International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 2 Issue 1, January- 2013

Steady State Thermal & Structural Analysis Of Gas Turbine Blade Cooling System

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Abstract

Cooling of gas turbine blades is a major consideration because they are subjected to high temperature working conditions. 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. The forced convection heat transfer from the blade to the cooling air will reduce the temperature of the blade to allowable limits. Finite element analysis is used in the present work to examine steady state thermal & structural performance for N155 & Inconel 718 nickel-chromium alloys. Four different models consisting of solid blade and blades with varying number of holes (5, 9 & 13 holes) were analysed in this paper to find out the optimum number of cooling holes.

The analysis is carried out using ANSYS software package. While comparing these materials, it is found that Inconel 718 is better suited for high temperature applications. On evaluating the graphs drawn for temperature distribution, von-mises stresses and deflection, the blade with 13 holes is considered as optimum. This conclusion was drawn based on the fact that the induced stresses are minimum and the temperature of the blade is close to the required value of 800 C. Any further increase in the number of holes will bring down the temperature below the required value of 800^0 C.

1. Introduction

With the advent in Gas turbine technology, its usage as a prime mover has become prominent, since last few decades. One of the most important applications of gas turbines is in power generation, though it has been in use for aircraft propulsion since long time. The efficiency and power output of gas turbine plants is dependent on the maximum temperatures attained in the cycle. Advanced gas turbine engines operate at high temperatures (1200–1500^{0}C) to improve thermal efficiency and power output. With the increase in temperatures of gases, the heat transferred to the blades will also increase appreciably resulting in their thermal failure. With the existing materials, it is impossible to go for higher temperatures. Taking into account the metallurgical constraints, it is necessary to provide cooling arrangement for turbine blades to keep their metal temperature with in allowable limits. Therefore, developments in turbine cooling technology play a critical role in increasing the thermal efficiency and power output of advanced gas turbines. The following three types of cooling methods have been adopted to varying degree of success.

1. Convection cooling
2. Film cooling
3. Transpiration cooling

While all three methods have their difference, they all work by using cooler air (bled from the compressor) to remove heat from the turbine blade. Convection cooling works by passing cooling air though passages internal to the blade. Heat is transferred by conduction to the blade and then by convection into the air flowing inside of the blade. A large internal surface area is desirable for this method, so the cooling passages are generally provided with small fins. Impingement cooling which is a variation of convection cooling, works by hitting the inside surface of the blade with high velocity air. This allows more heat transfer by convection then regular convection cooling.

Impingement cooling is often used on certain areas of the turbine blade, like the leading edge with standard convection cooling used in the rest of the blade.

The second type of cooling is film cooling. This type of cooling works by pumping cool air out of the blade through small holes in the blade. This air creates a thin layer of cool air on the surface of the blade, protecting it from the high temperature gases. The air holes are most often located along the leading edge. One consideration with film cooling is that injecting the cooler air into the gas flow reduces turbine efficiency. The drop in the efficiency increases as the amount of cooling flow increases. The drop in efficiency however is usually compensated by the increasing overall performance produced by the higher turbine temperature.

Transpiration cooling is the third major type of cooling and is similar to film cooling as it creates a thin film of cooling air on the blade, but it is different in that that air is lead though a porous shell rather than injected through holes. This type of cooling is effective at high temperature asit uniformly covers the entire blade with cool air.

The present paper attempts to study the effect of variation in number of cooling passages on the maximum temperatures attained and thermal stresses induced. It has to be emphasised that the blade has to be analysed under two categories of stresses. The first type is centrifugal stresses that act on the blade due to high angular speeds and second is thermal stresses that arise due to temperature gradient with in the blade material. The analysis of turbine blade mainly consists of the following two parts: Structural and thermal analysis. The analysis is carried out under steady state conditionsusing Ansys software. The study has been conducted with two different classes of Nickel based alloys i.e., Inconel 718 and N-155.

