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Effect of Heat Transfer Coefficient on Cooling of Gas Turbine Blades

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ABSTRACT

Modern gas turbine blades are optimized and designed to work on elevated temperature. Design of blade is carried out with maximum accuracy and aerodynamic shapes. The shape and design of blade will give him an ability to withstand at high temperature. There are different factors which affect the blade performance with respect to the heat and temperature. It is well known that the gas turbine blade working environment and the temperature is very high. It must possess an ability to work efficiently on this temperature. For that purpose, the effective cooling technique must be implemented in the gas turbines. There are several cooling techniques are used is gas turbines. Such as Convection, Film, Transpiration Cooling, Cooling Effusion, Pin Fin cooling Convection, Film, Transpiration Cooling, Cooling Effusion, Pin Fin cooling etc.

Heat Transfer coefficient is the important property of gas turbine blade material, as it affects the thermal performance. To work efficiently, heat must transfer rapidly from the blade. The value of Heat transfer coefficient will decide the heat transfer rate. It is also known that the heat transfer coefficient can affect the thermal conductivity and cooling capacity of material.

In this paper the effect of heat transfer coefficient on the cooling capacity is checked out by means of CAD, CAE and CFD tools. CATIA V5R19 and ANSYS 14.5 software are used to carry results. On the basis of results generated further conclusions are drawn.

Keywords : Heat Transfer Coefficient, Thermal Conductivity, CAD, CAE and CFD Tools.

I. INTRODUCTION

GAS TURBINES:

In A Gas Turbine is a type of turbine that uses pressurized gas to spin it in order to provide kinetic energy to an airplane or jet. The process to do so is called the Brayton cycle. In all modern Gas Turbines, the pressurized gas is created by the burning of a fuel like natural gas, kerosene, propane or jet fuel. The heat generated by this fuel expands air which flows through the turbine to supply useful energy. Gas Turbines are theoretically simple, and have three main parts as seen in Fig. 1.1

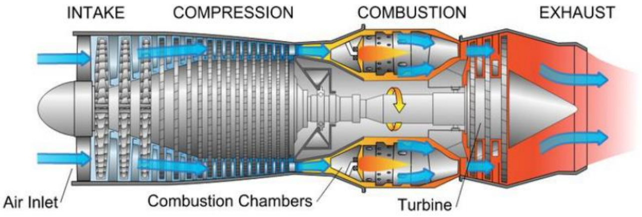


Fig. 1.1 : Schematic diagram of a Gas Turbine Engine

1. Compressor- Takes in air from outside of the turbine and increases its pressure.
2. Combustor- Burns the fuel and produces high pressure and high velocity gas.
3. Turbine- Extracts the energy from the gas coming from the combustor.

A Gas Turbine, also called a combustion turbine, is a type of continuous combustion, internal combustion engine. The main elements common to all Gas Turbine engines are:

i. An upstream rotating gas compressor;
ii. A combustor;
iii. A downstream turbine on the same shaft as the compressor.

A fourth component is often used to increase efficiency (on turboprops and turbofans), to convert power into mechanical or electric form (on turbo shafts and electric generators), or to achieve greater thrust-to-weight ratio (on afterburning engines).

The basic operation of the Gas Turbine is a Brayton cycle with air as the working fluid. Atmospheric air flows through the compressor that brings it to higher pressure. Energy is then added by spraying fuel into the air and igniting it so the combustion generates a high-temperature flow. This high-temperature high-pressure gas enters a turbine, where it expands down to the exhaust pressure, producing a shaft work output in the process. The turbine shaft work is used to drive the compressor; the energy that is not used for compressing the working fluid comes out in the exhaust gases that can be used to do external work, such as directly producing thrust in a turbojet engine, or rotating a second, independent turbine (known as a power turbine) which can be connected to a fan, propeller, or electrical generator. The purpose of the Gas Turbine determines the design so that the most desirable split of energy between the thrust and the shaft work is achieved. The fourth step of the Brayton cycle (cooling of the working fluid) is omitted, as Gas

Turbines are open systems that do not use the same air again.

