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Heat Transfer Simulation of Gas Turbine Blade with Film Cooling

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ABSTRACT

In advance gas turbine, improve the thermal efficiency and power output it is require to increase turbine inlet temperature, that may be exceeds the melting point of the blade material, for that reason blade cooling technique is required. There are several methods have been suggested for cooling of the blades and one of this methods is to have radial holes to pass high velocity cooling air along the blade span. This paper is mainly focus on gas turbine blade heat transfer analysis and effect of increase number of external film cooling holes rows with internal film cooling holes on blade performance and select the optimum design with three different models consist of blade without holes and blades include (2, 3) external rows of film cooling holes with Specific number of internal cooling holes for both last two models. Results have been discussed and it is found that model-2 is the optimum solution, because of maximum total heat transfer rate and reduction in the blade leading edge temperature about 50% are attained in this model compared to model-1 and model-3, and it is found increase number of external film cooling holes rows in the blade not always lowers the blade leading edge temperature, sometimes leads to reheating process this depends on the design location of this holes on the blade surface. Steady state thermal analysis is carried out using CFD, Inconel 718 alloy selection as material and Nitrogen is used as a coolant.

Keywords:*—Film cooling, Heat transfer rate, Gas turbine blade, Blade cooling, Blade temperature.*

I. Introduction

Gas turbine are essential component and widely used today's industrialized society like air craft propulsion, land based power generation and industrial applications, The gas turbine is preferred in using today compare to other turbines due to its high energy, size and weight. In 1960s, material properties limited gas turbine firing temperature and turbine blade temperature around 8000C. Advanced gas turbine engines operate at high temperatures (12000C-15000C), to improve the thermal efficiency and power output we needed to increase the temperature of the gases, the heat transfer to the blades will also increase appreciably resulting in their thermal failure. With the existing materials, it is not possible to go for higher temperatures. Therefore a technique cooling system must be developed to maintain safe operation of gas turbines with high performance.

II. Literature Review

The thermal analysis [1], of gas turbine blade with four different models consisting of blade with and without holes and blades with varying number of cooling holes has been examined with different blade materials of chromium steel and Inconel-718, he was found blade with 13 holes is considered as optimum and Inconel-718 is better thermal properties and induced stresses are lesser than the Chromium steel. [2], used Finite element analysis to analyze thermal and structural performance due to the loading condition, with material properties of Titanium- Aluminum Alloy. Examined six different models with different number of holes (7, 8, 9, 10, 11, and 12), it is found that when the numbers of holes are increased in the blade the temperature distribution falls down. For the blade configuration with 8 holes is the optimum solution.[3], simulate the conjugate heat transfer analysis methodology it has been defined and applied to an Air Force film cooled turbine vane consisting of 648 cooling holes. It is found that the cooled air from the film holes formed a protective layer around the airfoil surfaces and end walls as intended.

III. Measurement of Film Cooling Effectiveness

This analysis base on the blade mid diameter, this analysis for model-2 as example to other models and the equations is used are, the external heat transfer to the coolant is given by Newton's law of cooling.

$$q = h_g \; A_{(sg)} \, (T_{gi} - T_b) = h_c \; A_{(sc)} \, (T_b - T_{co}) \qquad (1)$$

Where: $A_{sg} = S_g \times H$

and similarity for Asc, the hot flow gas inlet Reynolds number based on the mid chord length and inlet velocity.

$$Re = (\rho \, c_m \, C_i)/\mu \qquad (2)$$

Nusselt number for hot and cooled flow gases is calculate by equations (3) and (4) respectively which are used to calculate heat transfer coefficient for both.

$$Nu_g = 0.664 \, pr^{(1/3)} \, Re^{(1/2)} \qquad (3)$$

$$Nu_c = 0.023 Re^{(4/5)} \, Pr \, 0.3 \qquad (4)$$

And the total mass flow rate for the coolant is estimated by equation (5)

$$m_c = V_c \, A_c \qquad (5)$$

The design aim for more efficient cooling systems to enhance the amount of heat which is transferred from the blade to the coolant; this is expressed by the cooling efficiency (6).

$$\eta c = (T_{co} - T_{ci})/(T_b - T_{ci}) \qquad (6)$$

The film cooling effectiveness is estimated by deal with the blade as a heat exchanger by using relation (7) & (8)

