https://dx.doi.org/10.22161/ijaers/3.12.43 ISSN: 2349-6495(P) | 2456-1908(O)

Thermal and Structural Analysis of Gas Turbine Blade with Varying Geometry of Cooling Air Passage

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Abstract— *Cooling of gas turbine blades is of paramount importance in the present technological scenario. Gas turbine blades are subjected to very high temperatures, which are at times above the melting point of the blade material itself. An increase in the inlet temperature of fluid increases the efficiency of the turbine. Therein lies the necessity of cooling the blades to temperatures within the safe operating conditions. Many methods of cooling have been proposed which include internal and external cooling. In this paper, air cooling of stainless steel turbine blades has been investigated with the use of varying geometry of air passages. Model Geometries have been created using SolidWorks Software. The Effectiveness of the design has been analyzed using Finite Element Method software, ANSYS Workbench. Using the Steady State Thermal and Static Structural modules of ANSYS, the effect of varying the air passage geometry on thermal and structural behavior of the blade has been realized on the given model.*

Keywords*— *ANSYS Workbench, SolidWorks, Static Structural analysis, Steady State Thermal analysis, V-type air passages.

I. INTRODUCTION

Gas turbines have become an indispensable part of the modern power generation systems, apart from their traditional use in aircraft propelling systems. The efficiency of the gas turbine bears a strong correlation to the maximum temperatures attained in the cycle. Sometimes, the temperatures might even exceed the melting point of the blade material. Usually the surfaces of blades are coated with ceramic thermal barrier coatings which help to avoid excessive heating of blades. This calls for an effective cooling system for the blades with due consideration to the structural integrity of the proposed design. The blade, along with thermal stresses, also experiences massive centrifugal forces causing corresponding structural stresses and deformation.

Currently, three types of cooling mechanisms have been implemented with varying degrees of success-Convective cooling, Transpiration cooling and Film cooling. While all three methods have their differences, they all work by using cooler air (bled from the compressor) to remove heat from the turbine blade. Though the above processes have been vastly used in the industry, their shortcomings are difficult to overlook. One major issue that these processes have in common is the drop in efficiency with increased flow of coolant. However, this loss is compensated by increasing the cycle temperature. Essentially a tradeoff is achieved between cooling effect and efficiency.

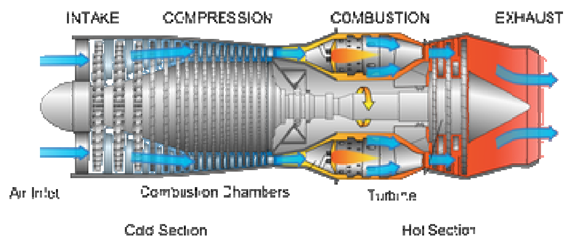

Fig.1: Gas turbine

In this paper, a novel method of convective air cooling using ingeniously designed air passages has been analyzed. Convection cooling works by passing cooling air through 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. One significant improvisation in the cooling passages designed is that the inlet and outlet flow openings are provided on the base of the blade itself. This is in contrast to the cooling holes conventionally designed which take the form of through holes. This development has certain advantages over the typical cooling holes. For one, since the projected end of the blade does not have any surface openings, the undesirable pressure variation in the chamber is avoided. Secondly, since the design has taken the form of a closed thermodynamic system in the sense that the cooling air is not released into the chamber, it can prevent the unnecessary turbulence created by continuous release of pressurized air into the same..

The air passages have been designed by taking the following aspects into consideration:

https://dx.doi.org/10.22161/ijaers/3.12.43 ISSN: 2349-6495(P) | 2456-1908(O)

- Increased surface area has been achieved by making angular air passages
- To prevent structural stresses from appearing, the design has been modeled without much complexities
- To prevent turbulence and increase cooling air flow, the design has incorporated gradual angular zones.

