CFD Analysis of A Thermal Barrier Coated Turbine Blade

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Abstract- The major objective of the present work is to study the thermal profile for a considered turbine Blade without Thermal Barrier Coating. Then, the thermal profile of the same blade with Thermal Barrier Coating is studied. A ceramic TBC coating like Yttria-stabilized Zirconia or SiC matrix composite is used as the coating for the turbine blade profile. Through extensive CFD analysis using NUMECA, the CFD tool used to generate and simulate the flow over the turbine blade, the objective is carried out. Flow behaviors over the two turbine blades and the data obtained post simulation are compared and the the effectiveness of the Thermal Barrier Coating is observed.

Index Terms- CFD, SiC matrix Composite, Thermal Barrier Coatings (TBC), Turbine Blade, Yttria-stabilized Zirconia

I. Introduction

The Turbine Blade is a work extraction device that balances the Aerodynamic, Structural and Thermal demands for the best performance.
The operating temperatures of gas turbine engines have been increasing from the past few decades for improving engine power and efficiency. Interest in bettering the efficiency of gas turbine engines for aviation applications has furthered investigation into higher combustion temperatures [8]. Nickel based super alloys operate around the temperature of 1300°C with internal cooling, and 950°C – 1175°C without internal cooling. Nickel is corrosion resistant, which is an invaluable property for the functioning elements in a jet engine. It's melting point is around 1,728K (1,455°C). It's ability to form alloys is another property of paramount importance, especially with Aluminum, which forms a compound known as gamma-prime that retains its strength at high temperatures [9]. Nickel alloys, almost up to 85 per cent of the melting point, retain their strength unlike Steel or Titanium, where a rapid decrease in the strength is seen, as 40-50 percent of the melting point is encountered. Hence, Nickel based super alloys serve at high temperatures quite well, which is a boon to aviation.

However, the barrier to temperature increase are material problems such as creep resistance, thermal fatigue, high-temperature Sulphur corrosion, and erosion. Therefore, it has become a constant necessity to advance the temperature withstanding capabilities of materials used in the aerospace sector. To tackle this, many types of coatings are suggested, and, implemented to protect various structural engineering surfaces, from problems like corrosion, erosion, and wear and to provide lubrication and thermal insulation.

Of all these, Thermal Barrier Coatings (TBCs) are used in the most demanding high temperature environment of industrial gas-turbines. They are highly advanced systems, commonly used to protect nickel-based super alloys from both melting and thermal cycling in aviation turbines [8]. TBCs are applied to metal surfaces, especially in aviation engine and gas turbine parts that operate at extremely high temperatures.

Combined with cool air flow, TBCs increase the allowable gas temperature above that of the super alloy melting point. It performs well in managing exhaust heat [8]. With today's jet engine operating temperatures, thermal barrier coating failure results in melting of the blade. But even without reaching such catastrophic failure, blades suffer from accelerated oxidation and, depending on the environment, hot corrosion. Coatings can considerably enhance the oxidation/hot corrosion resistance of these components [10].

Ceramic thermal barrier coatings (TBCs) offer the potential to significantly improve efficiencies of aero engines as well as stationary gas turbines for power generation. On internally cooled turbine parts temperature gradients of the order of 100 to 150 °C can be achieved.
Today, state-of-the-art TBCs, typically consisting of an Yttria-Stabilised Zirconia top coat and a metallic bond coat deposited onto a super alloy substrate, are mainly used to extend lifetime. Further efficiency improvements require TBCs being an integral part of the component, which in turn, requires reliable and predictable TBC performance [11]. Hence, an effective simulation of such environments could be highly beneficial towards developing better protective materials.

II. RESEARCH AND LITERATURE SURVEY

Interest in increasing the efficiency of gas turbine engines for aviation applications has prompted research into higher combustion temperatures.

Thermal barrier coatings (TBCs) made of low–thermal conductivity ceramics are now being used to provide thermal insulation to metallic components from the hot gas stream in gas-turbine engines used for aircraft propulsion, power generation, and marine propulsion. The use of TBCs (100 to 500 μm in thickness), along with internal cooling of the underlying superalloy component, provide major reductions in the surface temperature (100° to 300°C) of the superalloy [13].

