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Thermal Analysis of High Pressure Turbine Blade Platform for an Aero Gas Turbine Engine using Fem Analysis

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***Abstract:* -- To increase thermal efficiency, advanced gas turbine is designed to operate at increasingly higher temperature. Since the gas temperature exceed the allowable material temperature, cooling techniques of turbine components are increasingly important. Film cooling is a standard method applied to turbine blades and vanes, whereby cold air is injected from small holes which forms a thin layer over walls and protects the wall from high temperature gases.**

This study describes thermal analysis of film cooled High Pressure Turbine (HPT) blade platform for an Aero Gas Turbine engine using FEM analysis; platform is exposed to combustor exit gas temperature of 1700K and the coolant air at 800K temperature. During this work the coefficient of discharge (Cd) and film effectiveness (ε) of film cooling holes is estimated from CFD analysis. Film cooling adiabatic effectiveness estimation is done using Fluent commercial code, Version 14.5. For the Flat plate film cooling model three different RANS turbulence models are studied

I. Realizable k-ε turbulence model with enhanced wall treatment.
II. Standard k-ω turbulence model.
III. SST K-ω turbulence model.

With the cooling hole inclined at Ө the study is performed at density ratio 1.6 with the mainstream and coolant temperatures at298k and 188K respectively and for two different blowing ratios 0.5 and 1. Centreline adiabatic effectiveness and spanwise adiabatic effectiveness is extracted from the different models and compared with the experimental results. The predicted effectiveness and experimental data are in good agreement. The CFD prediction over predicts the effectiveness. Good quality hexa-mesh is created using ICEM CFD multi-blocking method. HPT blade top and bottom platforms is meshed using Tri elements in HYPERMESH and thermal analysis is performed in ANSYS APDL.The calculated adiabatic wall effectiveness is used to calculate the adiabatic wall temperature for both platforms. Isentropic mass flow, coefficient of discharge and blowing ratio through each film hole is determined. Convective HTC (Heat Transfer Coefficient) within the film hole, on the coolant side and along mainstream gas side is calculated based on geometric and flow parameters. Platform metal temperatures are estimated by considering the film cooling effect only and also the effect of impingement cooling combined with film cooling is considered.

***Key words*: ICEM, Film cooling, RANS Model, adiabatic effectiveness, cylindrical hole, CRVs, FEM, HPT NGV, HYPERMESH, HTC..**

I. INTRODUCTION

The advance gas turbine engine operates at high temperatures (1200-1800K) to improve thermal efficiency and power output. As the turbine inlet temperature increases the heat transferred to the turbine blade also increases. The level and variation in the temperature within the blade material (which causes thermal stress) must be limited to achieve reasonable durability goals [1].

The operating temperature is far above the permissible metal temperature. Therefore there is a need to cool the blade for safe operation. The blades are cooled by extracted air from the compressor ofthe engine. Since this extraction includes a penalty to the thermal efficiency, it is necessary to understand and optimize the cooling technique, operating conditions, and turbine blade geometry. Gas turbine blades are cooled internally and externally.

Internal cooling is achieved by passing the coolant through several enhanced serpentine passages inside the blades and extracts the heat from the outside of the blades. Both the jet impingement and pin fin cooling are also used as method of internal cooling. External cooling is also called as film cooling. Internal cooling air is ejected out through discreet holes or slots to provide a coolant film to protect theoutside surface of the blade from hot combustion gases [2].