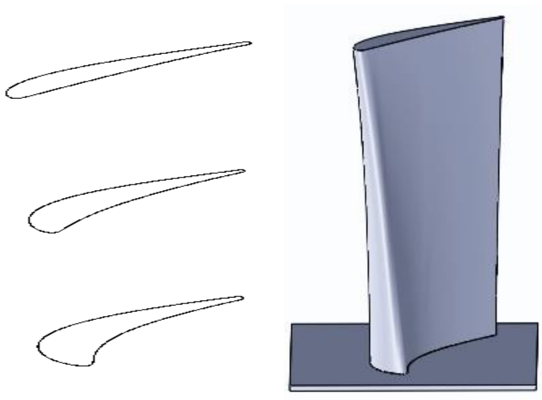
$$\varepsilon_{fc} = q/q_{max} \quad (7)$$

$$q_{max} = C_{(min)} (T_{gi} - T_{ci}) \quad (8)$$

From equation above it is found that the cooling efficiency and the film cooling effectiveness equal to 91% and 92% respectively.

IV. Modeling of Gas Turbine Blade

The blade model is generated by using solid works software. The blade is constructed from three airfoil hub, mid and tip. Which distribution at different span of blade height at 0% span, 50% span and 100% span respectively, each airfoil section involves about 162 points are imported in solid works in (x, y) plan with height in Z-axis direction then the (3D) model has been generated. This paper deal with three models, model-1 is consider soiled without cooling holes and model-2 & 3 includes different numbers of film cooling holes, blade design models are in (Figure 1 to 3) and design configuration parameters are in table-2.



(a) (b)

Figure 1. a - Blade Airfoils, b - Model-1 Blade (Without Cooling Holes)

Table 2: Blade Design Parameters

Parameters	value
blade height (m)	0.117
Inlet gas angle α_1 (o)	58.8
Exit gas angle α_2 (o)	12
Blade mid diameter (m)	0.36965
Mid airfoil chord length (m)	0.05967

Table 1: Nomenclature

Nomenclature				Greek symbols		Suffix	
E	Young's Modulus	q	heat flux	ε	Effectiveness	c	coolant
μ	Poisson's ratio	h	heat transfer coefficient	θ	hole angle tangential to the stagnation row	b	blade
K	K Thermal conductivity	Nu	Nusselt number	α	cooling hole incline angle to the blade span	o	outlet
C_p	specific heat at constant pressure	Re	Reynolds number	ρ	Density	i	inlet
d	film cooling hole diameter	Tu	turbulence intensity			f	film
s	hole pitch	Cm	mean chord length			g	gas
T	temperature	S	total external perimeter			m	mid
P	pressure	N	rotational speed				
A	area	PR	pressure ratio				
m	mass flowrate	pr	Prandtl number				
V	volume	H	blade height				
C	velocity	η	efficiency				

Table 3. Mechanical properties of Inconel718

Properties	Units	Inconel718
E	Mpa	205000
ρ	Kg/cu m	8190
K	W/m-k	25
μ	---	0.284
Cp	J/kg-k	586.2
Melting point	°C	1344
Yield stress	MPa	1067

