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Performance Analysis of Gas Turbine Blade Cooling by CFD

N.Nandakumar, N.Selva Moorthi

Abstract— Gas turbine engines are extremely prevalent in today's society, being used in power plants, marine industries and aircraft propulsion. Hence investigations for improving their performance are very important. Most engineering problems in gas turbine are extreme temperature, high pressure, high rotational speed, vibration and small circulation area which affects the blade life. So turbine blade requires cooling. One of the effective method is internal cooling, that involves extracting air from the compressor and forcing it through a plenum and into channels inside the blade. The effective cooling increases the blade life and also improves the thermal efficiency of the engine. An theoretical investigation was done to find the temperature reduction of the blade through internal cooling. The Turbine blade and cooling channels are modeled by PRO/E WILDFIRE 4.0. The fluid domains were meshed independently using ANSYS CFD meshing software. The fluid Flow can be visualized by ANSYS Fluent 12.1. The results observed in this work shows better temperature reduction rate than the gas turbine blade without cooling. Hence, internal cooling method is found better to reduce the temperature of the blade which improves the life span of the blade.

Keywords: Gas turbine engines, internal cooling, Turbine blade, cooling channels.

I. Introduction

Jaeyong Ahn, M.T. Schobeiri, Je-Chin Han, Hee-Koo Moon [1] have studied the Effect of rotation on detailed film cooling effectiveness distributions in the leading edge region of a gas turbine blade with three showerhead rows of radial-angle holes were measured using the Pressure Sensitive Paint (PSP) technique. Tests were conducted on the first-stage rotor blade of a three-stage axial turbine at three rotational speeds. The effect of the blowing ratio was also studied. The Reynolds number based on the axial chord length and the exit velocity was 200,000 and the total to exit pressure ratio was 1.12 for the first-stage rotor blade.. The corresponding rotor blade inlet and exit Mach number was 0.1 and 0.3, respectively. The film cooling effectiveness distributions were presented along with the discussions on the influences of rotational speed,blowing ratio, and vortices around the leading edge region. Results showed that different rotation speeds significantly change the film cooling traces with the average film cooling effectiveness in the leading edge region increasing with blowing ratio.

N.Nandakumar, Assistant Professor, Department of Mechanical Engineering, Government College of Technology (Coimbatore), India. (Email: nannthu@yahoo.com)

N.Selva Moorthi, PG Scholar, Department of Mechanical Engineering, Government College of Technology (Coimbatore), India. (Email: nselvamoorthibe@gmail.com)

Zhihong Gao, Diganta P. Narzary, Je-Chin Han [2] have studied the film cooling effectiveness on the surface of a high pressure turbine blade is measured using the pressure sensitive paint (PSP) technique. Four rows of axial laid-back, fan-shaped cooling holes are distributed on the pressure side while two such rows are provided on the suction side. The coolant is only injected to either the pressure side or suction side of the blade at five average blowing ratios ranging from 0.4 to 1.5. The presence of wakes due to upstream vanes is simulated by placing a periodic set of rods upstream of the test blade. Effect of the upstream wakes is recorded at four different phase locations with equal intervals along the pitch-wise direction. The freestream Mach numbers at cascade inlet and exit are 0.27 and 0.44, respectively. Results reveal that the tip leakage vortices and endwall vortices sweep the coolant film on the suction side to the midspan region. The film cooling effectiveness on the suction side is usually higher than that on the pressure side except the regions affected by the secondary vortices. The presence of upstream wakes results in lower film cooling effectiveness on the blade surface. The moderate blowing ratios (M = 0.6 or M = 0.9) give higher film cooling effectiveness immediately downstream of the film cooling holes. Further downstream of the holes, higher blowing ratios cover wider surface area.