In an ideal Gas Turbine, gases undergo four thermodynamic processes: an isentropic compression, an isobaric (constant pressure) combustion, an isentropic expansion and heat rejection. Together, these make up the Brayton cycle.

This, however, also translated into poor efficiency and reliability. More advanced Gas Turbines (such as those found in modern jet engines or combined cycle power plants) may have 2 or 3 shafts (spools), hundreds of compressor and turbine blades, movable stator blades, and extensive external tubing for fuel, oil and air systems; they use temperature resistant alloys, and are made with tight specifications requiring precision manufacture. All this often makes the construction of a simple Gas Turbine more complicated than a piston engine.

Moreover, to reach optimum performance in modern Gas Turbine power plants the gas needs to be prepared to exact fuel specifications. Fuel gas conditioning systems treat the natural gas to reach the exact fuel specification prior to entering the turbine in terms of pressure, temperature, gas composition, and the related wobbe-index.

The primary advantage of a Gas Turbine engine is its power to weight ratio. Since significant useful work can be generated by a relatively lightweight engine, Gas Turbines are perfectly suited for aircraft propulsion. Thrust bearings and journal bearings are a critical part of a design. They are hydrodynamic oil bearings or oil-cooled rolling-element bearings. Foil bearings are used in some small machines such as micro turbines and also have strong potential for use in small Gas Turbines/auxiliary power units.

II. GAS TURBINE BLADES

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. To survive in this difficult environment, turbine blades often use exotic materials like super alloys and many different methods of cooling that can be categorized as internal and external cooling , and thermal barrier coatings. Blade fatigue is a major source of failure in steam turbines and Gas Turbines.

Fatigue is caused by the stress induced by vibration and resonance within the operating range of machinery. To protect blades from these high dynamic stresses, friction dampers are used.

Blades of wind turbines and water turbines are designed to operate in different conditions, which typically involve lower rotational speeds and temperatures.

Fig. 2.1 : Gas Turbine Blade

In a Gas Turbine engine, a single turbine section is made up of a disk or hub that holds many turbine blades. That turbine section is connected to a compressor section via a shaft (or "spool"), and that compressor section can either be axial or centrifugal. Air is compressed, raising the pressure and temperature, through the compressor stages of the engine. The temperature is then greatly increased by combustion of fuel inside the combustor, which sits between the compressor stages and the turbine stages. The high-temperature and high-pressure exhaust gases then pass through the turbine stages.

The turbine stages extract energy from this flow, lowering the pressure and temperature of the air and transfer the kinetic energy to the compressor stages along the spool. This process is very similar to how an axial compressor works, only in reverse.

The number of turbine stages varies in different types of engines, with high-bypass-ratio engines tending to have the most turbine stages. [Citation needed] The number of turbine stages can have a great effect on how the turbine blades are designed for each stage. Many Gas Turbine engines are twin-spool designs, meaning that there is a high-pressure spool and a low-pressure spool. Other Gas Turbines use three spools, adding an intermediate-pressure spool between the high- and low-pressure spools. The high-pressure turbine is exposed to the hottest, highest-pressure air, and the low-pressure turbine is subjected to cooler, lower-pressure air. The difference in conditions leads to the design of high-pressure and low-pressure turbine blades that are significantly different in material and cooling choices even though the aerodynamic and thermodynamic principles are the same. Under these severe operating conditions inside the gas and steam turbines, the blades face high temperature, high stresses, and potentially high vibrations. Steam turbine blades are critical components in power plants which convert the linear motion of high-temperature and high-pressure steam flowing down a pressure gradient into a rotary motion of the turbine shaft.

III. TROUBLES TO GAS TURBINE BLADES

Turbine blades are subjected to very strenuous environments inside a Gas Turbine. They face high temperatures, high stresses, and a potential environment of high vibration. All three of these factors can lead to blade failures, potentially destroying the engine, therefore turbine blades are carefully designed to resist these conditions.