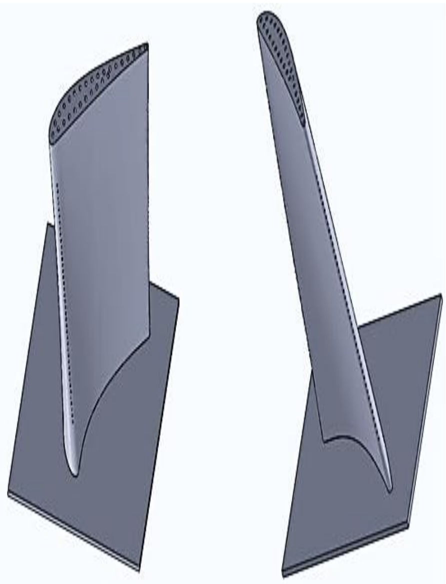


Figure 2. Both Sides of Blade Model-2

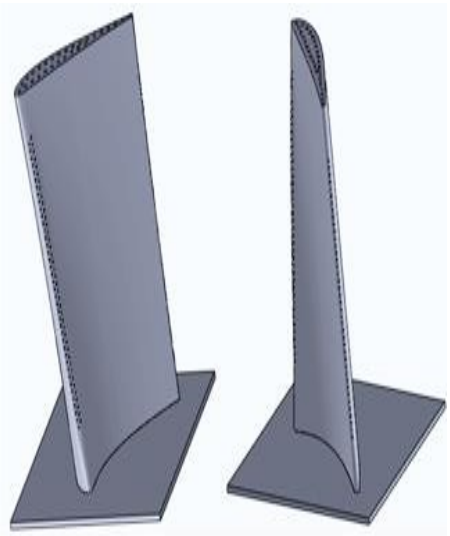


Figure 3. Both Sides of Blade Model-3

V. Mesh Generation

The analysis has been performed using ANSYS WORKBANCH 18.1 design modeler. The extruded geometry is meshed by CFX mesh. CFX- mesh uses unstructured tetrahedral meshes and this type of meshes is lead to reduce the amount of time spent in generating of meshes. The global curvature size function parameters are used to capture the features of the curves. Tetrahedron mesh has been used to meshing the blade and the flow domain. Volume mesh is generating by selecting Generate Volume mesh, Patch conforming mesh in the areas where it is not sweepable and sweep mesh in the areas where it is sweepable. In the current case, the patch conforming mesh was used. This method uses bottom up approach which means it will mesh the edges first followed by faces and finally the volume, as in (Figure 4). And mesh for second model blade with cooling holes (Figure 5) same parameters for mesh model-1has been applied on it with some modifications. As this case requires multiphase modeling i.e. Fluid-Fluid iteration of natural gas and Nitrogen and conjugate heat transfer between natural gas and blade & coolant and blade, care has be taken to ensure that the mesh connectivity exist throughout the domain. Also same parameters have been applied for model-3 but the mesh size become greater than the other due to increase number of cooling holes as in (Figure 6).

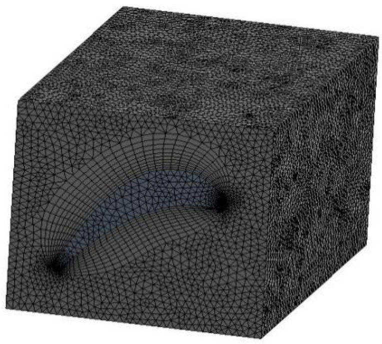


Figure 4. Meshed Domain for Model-1

Table 4. Mesh Details for Model-1

Domain	Nodes	Elements
Default domain	233208	803217

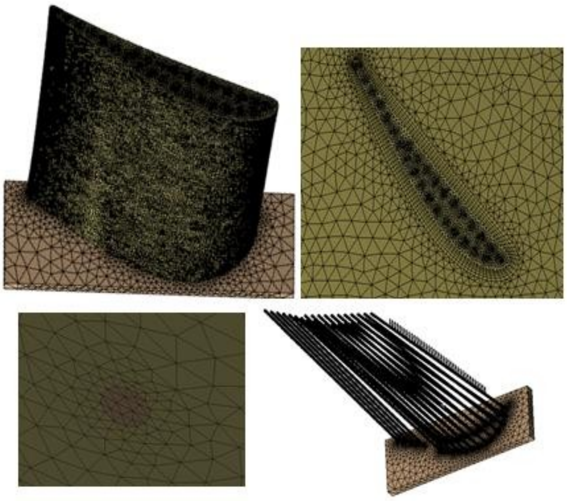


Figure 5 Mesh Details for Model-2

Table: 5 Mesh Details for Model-2

Domain	Nodes	Elements
Default domain	819386	4341532

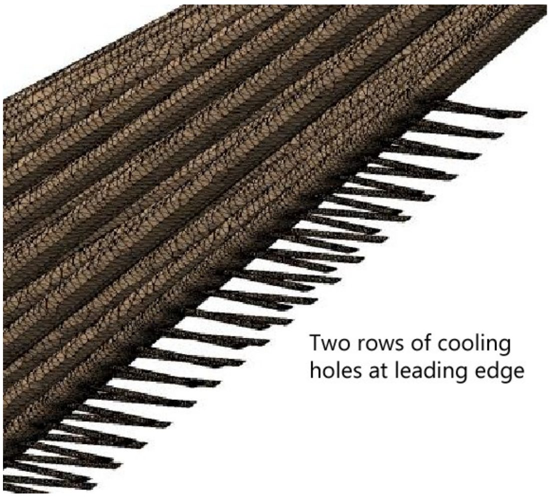


Figure 6. Mesh Details for Model-3

Table: 6 Mesh Details for Model-3

Domain	Nodes	Elements
Default domain	934559	4995753

VI. Gas Turbine Blade Analysis

This paper deal with three models model-1 is consider solid blade without cooling holes, model-2 include 108 cooling holes distribution at two rows one of them at the blade leading edge is the stagnation row and the other at the trailing edge with tip cooling holes and model-3 include 148 cooling holes distribution at three rows, two of them at the blade leading edge and the other at the trailing edge as well as the tip (internal) cooling holes. (each row involve 40 cooling holes) and the number of tip cooling holes are 28 holes in model-2&3. The film cooling holes details are explained in table 7 and the input boundary conditions of gas turbine blade which are used in CFD simulation are under table 8.