This has enabled modern gas-turbine engines to operate at gas temperatures well above the melting temperature of the superalloy (~1300°C) and a Turbine Entry Temperature (TET) of 1700°C and more, thereby improving engine efficiency and performance by reducing the cooling load up to 36% while maintaining the same creep life of the blade or increasing considerably the creep life of the blade while maintaining the same cooling load and efficiency, allowing the blade to operate at lower temperatures for the same TET.

Alternatively, at somewhat lower operating temperatures, TBCs help reduce metal temperature, making engine components more durable. TBCs are also being used, to some extent, in diesel engines, where higher operating temperatures translate into increased fuel economy and cleaner exhaust.

The following anatomy of a TBC as shown below (taken from [3]), will give a clear idea of the complexity involved in such a highly advanced system.

Structure of a Thermal Barrier Coating
The four layers in the current TBC system (Fig 1) are made of different materials with specific properties and functions. These layers are:
(i) the substrate,
(ii) the bond-coat,
(iii) the thermally grown oxide (TGO), and
(iv) the ceramic top-coat.

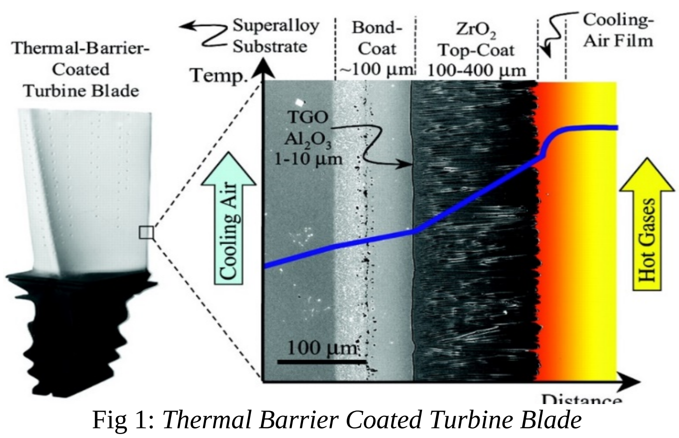

Fig 1: *Thermal Barrier Coated Turbine Blade*

(i) The substrate
The nickel- or cobalt-based structural superalloy is the substrate material, which is air-cooled from the inside or through internal hollow channels, thus establishing a temperature gradient across the component wall. The superalloy component is investment-cast in single-crystal or polycrystalline forms, and it contains as many as 5 to 12 additional elements that are added for the enhancement of specific properties such as high-temperature strength, ductility, oxidation resistance, hot-corrosion resistance, and castability.

(ii) The bond-coat layer

The bond-coat is an oxidation-resistant metallic layer, 75 to 150 μm in thickness, and it essentially dictates the spallation failure of the TBC. The bond-coat is typically made of a NiCrAlY or NiCoCrAlY alloy and is deposited by using the plasma-spray or the electron-beam physical-vapor deposition methods. Other types of bond-coats are made of aluminides of Ni and Pt and are deposited by electroplating in conjunction with diffusion-aluminizing or chemical-vapor deposition. In a minority of cases, the bond-coat consists of more than one layer, having a different chemical/phase composition.

(iii) The Thermally Grown Oxide (TGO) layer

At peak operating conditions the bond-coat temperature in gas-turbine engines typically exceeds 700°C, resulting in bond-coat oxidation and the inevitable formation of a third layer—the thermally grown oxide (TGO; 1 to 10 μm in thickness)—between the bond-coat and the ceramic top-coat. The interconnected porosity that always exists in the top-coat allows easy ingress of oxygen from the engine environment to the bond-coat. Moreover, even if the top-coat were fully dense, the extremely high ionic diffusivity of oxygen in the ZrO2-based ceramic top-coat renders it “oxygen transparent”.

