CFD ANALYSIS OF FILM COOLING IN GAS TUSRBINE BLADE

BACHELOR OF TECHNOLOGY

IN

MECHANICAL ENGINEERING

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CERTIFICATE

This is to certify that the thesis entitled as "**CFD ANALYSIS OF FILM COOLING IN GAS TURBINE BLADE**" submitted by **SANDEEP KUMAR, Roll no. 111me0306** in partial fulfillment of the requirements for the award of Bachelor of technology Degree in **Mechanical Engineering** at the National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

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ACKNOWLEDGEMENT

The research project has improved my life and has given me a chance to work in Fluent. I am extremely privileged to be a part of such a stimulating research project “CFD analysis of film cooling in gas turbine blade”. This project helped me to develop my ability to ponder and comprehend even though I started my research project with a scratch.

I am obliged to deeply express my gratitude to my project guide Dr. Ashok Kumar Satapathy for his splendid guidance, suggestions and constructive criticism which helped me successfully complete my project. I also thank Mr. Vishnu, an M.Tech student in the Department Of Mechanical Engineering for his help.

Additionally, I extend my sincere gratefulness to all my faculty members and associates for their thoughts and backing at every point for the successful completion of the project.

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ABSTRACT

This project is about an exhaustive investigation of film cooling of gas turbine blade using ANSYS WORKBENCH version 15.0. Film cooling has its application in gas turbine blade. Film cooling and turbulated internal cooling is used by Gas turbines to guard the outer surfaces of blades from hot gases. The study focuses on film cooling effect for modern turbine blades. The adiabatic film effectiveness and heat transfer coefficient are found out experimentally over a flat plate downstream of line of incline. The study also involves investigation of various advanced hole geometries that would result in effective film cooling effect over turbine airfoil and flat surfaces.

The systems of the jets are understood by film cooling predictions. FLUENT computer code was used to run the simulation of turbulent flows in film cooling. This simulation used RSM (Reynolds' Stress Transport Model).

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CHAPTER – 1

INTRODUCTION

1.1 INTRODUCTION

Gas turbine finds its application in aircraft propulsion and in industrial applications. For the aircraft propulsion, high performance piston engines were developed in 1930s. Even in military aircrafts two new airfoils propulsion systems are developed and introduced and they are rocket and gas turbine engines. Over the years technologies have been developed to improve the aircraft propulsion for achieve reduced engine sizes, higher thrust to weight ratios and higher velocity of flight.

It can be seen from the **figure 1.1** there are three main components of a gas turbine namely-compressor, combustor and turbine:-

- Compressor which compress the incoming air to high pressure
- Combustor which helps in burning of the fuel and develops high temperature and pressure.
- Turbine by which high energy of the gas is extracted.

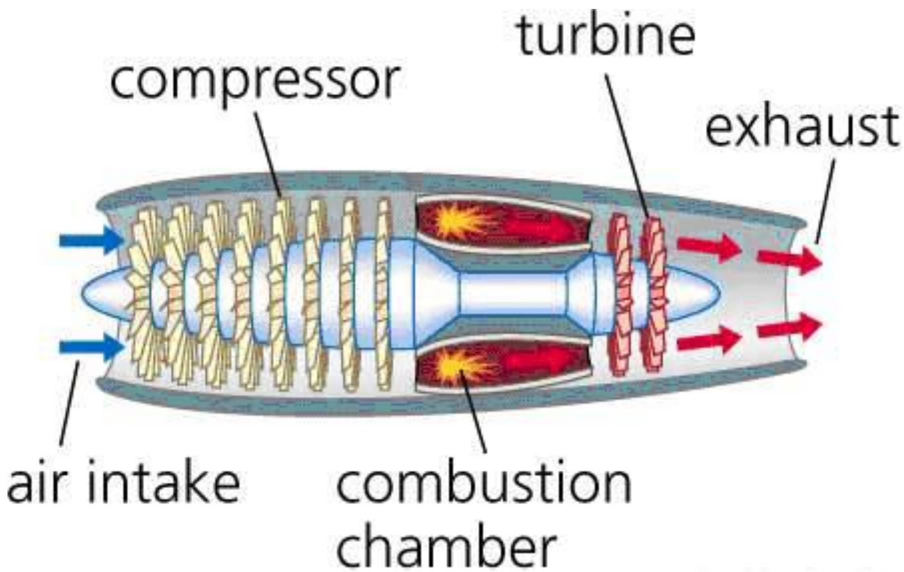


Fig 1.1 Engine of Gas turbine [1]

Many external and internal cooling techniques are utilized to decrease the temperature of blade below its melting point. As shown in the Fig 1.2, relatively cool air passed through hollow inside of the turbine blade and this air comes out through the compressor in internal cooling techniques. External cooling techniques is also called film cooling because the bypassed air exiting through small holes at various locations of blade protects the blade from the harsh environment.

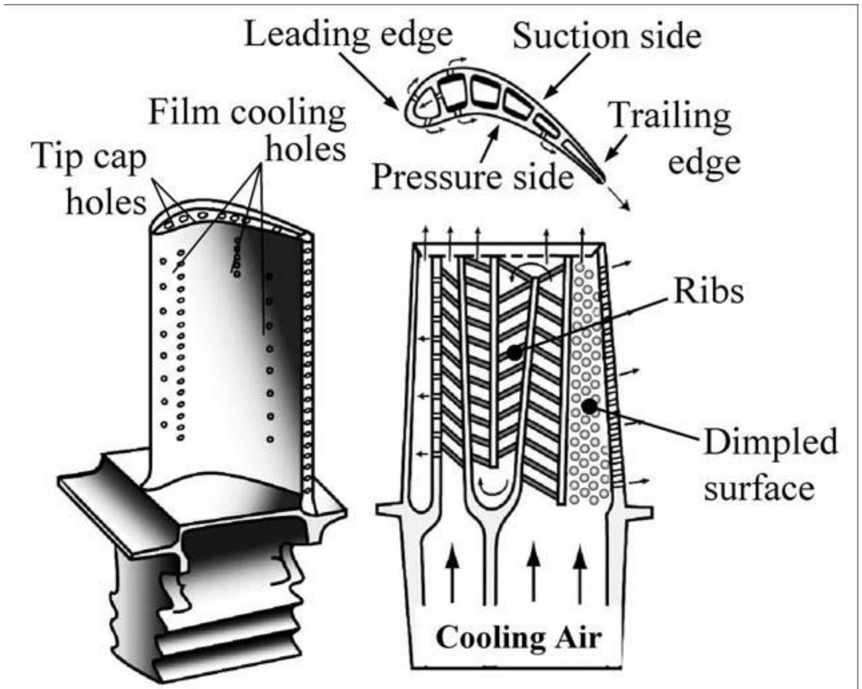


Fig 1.2 modern multi-pass turbine blade [2]

Discrete holes film cooling is able to cool turbine airfoils surfaces, blade tips, shrouds and end wall. The cooled is injected into the mainstream through various location through discrete holes. **Figure 1.3** is shown the typical cooled airfoils.