Cun-liang Liu, Hui-ren Zhu, Jiang-tao Bai, Du-chun Xu [3] have studied the Experimental tests to investigate the film cooling performance of converging slot-hole (console) rows on the turbine blade. Film cooling effectiveness of each single hole row is measured under three momentum flux ratios based on the wide-band liquid crystal technique. Measurements of the cooling effectiveness with all the hole rows open are also carried out under two coolant–mainstream flux ratios. Film cooling effectiveness of cylindrical hole rows on the same blade model is measured as a comparison. The results reveal that the trace of jets from both consoles and cylindrical holes is converging on the suction surface and expanding on the pressure surface by the influence of the passage vortex, while the influence of passage vortex on the jets from consoles is weaker. The film coverage area and the film cooling effectiveness of single/multiple console row(s) are much larger than those of single/multiple cylindrical hole row(s). When the console row is discrete and the diffusion angle of the console is not very large, the adjacent jets cannot connect immediately after ejecting out of the holes and the cooling effectiveness in the region between adjacent holes is relatively lower. On the pressure surface, the film cooling effectiveness of console rows increases notably with the increasing of momentum flux ratio or coolant–mainstream flux ratio. But on the suction side, the increase in cooling effectiveness is not very notable for console row film cooling as the coolant flux increases. Moreover, for the film cooling of single console row at the gill region of the suction surface, the jets could lift off from the blade surface because of the convex geometry of the suction surface.

J.P.E. Cleeton, R.M. Kavanagh, G.T. Parks [4] have studied Humidified gas turbine cycles such as the humidified air turbine (HAT) and the steam-injected gas turbine (STIG) present exciting new prospects for industrial gas turbine technology, potentially offering greatly increased work outputs and cycle efficiencies at moderate costs. The availability of humidified air or steam in such cycles also presents new opportunities in blade and disk cooling architecture. Here, the blade cooling optimisation of a HAT cycle and a STIG cycle is considered, first by optimising the choice of coolant bleeds for a reference cycle, then by a full parametric optimisation of the cycle to consider a range of optimised designs. It was found that the coolant demand reductions which can be achieved in the HAT cycle using humidified or post-aftercooled coolant are compromised by the increase in the required compression work. Furthermore, full parametric optimisation showed that higher water flow-rates were required to prevent boiling within the system. This corresponded to higher work outputs, but lower cycle efficiencies. When optimising the choice of coolant bleeds in the STIG cycle, it was found that bleeding steam for cooling purposes reduced the steam available for power augmentation and thus compromised work output, but that this could largely be overcome by reducing the steam superheat to give useful cycle efficiency gains.

Jury Polezhaev [5] has studied the Gas turbines Blade coolings. He declares that Turbine Blades are rapidly becoming the choice for current and future power generation systems, because they offer efficient fuel conversion and reduced cost-of-electricity. Both of these advantageous features are related to the development of gas turbines with higher firing temperatures and pressure ratios [Keppel, *VGB Kraftwerks-technik* 74, 324 (1994); Batenin *et al., Thermal Engg* 40, 790 (1993); Styrikovich *et al., Thermal Engg* 42, 838 (1995)]. The key to the successful evolution of gas turbine systems is a strong technology base focused on two critical areas: the introduction of new materials and/or the usage of steam for significant increases of turbine blades cooling. Aircraft engines have continued to push both materials and air-cooling technology to achieve operating conditions significantly higher than those introduced into commercial industrial/utility gas turbines. An alternative approach for commercial gas turbines is to move to an alternate cooling medium, e.g. steam [Batenin *et al., Thermal Engg* 40, 790 (1993)]. The use of steam (would require a change in design concept) would introduce the potential for significant increases in firing temperature without the losses associated with increased cooling air extraction. Transpiration gas cooling was selected for the critical high-temperature turbine blade. Cooling gas effused through a porous wire mesh skin to create an insulating film or boundary layer on the outer airfoil surfaces. To optimize steam usage, penetration of porous skin was selected to provide only that quantity of steam to meet constant wall temperature at the local gas steam temperature and pressure conditions. The transpiration gas-cooled blade concept had demonstrated its ability to maintain safe metal temperatures when operating at very high gas stream temperatures. The goal of 60% thermal efficiency for a gas turbine power plant is a major challenge for engineers, but developments to achieve this are already under way.

