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CFD Analysis of Effect of Turbulator on Cooling of Turbine Blade

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***Abstract*- The modern trends of gas turbine engines focus on increased turbine inlet temperatures in order to reduce the specific fuel consumption and increase the overall performance of the engine. However, operation at very high temperatures reduces the life time of turbine vanes and blades while the allowable temperature level of the cycle is limited by the melting point of the materials. Therefore, turbine blade cooling is necessary to reduce the blade metal temperature to acceptable levels for the materials increasing the thermal capability of the engine. Due to the contribution and the development of turbine cooling systems, the turbine entry temperature (TET) has been over doubled over the last 60 years.**

The objective of the analysis is to study the effect of reduction of temperature and to attain the maximum cooling efficiency on gas turbine blade cooling by varying the geometry of the cooling passages. An attempt is made to compare the performance of turbine blade configurations with and without turbulators. While comparing the temperature distribution across the blade, it is evident that overall comparison analyzed from CFD results shows that the net temperature distribution as well as the net heat transfer rate taken by the cooing air is significantly more in the case of turbulator configuration. Based on the results obtained by the CFD calculations it is found that: The temperature variation along the coolant passage with turbulators indicates that the temperature distribution is effective in the middle passage while comparing the side passage. As we use turbulators the blade leading edge temperature will decreases. Temperature will minimum for N155 material with turbulator i.e. 867.95K. Heat Transfer rate will maximum for N155 material with turbulator i.e. 8810.078 Using turbulator is better option as compared to staggered holes and inline holes. Average blade temperature reduces by 12.30 % when turbulators are used.

Index terms- Thermal analysis, Turbine Blade, CFD software FLUENT, Chromium steel and N155, Turbulators, Cooling

I. INTRODUCTION

The most important turbine elements are the turbine blades. They are the principal elements that convert pressure energy of working fluid into kinetic energy. A turbine blade is the individual component which makes up the turbine section of a gas turbine or steam turbine. The blades are responsible for extracting energy from the high temperature, high pressure gas produced by the combustor. The turbine blades are often the limiting component of gas turbines.

Turbine section of a gas turbine is made by the turbine blade. The blades extract energy from the high pressure, high temperature gas produced by the combustion chamber. The turbine blade is the limiting component the gas turbines. Modern gas turbines operate at very high temperatures (1200-1500°C) 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 turbine blades for their long life. Blades of gas turbine can be cooled either internally or externally.

With the increase in temperature of gases, the heat transfer to the blades will also increase appreciably resulting in their thermal failure. With the existing materials, it is impossible to go for higher temperatures. Therefore a sophisticated cooling scheme must be developed for continuous safe operation of gas turbines with high performance. 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 extracting the heat from the outside of the blades.

Advanced heat transfer and cooling techniques form one of the major pillars supporting the continuing development of high efficiency, high power output gas turbine engines. Conventional gas turbine thermal management technology is composed of five main elements including internal convective cooling, external surface film cooling, materials selection, thermal-mechanical design at the component and system levels, and selection and/or pre-treatment of the coolant fluid.

1.1 Methods of Cooling

The modern trends of gas turbine engines focus on increased turbine inlet temperatures in order to reduce the specific fuel consumption and increase the overall performance of the engine. However, operation at very high temperatures reduces the life time of turbine vanes and blades while the allowable temperature level of the cycle is limited by the melting point of the materials. Therefore, turbine blade cooling is necessary to reduce the blade metal temperature to acceptable levels for the materials increasing the thermal capability of the engine. Due to the contribution and the development of turbine cooling systems, the turbine entry temperature (TET) has been over doubled over the last 60 years.

Turbine blade cooling can be classified in two major sections: The internal, where the heat is removed by a variation of convection and impingement cooling configurations, where high velocity air flows and hits the inner surfaces of the turbine vanes and blades, and the external blade cooling, where cold air is injected through the film cooling holes on the external blade surface in order to create a thin film cooling layer. A wide range of internal and external cooling arrangements has been applied in the past; however, the aim in both cases is to keep the entire blade cool enough and also to ensure that temperature gradients within the blade (which might lead to thermal stresses) are kept to an acceptable level.