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Vol 2, Issue 5, May 2017

First stages of gas turbines located just downstream of the combustion chamber require a large amount of cooling air to survive the harsh environment with hot gas temperatures in the range of 1200-2000 K. Spending compressed air is expensive in terms of thermal efficiency of the gas turbine cycle. A well utilized method to increase the cooling efficiency is to eject thecoolant through small holes distributed on the wall surfaces of the blade passages to provide a protective film between hot gas and surface thereby reducing the heat transfer into the wall. Such “film cooling” is thus attractive for the highly cooled Nozzle Guide Vanes (NGV). The hot gas flow field varies significantly around the turbine parts. For example, the hot gas flow velocity varies from very low velocities at the inlet until transonic flow, thus leading to changing compressibility in accelerating and diffusing flow regions. Therefore there exist distinctly different regions on a vane component with respect to heat transfer [7].
Comparison of RANS turbulence models for predication of film cooling performance BY Katharine L. Harrison and David G. Bogard (2008) used the realizable k-ε, standard k-ω, and RSM turbulence models to stimulate flat plate film cooling experiments. Adiabatic stimulation revealed that using the standard k-ω model resulted in the closest agreement with experimental determined laterally averaged adiabatic effectiveness, but the worst agreement with centreline adiabatic effectiveness. Conversely, the realizable k-ε model agreed worst with experimental laterally averaged adiabatic effectiveness values and best with centreline values. Use of the anisotropic RSM model was not found to predict more realistic coolant spreading than the other models. Simulation to find heat transfercoefficient without film cooling showed good agreement with correlation for all three models, and closest agreement resulted from using the realizable k-ε model[5].

Numerical study on flat plate and leading edge film cooling by Eiji Sakai et.al (2009) Studied and described a 3-D computation for film cooling effectiveness investigation using fluent commercial code, Version 6.2. Two simulations, lateral spreading of film cooling is under-estimated in the RANS simulation, while in the DES, lateral spreading of film cooling is enhanced and shows adequate agreement with the previous experiments. Configurations examined are: (1) Flat plate, and (2) Semi-cylindrical leading edge with a flat after-body. Three different RANSturbulence models and DES based on Spalart-Allmaras model are utilized to see the difference in accuracy between DES and RANS approaches. In RANS simulation, lateral spreading of film cooling is under-estimated in the RANS simulation, while in the DES, lateral spreading of film cooling is enhanced and shows adequate agreement with the experiments results. [6].

II. PROBLEM DESCRIPTION

Thermal analysis of film cooled High Pressure Turbine (HPT) blade platform for an Aero Gas Turbine engine using FEM analysis is performed. The platform is exposed to combustor exit gas temperature of 1700K and the coolant air is at 800K temperature. During this work the coefficient of discharge (Cd) and film effectiveness (ε) of film cooling holes is estimated from CFD analysis. Film cooling adiabatic effectiveness estimation is done using Fluent commercial code, V14.5. For the Flat plate film cooling model three different RANS turbulence models are studied.

COMPUTATIONAL DOMAIN:

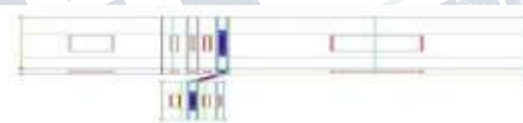


Fig.1 Computational Domain

The above figure shows the computational domain that is employed for the CFD analysis, the detail configuration of the model is given in the literature [3].This model is used to estimate the centreline and spanwise adiabatic effectiveness for the three different RANS models.

III. GRID GENERATION

Accuracy of CFD solutions is strongly depending on grid size. The 3D grid is generated for the computational domain using hexa mesh. The hexa mesh is generated in Ansys pre-processor shown in Fig.2. In the regions near to the bottom surface of the wall very fine mesh in done in order where the variations of flow parameters are expected to be high, fine grids are used for accurate simulation maintaining value of y+ < 1. The region near the wall is finely meshed to accurately visualise the boundary layer turbulence characteristics. A growth rate of 0.0154 is used for grid generation near the wall. The grid size is gradually expanded as it situated away from wall as shown in Fig.2.