(iv) The ceramic top-coat layer

This layer provides the thermal insulation and is typically made of Y2O3-stabilized ZrO2 (YSZ). YSZ possesses a suite of desirable properties that make it the material of choice for the top-coat. It has one of the lowest thermal conductivities at elevated temperature of all ceramics [~2.3 $W\cdot m^{-1}\cdot K^{-1}$ at 1000°C for a fully dense material because of its high concentration of point defects (oxygen vacancies and substitutional solute atoms), which scatter heat-conducting phonons (lattice waves). YSZ also has a high thermal-expansion coefficient (~11×10^{-6} °C^{-1}), which helps alleviate stresses arising from the thermal-expansion mismatch between the ceramic top-coat and the underlying metal (~14×10^{-6} °C^{-1}).

To further alleviate these stresses, microstructural features such as cracks and porosity are deliberately engineered into the top-coat, making it highly compliant (elastic modulus ~50 GPa) and “strain tolerant.”

YSZ has a relatively low density (~6.4 $Mg\cdot m^{-3}$), which is important for parasitic-weight considerations in rotating engine components.It also has a hardness of ~14 GPa, which makes it resistant to erosion and foreign-body impact. YSZ is resistant to ambient and hot corrosion. Finally, YSZ has a high melting point (~2700°C), making it suitable for high-temperature applications.

[1] HIH Saravanamutto in his book “Gas turbine theory” explains that the Turbine efficiency is strongly correlated with combustion temperature. Higher temperature combustion improves the thermodynamic efficiency of the machine, giving a more favorable ratio of work generated in relation to waste heat.

[2] Marek Chalimoniuk in his paper “Types of Damages to Turbines of Aircraft Turbine Engines; Diagnosing Capabilities”, describes the various types of damages the aircraft gas turbine blades are prone to, and suggests the use of protective coatings over engine components for the purpose of thermal, creep and corrosion protection.

[3] Bilge Saruhan in his research paper “Advanced Coatings for rotating Aero Engine Components” explains that Thermal barrier coatings are commonly used to protect nickel-based super alloys from both melting and thermal cycling in aviation turbines. Combined with cool air flow, TBCs increase the allowable gas temperature above that of the super alloy melting point. A thermal barrier coating (TBC) is a highly advanced system applied to surfaces, like metals, especially in aviation engine and gas turbine parts that operate at extremely high temperatures. It performs well in managing exhaust heat. With today's jet engine operating temperatures, thermal barrier coating failure results in melting of the blade. But even without reaching such catastrophic failure, blades suffer from accelerated oxidation and, depending on the environment, hot corrosion. Coatings can considerably enhance the oxidation/hot corrosion resistance of these components.

[4] Chen Jiang goes on to state the the role of thermal barrier coatings (TBC) is, as their name suggests, to provide thermal insulation of the blade and a coating of about 1-200 μm can reduce the temperature by up to 200°C.

[5] Prof. Nageswara Rao Muktinutalapati in his thesis “Material for Gas Turbine – An Overview” published in November 2011 specifies the different processes by which TBCs can be manufactured.

III. SIMULATION IN NUMECA

COMPUTATIONAL FLUID DYNAMICS

For optimum results, a tool exclusive for turbo machinery “NUMECA” has been developed. This tool helps promote flow analysis over any turbomachinery component and the real time design of Gas Turbine Blade is taken as the model.