Table 7. Film Cooling Holes Configurations

Hole Row	d(mm)	s/d	Tangen-tial angle From surface θ (deg)	incline angle to blade span α (deg)
Row1 LE	0.36	5.97	0	45
Row 2 LE	0.36	5.97	-30	45
Row 3TE	0.36	5.97	0	90
Tip	1.2	3	------	-------

Table 8. Input Boundary Conditions

Parameters	Values
Hot gas inlet velocity (m/sec)	499.49
Rotational speed (rpm)	8912
Inlet temperature of coolant T_{ci} (K)	300
Coolant velocity (m/sec)	75
rotor blade inlet temperature T_{gi} (K)	1423
Pressure ratio PR	1.9
Hot gas inlet turbulence intensity	5%

VII. Results and Discussions

In the presented results it is found that model-1 (without cooling holes) the blade temperature is near or equale to hot gas inlet temperature from (Figure 7), velocity increase to maximum value (Figure 8) when air leaves the turbine blade compares to the inlet, because of the converging form of the blade and the total heat transfer rate is very low near to zero. It is observing that from (Figure 9) the static pressure of the blade is maximum in pressure side, because of the hot air enters at a high velocity from leading edge to trailing edge that leads to temperature, pressure and velocity are varying as in (Figure 10 to 13), For one stream line in a particular location at mid chord length of the blade.