Turbine blades are subjected to stress from centrifugal force (turbine stages can rotate at tens of thousands of revolutions per minute (RPM)) and fluid forces that can cause fracture, yielding, or creep failures. Additionally, the first stage (the stage directly following the combustor) of a modern turbine faces temperatures around 2,500 F (1,370 C), up from temperatures around 1,500 F (820 C) in early Gas Turbines. Modern military jet engines, like the Snecma M88, can see turbine temperatures of 2,900 F (1,590 C). Those high temperatures weaken the blades and make them more susceptible to creep failures. The high temperatures can also make the blades susceptible to corrosion failures. Finally, vibrations from the engine and the turbine itself can cause fatigue failures.

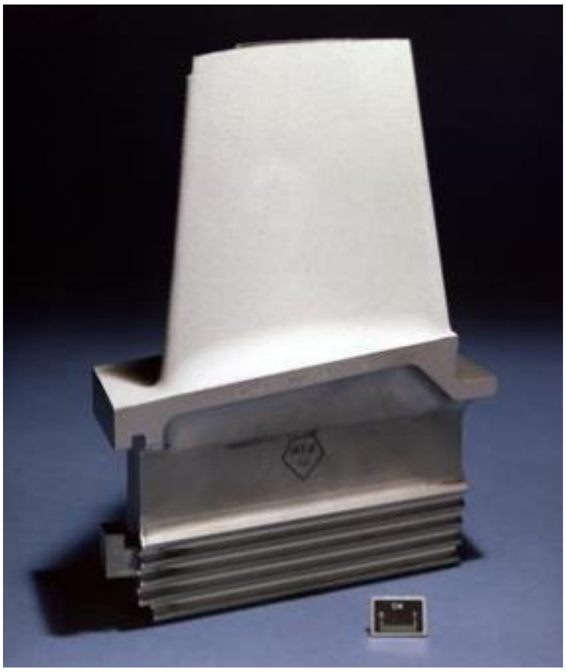


Fig. 3.1: Gas Turbine Blade with Thermal Barrier Coating

IV. INTRODUCTION TO COOLING OF GAS TURBINE BLADES:

Cooling of GT blade is the most important issue, as working temperature is too high. There are many techniques are utilized to cool the GT blade like Convection, Film, Transpiration Cooling, Cooling Effusion, Pin Fin cooling etc. Before knowing these technique we must have to know the necessity of cooling and its primary factions for effective cooling.

The main work of cooling technique to cool GT Blade effectively so that failure of GT Blade can be ignored.

● COVECTION 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. Cooling is achieved by passing the air through these passages from hub towards the blade tip. This cooling air comes from an air compressor.

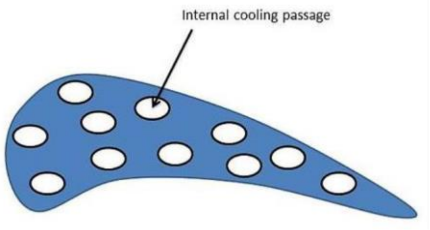


Fig. 4.1 : Blade Cooling by Convection

● 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.

● FILM COOLING:

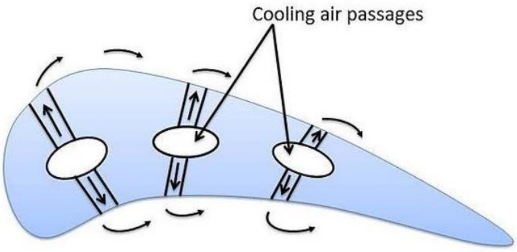


Fig. 4.2 : Film Cooling

This technique consists of pumping the cooling air out of the blade through multiple small holes or slots in the structure. A thin protective 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 Kelvin) can exceed the melting point of the blade material (1300–1400 kelvins).

● COOLING EFFUSION:

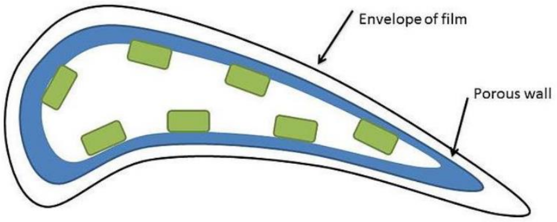


Fig. 4.4 : Cooling by Effusion

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 forms a protective film or cooler boundary layer.

- **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.

- **TRANSPIRATIONAL 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.

