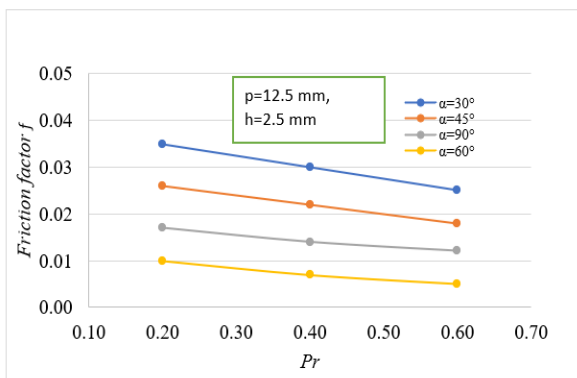


Fig.15 Friction factor f verses Pr with angle

Fig.15 describes Friction factor f with Pr for different values of rib angle α . With increasing Pr Friction factor f slightly decreases. On the other hand, friction factor f increases gradually with decreasing angle. Because decreasing angle augmentation of co-efficient of friction. At angle 60° co-efficient of friction is lower due to lower contact surface of fluid with ribbed channel.

4. Conclusion

The numerical simulation with ANSYS Fluent is employed in this investigation to evaluate the heat transfer characteristics of the mist cooled baffle with Rib channel. Heat transfer characteristics of the designed Mist cooled baffle with Rib channel are investigated numerically with different Re ranges from 10,000 to 90,000 by ANSYS workbench. The major findings are depicted below.

1. Changing of Reynolds number (Re), Rib angle (α) & Prandtl number (Pr) change the heat transfer

characteristics and friction factor in the mist cooled ribbed channel compared with literature [3] 5.6 % and 5.4 % respectively.

2. An augmentation of Reynolds Number augmentation in Nusselt Number. Increase of Rib angle Nusselt Number increases. But this is not satisfactory at rib angle 60° . At angle 60° Nusselt Number is comparatively lower.
3. Increase of Nusselt Number increases Prandtl Number.
4. Increase of Reynolds number & Prandtl number decreases of Friction factor. At angle 60° co-efficient friction is lower.

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NOMENCLATURE

Nu	Nusselt Number
Nu_0	Average Nusselt Number at Smooth Tube
Re	Reynolds Number
Pr	Prandtl Number
f	Friction Factor

f_0	Friction Factor at Smooth Tube
p	Rib Pitch in mm
q	Heat Flux in kw/m^2
P	Static Pressure in KPa
Δp	Pressure drop in Pa
L	Channel Length in mm
H	Height of the Channel in mm
w	Width of the Channel in mm
u_{in}	Velocity at inlet in mm
T	Temperature in K
T_f	Reference Temperature in K
T_w	Channel Inner Wall Local Temperature in K
F	Thermal Performance Factor
α	Angle of Rib in °
ν	Kinematic Viscosity in m^2
ρ	Steam Density kg/m^3
λ	Thermal Conductivity of Steam in $w/m/^\circ c$
λ_s	Thermal Conductivity of Stainless Steel in $w/m/^\circ c$
δ	Thickness of Wall in mm