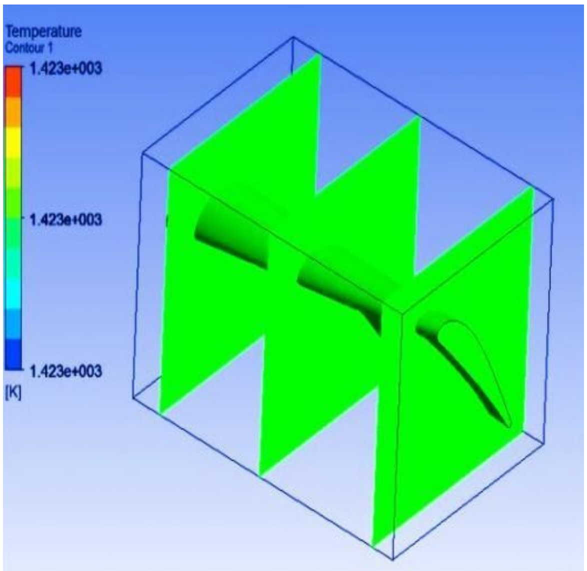


Figure 7. Blade Temperature Distribution for Model-1

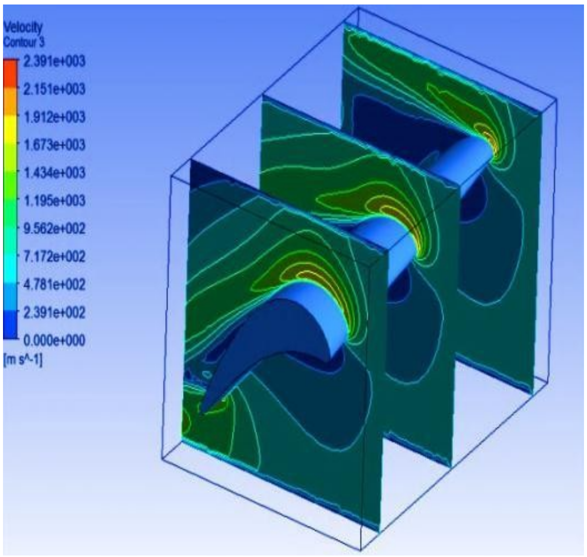


Figure 8. Velocity Variation for Model-1

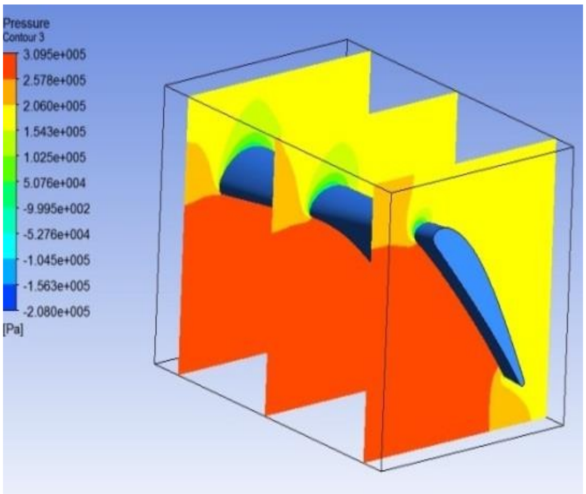


Figure 9. Pressure Couture for Model-1

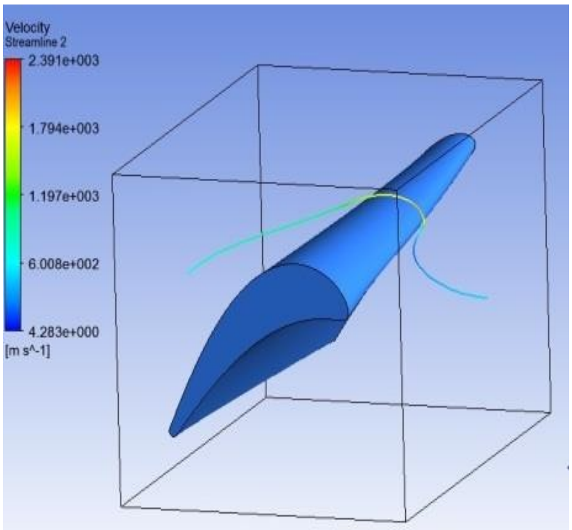


Figure 10. Velocity Stream Line at Mid-Section of Blade for Model-1

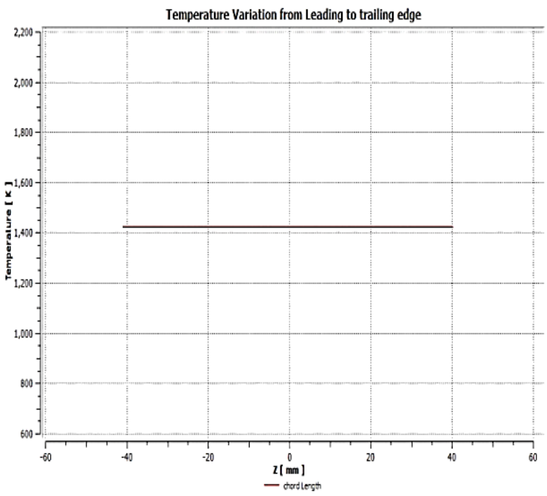


Figure.11 Temperature Distribution for Model-1

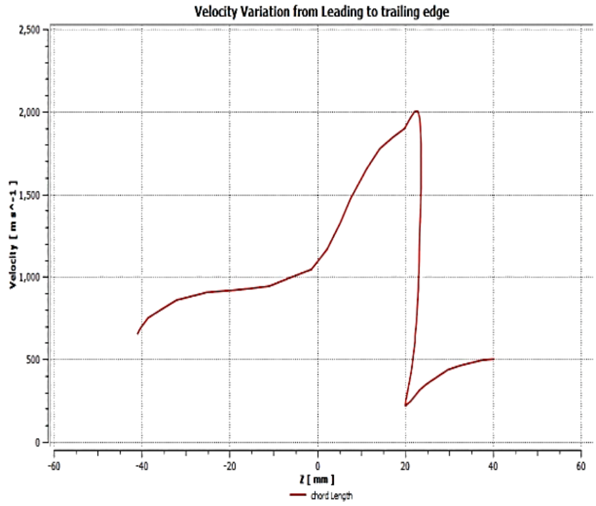


Figure 12. Velocity Distribution for Model-1

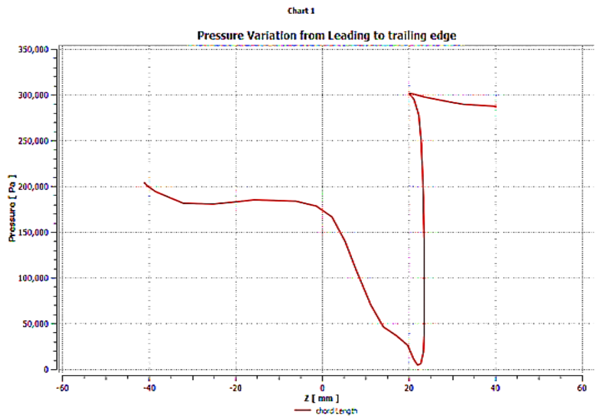


Figure 13: Pressure Distribution for Model-1

It is found that the model-2 is the optimum solution because of the reduction in the blade leading edge temperature reached about 50% from (Figure 14) and maximum increase in the total heat transfer rate is bout of (6.2958×105w/m2) is attained in model-2 compare to model-3, both the superficial velocity and pressure from (Figure 16 & Figure 18) are increased. And it is found that there is reduction in the blade leading edge temperature for model-3 but at a value little more than 50% compare to model-2, although the number of cooling holes rows are more than model-2 and both the superficial velocity, pressure are decreased (Figure 17 & Figure 19) and the total heat transfer rate is decrease to about of (5.9423×105w/m2).