V. HEAT TRANSFER COEFFICIENT

The heat transfer coefficient or film coefficient, or film effectiveness, in thermodynamics and in mechanics is the proportionality constant between the heat flux and the thermodynamic driving force for the flow of heat the heat transfer rate is:

$Q=Ah(T_2-T_1)$

Where;

A: surface area where the heat transfer takes place, m2
T_2: temperature of the surrounding fluid, K
T_1: temperature of the solid surface, K.

It is used in calculating the heat transfer, typically by convection or phase transition between a fluid and a solid. The heat transfer coefficient has SI units in watts per square meter Kelvin: W/(m2K).

It is important property of metal which affect the heat transfer from the blade. And the thermal conductivity. To find its effect on cooling of gas turbine blade, we have prepared the CAD model of GT blade in CATIA V5R19 software.

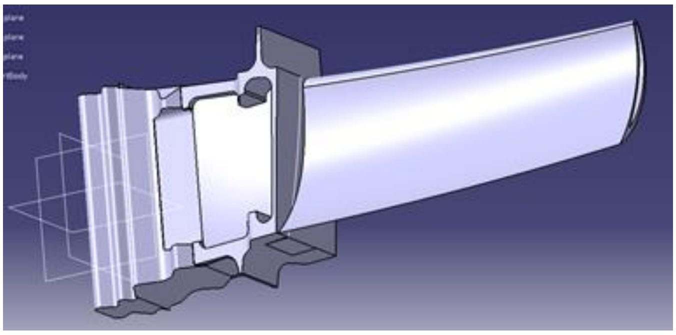
VI. LITERATURE SURVEY

By performing deep survey of literature available, following points can be concluded.

i. Less literature is available on remedies of failure.
ii. Gas Turbine blades are mostly failed due to high temperature.
iii. Working pressure, surrounding environment are the other reasons of failure.
iv. Leading edge is mostly suffered with high temperature.
v. Failure causes from top of the Gas Turbine Blade and propagate along the profile.

VII. CAD MODELING OF GAS TURBINE BLADE

By using the dimensions provided by the patent obtained by Tsifourdaris et al on date 14 July 2009 possesses the patent number US 7,559,746 B2 and other references, we have developed the CAD model of first stage Gas Turbine blade, which is shown as Fig. 7.1. CATIA V5R19 software is utilized to develop the Gas Turbine blade. There are several commands are utilized for the generation of CAD model of Gas Turbine bade from sketcher and part module like Pad, Pocket, Rib, Multi-section solid etc. and line, spline, profile etc. from sketcher module.



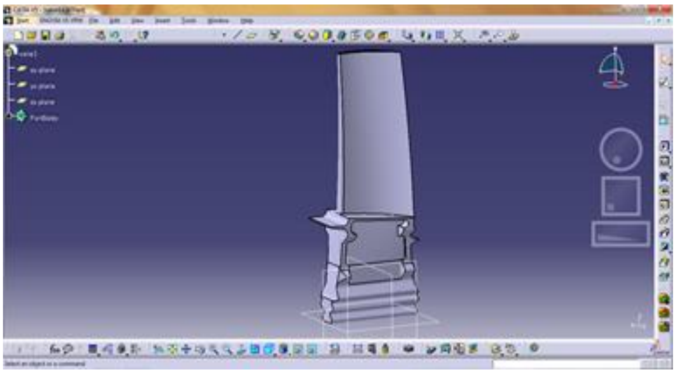


Fig. 7.1: Gas Turbine Blade Model prepared in CAD Software

VIII. CFD ANALYSIS OF GT BLADE

CFD Analysis will give us the pressure and temperature contours which are helpful to understand the thermal behaviour of GT Blade profile. By performing CFD Analysis the pressure, velocity, temperature and turbulence contours can be obtained. Properties of air are already available in ANSYS 14.5 Fluent software. We have utilized the same for CFD analysis. Also we have used N155 as a GT blade material which are also required to perform analysis. Physical properties of GT Blade material i.e. N155 are as follows.