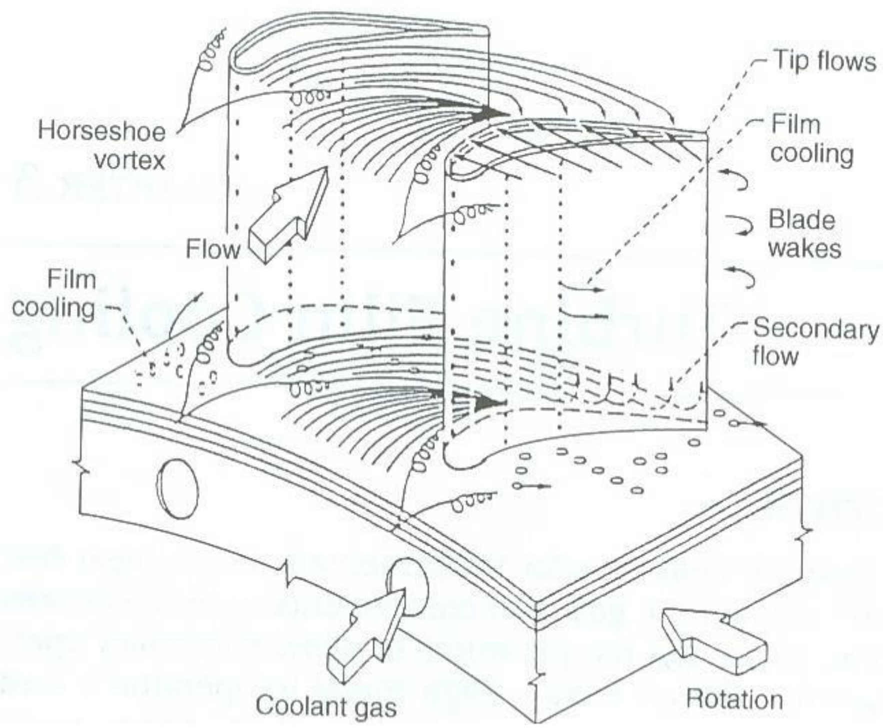


Fig 1.3. A typical cooled airfoil [3]

1.2 RESEARCH OBJECTIVES

The key motivation behind this project is to best develop the geometries of film cooling holes for better cooling effectiveness over turbine blades. The standards should be adjusted to directly contact the surface. Which is to be tested. There will be variations in geometry of the film cooling holes and this needs to be studies so that it supports designs changes in the future. To find out the jet mainstream interactions, numerical predictor with the help of FLUENT was done to comprehend the interactions between the second stream & ejected coolant.

1.3 LITERATURE REVIEW

A lot of research work has been done on flat surface film cooling before.

An effectiveness of single hole with inclination angle of 15 & 35 degree was in investigated & described by Goldstein et al. [4]. It was reported by them that the temperature field gets widened & the peak effectiveness decrease by lateral injection when the blowing ratio is 0.5.

The influence of high mainstream turbulence on heat transfer coefficient and leading edge film cooling effectiveness was studied by Mehendale and Han [5]. With 90 degree orientation it was shown that film effectiveness was inversely proportional to blowing ratio i.e. when the former decrease, the later increase. But for the heat transfer coefficient, the opposite was true.

The behavior of jet injected cover flat surface with 90 degree orientation of holes was described by Honami et al [6]. They used liquid crystals to measure the boundary layer temperature fields, mean velocity and effectiveness distribution. They obtained results which showed that an asymmetrical structure with big scale vortex wave on one side was formed by contact with mainstream when the angles of the holes was at 90 degree. Furthermore, it was their conclusion that would be low film cooling effectiveness as the unsymmetrical would be promoted by increase in mass flux ratio.

The film cooling holes injecting cryogenically cooled, higher density air was effectiveness of film cooling using of inclined holes in single row measured by Schmidt et al. [7]. They showed that there would be an increase in effectiveness values even higher than stream wise directed holes if the orientation angle. Also, the effectiveness improved significantly.

Film cooling effectiveness is effected by high stream turbulence and it was studied by Bons et al. [8]. Large heat transfer coefficient improvement due to large turbulent mixing between jet mainstream is produced by film injection.

Effectiveness results for only two density ratio was provided by Ekkad et al. [9]. Adopting transient liquid crystal technique with orientation angles of 0, 45 and 90 degree, it was reported by them that the film effectiveness is increased, the higher effectiveness was obtained.

1.4 Motivation of work

Film cooling in gas turbine cavities has been a topic for more experimental and numerical studies found in the paper. From practical and industrial point of view, the interest is defended by its many applications, which incorporate heating and cooling of structures, energy drying procedures, solar energy collectors, and so on the most majority of the published works covering film cooling in enclosures that exist today can be grouped into two groups: differentially heated enclosures and enclosures heated from below and cooled from above (Rayleigh Benard problems). Benchmark arrangements identified with differentially heat enclosures can be found in more numerical problems. However, CFD benchmark arrangements identified with the least difficult instance of 2D differentially heated enclosure area are less encountered in the literature.

CHAPTER- 2

PROBLEM FORMATION AND METHODOLOGY

2.1 PROBLEM FORMATION

The overall objective of this research is to investigate the potential for reducing computational cost of CFD calculations for studying different aspects of film cooling in the early stage of gas turbine film cooling design. This has to be established by validating the CFD results using experimental measurements. In order to accomplish this, steps have been followed.

In the first step a computational domain without any cooling holes which follows experimental apparatus has been facilitated for validation of the model, using aerodynamic results (this is called the full model). This model was rather large and had disadvantage of high computational cost, thus not appropriate for investigation of different film configurations. Therefore, the computational domain is reduced.