1.1.1 Internal cooling

(i) Convective cooling: It works by passing cooling air through passages internal to the blade. Heat is transferred by conduction through 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 paths tend to be serpentine and full of small fins.

The internal passages in the blade may be circular or elliptical in shape. Cooling is achieved by passing the air through these passages from hub towards the blade tip. This cooling air comes from an air compressor. In case of gas turbine the fluid outside is relatively hot which passes through the cooling passage and mixes with the main stream at the blade tip.

(ii) Impingement cooling: A variation of convection cooling, impingement cooling, works by hitting the inner surface of the blade with high velocity air. This allows more heat to be transferred by convection than regular convection cooling does. Impingement cooling is used in the regions of greatest heat loads. In case of turbine blades, the leading edge has maximum temperature and thus heat load. Impingement cooling is also used in mid chord of the vane. Blades are hollow with a core. There are internal cooling passages. Cooling air enters from the leading edge region and turns towards the trailing edge.

1.1.2 External cooling

(i) Film cooling: Film cooling (also called thin film cooling), a widely used type, allows for higher heat transfer rates than either convection or impingement cooling. This technique consists of pumping the cooling air out of the blade through multiple small holes in the structure. A thin layer (the film) of cooling air is then created on the external surface of the blade, reducing the heat transfer from main flow, whose temperature (1300–1800 kelvins) can exceed the melting point of the blade material (1300–1400 kelvins). The air holes can be in many different blade locations, but they are most often along the leading edge.

(ii) Cooling effusion: The blade surface is made of porous material which means having a large number of small orifices on the surface. Cooling air is forced through these porous holes which form a film or cooler boundary layer. Besides this uniform cooling is caused by effusion of the coolant over the entire blade surface.

(iii) Pin fin cooling: In the narrow trailing edge film cooling is used to enhance heat transfer from the blade. There is an array of pin fins on the blade surface. Heat transfer takes place from this array and through the side walls. As the coolant flows across the fins with high velocity, the flow separates and wakes are formed. Many factors contribute towards heat transfer rate among which the type of pin fin and the spacing between fins are the most significant.

(iv) Transpiration cooling: This is similar to film cooling in that it creates a thin film of cooling air on the blade, but it is different in that air is "leaked" through a porous shell rather than injected through holes. This type of cooling is effective at high temperatures as it uniformly covers the entire blade with cool air. Transpiration-cooled blades generally consist of a rigid strut with a porous shell. Air flows through internal channels of the strut and then passes through the porous shell to cool the blade. As with film cooling, increased cooling air decreases turbine efficiency, therefore that decrease has to be balanced with improved temperature performance.

II. LITERATURE REVIEW

Many external and internal cooling techniques are utilized to decrease the temperature of blade below its melting point. A lot of research work has been done on turbine blade cooling before.

Fathimunnisa Begum et.al. [2017]- work is carried out by performing the heat transfer analysis of gas turbine with four different models consisting of blade with, without holes and blades with varying number of holes (5, 9&13). The analysis is carried out using commercial CFD software FLUENT. On evaluating the graphs drawn for total heat transfer rate and temperature distribution, the blade with 13 holes is considered to be more optimum. The Steady state thermal and structural analysis is done using ANSYS software with different blade materials such as Chromium steel and N155. While comparing the results, N155 has proved to have better thermal properties and also induced stresses are less than the Chromium steel.

Priyanka Singh et.al. [2015]- Examine Heat Transfer Analysis of Gas Turbine Rotor Blade Cooling through Staggered Holes using CFD. 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.