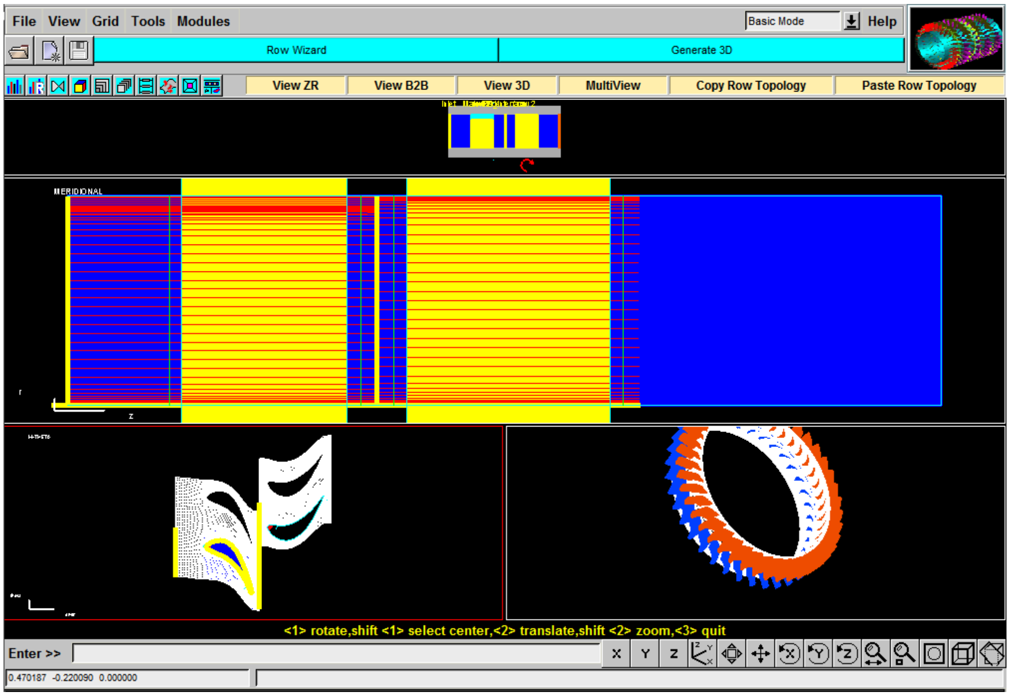

Fig 2: *Meshed multi – views of the generated Turbine Blade*

The mathematical model used here is Navier – Stokes Equation and the Turbulence model is Spalart – Allmaras Equation, as the analysis involves Wall – Bounded Flow.
Boundary Conditions provided for Temperature Distribution are Heat Flux & Convection (Conjugate Heat Transfer) . For this analysis, Thermal Conductivity was the required mechanical properties for the Thermal Barrier Coatings. The Flow Analysis is performed using NUMECA which was used to demonstrate & understand the flow over turbine blade through velocity & pressure.

The Boundary condition applied are inlet velocity, Exit pressure, outlet pressure, Temperature, Inlet turbulence intensity.
After extensive literature survey, the average values of Thermal Conductivities of the Bond Coat and the Ceramic Top Coat is taken as 1 W/mK and 2.2 W/mK and their corresponding thickness over the Turbine Blade's surface is approximately 150 and 250 microns respectively.