Finally, this work aims to show the applicability of the introduced strategy for industrial applications where from industry perspective there might be computer power limitations for performing CFD analysis. Thus they can investigate different aspects of film cooling at low computational cost and turn-around time and validate obtained results with their experimental results.

2.2 SPECIFIC AIRFOILS FILM COOLING CONFIGURATION

In open literature most of the studies and researches have investigated film effectiveness of the generic film cooling configurations using flat surface facilities. This is while in order to investigate film effectiveness on real turbine engines, it is essential to have special considerations for film cooling configurations which are utilized for turbine airfoils. This is due to the fact that for airfoil like geometries the flow conditions would be rather different than flat plates.

In turbine airfoils, cooling of the leading edge has been reported to be of a greater importance. This is firstly due to maximum heat load, which in general occurs at leading edge. In addition, flow around the stagnation point at the leading edge of the turbine airfoils has been proven to be complex and it is necessary to consider such complexity when studying film cooling performance.

In this context, film effectiveness can be investigated with respect to different aspects such as surface curvature, surface roughness, hole blockage etc. In general, arrays of closely spaced coolant holes are involved for film cooling of turbine airfoils leading edge, which can provide a dense coverage of coolant and consequently reduce the heat loads in this region.

Significant differences in film effectiveness performance between the turbine airfoil leading edge and flat plate facilities or over the main body of airfoil has been reported. This difference is reported to be due to the big difference between interaction of the mainstream and coolant holes in these cases.

Typically the suction side of turbine airfoils is consisting of strong convex curvature, which can conclude to increase in film effectiveness. On the other hand, the pressure side have region of mild to strong concave curvature. It is known that concave curvature can decrease the film effectiveness [10].

In conclusion, special considerations should be given to film cooling design of turbine engine airfoils particularly.

2.3. Numerical Modelling Method For Film Cooling

Protection of the airfoils from the hot crossflow can be maintained if coolant jets can provide effective coolant-film coverage on the airfoil surface. In order to have effective film cooling it is essential to reduce the penetration of the coolant-jet and the mixing of the jet with the crossflow. It has been mentioned that different factors contribute in defining effective film cooling such as hole size, hole shape, blowing ratio, etc.

Therefore, comprehensive understanding about the role of these parameters is desirable for designing an optimum film cooling configuration for the airfoil. In addition, it is important to find predictive approaches which can provide accurate predictions about the cooling effectiveness and heat transfer coefficient at the airfoil surface. This become more evident if one takes into account the complexity of the geometry, turbulent nature of the flow etc.

Though, film cooling dynamics is defined based on large scale structures, this is the turbulence which controls the mixing behavior. Therefore, the turbulence calculation should be such that the anisotropic behaviors of the entire spectrum of scales are accurately modeled. Indeed the anisotropic behaviors of large scales are not well-predicted by universal models so far.

2.4 Boundary Condition

It is recommended that for compressible flows mass-flow inlet boundary condition can be applied. This type of boundary condition however was not the best choice here, due to the following discussion. Since simulating the suction side of the blade was of interest, the domain was trimmed down above the stagnation point. This region owns a rather complex flow and requires a detail flow filed for accurate predictions of film cooling.

For the above domain, left wall is considered hot wall which is maintained at 450°C and right wall is considered cold wall which is maintained at 50°C. The other two walls, i.e. top and bottom are considered to adiabatic walls i.e. heat flux. Rayleigh number calculation based on dimension of domain and assuming constant properties.

Coolant temperature is set to 293.6 K in order to follow experimental settings. Different blowing ratios are obtained based on changing the mass-flow rate of the coolant. That is the plenum inlet will take different mass-flow rates, which corresponds to blowing ratios of 0.5, 0.7 and 1. Blowing ratio is defined as follows:

$$BR = \frac{\rho_c v_c}{\rho_m v_m}$$

Where ρ and v represent density and velocity, c and m stand for coolant and mainstream flows, respectively. It should be noted that, for mainstream, average velocity and density evaluated from lines through the holes positioned outside of the boundary layer has been used.

2.5 GOVERNING EQUATIONS

With the boundary layer approximations the governing equations for convection are as follows:

Continuity Equation

$$\frac{\partial}{\partial x}(\rho u)+\frac{\partial}{\partial y}(\rho v)=0$$

Momentum Equation

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=g\left(\rho_{\infty}-\rho\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)$$

Energy Equation

$$q_o=h_o\left(T_{\infty}-T_w\right)$$

Rayleigh Number

$$Ra=\frac{g\beta\Delta tL^3}{\alpha\gamma}$$

Nusselt number

$$Nu=\frac{k\left(\dfrac{\partial t}{\partial x}\right)}{k_m\left(\dfrac{t_h-t_c}{L}\right)}$$

2.6 FILM COOLING OF PERFORMANCE

In general, understanding and quantification of adiabatic effectiveness, heat transfer coefficients and discharge coefficients which define film jet characteristics clarifies film cooling technology.

Consequently, the majority of the researches have been focusing on this understanding, while less attention is given to the systems aspects that define the freestream conditions, the coolant supply conditions etc.

The aim of this section is to explain the fundamentals of film effectiveness performance. In particular the focus would be on definitions and interpretation of film effectiveness and heat transfer coefficient. As discussed these quantities contribute in defining film jet characteristics.

2.6.1 Film Effectiveness

The term of normalized temperature along both the centerline and span wised average from leading edge to trailing edge can give indications of thermal profile of a coolant jet. The freestream temperature $T\infty$, coolant temperature T_c and the gas temperature T contribute in defining the normalized temperature written as follows:

$$\theta = \frac{T\infty - T}{T\infty - Tc}$$

If θ=1 It is normalized initial coolant temperature.
If θ=0 It is normalized mainstream coolant temperature.

In film cooling, coolant air is drawn from compressor and directed into the cooling channel of turbine blades after bypassing the combustion chamber. It is then injected through small holes onto the blade surface in a proper angle to form a thin layer and blanket the surface. The thin film with relatively low temperature is later deteriorated in the downstream be-cause of the mixing of hot gas and coolant. The quality of film cooling is generally measured by an adiabatic film cooling effectiveness, η, which is defined as:

$$\eta = \frac{Tg - Taw}{Tg - Tc}$$

Where T_g is hot gas temperature, T_{aw} is adiabatic wall temperature and T_c is the temperature of cooling air. The cooling effectiveness ranges between 0, where there is no cooling, and 1, where the surface is perfectly protected.