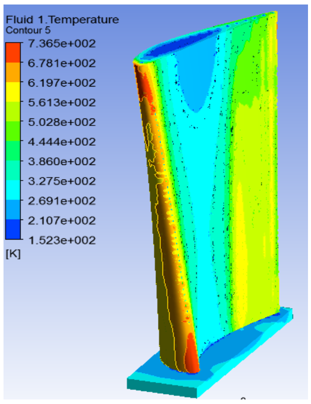


Figure 14. Temperature Distribution for Model-2

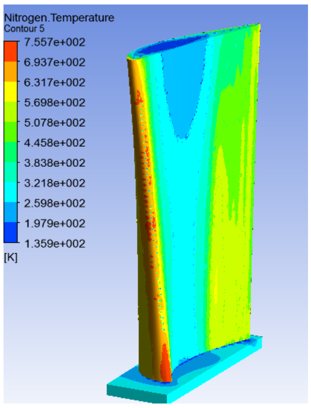


Figure 15: Temperature Distribution for Model-3

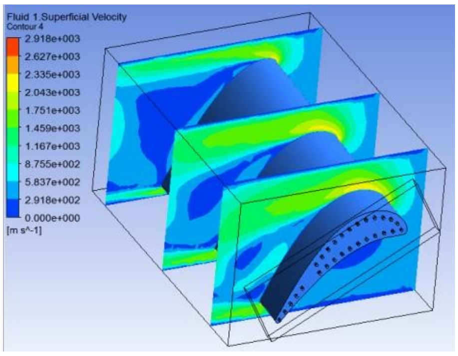


Figure 16: Velocity Distribution for Model-2

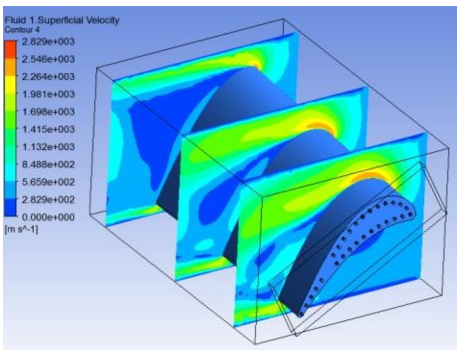


Figure 17: Velocity Distribution for Model-3

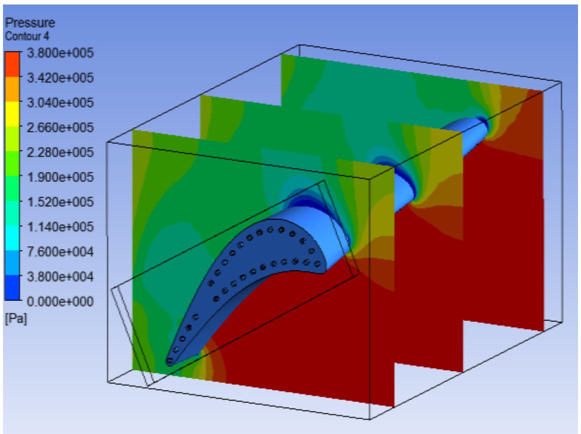


Figure 18. Pressure Distribution for Model-2

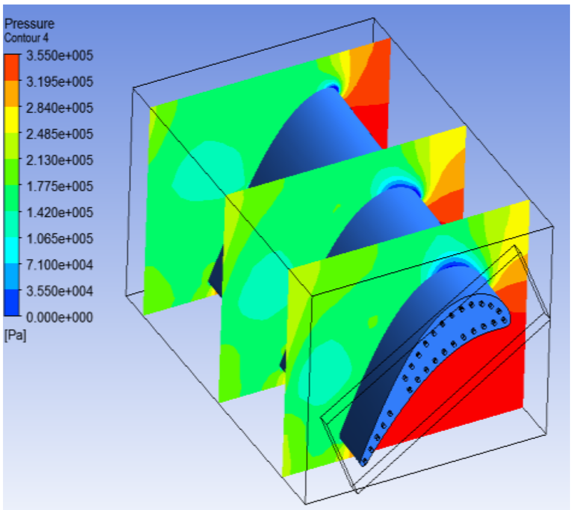


Figure 19. Pressure Distribution for Model-3

Because of increased number of cooling holes rows in the location opposite to emission of hot gasses this helps to enter some amount of hot gas at a high velocity into the inside of the blade from external holes in the direction opposite to the direction of exit cooling gas velocity from internal holes at blade leading edge this is causes reaction and reheating process, which lead to slightly increase in the blade leading edge temperature compare to model -2. Finally film cooling effectiveness will reduce about to 86% in model-3. And similarly of model-1, can see the effect of cooling holes for the parameters variation from leading edge to trailing edge for one stream line for both model-2 & 3 as in (Figure 20 to 27)