The design has been created using the SolidWorks software. In the present paper the effect of varying the air passage geometry has been investigated. The effect of increasing the complexity and surface area of the air passages has also been studied. To complement the thermal analysis, a structural analysis has been performed to investigate the effect of air passage geometry on the structural integrity of the turbine blades. The study has been performed assuming steady state conditions using ANSYS software.

II. METHODOLOGY

The methodology used for performing the investigation followed a three stage path- Design, Thermal analysis and Structural analysis. The geometry design has been generated using SolidWorks software. The airfoil geometry has been mapped and extruded to generate the three dimensional model. The base has been integrated into the blade profile in order to include the same in the analysis. Further, air passages have been designed in three variants-Single V (1V) type, Double V (2V) type and Triple V (3V) type, in order to examine the effect of change in the surface area of the air passages.

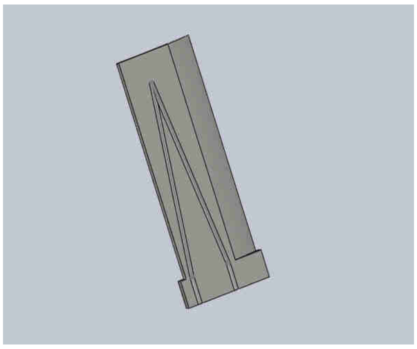

Fig. 2: Sectional view of 1V type

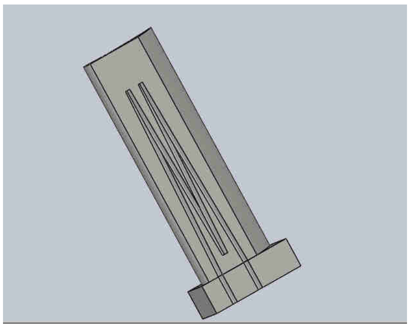

Fig. 3: Sectional view of 2V type

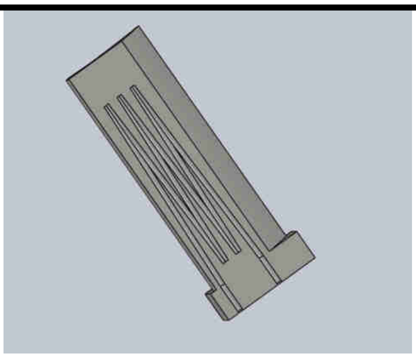

Fig. 4: Sectional view of 3V type

The thermal analysis has been performed using the Steady State Thermal module of Finite Element Method software, ANSYS. In order to initiate the finite element model, fine mesh has been generated on the 3-Dimensional geometry. The calculated heat transfer coefficient has been applied for convection in the air passages. The thermal operating conditions have been applied on the blade material in order to simulate real time conditions. Each design has been subjected to same conditions and the results of temperature variation have been plotted for the same.

The structural analysis has been performed using the Static Structural module of ANSYS software. In this analysis, after generating the mesh on the imported geometry, the base of the blade has been fixed(zero displacement). The centrifugal force acting on the blade has been calculated for different rotor speeds of 6000, 8000, 10000 RPM. The calculated forces have been applied on the blade in radially outward direction of the shaft. It is to be noted that three different analyses corresponding to varying angular velocities have been performed on each blade designs. The results of both thermal and structural analysis have been compared in order to conclude the most suitable design.

Following parameters have been taken for the calculation of Heat transfer coefficient:

Velocity of cooling air (V) = 50 m/s

Diameter of air passage (D) = 2.5 mm

Density of air (ρ) = 1.128 kg/m^3

Dynamic viscosity (μ) = 19.12*10^{-6} Ns/m^2

Thermal conductivity of air (K) = 0.02756 W/m-K

Prandtl number (Pr) = 0.699

Reynolds number can be calculated using the following formula:

$$Re = V * D * \rho/\mu$$

Relation between Nusselt number, Prandtl number and Reynolds number is given by the Dittus-Boelter equation:

$$Nu = 0.023 * (Re)^{0.8} * (Pr)^{0.4}$$

Heat transfer coefficient (h) can be obtained from the relation: Nu = hD/K

$$h = 273\ W/m^2K$$

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Following parameters have been taken for the calculation of centrifugal force:
Mass of each blade (m) = 0.52 kg
Rotar radius (R) = 0.25 m
Blade height (H) = 0.135 m
Mean radius (R_m) = (0.25+0.385)/2 = 0.3175 m
Speed (N) = 6000, 8000, 10000 rpm
Angular velocity (ω) is calculated using the following formula:

$$\omega = \frac{2\pi N}{60}$$

$$\text{Centrifugal force } (F_c) = m * R_m * \omega^2$$

Centrifugal forces calculated for the speeds of 6000 rpm, 8000 rpm, 10000 rpm are 65320 N, 114090 N and 181053N respectively.

III. THERMAL AND STRUCTURAL ANALYSIS OF GAS TURBINE BLADE

When external temperatures are 800^0 C, and coolig air is passed through the passages, following temperature distributions are obtained for 1V, 2V abd 3V types.

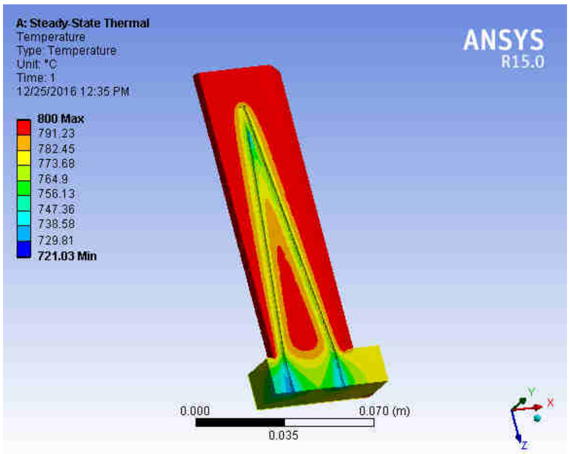

Fig. 5: Temperature distribution in 1V type

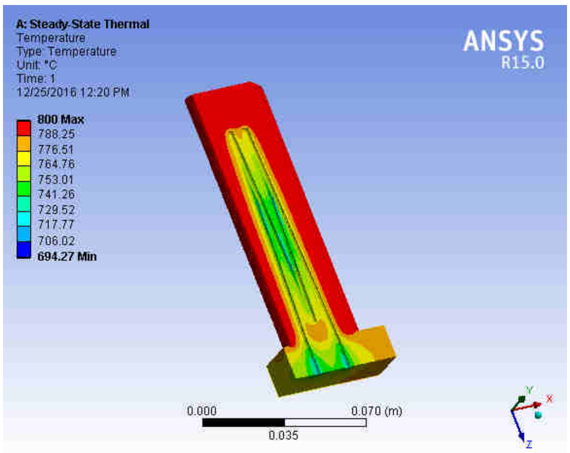

Fig. 6: Temperature distribution in 2V type

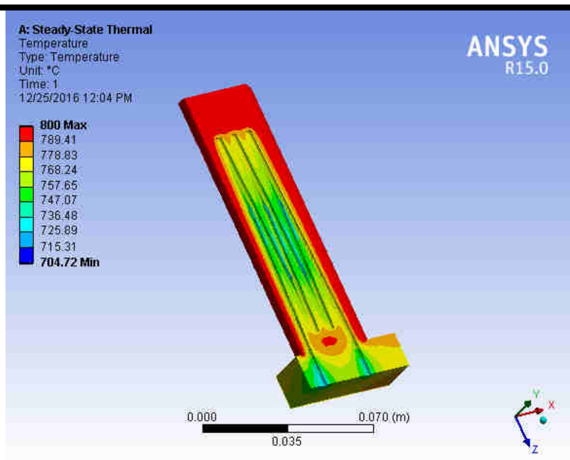

Fig. 7: Temperature distribution in 3V type

Following are the stress distributions and deformations of 1V, 2V and 3V types at 6000, 8000 and 10000 RPM.