Table 1 : Mechanical Properties of N155 Gas Turbine Blade Material

Properties	Units	N 155
E	Pa	143 E09
ρ	Kg/cu m	8249
K	W/m-K	20.0
μ	---	0.344
α	E-06/0C	17.7
Cp	J/Kg K	435

Where,

ρ= Density
α= Coefficient of Thermal Expansion
E= Young's Modulus
μ= Poisson's Ratio
K= Thermal Conductivity
Cp= Specific Heat

To perform CFD analysis we have to follow below steps.
Step 1: Change the units from metre to millimetre.
Step 2: Check the mesh.
ANSYS FLUENT will report the results of the mesh check in the console.

```
Domain Extents:
x-coordinate: min (m) = -2.032000e-01, max (m) = 2.032000e-01
y-coordinate: min (m) = -2.286000e-01, max (m) = 2.032000e-01
z-coordinate: min (m) = -2.332952e-18, max (m) = 5.080000e-02
Volume statistics:
minimum volume (m3): 1.148430e-10
maximum volume (m3): 5.741104e-08
total volume (m3): 2.633922e-03
Face area statistics:
minimum face area (m2): 2.147325e-07
maximum face area (m2): 3.444069e-05
Checking mesh........................
Done.
```

Step 3: Set up the models for the CFD simulation by Meshing.
Enable heat transfer by activating the energy equation.
Enable the K-Ɛ turbulence model.
Step 4: Set up the materials for the CFD simulation.
Assign the Properties to blade and vane material.
Also all Air Properties are taken which are already available with CFD tool.
Step 5: Set up the cell zone conditions for the CFD simulation (Assigning material to each object).
Step 6: Set up the boundary conditions for the CFD analysis.
Step 7: Set up solution parameters for the CFD simulation.
Step 8: Calculate a solution.
Start the calculation by requesting 100 iteration.

IX. RESULTS IN ANSYS FLUENT AND CFD-POST

In this step, we will display the results of the simulation in ANSYS FLUENT, display the results in CFD Post, then review the list of files generated by ANSYS Workbench.

Results calculated by performing CFD analysis are shown below.

