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Heat Transfer Analysis of Gas Turbine Rotor Blade Cooling Through Staggered Holes using CFD

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Abstract:- **In a gas turbine engine, the turbine blade operated higher temperature then the melting point of the blade material. Cooling of gas turbine blades is a major consideration for continuous safe operation of gas turbines with high performance. Several methods have been suggested for the cooling of blades and one such technique is to have radial holes to pass high velocity cooling air along the blade span. In the present work CFD analysis is used to examine the heat transfer analysis of gas turbine with six different model consisting of 5,9&13 inline one row of holes and compared with 9&13 model in staggered holes arranged in the three rows and developed a new model with 14 holes in the staggered arrangement. The prediction is commonly used CFD software FLUENT (a turbulence realizable k-e model with enhanced wall treatment). On evaluating the contour plot of the pressure, velocity& velocity vector we found that the temperature distribution on the 13 staggered holes, uniformly distributed along the blade area, as compared to 13 inline holes. And the heat transfer is also increases in the 13 & 14 staggered holes arrangements.**

Key Words- Computational fluid dynamics (CFD), staggered holes, Heat transfer rate, CAD, Turbulent-Intensity model.

I. INTRODUCTION

A gas turbine is also called a combustion turbine is a type of internal combustion engine. Gas turbines are the prime movers, which is used in many industries such as power generation, aircraft propulsion and in processing plant. the gas turbine is found in most common form of rotary heat operator in which there are various processes such as air taken from the atmosphere , temperature of gas increases and fuel is burnt in constant pressure process continuously.
The gas turbine used in power plant, where a great amount of energy produces for its weight and size. Gas turbine engine is a single turbine section which is made from Disk or Hub, and this disk or hub holds number of turbine blades. Turbine section is connected to compressor section through shaft, and this shaft is also called as Spool. There are two types of compressor section can be used Axial or Centrifugal. In compressor the temperature and pressure of air increases and air will be compressed. Most of the gas turbine engines having twin spool design means high pressure spool and low pressure spool but some gas turbines using three spools, Intermediate pressure spool between the high and low pressure spool.

Turbine Blade

A turbine blade is a component which made the turbine section of a gas turbine. The blades are extracted energy from the high temperature, and high pressure gas produced by the combustor. the turbine blades are the limiting component the gas turbines. Modern gas turbines are operated at very high temperatures (1250-1550C) for increasing power output, thermal efficiency and performance of the turbines. But material melting temperature of the turbine blades may exceed the limiting factor. Hence proper cooling system is used for the cooling of the turbine blades for their long life. Blades of gas turbine can be cooled either internally or externally.

Methods of Cooling

Components of gas turbine can be cooled by **air** or **liquid cooling**. Liquid cooling is more attractive because of high specific heat capacity and evaporative cooling but liquid cooling having problem of corrosion, choking, and leakage. Air cooling allows the discharged air into main flow without any problem. For air cooling less quantity of air required such as 1.5-3% of main flow and blade temperature can be reduced by 250-300C. There are many types of cooling used in gas turbine blades.

1. ***Internal Cooling***
   - Convection cooling.
   - Impingement cooling.
2. ***External Cooling***
   - Film cooling.
   - Cooling effusion.
   - Pin fin cooling.
   - Transpiration cooling.

II. LITERATURE REVIEW

K hari brahmaiah et.al.[1]- Examine the heat transfer analysis of gas turbine with four different models consisting of blade with and without holes and blades with varying number of holes(5,9&13) were analyzed. Transfer rate and temperature distribution, the blade with 13 holes is considered as optimum. Steady state thermal and structural analysis is carried out using ANSYS software with different blade materials of Chromium steel and Inconel-718. While comparing these materials Inconel-718 is better thermal properties and induced stresses are lesser than the Chromium steel.

R d v Prasad et.al.[2]- Examine steady state thermal& structural performance for N155& Inconel 718 nickel-chromium alloys. Using finite element analysis Four different models consisting of solid blade and blades with varying number of holes (5, 9&13 holes) were analyzed of cooling holes. The analysis is carried out using ANSYS software package. While comparing materials, it is found that Inconel 718 is better suited for high temperature .the graphs drawn for temperature distribution, von-misses stresses and deflection, the blade with 13 holes is considered as optimum. the induced stresses are minimum and the temperature of the blade is close to the required value of 800C.