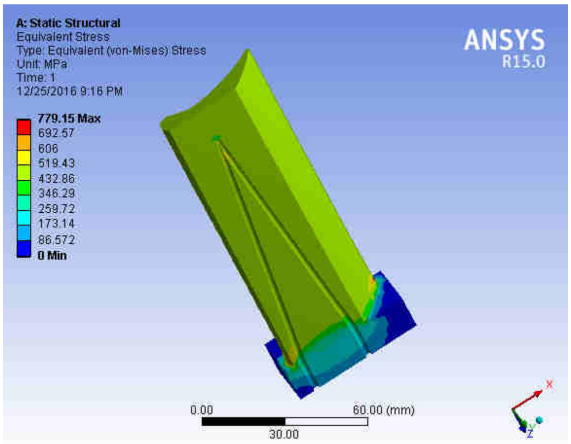

Fig. 8: von Mises stress of 1V type at 10,000 RPM

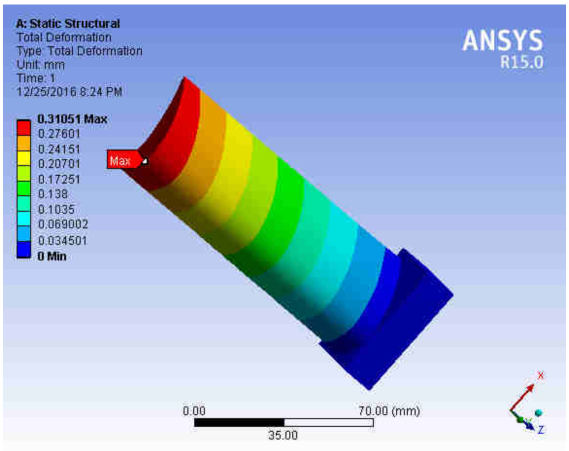

Fig.9: Deformation of 1V type at 10,000 RPM

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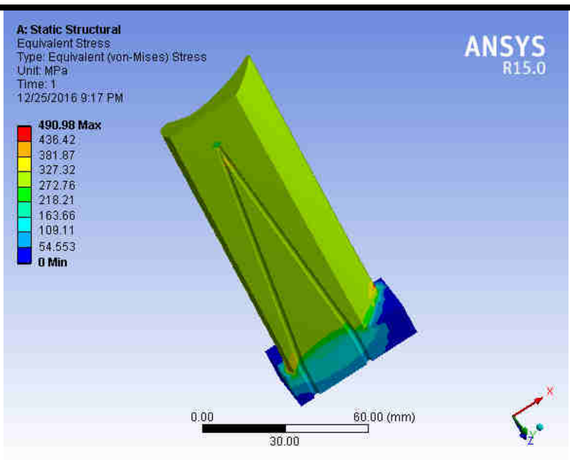