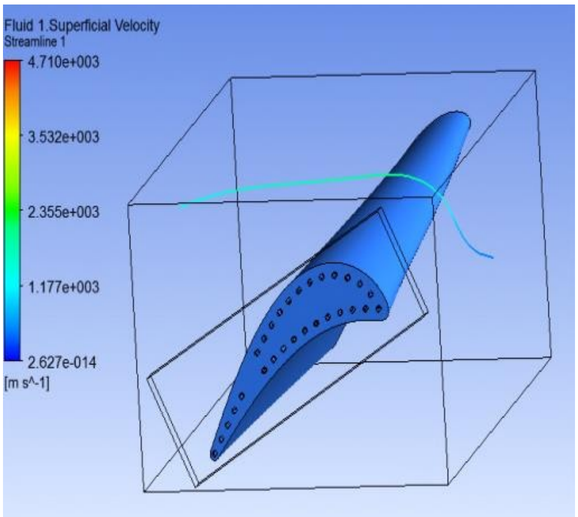


Figure 20. Superficial Velocity Stream Line at Mid–Section of the Blade Model-2

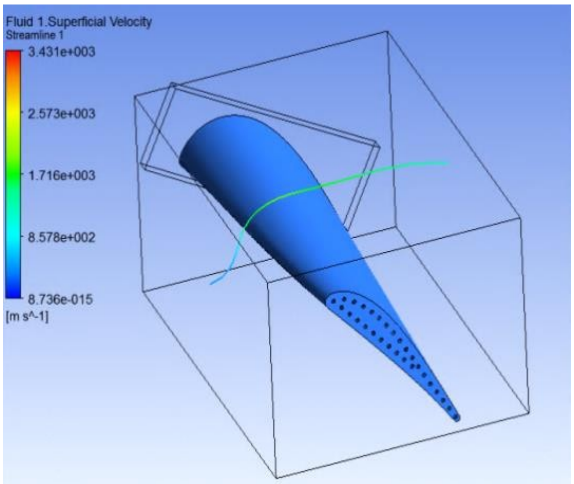


Figure 21. Superficial Velocity Stream Line at Mid–Section of the Blade Model-3

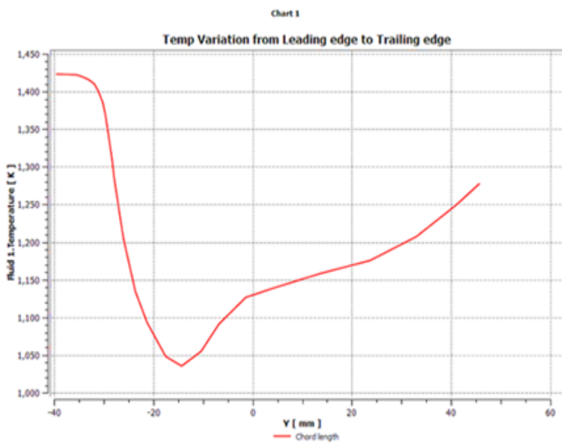


Figure 22. Temperature Variation at Mid Chord Length of Blade Model-2

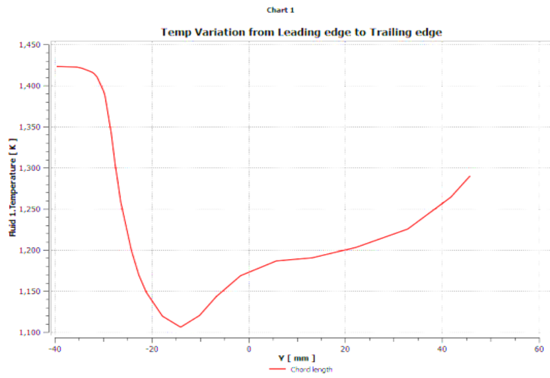


Figure 23. Temperature Variation at Mid Chord Length of Blade Model-3

For this stream line the maximum reduction in blade temperature is attained in model-2 from (Figure 22). And (Figure 24 & Figure 26) show maximum velocity and pressure in this location reached to about of 2100 m/sec and to 3.8 bar respectively for model-2.