B deepanraj et.al.[3]- using finite element analysis thermal and structural performance due to loading condition, with material properties of Titanium- Aluminum alloy. Six different models with different number of holes (7, 8, 9, 10, 11&12) were analyzed. Using ANSYS, bending stress, deflection, temperature distribution, for number of holes are analyzed. 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, the temperature near to the required value i.e., 800C is obtained.

G. Narendranath et.al.[4]- examine the first stage rotor blade off the gas turbine analyzed using ANSYS 9.0. The material of the blade was specified as N155. Thermal and structural analysis is done using ANSYS 9.0 Finite element analysis software. The temperature variations from leading edge the trailing edge on the blade profile is varying from 839.5310C to 735.1620C at the tip of the blade. It is observed that the maximum thermal stress is 1217 and the minimum thermal stress is the less than the yield strength value i.e., 1450.

V.Vijaya Kumar et.al.[5] - examine the "preliminary design of a power turbine for maximization of an existing turbojet engine". For a clear understanding of the combined mechanical and the thermal stresses for the mechanical axial and centrifugal forces. The peripheral speed of rotor and flows velocities is kept in the reasonable range so to minimize losses. In which the base profiles is analyzed later for flow condition through any of the theoretical flow analysis method such as "potential flow approach".

III. METHODOLOGY

CFD (computational fluid dynamics) analyzes thermal analysis by computer based simulation these analysis are based on the fluid flow, heat transfer, and related phenomenon such as chemical reactions. This project uses CFD analysis of flow and heat transfer. The application areas of gas turbine are aerodynamics lift and drag (i.e. airplane or windmill wings), power plant combustion, chemical processes, heating/ventilation and even biomedical engineering (simulating blood flow through arteries and veins). CFD analysis is carried out in the various industries are used in R&D and manufacture of aircraft, combustion engines, as well as many other industrial products.

The general concepts and theory related to using CFD to analyze heat transfer as relevant to this project. It begins with a review of the tools needed for the carrying out the CFD analysis and processes required, followed by a summery of the governing equations and turbulence models and solution algorithm is presented.

Basic steps to perform CFD analysis-

1) Preprocessing

- **CAD Modeling-** The generation of model is done on the CAD modeling. In the working plane the key points created and these points are joined by spline curves through spline command in CAD to obtain a smooth contour. By extrude command the contour (2D model) is then converted into area and then volume (3D model) was generated. The hub is generated through rectangle

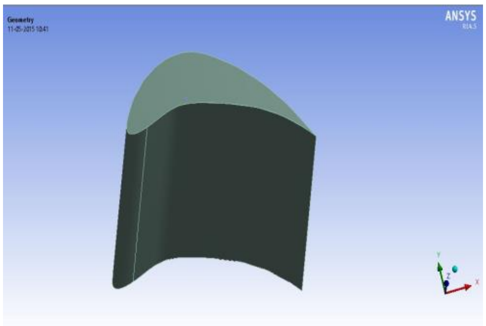

Fig.1 Blade geometry

command a rectangle is created in 2D model and then this 2D model is converted into 3D model and then extrude command is used. And finally these two volumes are combined into single volume.

- **Meshing-** In this operation, the CAD geometry is descretized into large numbers of small elements and nodes. The arrangement of nodes and elements in space in a proper manner is called mesh. Various models of blade profile with holes and their meshing are shown in figure. In the blade profile without holes is **No of elements = 150240, No of nodes =166911**

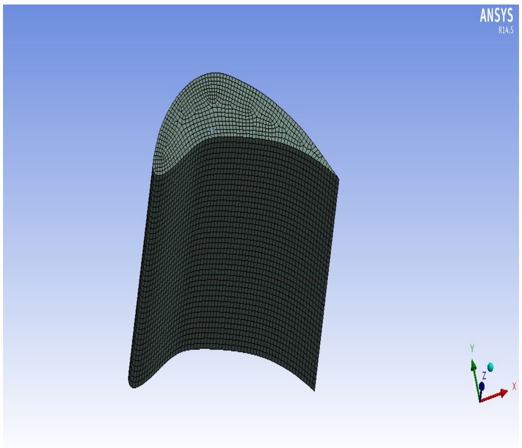

Fig.2 Meshing of the blade profile.