Fig. 10: von Mises stress of 1V type at 8,000 RPM

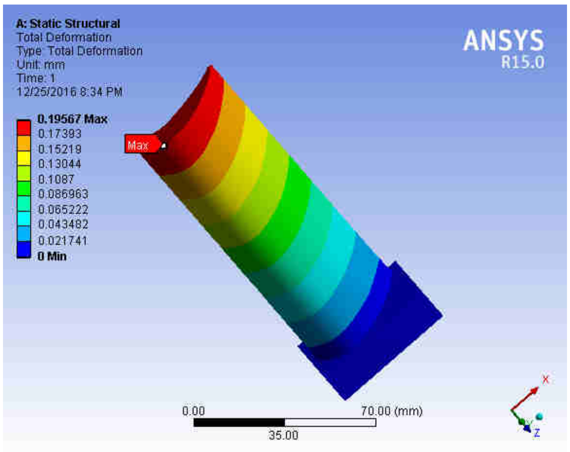

Fig. 11: Deformation of 1V type at 8,000 RPM

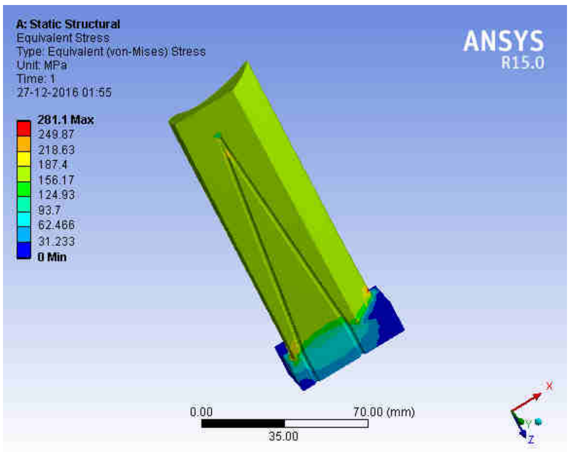

Fig. 12: von Mises stress of 1V type at 6,000 RPM

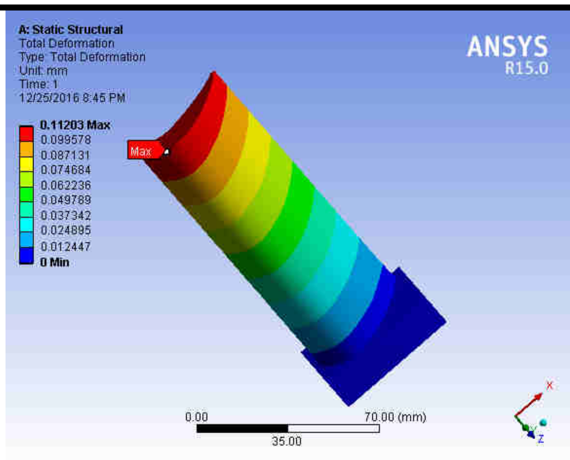

Fig. 13: Deformation of 1V type at 6,000 RPM