Rdv Prasad et.al. [2014]- Examine thermal& structural performance in steady state for N155& Inconel 718 nickel-chromium alloys. Using finite element analysis; there are four different models of solid blade and blades with various number of hole (5, 9&13 holes) were analyzed; in this paper the study is done for the optimum numbers of cooled holes. Analysis is carrying out using ANSYS software package; and in the comparison of materials, it has been found that Inconel 718 is mostly suited for high temperature uses. On the evaluation of the graph the temperature distribution, von-misses stresses and variation, the blade with 13 holes is choose as optimum. This concludes the induced stress is low and the temperature of the blades is closed to the demanded value of 800°C. If increasing the numbers of holes will temperature below the demanded value of 800°C.

Experimental tests to estimate the cooling efficiency of gas turbine elements are complicated. In recent years, it is more frequently used to perform the computer modeling of the thermal state of the cooling elements based on the finite element method. Whilst such an approach is significantly less expensive, the results have a good compliance with the experimental data.

III. RESEARCH OBJECTIVES

The objective of the analysis is to study the effect of reduction of temperature and to attain the maximum cooling efficiency on gas turbine blade cooling by varying the geometry of the cooling passages. An attempt is made to compare the performance of turbine blade configurations with and without turbulators.

- To study the heat transfer performance of turbine blade.
- To observe which configurations and parameters that gives the best results.

- To study and modeling the cooling of turbine blade using CFD simulation.
- To simulate the flow and temperature fields in turbine blade passages.

IV. METHODOLOGY

All the design of blade geometry is based on the polar co-ordinate of the blade which are same as the research paper of Fathimunnisa Begum Et.al. [2017].

Table 1: The airfoil co-ordinates of gas turbine blade

X	Y	Z
48.5	0.5	0
45	3.95	0
38.2	8.77	0
26	13.6	0
21.1	14.9	0
16.18	15.5	0
3.2	13.5	0
2.6	17.3	0
5.82	21.5	0
10	25	0
14.8	26.6	0
22.9	25.3	0
24.5	24.7	0
28	23	0
33.4	19.5	0
38	15.3	0
42	10.9	0
45.4	6	0
48.5	0.5	0

The entire geometry of blade is sketched out in the design modular. First the all the points are marked in the sketches manually and they are joint by Espiline and makes an outer boundary of blade .Then the model is converted into 3-D model. After generation of 3-D model of blade the rectangular turbulator are attached in their blades geometry. Then design the zone of hot and cold air.

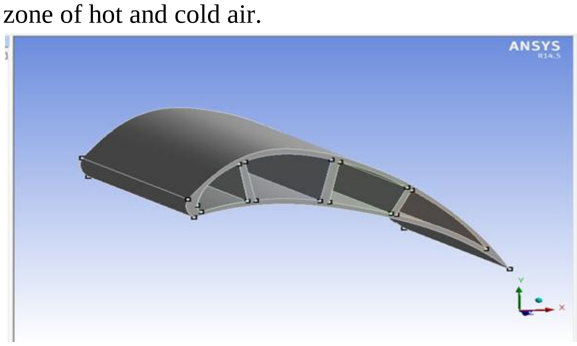

Figure 1. Geometry of turbine blade with rectangular turbulator

No. of Nodes- 168257
No. of elements-139882
Meshing Type- Tetrahedral

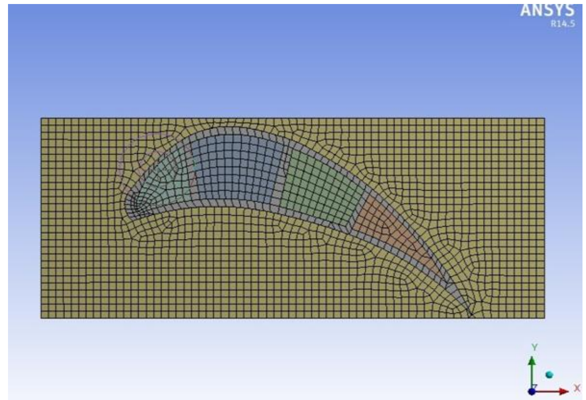

Figure 2. Meshing of gas turbine blade with turbulator

The governing equations are discretized by finite volume method and solved in steady-state implicit format. The second order upwind scheme is applied and standard k-ε turbulent model with standard wall function is selected.