2.6.2 Heat Transfer Coefficient

The parameter heat transfer coefficient, *h*, relates the convective heat flux to a surface and the temperature difference between the free stream flow, T_∞ and wall temperature, T_w,

$$q = h\left(T_\infty - T_w\right)$$

This relation however shows its inadequacy for film cooling applications, since it does not directly account for the lower near wall temperatures due to coolant jet. This is due to the fact that the lower near wall temperatures indicated from coolant jet does not have direct contribution in this relation. There exists though alternative formulation for film cooling flows which does not have deficiency, i.e. high variation of heat transfer coefficient depending on the local coolant jet temp, concluded from applying relation above to a film cooling flow. This alternative formulation is written as:

$$q_f = h_f\left(T_{aw} - T_w\right)$$

This equation is in fact used for film cooling, and thereby q_f and h_f represent heat flux and heat transfer coefficient with film cooling, respectively. Note that presumption for this equation is that for the overflowing gas stream the effective gas temperature reflects the adiabatic wall temperature. There would be short discussion on validation and limits of this presumption in the following, see discussion under heading Validation and Limits for Using Adiabatic Wall Temperature.

In general, estimation of film cooling performance can be done by comparing the heat flux to the wall, which occurs with film cooling and the one that occurs without film cooling. Heat flux for film cooling case can be obtained from relation (3), whereas the heat flux without film cooling, q_0, can be found as:

$$q_o = h_o\left(T_\infty - T_w\right)$$

In this equation h is the heat transfer coefficient without film cooling. This is calculated when there is a clean surface without coolant hole. By combination of equations (3) and (4) one can obtain the net heat ϕ follows:

$$\Delta q_r = 1 - \frac{q_f}{q_o} = 1 - \frac{h_f\left(T_{aw} - T_w\right)}{h_o\left(T_\infty - T_w\right)}$$

By using definition of film effectiveness $\acute{\eta}$ this equation can be simplified to:

$$\Delta q_r = 1 - \frac{hf}{ho}\left(1 - \frac{\eta}{\phi}\right)$$

In this relation ϕ indicates the normalized wall temperature. This parameter for metal airfoil can be defined as:

$$\phi = \frac{T_\infty - T_w}{T_\infty - T_{c,\mathrm{int}ernal}}$$

In above equation $T_{c, internal}$ is the coolant temperature, which flows from cooling passage of turbine airfoil to the surface. One can visualize the relation between the heat transfer coefficients ratio with and without film cooling h_f/h_o and film effectiveness for the net reduction in heat transfer to the metal airfoil.

Harison [11] conducted a numerical simulation towards checking the validity of this approximation. In this investigation he has utilized equations (1) and (3) and also a conducting model for estimation and comparison of the heat flux into the surface. Essentially there is an assumption for assuming that the adiabatic wall temperature and the effective free stream temperature are relatively equal. That is one should assumes that the coolant jet is relatively much thicker than the thermal boundary layer which develops in the flow direction.

CHAPTER-3

CFD MODELLING

3.1 Geometry

The blade profile was produced utilizing ANSYS-15.0 Design Modeler programming. The cross-section of the edge was made by importing 374 points and afterward drawing a spline utilizing those points. The spline was then extruded to a length of 140 mm & hole diameter is 1mm and the distance between two hole is 8mm.