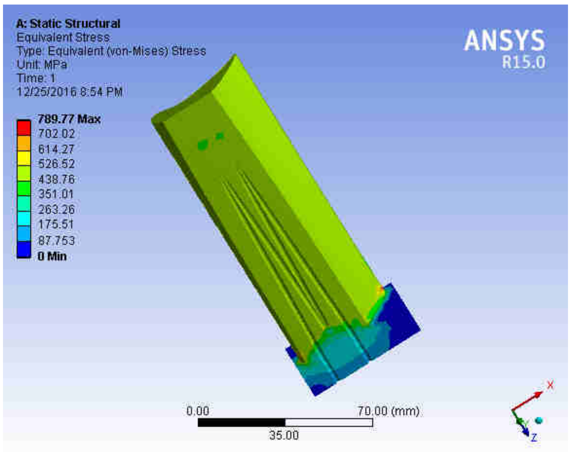

Fig. 14: von Mises stress of 2V type at 10,000 RPM

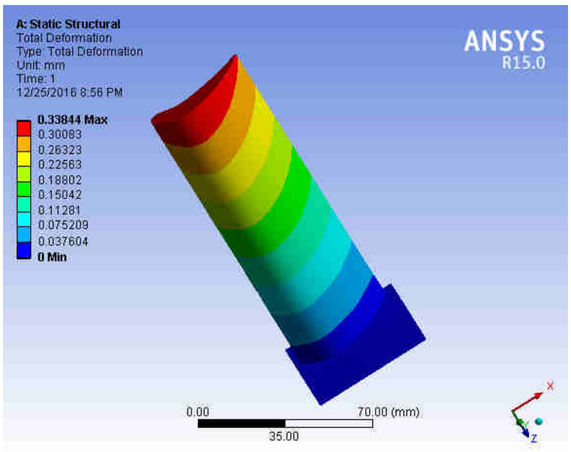

Fig. 15: Deformation of 2V type at 10,000 RPM

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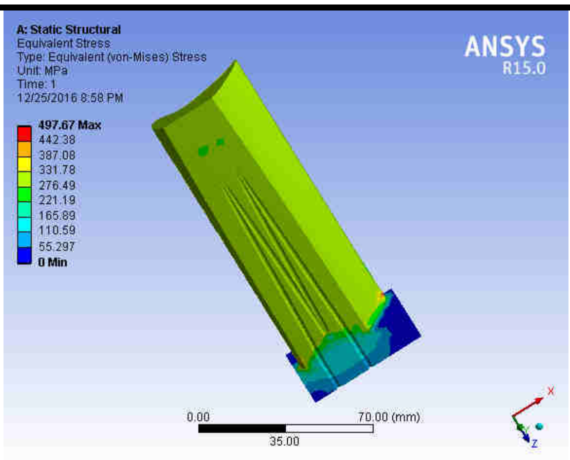