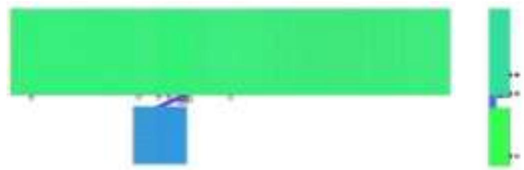


Fig.2 Computational Grid

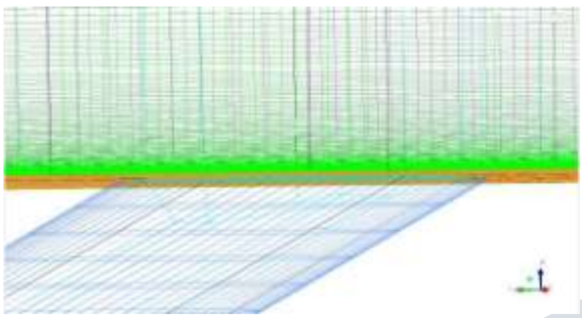


Fig.2.1 Fine mesh near the bottom wall of mainstream domain

IV.FORMULATION AND NUMERICAL METHOD OF SOLUTION

In the present study, the flow in the computational domain is assumed to be steady, non- reacting and turbulent. The steady state pressure based solver is employed to solve the computational domain. The discretization of the flow and the turbulence equations are second order upwind scheme and are solved through the segregated implicit method. Convergence is considered to be achieved when all the residual values are less than 1x10-6.Three different RANS models, Realizable k-ε turbulence model with enhanced wall treatment. Standard k-ω turbulence model, SST K-ω turbulence model are used for the CFD analysis.

V.BOUNDARY CONDITIONS

Boundary conditions specify the flow and thermal variables on the boundaries of the physical model. They are a critical component of the simulation and it is important that they are specified appropriately. Velocity boundary conditions are used to define the fluid velocity at flow inlets and the temperature at the mainstream and coolant inlet are defined along with all other properties of the flow. This condition is suitable for incompressible ideal gas, and the Mach number is maintained subsonic for this reason.Incompressible ideal gas is used as the material property of air (density). The one of the adjacent planes of the duct is modelled as symmetry. The table 1.1 shows the boundary conditions applied to the model for blowing ratio of 0.5and 1

B.R=0.5	**Coolant side**	**Mainstream side**
Inlet velocity(m/s)	6.25	20
Temperature(k)	188	298
Operating pressure(Pa)	101325	

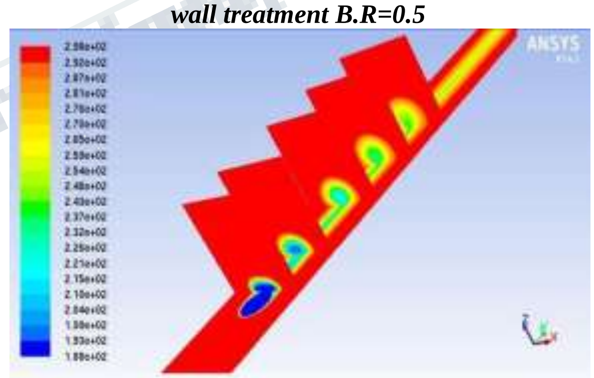
B.R=1	**Coolant side**	**Mainstream side**
Inlet velocity(m/s)	12.81	20
Temperature(k)	188	298
Operating pressure(Pa)	101325	

Table 1.1Boundary conditions applied at BR of 0.5 &1

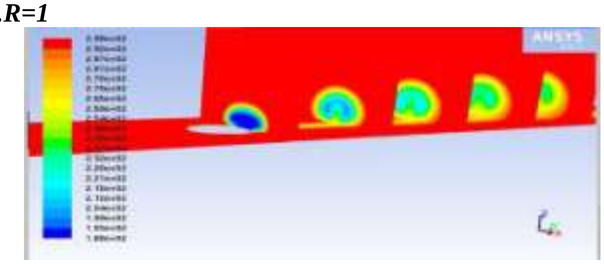
VI. CONTOURS OF STATIC TEMPERATURE FOR DIFFERENT MODELS

In order to get the better visualisation of flow of coolant and mainstream an isosurface is created at a distance of D, 2D, 4D, 6D, and 8D