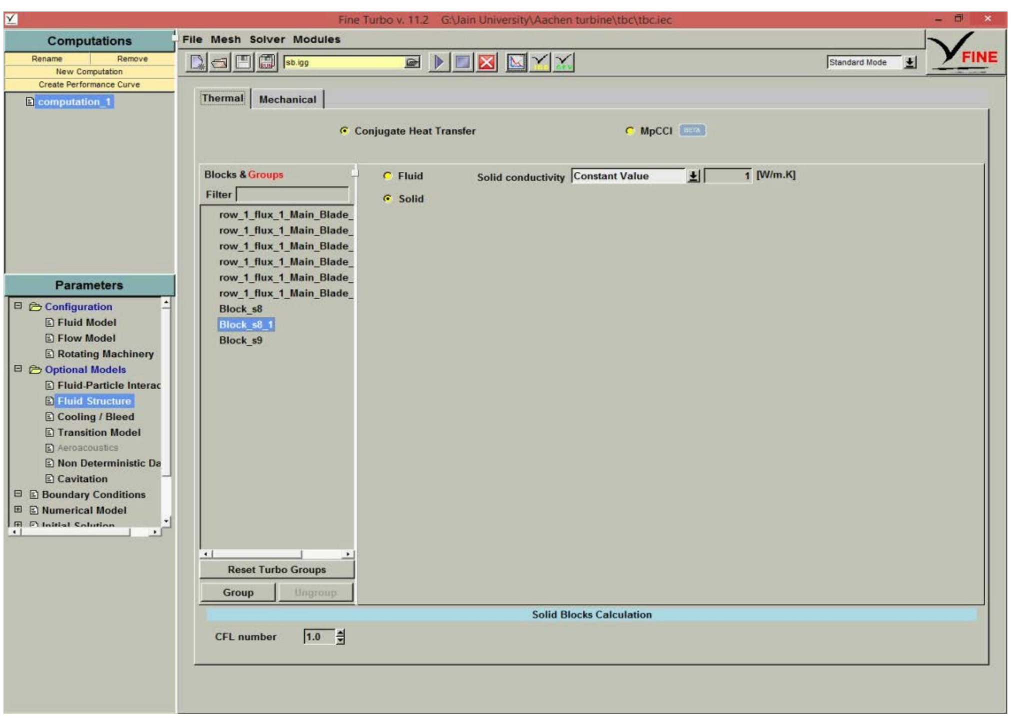

Fig 3: *Setting the Thermal Conductivity of Bond Coat*

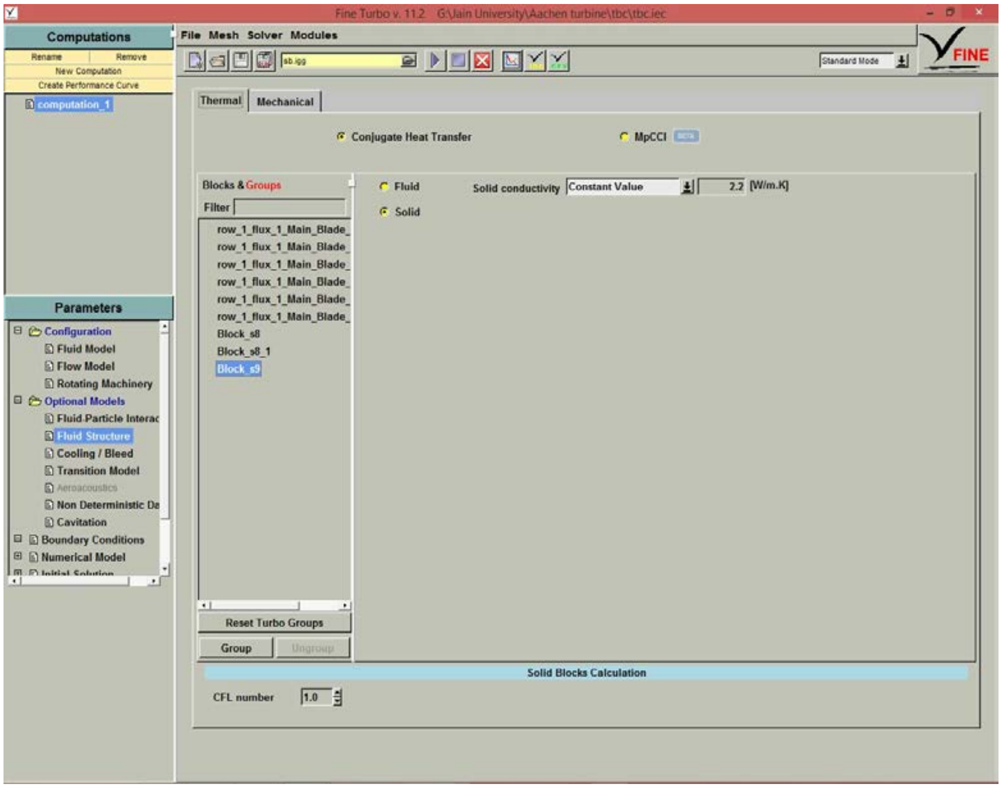

Fig 4: *Setting Thermal Conductivity of the Ceramic Top Coat*

For an Inlet Temperature of 2000K, The analysis was carried out for steady state heat transfer conditions. The difference between uncoated & coated turbine blade in temperature distribution is observed from results. The Temperature Distribution over the Turbine Blades' surfaces are shown in the Results below.