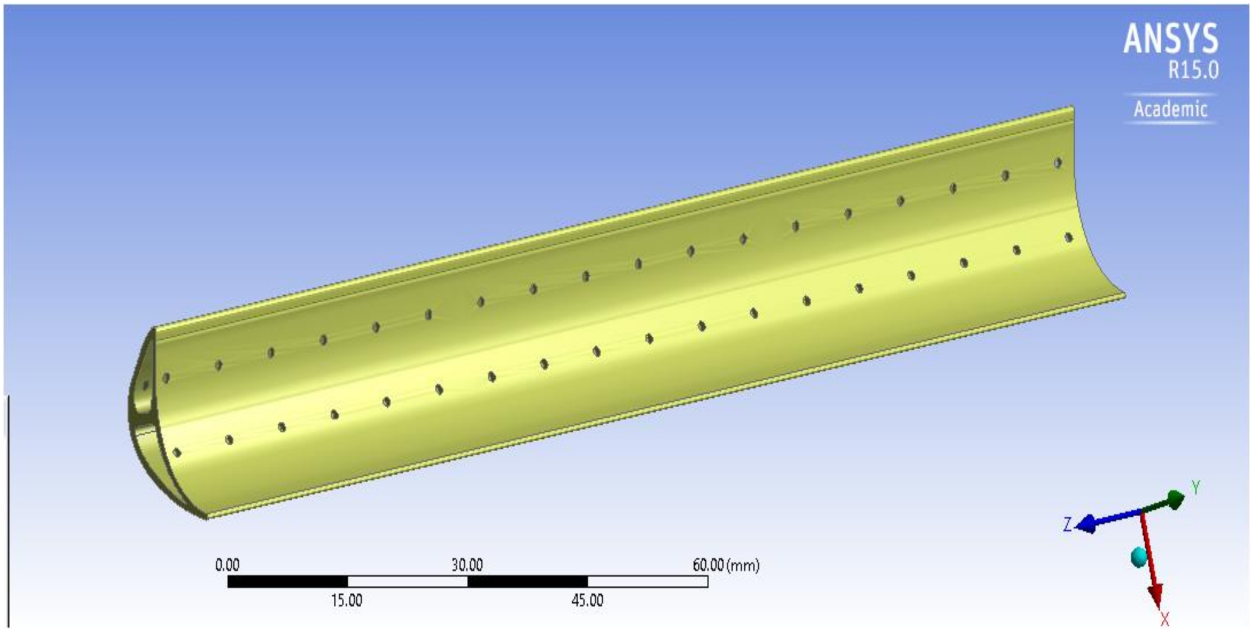


Fig 3.1- film cooling turbine blade

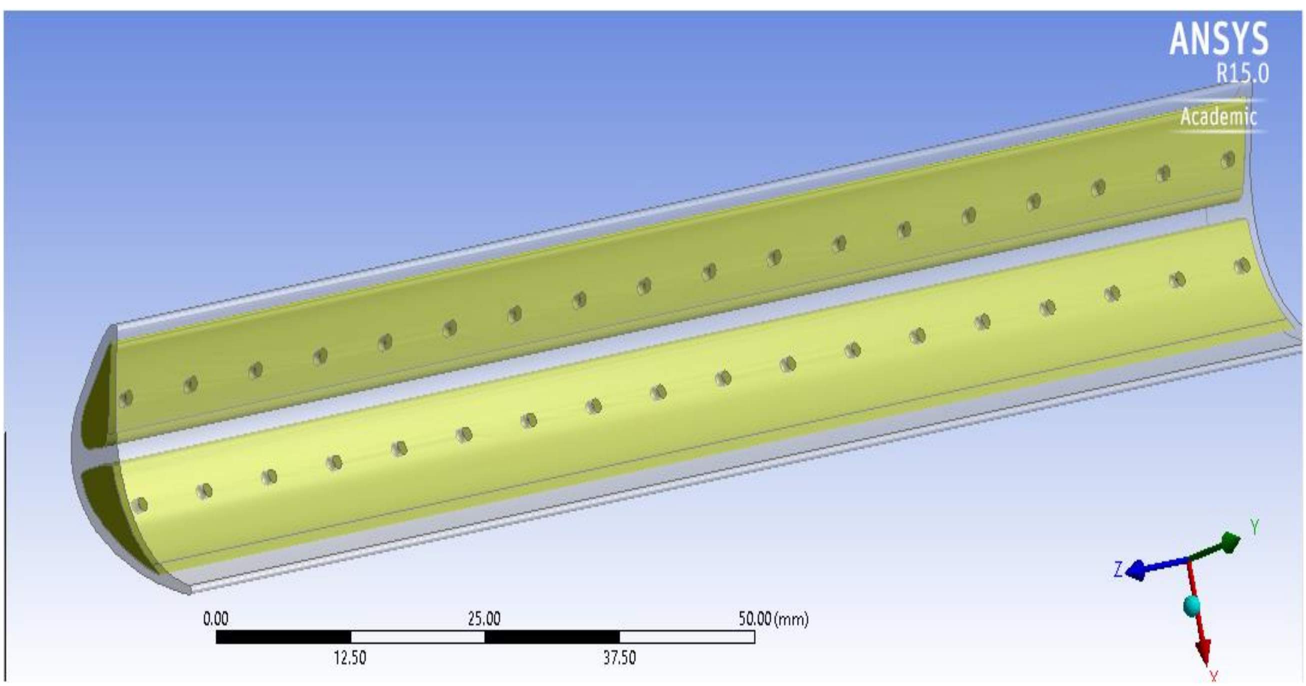


Fig-3.2 fluid flow domain

3.2 Mesh

The mesh is the grid used for calculations in the simulations. There exists two general types of computational grids, structured and unstructured. The structured grids are usually created manually, consisting of hexahedral elements. Unstructured grids are generated automatically and can consist of a number of different element types,

TABLE NO.1

Nodes	30740
Elements	30729
Mesh matric	Orthogonal Quality
Min	0.155258891395384
Max	1
Average	0.908633988170596
Standard deviation	0.107976775687622

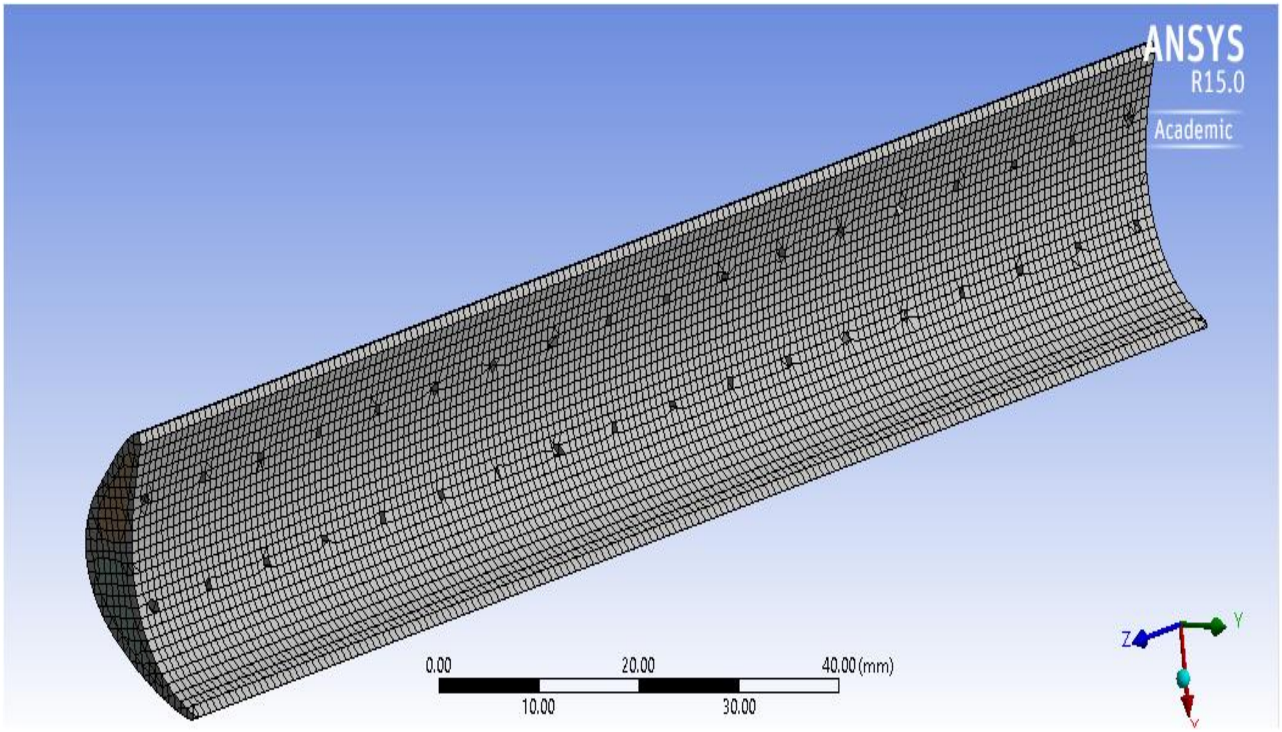


Fig 3.3: Grid of mesh

3.3 **Setup**

The blade material was taken to be a nickel-super alloy Inconel-718, [12]
TABLE NO. 2