D. Lakehal, G. S. Theodoridis, W. Rodi [6] have studied that Film cooling of a symmetrical turbine-blade model by lateral and non-lateral injection from one row of holes placed on each side near the leading edge is calculated with a 3D finite-volume method on multi-block grids. For various blowing rates, the flow and temperature fields are predicted, and in particular the contours of film-cooling effectiveness on the blade surface, which are compared with measurements. Various versions of the k–ε turbulence model are employed: the standard model with wall functions (WF), a two-layer version resolving the viscous sublayer with a one-equation model and an anisotropy correction due to Bergeles et al. [Num. Heat Transfer 1 (1978) 217–242] which acts to promote the lateral turbulent exchange. The original Bergeles proposal is modified for application in the viscous sub-layer. With the standard model, the lateral spreading of the temperature field is under predicted, leading to averaged film-cooling effectiveness values that are too low. The situation is improved by using the Bergeles correction, especially when the modified correction is applied with the two-layer model (TLK). This yields effectiveness contours in reasonably good agreement with the measurements, but the laterally averaged effectiveness is not predicted in all cases with good accuracy. However, the trend of the various influence parameters is reproduced correctly.

Mahfoud Kadja, George Bergeles [7] have presented the article on a two-dimensional numerical model for the injection of a fluid through a slot into a free stream. The model is based on a finite-volume integration of the equations governing mass, momentum and heat transport. The solution accuracy was improved by using local grid refinement. The storage of variables was done in a collocated manner, thus allowing the reduction of storage requirements and a more accurate interfacing of the various sub-domains of the grid. The model developed was validated doubly by comparison with available experimental data and the results of an analytical method proposed for two-dimensional injection of an irrotational inviscid fluid.

Innocenti Bruno Facchini, Giovanni Ferrara, Luca [8] has proposed a paper on theoretical study of some alternative solutions to improve the blade cooling in the heavy-duty gas turbine. The study moves to the evaluations of the air coolant reduction temperature effects, considering two different methods: a water surface exchanger (WSE) and a cold water injection (CWI). A logical development of these possible cooling system improvements is the steam cooling application, particularly suitable for mixed or combined gas–steam cycles; the steam cooling is evaluated using open and closed loop configurations; the possible interaction of steam and air cooling is also studied. All the simulation is realized with a family of modular codes developed by authors and the study is conducted with the analysis of the characteristic cooling parameters (efficiency, effectiveness) and by the evaluation of blade temperature distribution. The study is related to a typical configuration of heavy-duty rotor blade with a standard air cooling scheme and the possible variations are related to coolant characteristics only. The results show the interesting possibility due to air coolant temperature reductions, particularly for the CWI method, but the steam cooling turns out to be more incisive. All of the considered techniques show the possibility of a mass coolant reduction and/or the possibility of a maximum cycle temperature increase in comparison to the standard air-cooling. The best results are obtained for an innovative closed–open/steam–air cooling system.

Yiping Lu, David Allison, Srinath V. Ekkad [9] have studied about the detailed film cooling measurements on a turbine blade leading edge model with three rows of showerhead holes. Experiments are run at a mainstream Reynolds number of 19,500 based on cylindrical leading edge diameter. One row of holes is located on the stagnation line and the other two rows are located at 615° on either side of the stagnation line. The three rows have compound angle holes angled 90° in the flow direction, 30° along the span-wise direction, and the two holes on either side of the stagnation row have and additional angle of 0°, 30°, and 45° in the transverse direction. The effect of hole shaping of the 30° and 45° holes is also considered. Detailed heat transfer coefficient and film effectiveness measurements are obtained using a transient infrared thermography technique. The results are compared to determine the advantages of shaping the compound angle for rows of holes off stagnation row. Results show that, the additional compound angle in the transverse direction for the two rows adjacent to the stagnation row provide significantly higher film effectiveness than the typical leading edge holes with only two angles. Results also show that, the shaping of showerhead holes provides higher film effectiveness than just adding an additional compound angle in the transverse direction and significantly higher effectiveness than the baseline typical leading edge geometry. Heat transfer coefficients are higher as the span-wise angle for this study is larger than typical leading edge geometries with an angle of 30° compared to 20° for other studies.

II. EXPERIMENTAL ANALYSIS

A. Modeling

Turbine Blade Model has been imported from the references and the shape, specifications are observed to study the flow rate of the flue gases.

B. Overview of Turbine Blade

Fig. 2.2.1. shows Imported Model of a Turbine Blade.