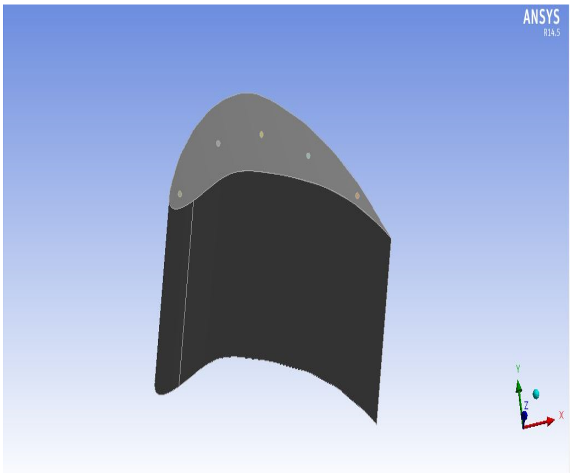

Fig. 3 Five inline holes

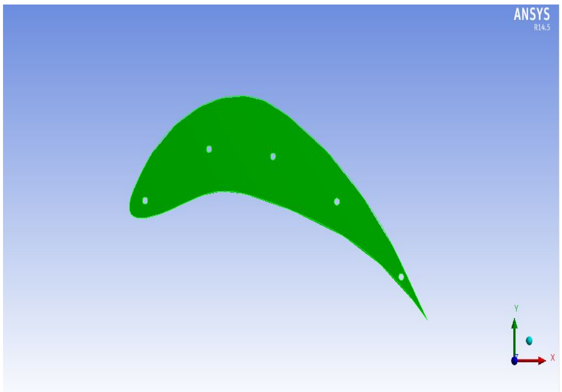

Fig.4 Blade profile with holes.

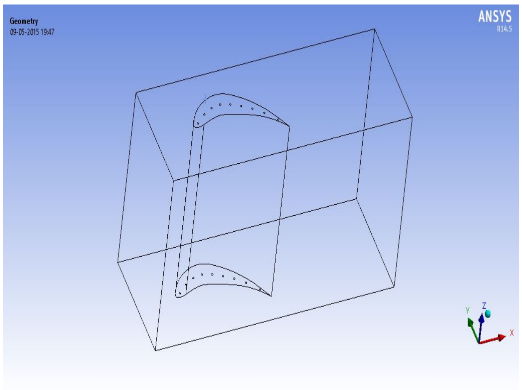

Fig.5 CAD Model of 9 inline holes.

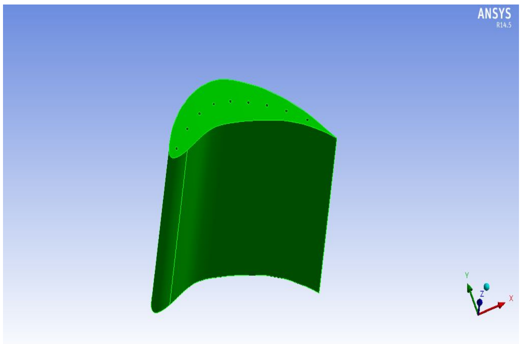

Fig.6 Blade profile of 9 inline holes

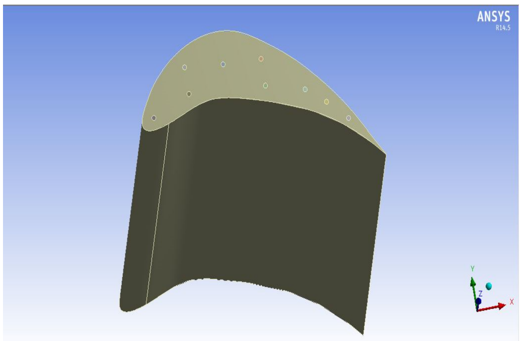

Fig.7 Blade profile 9 staggered holes.