Material name	Thermal conductivity k	Density ρ	Specific heat capacity Cp
Inconel-718	11.4W/m-k	8190 kg/m3	435J/kg-k

3.4 **Solution Method**

Energy equation was turned on and the k-ε model, with standard wall functions was used to model the turbulent behavior.
Scheme: SIMPLEC
Gradient: Least Square Cell Based
Pressure: Linear
Momentum: Power Law
Turbulent Viscosity (k): Power Law
Turbulent Dissipation (ε): Power Law
Energy: Second order upwind

CHAPTER – 4

Result and Discussion

In order to have a comprehensive understanding of the flow and to compare different flow scenarios, the results of the simulation have been presented in different formats. A number of trend graphs were also drawn to show the variation over the blade volume.

- The trend of the average temperature of the blade cross-section at intervals of 10 mm was plotted with respect to distance from the inlet.
- Isometric views of the temperature contours of the blade for blade channel.
- Temperature contours of the blade at outlet.
- Temperature contours of the fluid flow domain of the blades.
- The trend of average Nusselt Number of surfaces respect to distance from the inlet.
- The trend of average heat transfer coefficient of surfaces with respect to distance from the inlet.

4.1 Temperature Contours of Blades

Mass flow rate : 0.01 kg/s

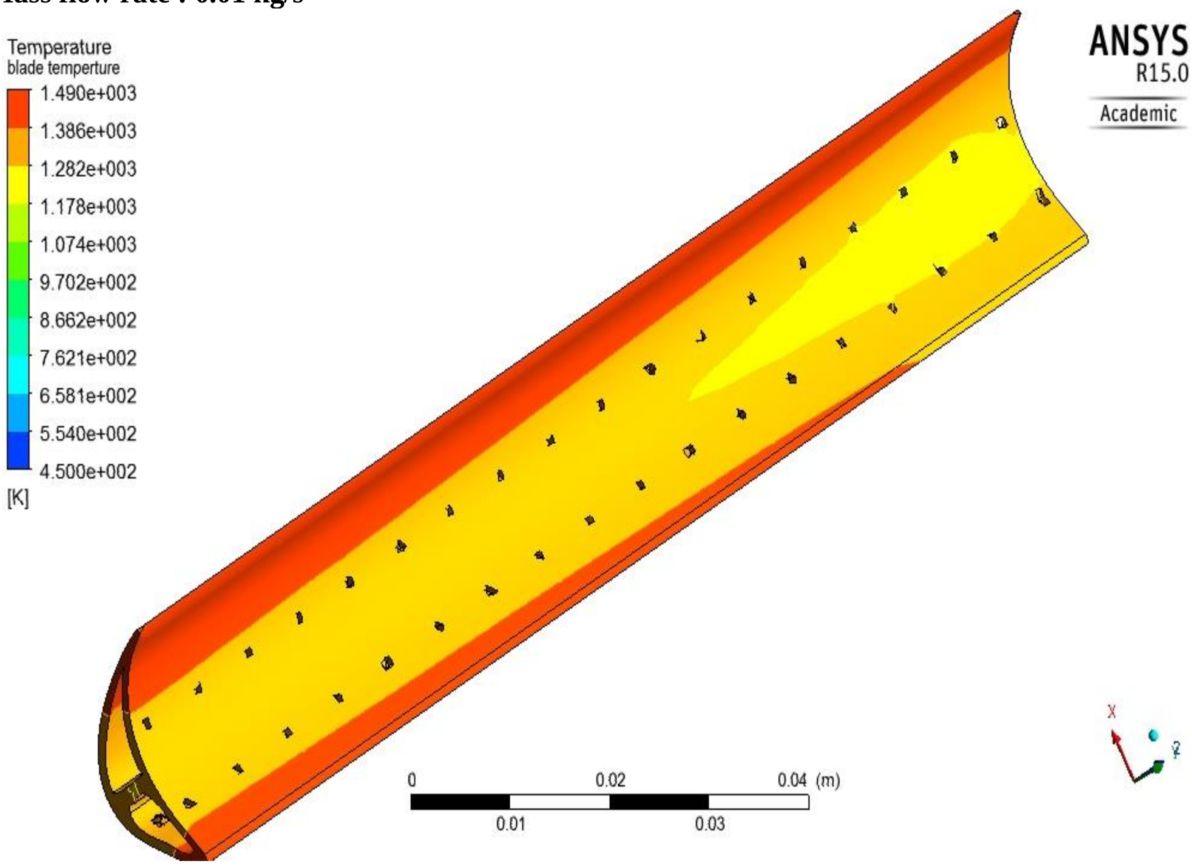


Fig4.1- Temperature contour of blade

4.2 Temperature of fluid domain

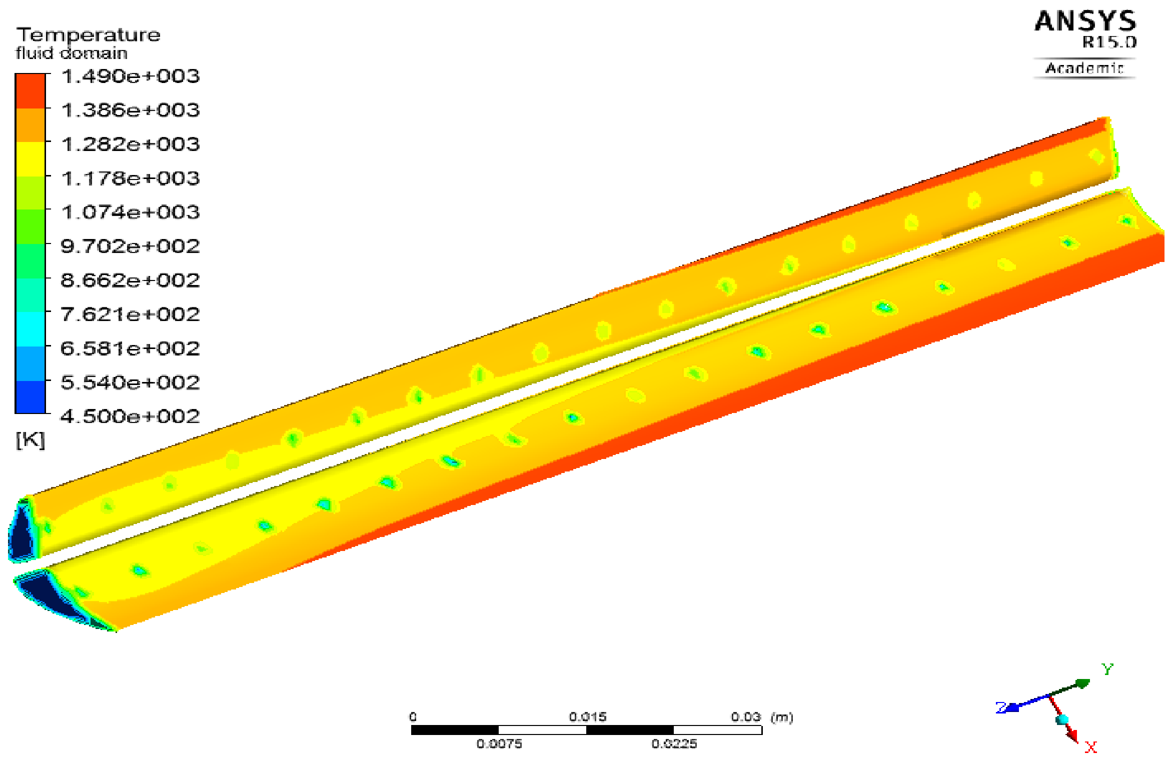


Fig4.2- Temperature of Fluid Domain

4.3 <u>Average Fluent Temperature Trends</u>

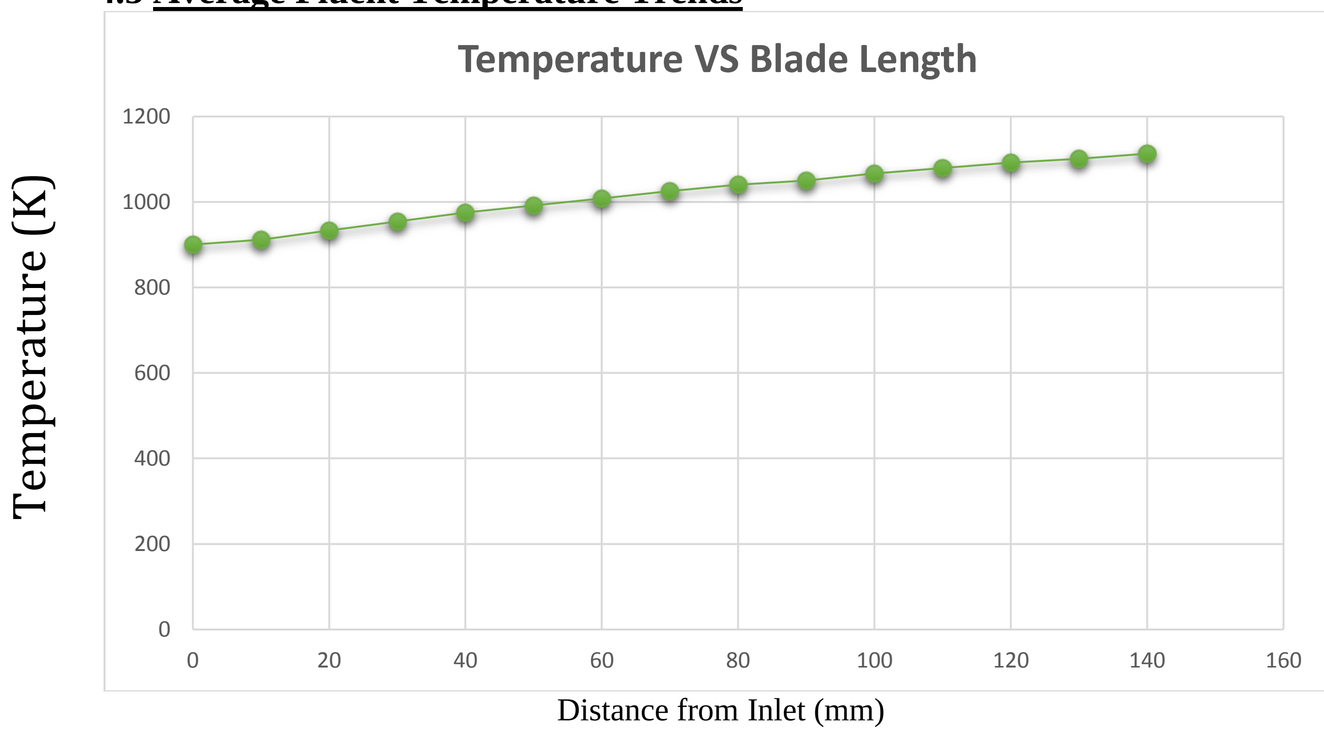
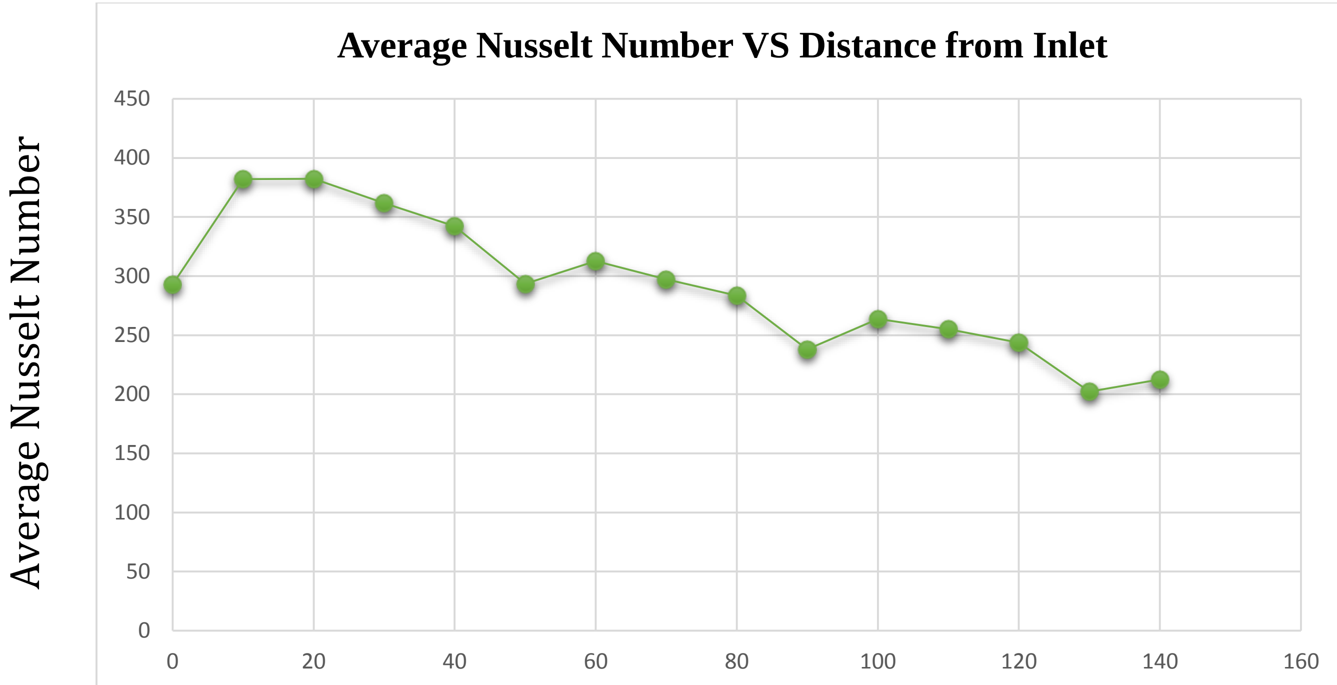