Fig. 2.2.1. Imported Model of a Turbine Blade

The coolant air is sent through the plenum in the holes to extract heat. FIG. 2.2.2. shows the Imported Model of internal details of a Turbine Blade**.**

Fig. 2.2.3. shows the Sectional Elevation of a Turbine Blade with Cooling Passages

Fig. 2.2.2. Imported Model of internal details of a Turbine Blade

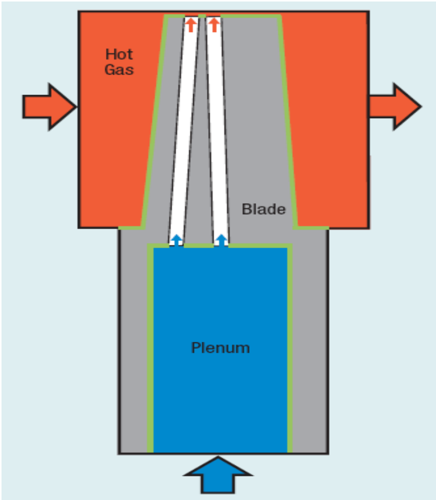


Fig. 2.2.3. Sectional Elevation of a Turbine Blade with Cooling Passages.

III. Blade Specifications

Table 3.1 Blade Specifications.

Number of blades	:	1
Chord length	:	140 mm
Pitch	:	105 mm
Pitch to chord ratio	:	0.75
Axial chord length	:	83 mm
Throat width	:	30 mm
Gauging angle	:	74°
Inlet flow angle	:	0°
Outlet flow angle	:	70°-78°
Stagger angle	:	51.9°
Span	:	454 mm
Trailing edge thickness	:	3.2 mm

A. Schematic Diagram of Turbine Blade

Fig.3.1 shows the Schematic Diagram of a Turbine Blade.

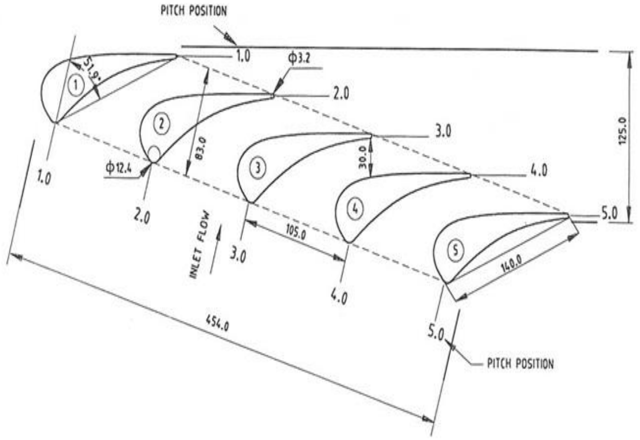


Fig.3.1.1 Schematic Diagram of a Turbine Blade.

B. D Model of a Turbine Blade

Fig. 3.2.1. shows the 3D Model of a Turbine Blade.

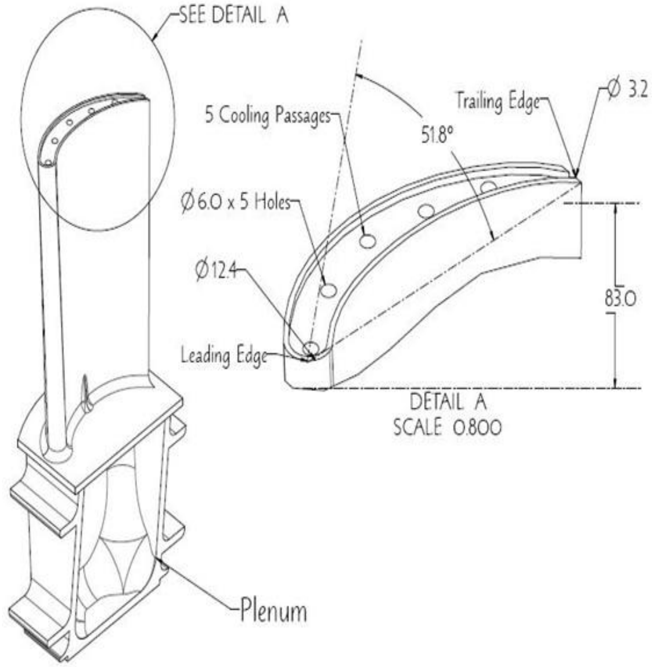


Fig. 3.2.1. 3D Model of a Turbine Blade

C. Shaded Model of a Turbine Blade describing Cooling Passages

Fig. 3.3.1 shows the Shaded Model of a Turbine Blade describing Cooling Passages.