MODEL1: Realizable k-ε Turbulence Model with Enhanced wall treatment B.R=0.5



B.R=1



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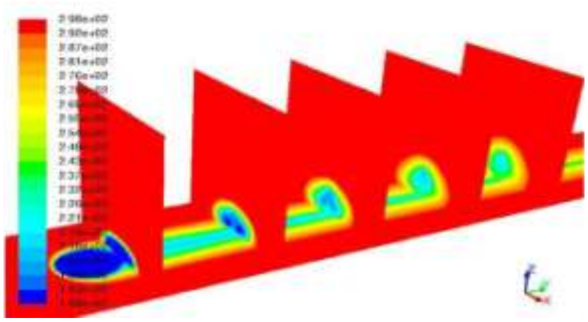
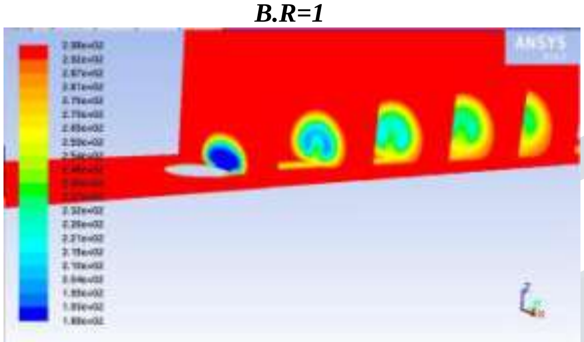
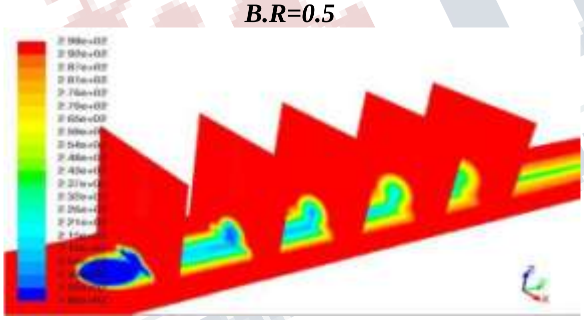
Model 2: Standard k-ω turbulence model
B.R=0.5



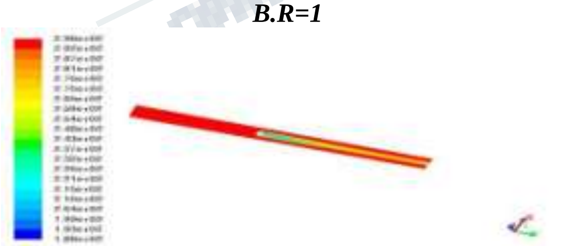
B.R=1



Model 3: SST k-ω turbulence model
B.R=0.5



B.R=1



VII. SELECTION OF SUITABLE TURBULENCE MODEL

CFD study is carried out over cylindrical hole model which is inclined at Θ for a blowing ratio of 0.5 to determine the suitable turbulence model that can give results closer to the experimental results for both centreline effectiveness and spanwise effectiveness. Realizable k-ε turbulence model with enhanced wall functions, Standard k-ω turbulence model and k-ω SST turbulence model are considered for this CFD analysis

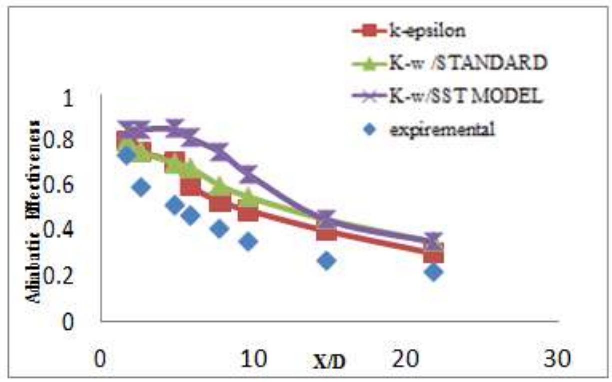


Fig.4 Comparison of experimental and CFD film effectiveness (centerline) for cylindrical hole model