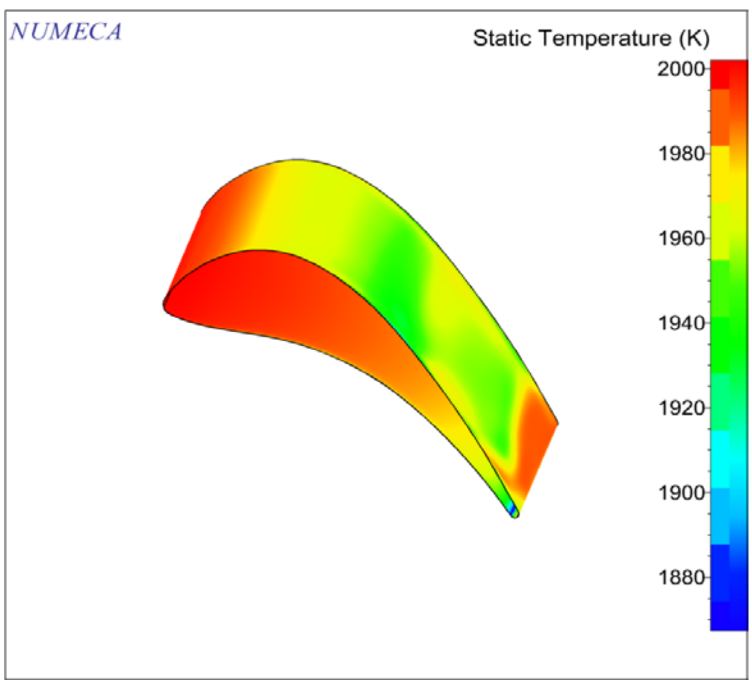

Fig 5: *Temperature Distribution over the Turbine Blade without TBC*

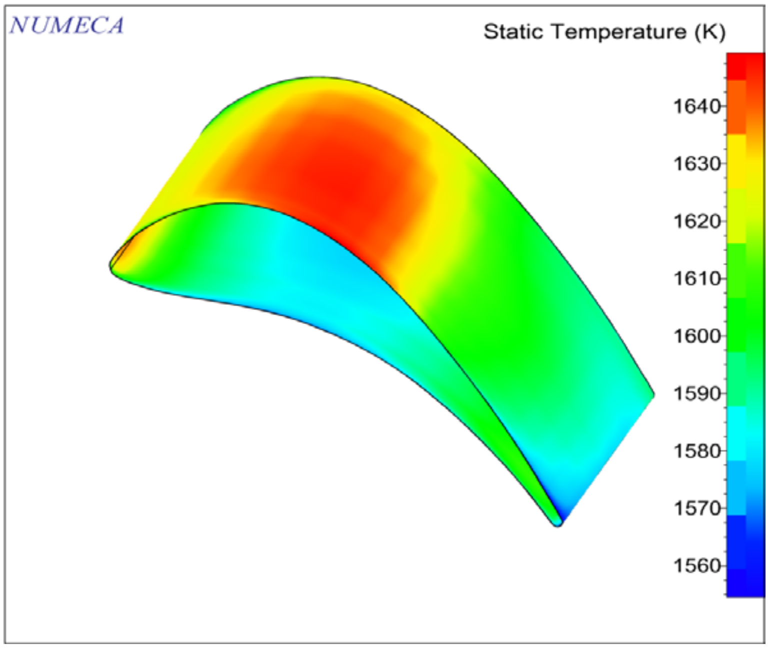

Fig 6: *Temperature Distribution over the Turbine Blade with TBC*

It is observed that the maximum temperatures (2000K) are prevailing at the leading edge of the blade due to the stagnation effects. The surface 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. From the above result, the Blade with coated exhibits Better dissipation of heat compared to uncoated Blade. The coated Blade generates less heat compared to the other Blade so it's recommended for Higher Thermal operating Conditions.
The Plots for the Temperature Variation is shown as the Distribution of Temperature on the Suction Side and the Pressure Side as shown below :