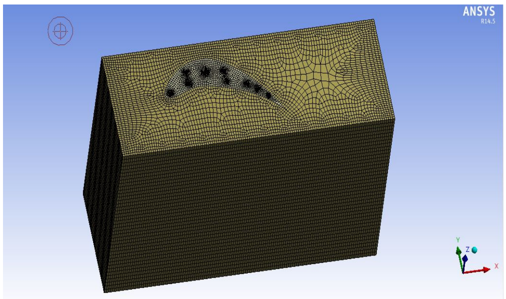

Fig.8 meshing of 9 staggered holes.

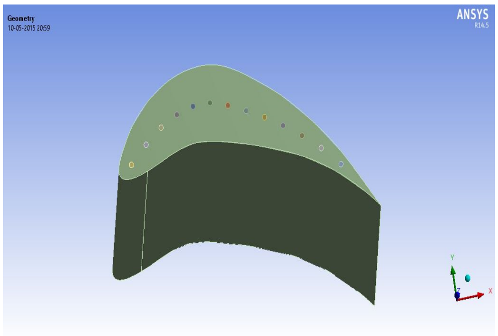

Fig 9 blade profile 13 inline holes

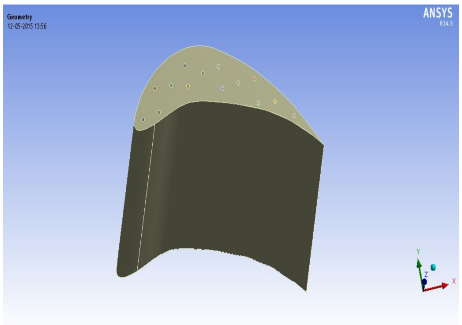

Fig 10 Blade profile 14 staggered holes

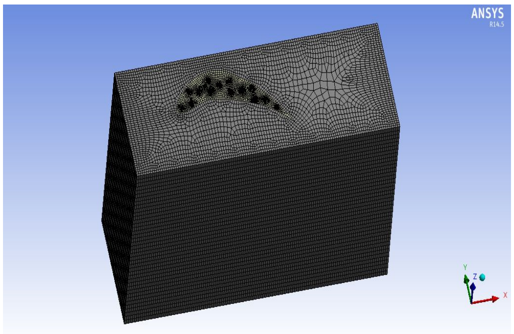

Fig 11 Meshing of 14 staggered holes.

IV. NOMENCLATURE

α Coefficient of thermal expansion
E Young's modulus
μ Poisson's ratio
L Length
D Diameter of shaft
N Speed of turbine in RPM
K Thermal conductivity
d Diameter of cooling air passage

Details of turbine blade-
D = 1308.5 mm, N = 3426 RPM, L = 117mm, d = 2mm

2) Solution

- **Type of solver-** Pressure based.
- **Physical model-** Turbulent (k-e), energy equation.
- **Material property-** Property of fluid such as air.
- **Boundary condition-** Pressure, velocity inlet, velocity outlet wall etc.
- **Solution method-** Choosing the solution method such as momentum equation, turbulent energy equation etc.
- **Solution initialization-** Initialize the solution to get the initial solution of the problem.
- **Run solution-** Run the solution by giving no of iteration for solution to converge.

3) Post processing

Post processing is used for viewing and interpretation of result. The results can be viewed in various animations, graph etc.

Table 1- Mechanical properties of Chromium steel and Inconel 718

Properties	Units	Chromium steel	Inconel 718
E	Mpa	80705	205005
P	Kg/m^3	7754	8192
K	W/m-k	24.5	25.8
μ	- - -	0.291	0.293
Cp	j/kg-k	435.801	586.253
Melting point	^{0}C	1415	1346
Yield stress	Mpa	656	1068

V. RESULT ANALYSIS

The temperature distribution and total heat transfer rate of the blade depends on the heat transfer coefficient for gases and the thermal conductivity of the material. The calculation of heat transfer coefficient is doing by some iterative methods such as turbulence realizable(k-e) models. It is observed that the maximum temperatures are prevailing at the leading edge of the blade. There is a temperature fall from the leading edge to the trailing edge. In first observation of the blade with 9 inline holes drilled readily to pass the cooling air through cooling holes , it can be observed from the fig 12 the temperature at the cooling holes is lower.