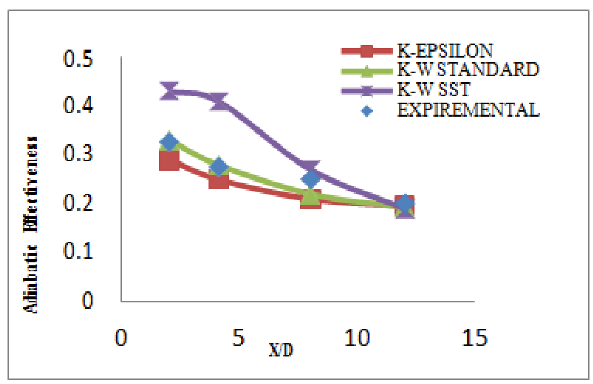


Fig.5 Comparison of experimental and CFD film effectiveness (spanwise) for cylindrical hole model

Figure 4 and Figure 5 show the comparison of centreline film cooling effectiveness and spanwise film cooling adiabatic effectiveness between experimental data &CFD data for k-ε model, standard k-ω, k-ω SST model forcylindrical hole model respectively. The analyses are carried out at blowing

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Vol 2, Issue 5, May 2017

ratio of 0.5. It is clear from the figure 4 that the CFD results with Realizable k-ε Turbulence Model with Enhanced wall treatment predict centreline adiabatic effectiveness closer to the experimental value compared to other models but k-ε slightly disagreedwith the experimental span wise average adiabatic effectiveness value , but standard k-ω model resulted in the closest agreement with experimentally determined spanwise averaged adiabatic effectiveness but slightly disagreed with centreline adiabatic effectiveness. And in case of SST k-ω turbulence model resulted in the large deviation for both the centreline adiabatic effectiveness and the span wise adiabatic effectiveness.

The adiabatic effectiveness obtained from the CFD results is used to calculate the adiabatic wall temperature of HPT platforms.

VIII. NOZZLE GUIDE VANE

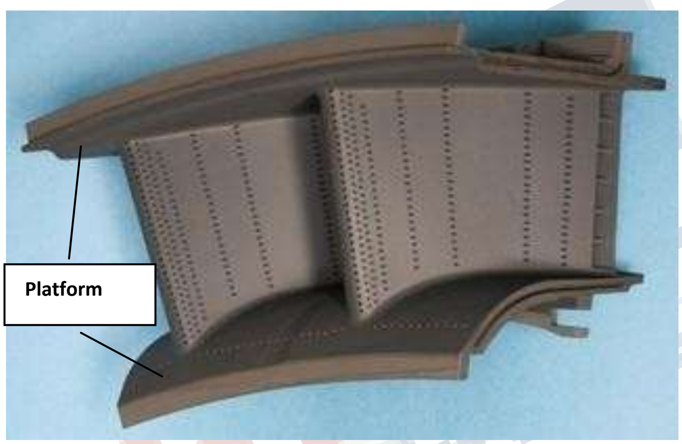


Fig.6Nozzle guide vane

Guide vanes are stationary and are used to guide the flow over the rotor blade smoothly and increase the velocity of the flow to the required extent. These guide vanes are the prime facie of high temperature high pressure gas coming out of combustion chamber when used for high pressure turbine. The Nozzle Guide Vanes (NGV) of a turbine are convex and shaped like airfoils as shown in Fig 6 Gas coming from the combustion chamber passes through the nozzle guide vanes, where because of their convergent shape accelerates.