Table 2. Blade material was taken to be a chromium steel and N155.

Material Name	Thermal Conductivity(W/m-K)	Density(Kg/m^3)	Specific heat capacity (J/Kg-K)
Chromium steel	24	7750	435
N 155	20	8249	435

Table 3. Boundary conditions for fluid flow.

Material	Inlet Temperature (K)	Velocity (m/s)	Inlet Pressure (Pa)
Hot air	1112.22 K	277.16 m/s	101325 Pa
Cold air	573 K	30 m/s	101325 Pa

V. RESULTS AND DISCUSSIONS

The temperature distribution and total heat transfer rate of the depends upon blade the heat transfer coefficient for gases and the thermal conductivity of the material, calculation of heat transfer coefficient is doing by some iterative methods such as turbulence realizable (k-ϵ) models. This is observed that there are prevailing at the leading edge of the blade is maximum temperatures. There is a temperature fall from the leading edge to the trailing edge.

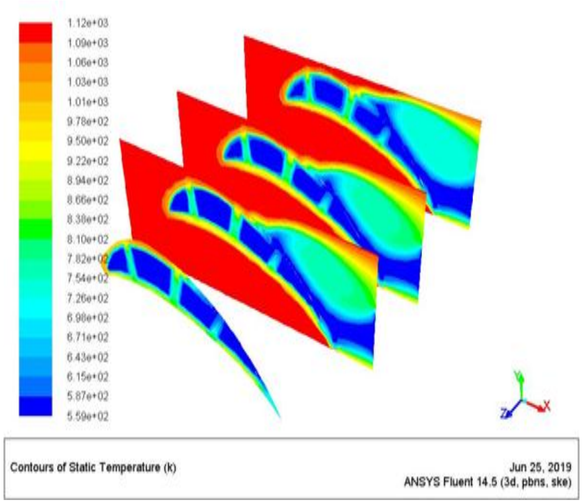

Figure 3. Temperature contour for N155 with Turbulator

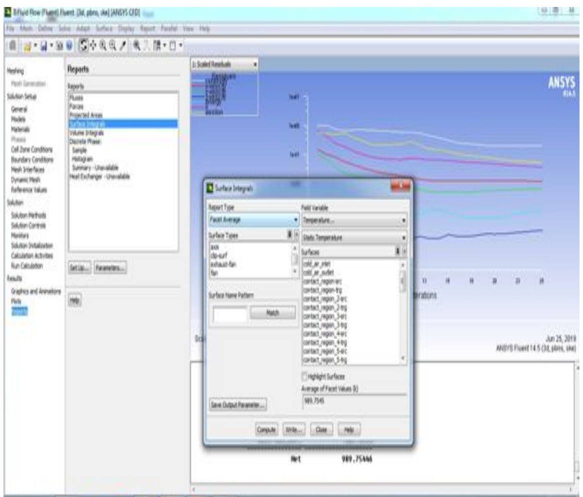

Figure 4. Leading edge temperature for N155 with Turbulator

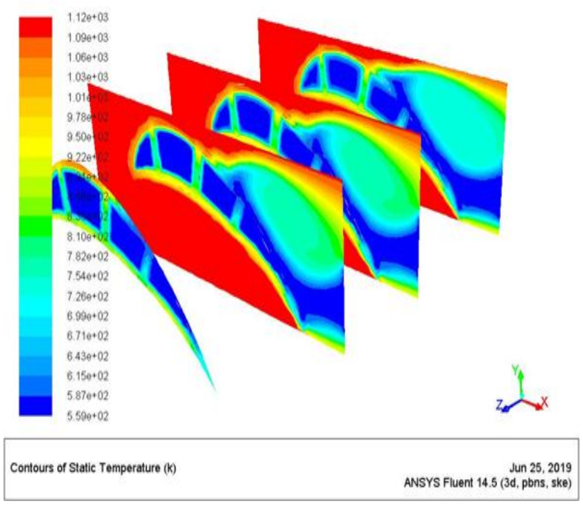

Figure 5.Temperature contour for Chromium steel with Turbulator

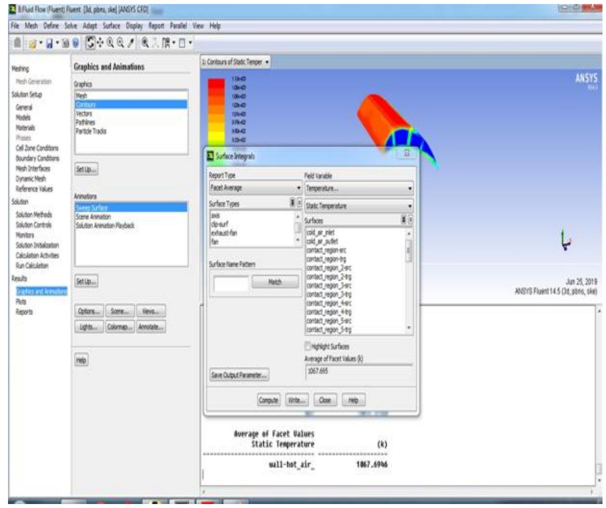

Figure 6. Leading edge temperature rate for Chromium steel with Turbulator

Comparison of Chromium steel and N155 with and without turbulator

Table 4. Shows the value of heat flux, Heat transfer rate and Leading edge temperature of N155 and chromium steel with and without turbulator.

Material	Heat flux (W/m^2)	Heat transfer rate(W)	Leading edge temperature (K)