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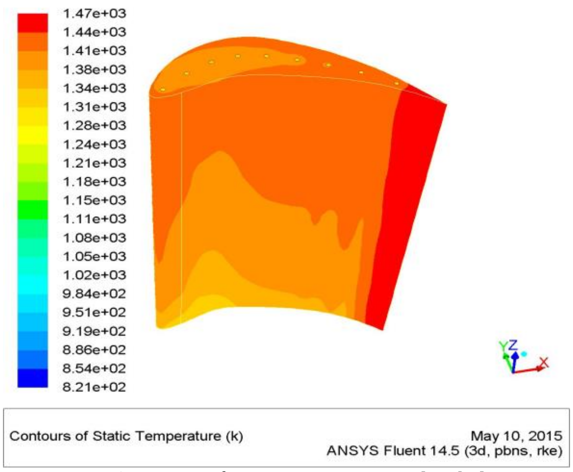

Fig.12) Contour of static temperature 9 inline holes.

But if I drilled the 9 holes in staggered form then the temperature variation are shown in figure. The temperature of the blade is lower more then inline drilled holes. The blade temperature decreases 1397.663K to 1343.653K in the same number of the holes only changing on the arrangement. In the fig 13 holes are drilled in the one line then the blade temperature were obtained as 1301.362K. and on the staggered 13 holes two row the tempera ion were obtained as 1303.689K. but the uniformity of the temperature distribution is better in the fig 13 as compared to the fig 12.

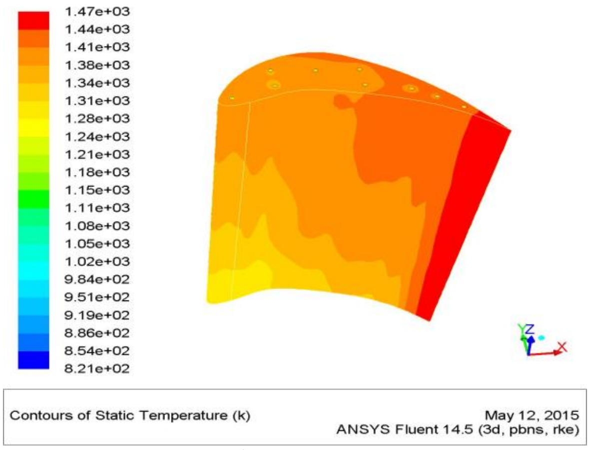

Fig.13) Contour of static temperature 9 staggered holes.