IX.TOP PLATFORM MODEL OF HPT

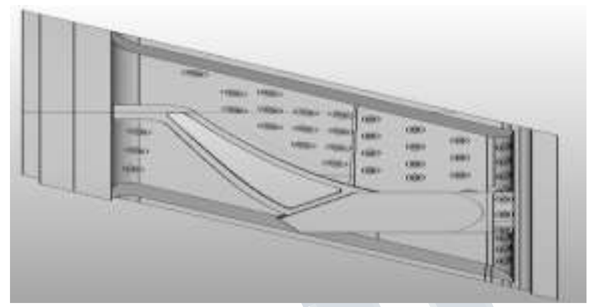


Fig.7 Top view

The top platform model of a HPT NGV consists of 42 film cooling holes. Out of 42 holes, 16 holes are arranged along the direction of flow of mainstream, 21 holes are arranged in an angle to the mainstream flow and 5 holes are provided on the platform walls as shown in figure 7.These holes are arranged in different direction in order to check whether the coolant will flow properly over the surface or not. for example if the velocity of the mainstream in very high and the coolant hole are made only in the direction of mainstream then these coolant air is blown off by the mainstream, so in order to overcome this problem holes are inclined at anangle to themainstream as shown in figure 7.When thesecooling holes are arranged in at an angle to the mainstream then this coolant air offers the resistant to the mainstream which causes the velocity drop at that point and avoids the blowing off of the coolant in the mainstream. Then we need to identify nature of the flow of the mainstream because on these platforms rotor curvature and edges of the platforms is present because of which a vortex flow is created. In some location this vortex flow is beneficial for the film cooling but some time it hinders the film cooling so we need to identify it using CFD.

X. BOTTOM PLATFORM MODEL OF HPT

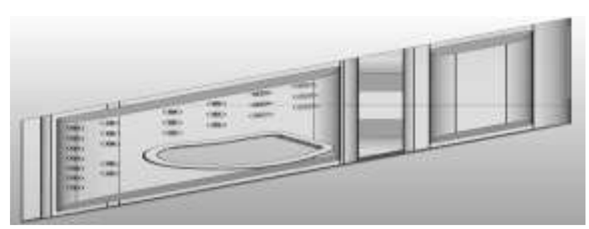


Fig.8 Top view

The bottom platform model of a HPT NGV consists of 24 film cooling holes.In these 6 holes are arranged along the direction of flow of mainstream, 18 holes are arranged in an angle to the mainstream flow as shown in figure 8.These holes are arranged in different direction in order to create the necessary velocity drop and to achieve the effective film cooling

XI. TOP PLATFORM MODEL MESHING

Fig.9Top platform model meshing

1) Software Used: Hyper Mesh V12
2) Element Type: Tri, 3d Mesh
3) Mesh Density: 3, 69,307 Nodes 20, 49,040 Elements
4) Mesh Quality: Warpage: 0

Aspect Ratio: 5
Skew: 49.82
Jacobian: 0.60

XII. BOTTOM PLATFORM MODEL MESHING

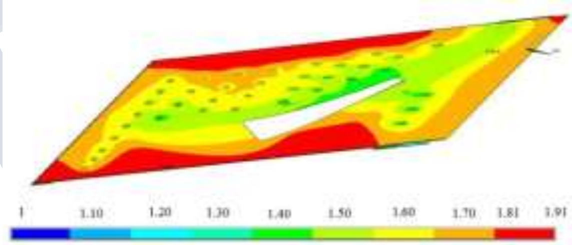
Fig.10Bottom platform model meshing

1) Software Used: Hyper Mesh V12
2) Element Type: Tri, 3D Mesh
3) Mesh Density: 3, 64,869 Nodes 2026354 Elements
4) Mesh Quality: Warpage: 0

Aspect Ratio: 5.19
Skew: 44.28
Jacobian: 0.62

XIII. RESULTS AND DISCUSSIONS

Thermal analysis is carried in ANSYS APDL & SOLID 70 is assigned as element type
Case: 1
(Film cooling with coolant HTC 100)
Top platform