2. Literature survey

Extensive work has been reported in the literature on cooling of gas turbine blade. Deepanraj et.al.[1] have considered titanium – aluminium alloy as the blade material and performed structural and thermal analysis with varying number of cooling passages. They also studied the effect of varying the cooling air temperature on the temperature distribution in the blades. It is concluded that the blade configuration with 8 holes gives an optimum blade temperature of 800^{0}C. Bhatti et al. [2] performed transient state stress analysis on an axial flow gas turbine blade and disk using finite element techniques. They have chosen Inconel 718, a high heat resistant alloy of chromium, nickel & niobium. The study was focused on centrifugal & thermal stress arising in thedisk. A.K.Mattaet.al.[3]studied the stressanalysis for N – 155 & Inconel 718 material. On solid blades it is reported that Inconel 718 is better suited for high temperature operation. It is suggested byErvan [4] that high turbine efficiency can be obtained by minimising the air flow required for cooling by effectively utilising its cooling potential. He suggested a cooling technology which has three main parts: a) The leading edge is provided with impingement cooling; b) the middle section of blade contains cooling pipes with obstacles provided along the length to enhance turbulence in the cooling air and c)the trailing edge of the blade is provided with pin – fins for effective cooling.

3. Modelling and Analysis of gas turbine Blade

The blade model profile is generated by using CATIA software. Key points are created along the profile in the working plane. The points are joined by drawing B spline curves to obtain a smooth contour. The contour (2D model) is then converted into area and then volume (3D model) was generated by extrusion. The hub is also generated similarly. These two volumes are then combined into single volume.

This model of turbine blade is then imported into ANSYS software. The blade is then analysed sequentially with thermal analysis preceding structural analysis. The model is discretised using 10 noded tetrahedral solid element (Solid 87).The surface of the blade is applied with Surface element (Surf 152) for applying the convection loads. The temperatures of blade are then determined by thermal analysis. Followed by this, the structural analysis is carried out by importing the temperatures determined in thermal analysis. 10 noded tetrahedral solid element (Solid 187)was used for structural analysis. The loads considered for structural analysis are centrifugal, axial & tangential forces.

4. 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

4.1 Details of Turbine blade

D = 1308.5 mm, N = 3426 Rpm, L = 117 mm, d = 2mm

Table 1 Mechanical properties of N155 & Inconel 718

Properties	Units	N 155	Inconel 718
E	Pa	143 E09	149 E09
ρ	Kg/cu m	8249	8220
K	W/m-K	20.0	25.0
μ	---	0.344	0.331
α	E-06/^{0}C	17.7	16.0
C_p	J/Kg K	435	586.2
Melting Point	^{0} C	1354	1344
Yield stress	MPa	550	1067

5. Results & Discussions

The Temperature distribution of the blade depends on the heat transfer coefficient for gases and the thermal conductivity of the material. The heat transfer coefficients are calculated by iterative process and the same were adopted. The analysis was carried out for steady state heat transfer conditions. It is observed that the maximum temperatures are prevailing at the leading edge of the blade due to the stagnation effects. The body temperature of the blade doesn't vary much in the radial direction. However, there is a temperature fall from the leading edge to the trailing edge of the blade as expected. It is observed for solid blade model from fig1(N - 155) and fig2 (Inconel 718), that the blade temperatures attained for Inconel 718 are marginally lower. This can be attributed to the lower thermal conductivity of Inconel 718.

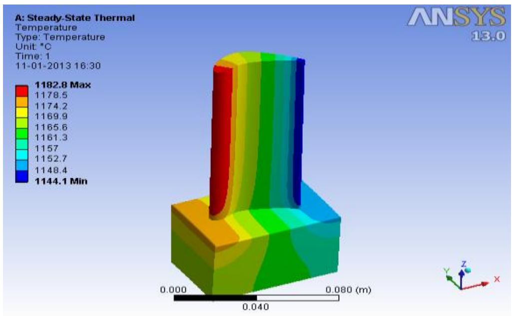

Fig 1.Temperature distribution for solid(N155)