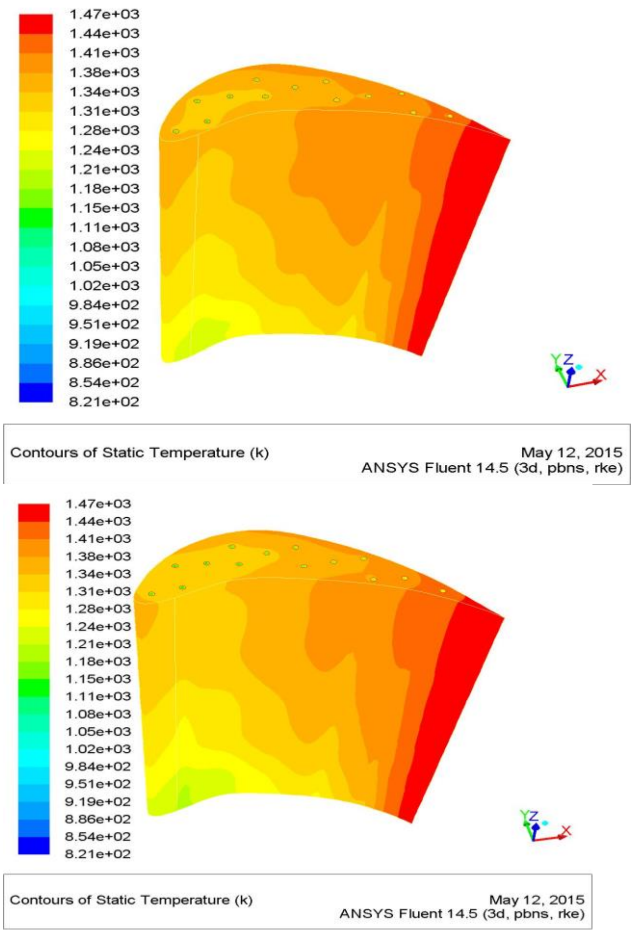

Fig.14) Contour of static temperature of 13 inline and staggered holes

Up to the 13 inline holes studies are concerned that the number of holes are restricted because RDVPrasad obtained the minimum temperature as 1099.96K at the 13 holes and K Hari Brahmaiah also obtain 1112K but I obtained the 1303.689K at the 13 holes in staggered form. As both are explained that the decreasing temperature will lead to lower the thermal efficiency, because larger portion of air is utilized for cooling purpose and reduced quantities of air flows into the combustion chamber of gas turbine plant. The reduced mass flow rate of the gas and the decreased temperature of the blade will reduce the power output and efficiency of the plant. But at the 13 holes I obtained the temperature 1303.689K at the same material. So that I have studied on the 14 holes drilled in the staggered form and the temperature is obtained as 1291.784K.