Bottom platform

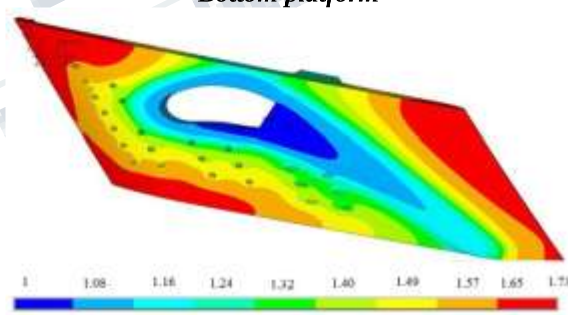


Fig.11 Considering Film cooling

During this case different convective HTC value is given inside the holes and constant HTC of the coolant is given on the coolant side i.e. 100 W/m2K. Similarly constant HTC is given on the mainstream hot gas side for the different zones i.e. 3400W/m2K. From the figure it is observed that at the leading edge and the trailing edge and some part near the edges of the platform temperatures are high because there is no film cooling holes due to which there will be no cooling near these surface .But near the holes and aerofoil surface there is a considerable drop in temperature due to the effect of coolant across these regions.

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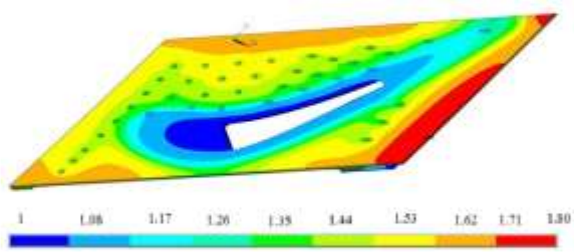
Vol 2, Issue 5, May 2017

Case: 2 (by taking impingement cooling into consideration)

Top platform



Bottom platform

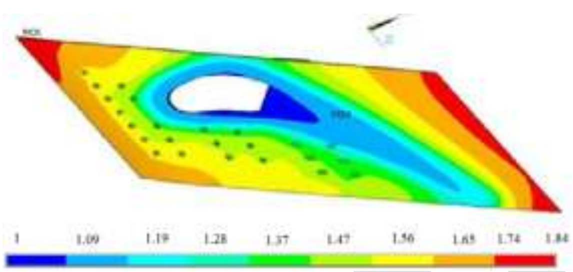


Fig.12 Considering Impingement cooling and film cooling

In this case an impingement cooling on the coolant side is also taken into consideration along with the film cooling. As a result of the combined effects of impingement and film cooling there is a great reduction in the temperature on the surface of the platform. But at some regions of the leading edge and trailing edge temperature is more compared to other region, this is due to the absence of the film cooling holes.

XIV.CONCLUSION

Thermal analysis of high pressure turbine blade platform for an aero gas turbine engine has been carried out using ANSYS FEM analysis. CFD analysis is done on a flat plate model for film cooling studies using different turbulence models, the respective adiabatic centerline and span wise effectiveness is calculated and this effectiveness are compared with the experimental results.

1) CFD results with Realizable k-ε Turbulence Model with Enhanced wall treatment predict centerline adiabatic effectiveness closer to the experimental value compared to other models but k-ε slightly disagreed with the experimental span wise average adiabatic effectiveness value ,

2) Standard k-ω model resulted in the closest agreement with experimentally determined spanwise averaged adiabatic effectiveness but slightly disagreed with centerline adiabatic effectiveness.

3) SST k-ω turbulence model resulted in the worst agreement for both the centerline adiabatic effectiveness and the spanwise adiabatic effectiveness.

4) Coolant air heat transfer coefficient of 100 W/m2K is considered and it is observed that effect of coolant is improved and good temperature distribution profile is visualized. Convection inside holes also helps to reduce temperatures significantly

5) Impingement cooling is taken into consideration along with the film cooling. Due to the combination of both types of cooling the heat transfer coefficient of coolant air reaches 2000 W/m2K. This results in a great reduction in the temperature on the surface of the platform.

NOMENCLATURE

B.r⇨ Blowing Ratio
Cfd⇨ computational fluid dynamics fem⇨ finite element method
HTC⇨ Heat Transfer Coefficient

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