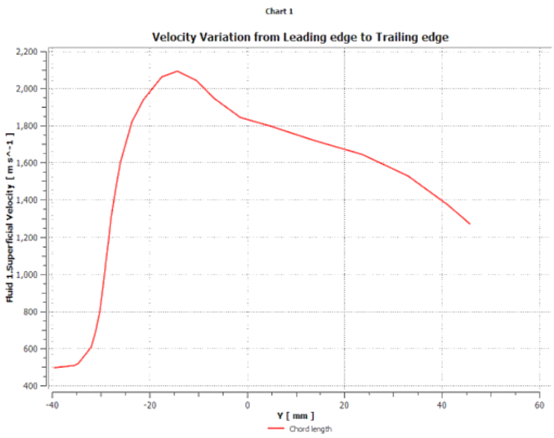


Figure 24. Velocity Variation at Mid Chord Length of Blade Model-2

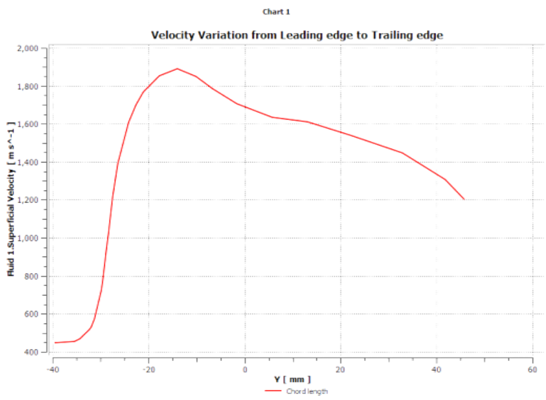


Figure 25. Velocity Variation at Mid Chord Length of Blade Model-3

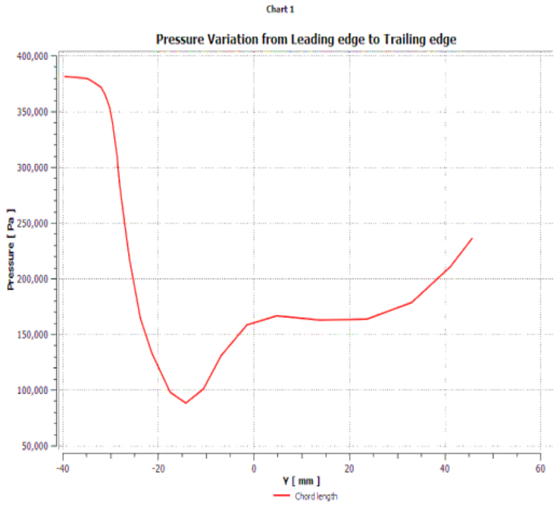


Figure 26. Pressure Variation at Mid Chord Length of Blade Model-2

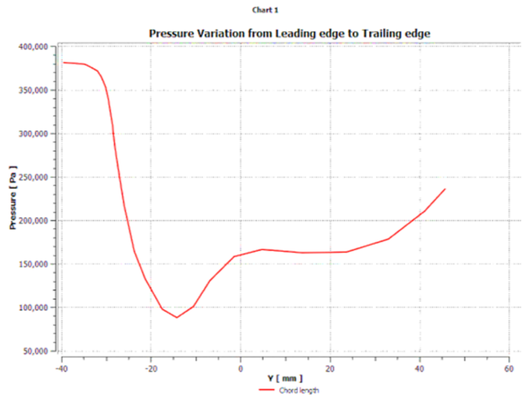


Figure 27. Pressure Variation at Mid Chord Length of Blade Model-3

VIII. CONCLUSIONS

The Temperature distribution of the blade depends on the heat transfer coefficient for the gases and the thermal conductivity of the material. It is observed that the maximum temperature is attained at the blade leading edge because of it is direct confrontation to the emissions of the hot gases. It is found that the maximum reduction in the blade leading edge temperature is about of 50% attained in model-2 with maximum increased in the total heat transfer rate, because of the cooling air makes a thin film on concave surface of the blades to protect it from the high temperature, while the pressure and velocity are also increased, so that this model is considered is the optimum solution compare to other models. However, increased the velocity in model-2 because of film cooling holes effect in this model, in this case the velocity of cooling gas flowed inside the internal cooling holes passages to the out of the blade and mix with the hot gas velocity, resulting increase in the velocity and form the superficial velocity around the blade surface. From model-3 it is found that increased the external number of film cooling holes rows in the location opposite to emission of the hot gasses lead to reheating process, this give blade leading edge temperature maximum than models have lower number of film cooling holes as in model-2. From temperature counters figures it can be observed that the temperature at the cooling holes is lower and it can be increased towards the leading edge and trailing edge of the blade, and it is observe that the temperature distribution from cooling air inlet to the cooling air outlet is increased.

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