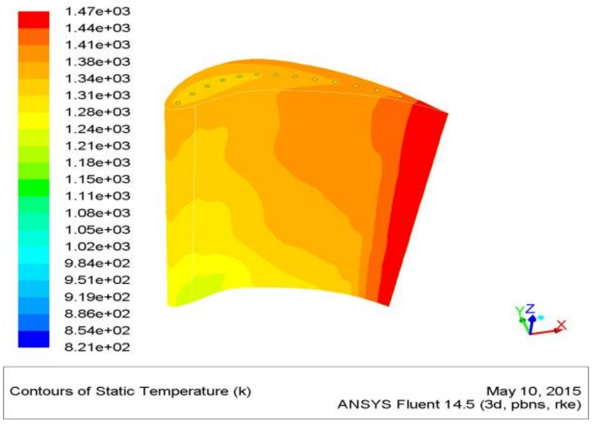

Fig.15) Contour of static temperature of 14 staggered holes

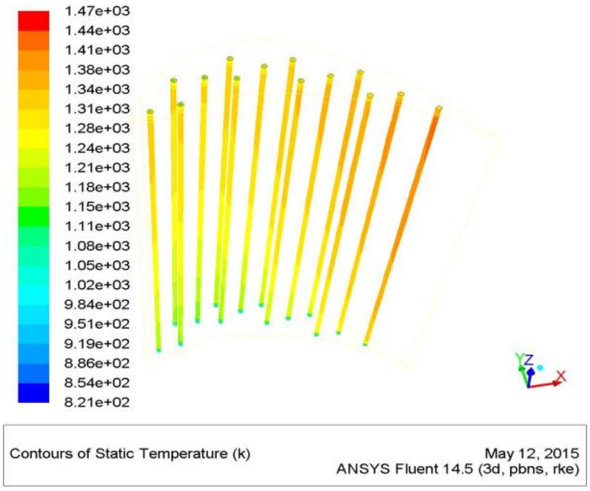

Fig.16) contour of static temperature 14 holes on the whole blade

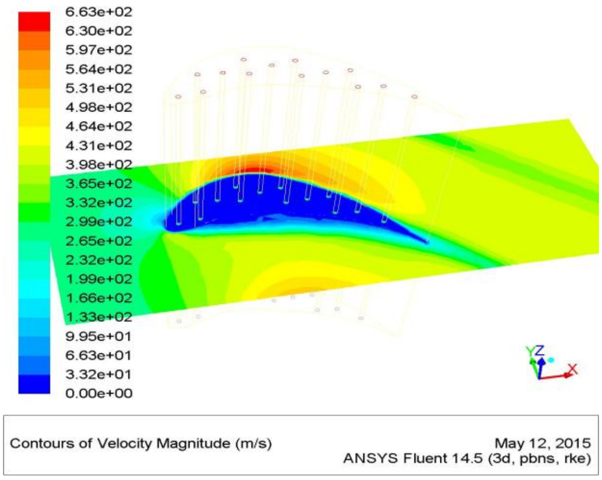

Fig.17) Contour of velocity magnitude of 14 staggered holes

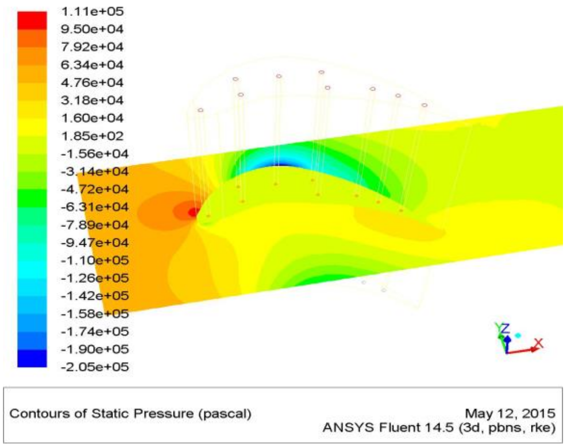

Fig.18) contour of static pressure of 9 staggered holes

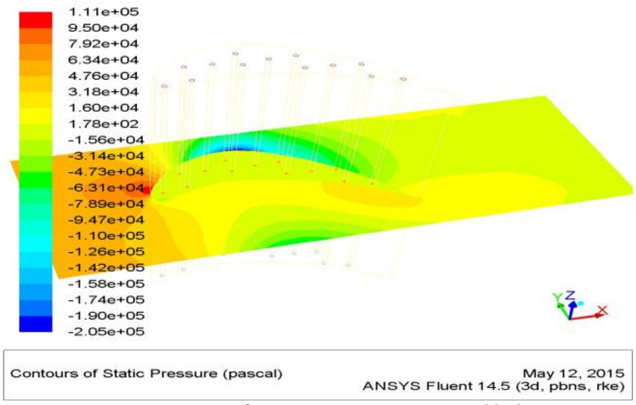

Fig 19 Contour of static pressure 13 staggered holes

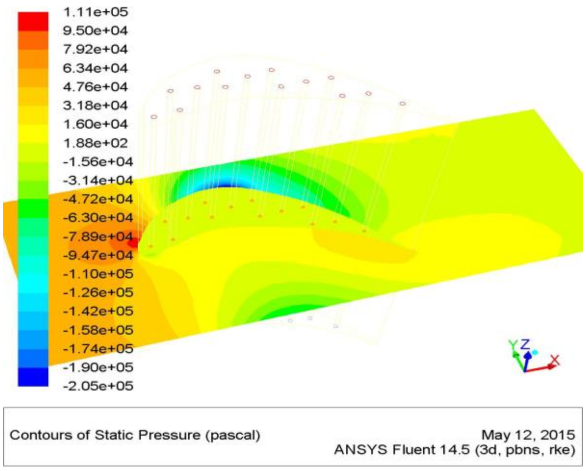

Fig 20 Contour of static pressure 14 staggered hole

By observing the fig 18,19&20 the static pressure of the blade is decreases with the increasing number of holes. But due to the reason of the thermal efficiency we can not increase the number of holes from optimum value. As K Hari Brahmaiah discussed that Inconel 718 material is best suited for the blade cooling because it gives maximum heat transfer rate and lesser amount of stresses and strain then Chromium steel. So that I taking that references and supposing the Inconel 718 is a best material.

No of holes	0	5	9	13
Total heat transfer rate (watts)	72.5	2190	3862	5032

Table No. 2 Total heat transfer rate Vs No of holes (inline) [Inconel 718]

No of holes	9	13	14
Total heat transfer rate (watts)	3752	5081	5336.5

Table No.3 Total heat transfer rate & No of holes (staggered)[Inconel 718]

No of holes	0	5	9	13
Blade leading edge temperature(K)	1473.15	1374.138	1397.663	1301.362

Table No.4 Blade leading edge temperature Vs No. of holes(inline)

No of holes	9	13	14
Blade leading edge temperature (K)	1343.653	1303.689	1291.984