Chromium Steel(without turbulator)	61	6714.21	1112
N155(without turbulator)	64	6952.31	989.75
Chromium Steel (with turbulator)	110.2	8608.5	1067.695
N155(with turbulator)	117.931	8810.078	867.95

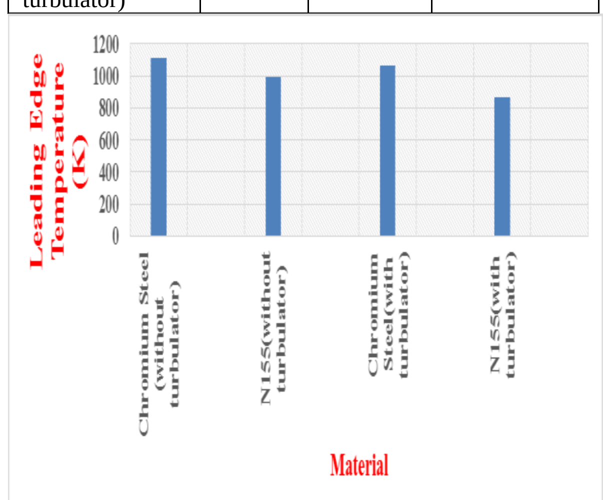

Figure 7. shows the value of Leading Edge Temperature for N155 and chromium steel with and without turbulator

VI. CONCLUSIONS

While comparing the temperature distribution across the blade, it is evident that overall comparison analyzed from CFD results shows that the net temperature distribution as well as the net heat transfer rate taken by the cooing air is significantly more in the case of turbulator configuration. Based on the results obtained by the CFD calculations it is found that:

- The temperature variation along the coolant passage with turbulators indicates that the temperature distribution is effective in the middle passage while comparing the side passage.
- As we use turbulators the blade leading edge temperature will decreases.
- Temperature will minimum for N155 material with turbulator i.e. 867.95K.
- Heat Transfer rate will maximum for N155 material with turbulator i.e. 8810.078 W.
- Using turbulator is better option as compared to staggered holes and inline holes.
- Average blade temperature reduces by 12.30 % when turbulators are used.
- Average heat transfer rate increases by 21 % when turbulators are used.
- By observing the thermal analysis results, the thermal flux is more for N155 with turbulator than the other materials.

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