Fig4.3: temperature and mass flow rates

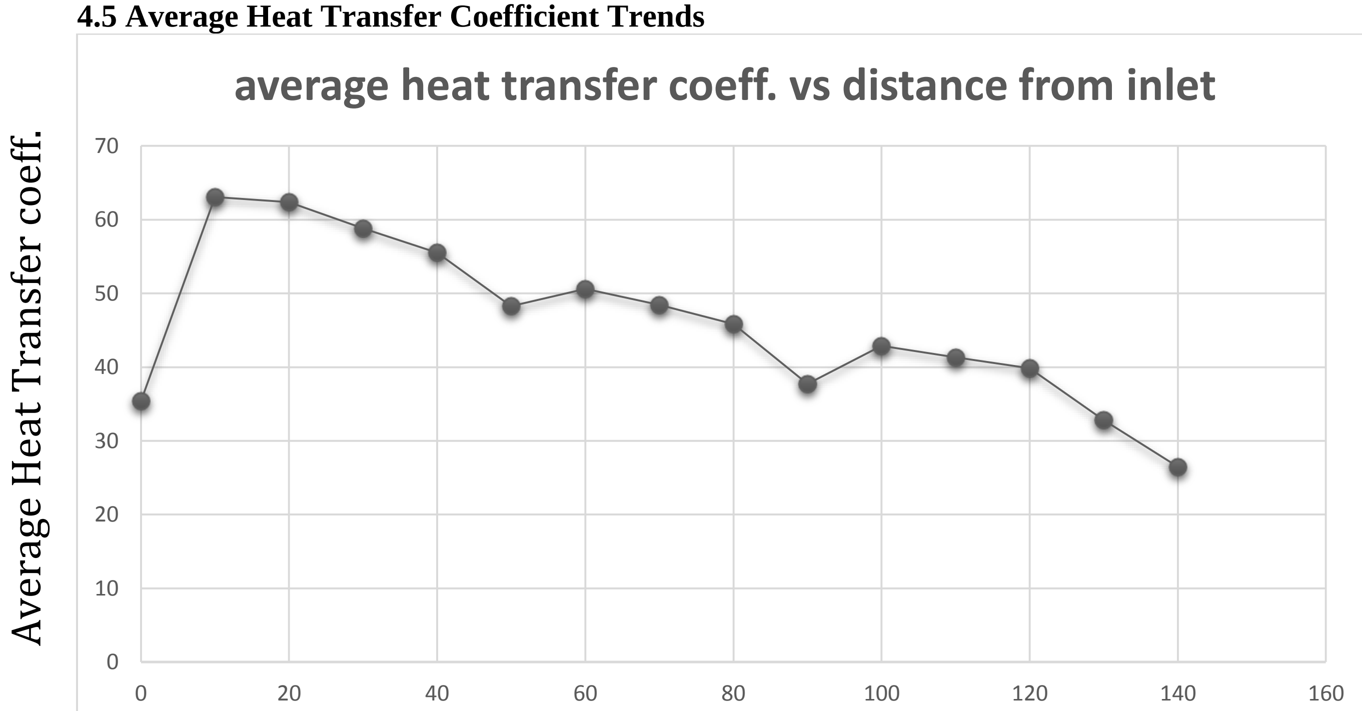
4.4 Average Nusselt Number Trends



Distance from Inlet (mm)

Fig4.4: Nusselt number and mass flow rates

4.5 Average Heat Transfer Coefficient Trends



Distance from Inlet (mm)

Figure 4.5: Heat transfer coefficient and mass flow rates

4.6 Discussion

The average heat transfer coefficient and average Nusselt number gradually decreases with increasing distance from inlet. This is to be expected as the air becomes hotter as it travels down the channel and thus it's cooling capacity decreases. Therefore, as expected, the average blade temperature increases with increasing distance from inlet. This also shows that the cooling effect due to air flow decreases with increasing distance from inlet.

CHAPTER- 5

FUTURE WORK AND CONCLUSION

5.1 **CONCLUSIONS**

It can be concluded that the claims made by various researchers in the past regarding the cooling effects of film cooling channels are true and unquestionable. The film cooling channels provide cooling effect by enhancing the heat transfer. Further, mass flow rate was increased to obtain an optimal mass flow rate but it could not be obtained as the trend was unsettled. Also, average heat transfer coefficient, average skin friction coefficient and average Nusselt number is directly proportional to mass flow rate and they increase monotonously with increasing mass flow rate.

5.2 **FUTURE WORK**

As the effect of slip is influential and essential under specific circumstances, therefore, it gives space for the investigation of effect of slip along with temperature jump condition for distinctive areas and Rayleigh number.

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