Table No. 5 Blade leading edge temperature Vs No. of holes (staggered)

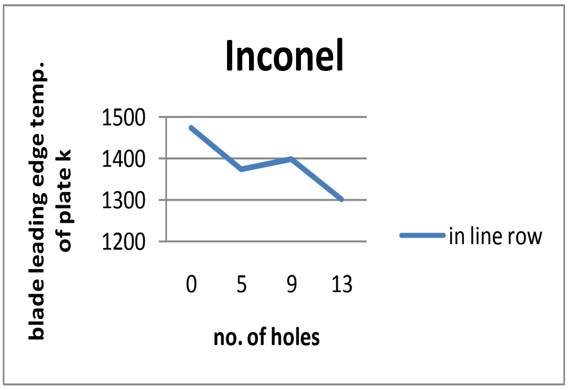

Chart 1 No. of holes Vs blade leading edge temperature. (inline holes 5,9,13)

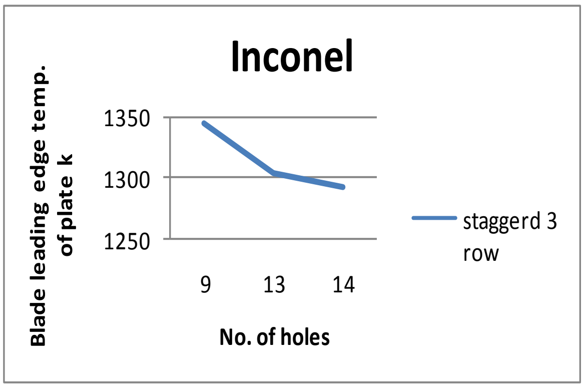

Chart 2-No. of holes Vs blade leading edge temperature. (staggered holes 9,13,14)

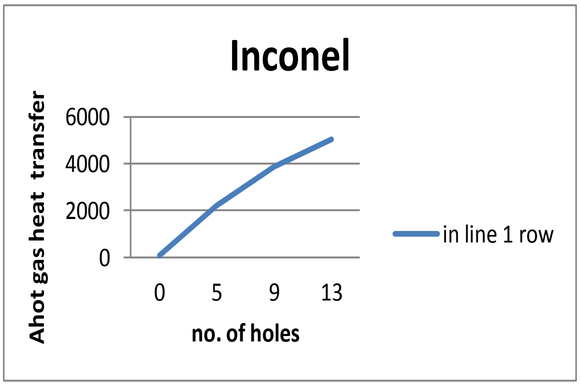

Chart 3- No of holes Vs heat transfer rate (inline holes 5,9,13)

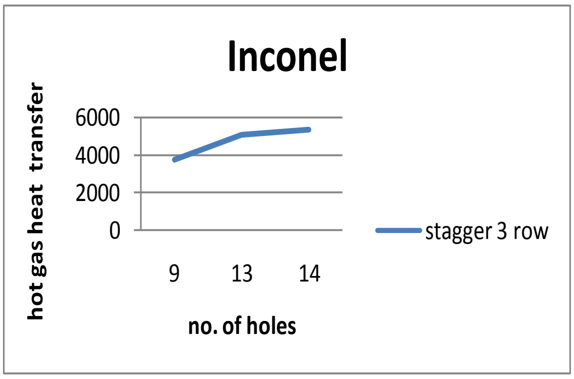

Chart 4- No of holes Vs heat transfer rate (staggered holes 9,13,14)

VI. CONCLUSION & FUTURE SCOPE

CFD analysis of gas turbine blade is carried out with different models consisting of staggered varying number of cooling holes.

- In the overall stresses the temperature show the significant effect in the turbine blade.
- The blade leading edge is minimum for the blade consisting of 14 staggered holes and the total heat transfer rate is maximum.
- In the maximum curvature of the blade profile the temperature distribution is almost uniform.
- In the blade section the temperature is linearly decreasing from the tip to the root .

Further scope will be that we can increasing the number of holes up to the 16 in staggered form because staggered holes consumes less area as compared to inline holes. And it will give more heat transfer rate as well as minimum leading edge temperature. And also the strength of the blade is main consideration.

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