Fig. 16: von Mises stress of 2V type at 8,000 RPM

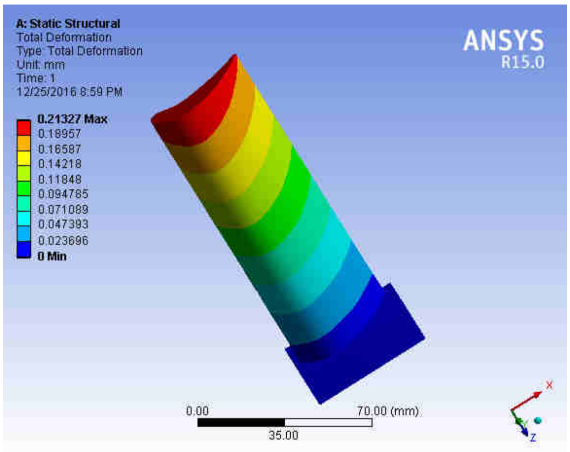

Fig. 17: Deformation of 2V type at 8,000 RPM

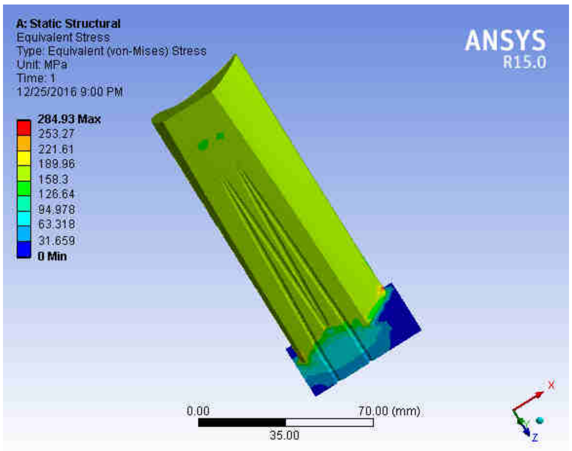

Fig. 18: von Mises stress of 2V type at 6,000 RPM

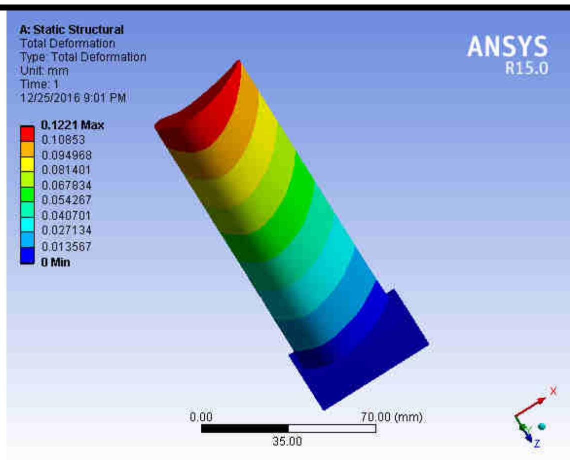

Fig. 19: Deformation of 2V type at 6,000 RPM

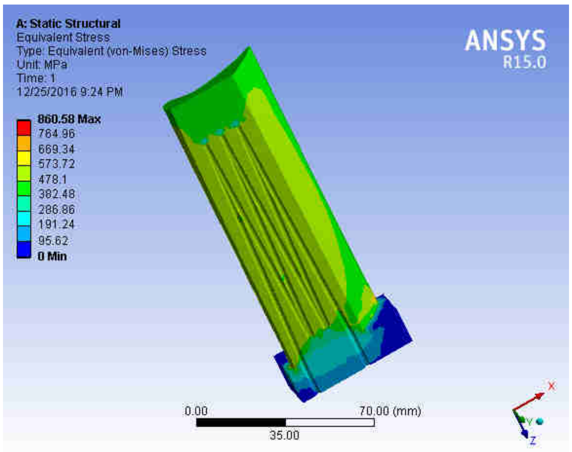

Fig. 20: von Mises stress of 3V type at 10,000 RPM

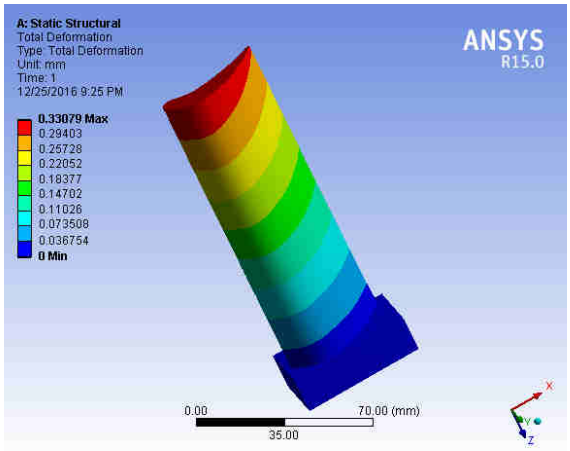

Fig. 21: Deformation of 3V type at 10,000 RPM

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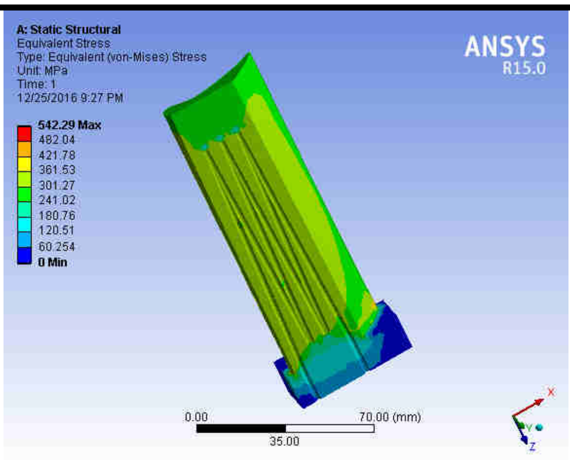