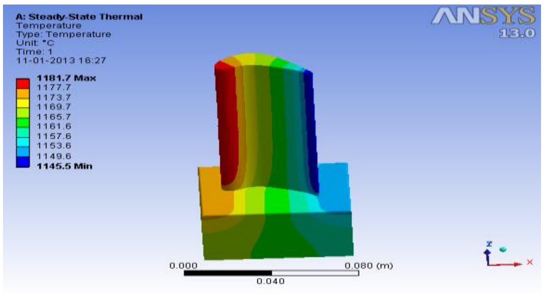

Fig 2.Temp distribution for solid(Inconel718)

When holes are drilled radially for passage of cooling air, there is an appreciable variation of temperature profile of the blade. It can be observed from the figs. 3&4(5 holes) that the temperature at the root of the blade is lower and it increases towards the tip of the blade. This characteristic can be explained from the fact that the cooling air is at its lowest temperature (300^0 C) while flowing through the hub and root of theblade and it goes on increasing along the radial direction. This phenomenon is also observed in blade models of 9 & 13 holes, figs.(5,6,7&8).

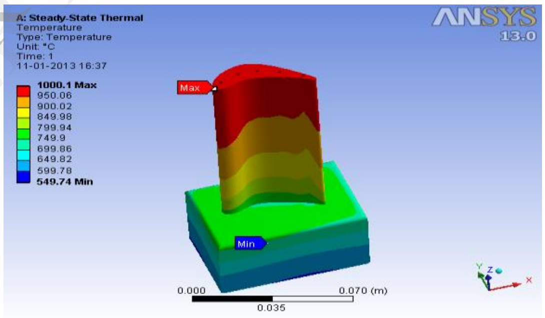

Fig 3.Temp.Distribution for 5 holes(N - 155)

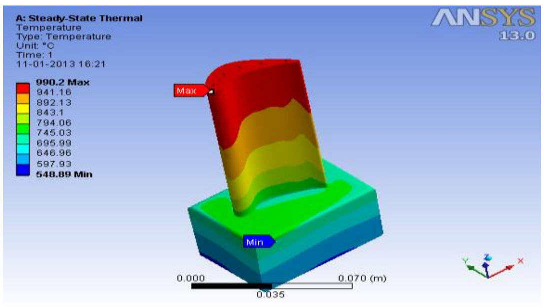

Fig 4.Temp.distribution for 5holes (Inconel 718)