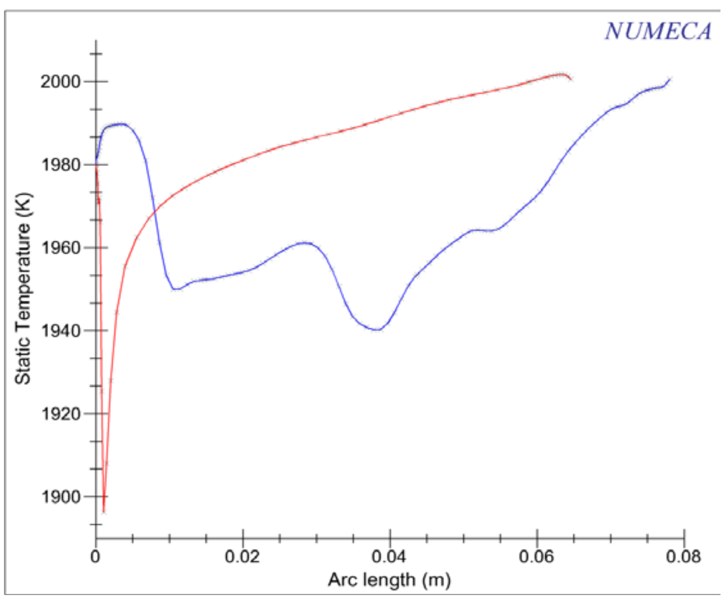

Fig 7: *Temperature variation over Suction surface (blue) and Pressure surface (red) of the blade without TBC*

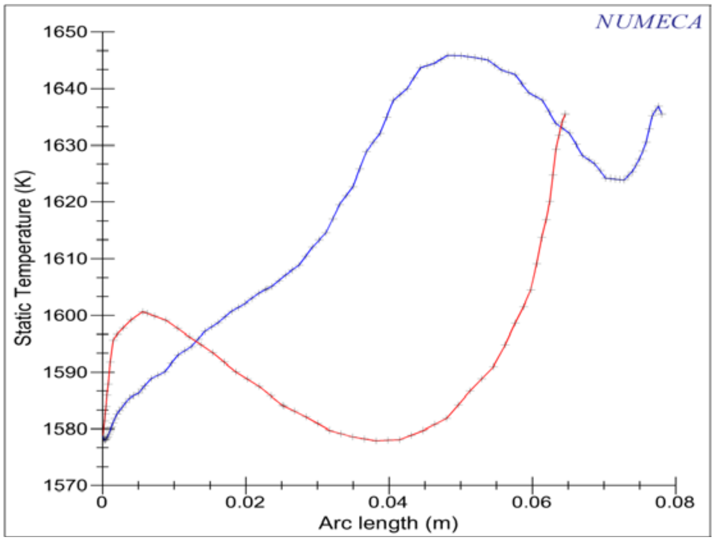

Fig 8: *Temperature variation over Suction surface (blue) and Pressure surface (red) of the blade with TBC*

It is observed in Fig 7, that for the Blade without TBC coating, the temperature at the inlet is 2000K and it decreases along the surface as air flows from the hub to the shroud to the outlet, i.e, there is a gradual decrease in Temperature of the blade along the flow as expected. Temperature on the suction side is higher than the Pressure side.

From Fig 7, it is seen that the temperature range over the turbine blade surface without TBC is 1867.49K – 2001.89K. The Average Temperature on the blade without TBC is 1974.39K.

From Figure 8, It is seen that the temperature range over the Blade's surface is 1554.61K – 1649.22K and the average temperature of the Blade with TBC is 1604.55K.

Max. Temperatures (hot spots) are observed on the leading edge and trailing edge of the blade. Figures 7 and 8 show blade surface temperature comparison between two calculated cases (Without TBC and TBC with lower thermal conductivity). The biggest temperature drop can be observed in the middle section of the airfoil surface. This fact confirms the impact of thermal barrier coatings on blade temperature level in steady state conditions.

IV. CONCLUSION

The simulations and analysis for the turbine blades have been successfully carried out.

This analysis was aimed at comparing the thermal profiles of a turbine blade in the high temperature zone with and without having TBC layers coated on it. The TBC characteristic adapted in this simulation is comparable to a simple YSZ TBC Coat.

After obtaining the results of both the analyses and upon comparison of the Static Temperature contours and the temperature variation plots of the blade without thermal barrier coating with that of the blade with thermal barrier coating, a reduction in average static temperature of the base metal of the turbine blade of 369.84K or 96.69°C was seen.

The results obtained (contours & plots) have shown that the blade with a TBC layer had lesser temperatures on the blade surface as when compared to the blade without TBC. Hence, the basic YSZ Thermal Barrier Coating has proved to be effective.

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