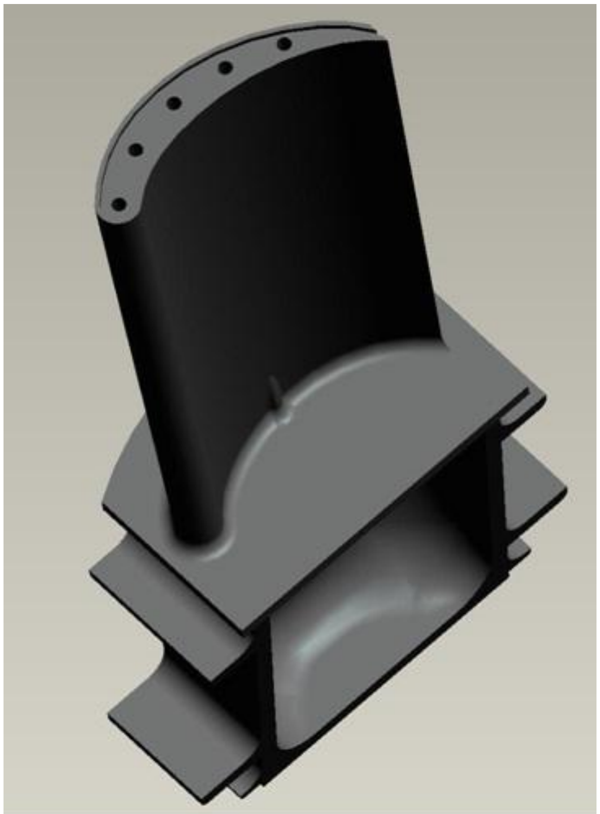


Fig. 3.3.1 Shaded Model of a Turbine Blade describing Cooling Passages

IV. THERMAL ANALYSIS OF BLADE

A. Technical Data Adopted

Blade Surface Temperature	1000 K to 1100 K
Coolant Inlet Velocity	204 m/s
	272 m/s
	340 m/s
Flow Type	Uniform Flow
Diameter of the hole	15mm to 17.5mm
Turbine Blade Material	Cobalt Alloy

B. Meshed View Of Turbine Blade

FIG. 4.2.1.shows the Meshed View of Turbine Blade

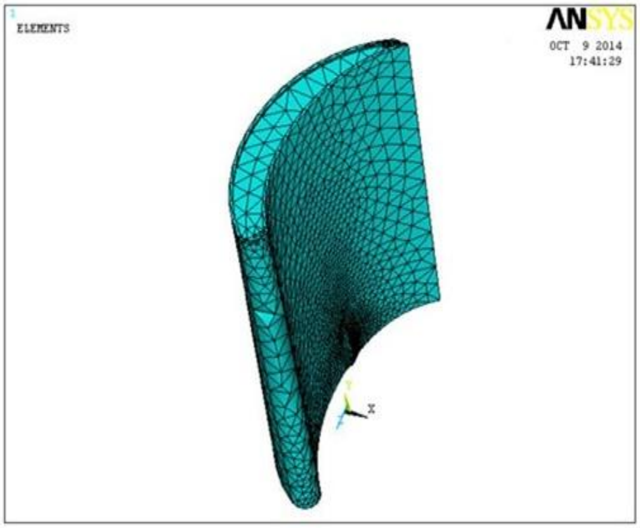


Fig. 4.2.1. Meshed View of Turbine Blade

Results obtained using solid 90 geometry from the Meshed view of the Turbine Blade.

Type of analysis : Thermal
Element Type : 20node90
No. of Node : 17518
No. of Element : 10291