N – 155 Material

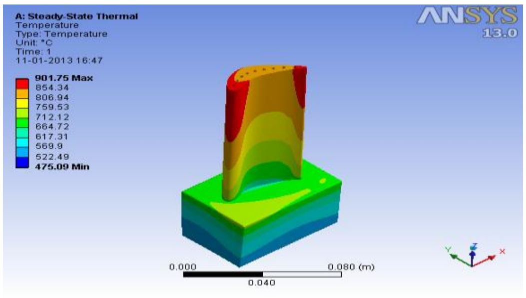

Fig 5 .Temperature distribution for 9holes

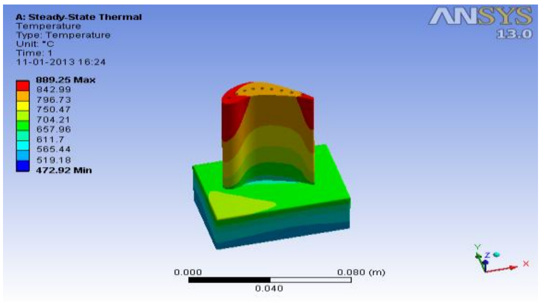

Fig 6.Temperature distribution for 9holes

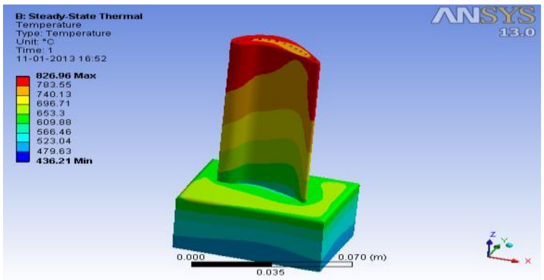

Fig 7.Temperature distribution for 13holes

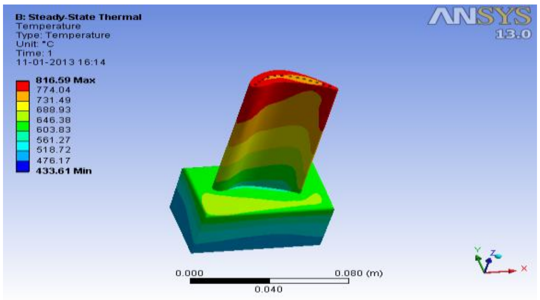

Fig 8.Temperature distribution for 13holes

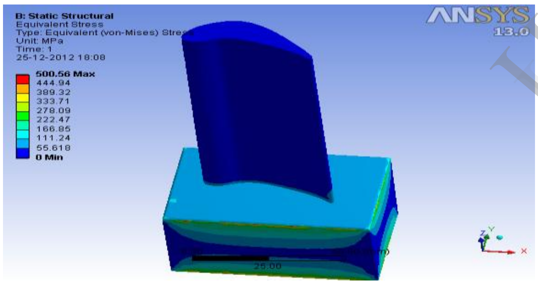

Fig 9.Stress distribution for solid

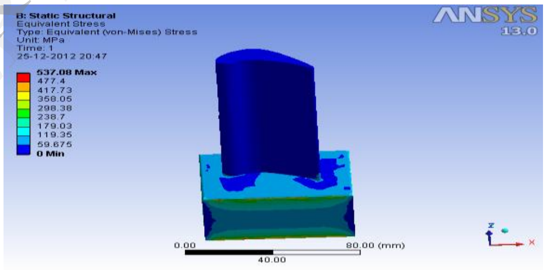

Fig 10.Stress distribution for solid

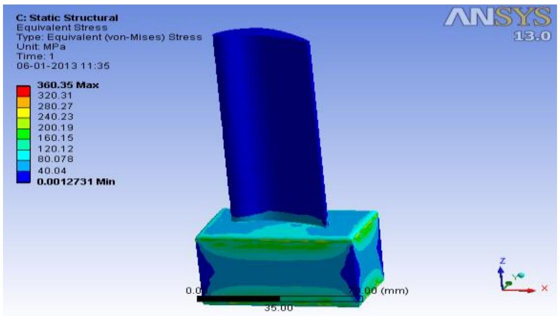

Fig 11.Stress distribution for 13 holes

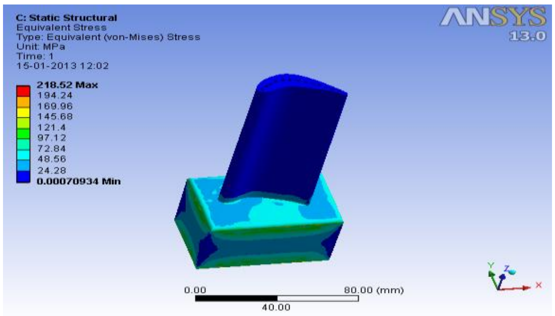

Fig 12.Stress distribution for 13 holes

Inconel 718

From the fig 13,it can be seen that the maximum temperature attained in the blade goes on decreasing with increasing number of holes. It is found that for 13 holes the maximum temperature

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 2 Issue 1, January- 2013

attained is about 812^{0}C. It has been reported by Deepanraj [1] that a decreasing temperature will lead to lower thermal efficiency, as larger portion of air is utilised for cooling purpose and reduced quantities of air flows into the combustor chamber of gas turbine plant. The reduced mass flow rate of the gas and the decreased temperature of the blade will reduce the power out and efficiency of the plant. Hence the number of holes is restricted to 13.