Fig. 22: von Mises stress of 3V type at 8,000 RPM

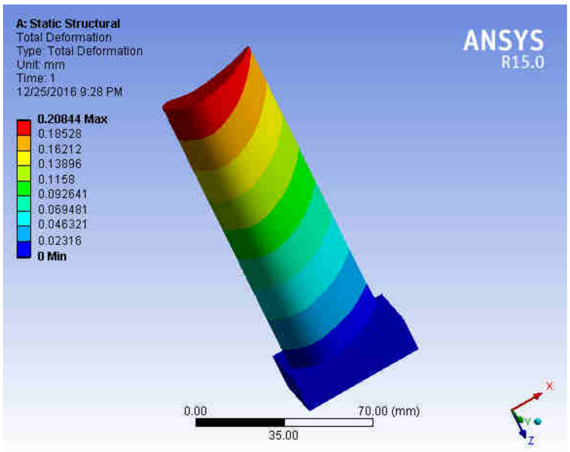

Fig. 23: Deformation of 3V type at 8,000 RPM

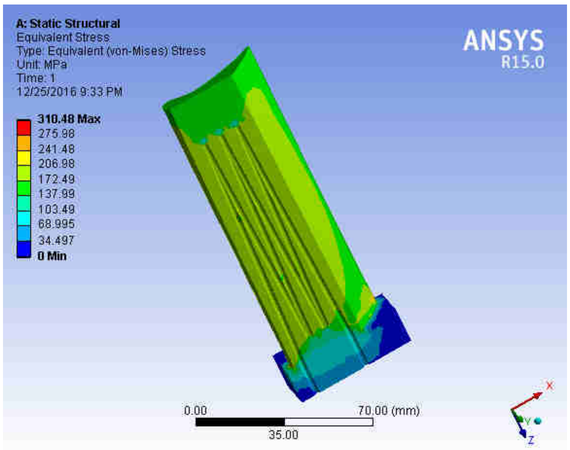

Fig. 24: von Mises stress of 3V type at 6,000 RPM

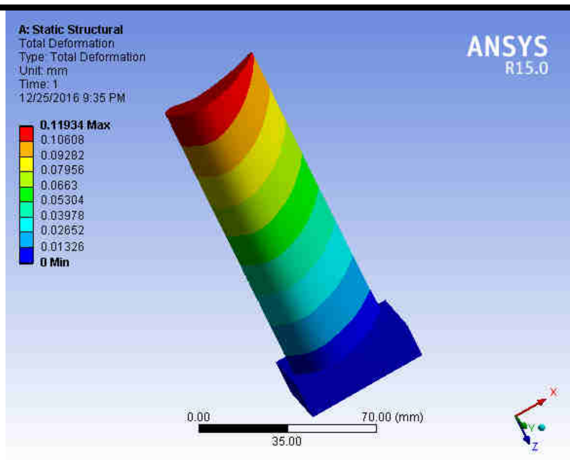

Fig. 25: Deformation of 3V type at 6000 RPM

IV. RESULTS AND DISCUSSIONS

Following table summarizes the Minimum temperatures attained in by passing cooling air through different air passage geometries.

Table 1: Minimum temperatures in blades

PARAMETER	SINGLE V	DOUBLE V	TRIPLE V
MINIMUM TEMPERATURE(°C)	721.03	694.27	704.72

Following table summarizes the Maximum von Mises stresses developed in different blade models at three different operating speeds.

Table 2: Maximum von Mises stresses developed (MPa)

SPEED(RPM)	SINGLE V	DOUBLE V	TRIPLE V
6000	281.1	284.93	310.48
8000	490.98	497.67	542.29
10000	779.15	789.77	860.58

On performing the analyses, certain interesting observations have been made. The thermal analysis of the blade shows that the more effective design among the three is Double V type, since it gives us the least temperature on the blade. Moreover, it has been noticed that the cooling effect produced by the Triple V type design is not as effective as the Double V type, though the former occupies greater cooling passage area.

The structural analysis gives us an insight into the stresses developed in the blade due to the centrifugal force. A general observation of the results shows that with increasing rotor speed, in all cases, the stresses developed also increase proportionally. Further, it is noticeable that the increase in stresses in the Double V design in comparison to the Single V design is negligible. However, if the Double V design is compared to the triple V design, it is observed that the increase in the stress is quite large. In all three cases of structural analyses, an increase in the total deformation is noticed at higher speeds of rotation of rotor.

V. CONCLUSION

In this paper a Steady State Thermal and Static Structural analysis has been performed on a stainless steel gas turbine blade with varying geometries of the cooling air passages. Contrary to the conventional idea of creating through holes for convective cooling, the use of V shaped passages for cooling has been analyzed. From the observation of the analysis it can be concluded that the 2V type air passages are more effective in producing the desired cooling effect when compared to the other geometries. More than 100^0C drop in minimum temperature was seen in the 2V type blade. Moreover, the structural analysis results prove that the stresses induced in the 2V type blade are almost similar to those in the 1V type. Therefore, the 2V type design is feasible and economical since it produces a massive drop in the minimum temperature of a conventional material without sacrificing the structural strength of the blade.

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