C. Temperature Distribution On Turbine Blade Area

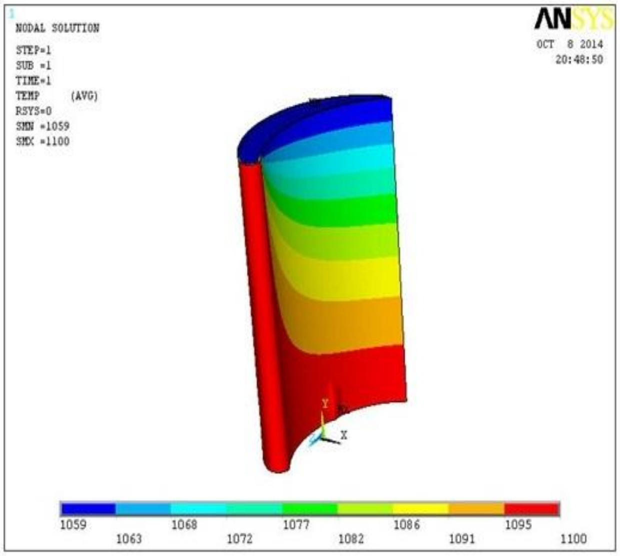


Fig.4.3.1. Temperature Distribution on blade area

Fig. 4.3.1 describes the Temperature Distribution over entire area of turbine blade. The base temperature received (1100K) is distributed along the entire surface area and the temperature distribution at the various segments are observed by ANSYS. Result shows that the top trailing edge exhibit the minimum temperature (1059K). This temperature reduction gained is purely due to temperature distribution along the area and the temperature is reduction obtained by ambient air.

D.Turbine Blade With Cooling Passages

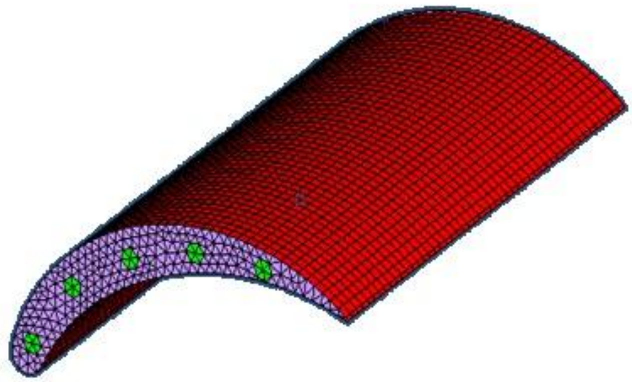


Fig.4.4.1. Meshed View of Turbine Blade with Cooling Passages

The Turbine Blade area with cooling passages considered for temperature distribution is developed by using CFD boundary conditions and the meshed view describes the element and nodal conditions.

E. Temperature Distribution Analysis By Fluent

Analysis has been done for the cooling medium sent through the passages the temperature reduction at the various points of the turbine blade has been observed for various velocities of the cooling medium, that is for v=204 m/s, v=272 m/s, v=340 m/s and Mach Nos. 0.6, 0.8 and 1.0.

4.5.1.CASE : I

Fig. 5.8.1. shows Temperature Distribution for Main fluid Velocity v=204 m/s and Blade Temperature of 1100 K & Mach
Number=0.6

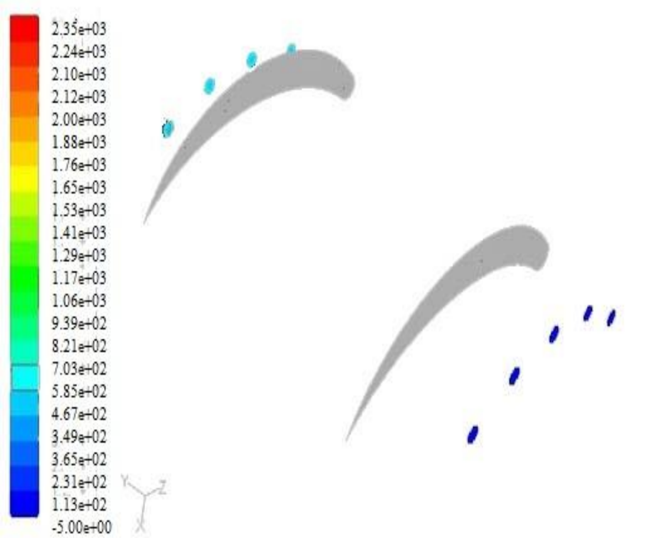
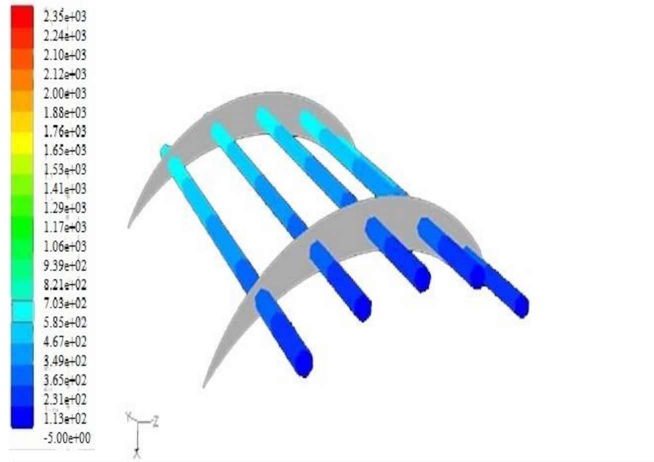


Fig. 5.8.1. Temperature Distribution for v =204 m/s

The result obtained : The Temperature of the cooling medium at the entry point is 113K and the temperature of the cooling medium at the exit point is 703K.