The temperatures obtained from the thermal analysis are imported to structural analysis to determine the thermal stresses. The Centrifugal, Axial and Tangential forces acting on the blade are considered as loads in structural analysis.

From the structural analysis, it can be observed from the figures 9&10 for solid blade, that the stresses induced in the blade section are very low compared to the hub portion. But consideration should also be given to the temperatures of the blade section which are higher. In order to limit these temperatures, forced convection cooling is adopted through passages provided in the blade. The velocity of cooling air is considered as 330m/sec.

The provision of cooling passages reducesthe body temperature of the blade and hub and the temperature drops with the increase in number of holes. It is also observed that the stresses induced in the hub are higher compared to the blade portion since it is fixed. The provision of cooling passages will decrease stresses induced in the hub while a slight increase in the stresses induced in the blade portion are observed from figures11&12. It can also be observed that the maximum temperature,stresses and deflection produced in the blade areminimum for 13 holes.Hence the optimum number of holes that are to be providedstands at 13.Any further increasing in number of holes will reduce the blade temperature further adversely affecting the thermal efficiency and power output of the turbine.

It can be observed from thefigs.13,14&15 that the temperatures, stressesand deflection are on higher side for N155 material compared to Inconel 718. Hence, it can be concluded that Inconel 718 is best suited for gaseshigher than the 1200^{0}Ctemperature, as N – 155has poor thermal properties whencompared with Inconel 718 and it is highly unsuitable for such applications.

Table 2.Max. Temperature Vs. No.of holes

No.of Holes	0	5	9	13
N -155	1182.8	1000.1	901.75	826.96
Inconel 718	1181.7	990.2	889.25	816.59

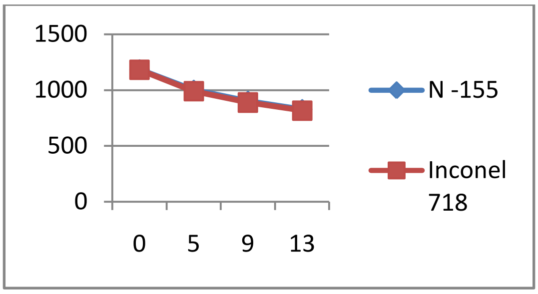

Fig 13.Max. Temperature Vs. No.of holes

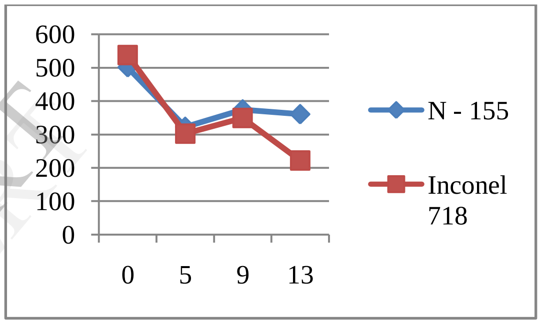

Fig 14.Max. Stress Vs. Number of holes

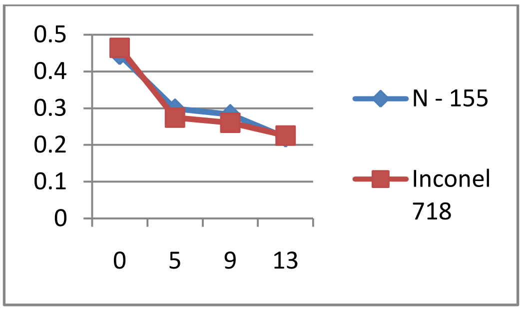

Fig 15.Max. Deflection Vs. Number of holes

6. Conclusions:

Gas turbine blade cooling is studied for two different materials of constructions that is N - 155 & Inconel 718. It is found that Inconel 718 has better thermal properties as the blade temperatures and thermal stresses induced are lesser. The provision of cooling passages in the blades is found to alleviate the problem of high temperatures and thermal stresses. On analysing 4 different models with varying number of holes, it is inferred that the blade model with 13 holes is best suited.

7. REFERENCES

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