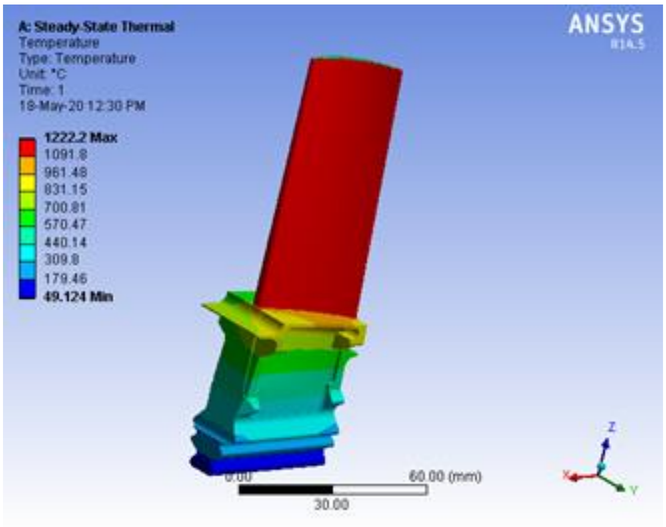


Fig. 9.1: Temperature Contours by considering Cooling Air Flow

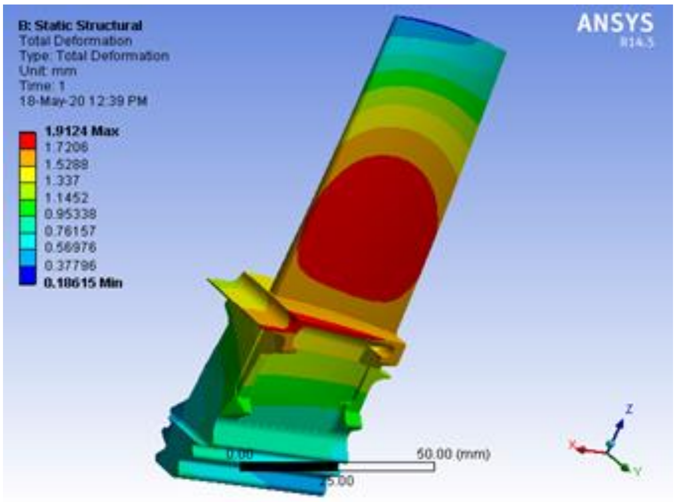


Fig. 9.2: Thermal Expansion of blade due to Heating

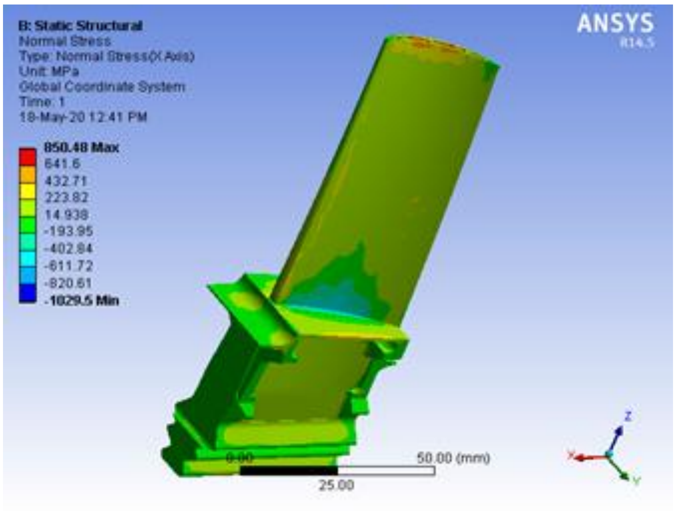


Fig. 9.3: Stresses developed due to Thermal Expansion

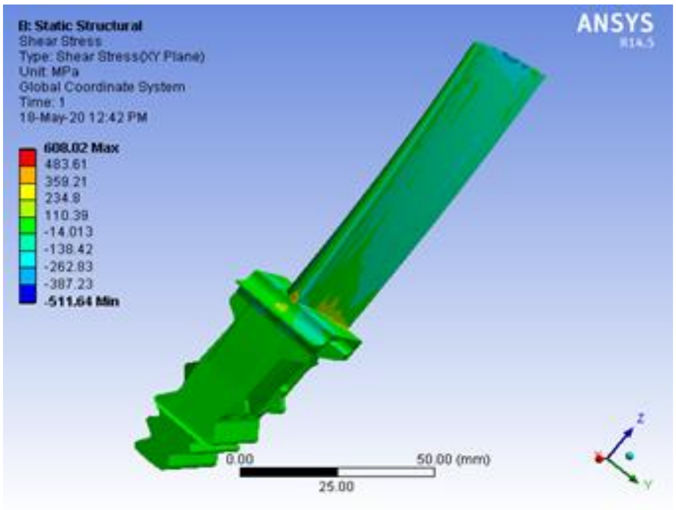


Fig. 9.4: Shear Stresses due to Expansion

Above figures illustrates the thermal effects on blade profile, by above analysis results we can tabulate results as per following.

Table 2 : Results obtained by performing CFD Analysis

Sr. No.	Properties	Minimum Value	Maximum Value
1	Temperature Contours	49.124 ^{0}C	1222.2 ^{0}C
2	Thermal Expansion	0.186 mm	1.91 mm
3	Normal Stress	-1029.5 MPA	850 MPA
4	Shear Stress	-511 MPA	608 MPA

X. CONCLUSION

The heat transfer distribution associated with the various aerodynamic flow regimes on the aerofoil. For the blade, the peak heat transfer coefficient value is at the leading edge, which then decreases gradually on the suction side until the trailing edge. However, on the pressure side, the heat transfer coefficient reduces rapidly from the leading edge, and then there is a transition to higher values until the trailing edge. These typical trends in the non-uniformity of the heat transfer coefficient are generally observed on most turbine vanes and blades. However, in addition to these generalized aerofoil heat transfer distributions, actual industrial gas turbines blades are also affected by several other parameters, such as; inlet pressure and temperature profiles, aerofoil shape and curvature, position of film cooling holes, thermal barrier coating roughness, transient wakes from upstream vanes, and blade passage turbulence intensity levels.

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