4.5.2. CASE : II

FIG. 5.8.2. shows Temperature Distribution for Main fluid Velocity v= 272 m/s and Blade Temperature of 1100 K& Mach No : 0.8



The result obtained : The Temperature of the cooling medium at the entry point is 113K and the temperature of the cooling medium at the exit point is 703K.

4.5.3.CASE: III

Fig. 5.8.3.shows Temperature Distribution for Main fluid Velocity v=340 m/s and Blade Temperature of 1100 K & Mach no : 1

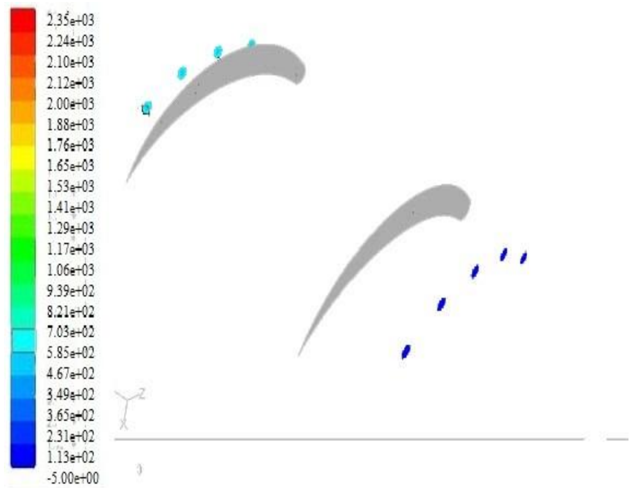


Fig. 5.8.3. Temperature Distribution for v =340 m/s

The result obtained : The Temperature of the cooling medium at the entry point is 113K and the temperature of the cooling medium at the exit point is 703K. By the above analysis by fluent, the results produce the same output (i.e., exit temperature) for various Mach Nos. 0.6, 0.8 and 1.0. So the average output for the various velocities of cooling medium is 713K.

V. RESULT AND DISCUSSION

A. Temperature Difference Achieved For Both The Blade Models

Table.5.1.1. Temperature Difference achieved

Description	Base/Entry Temperature in K	Trailing Edge/Exit Temperature in K	Temperature Difference in K
Temperature Distribution of blade Without Cooling Passages	1100	1059	41
Temperature of the coolant	113	703 (similar TOT for Mach.Nos.0.6,0.8&1.0)	590
Temperature Reduction of blade by cooling passages	1100	510	590

The turbine models are created by PRO/E and the temperature distribution along the turbine area is analysed by ANSYS and the temperature reduction achieved allowing the cooling medium at various velocity rates is observed by CFD.The expected performance is achieved. The temperature has been reduced drastically at the trailing edge of the turbine blade.

VI. CONCLUSION

- The need for high operating pressures and temperatures in turbine blade has been a subject to much discussion and effort over the past years. As temperatures are increased above 1500 K, cooling of turbine blades offers a practical approach with promise of equally high performance.
- This thesis has presented an investigation into the base temperature of a turbine blade when coolant is ejected from the trailing edge at a span-wise angle. Thus the current study measures the effect on the temperature difference when coolant is ejected from the trailing edge of turbine blade.
- Thus temperature reduction rate of the turbine blade without cooling passages is 3.727% and for the blade with cooling passages is 53.63%.
- Hence, internal cooling method is found better to reduce the extreme temperature of the blade and which increases the span of the blade.
- An analytic investigation has been done in this work to increase the Gas Turbine blade cooling. Internal cooing is an effective method to increase the cooling effect. In this investigation has been done for the internal cooling in which extracts the air from the compressor and forcing it through a plenum and into Channel inside the blade.

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