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Modelling and Simulation of Gas Turbine Blade with Different Geometrical Perforated Holes and Blade Materials: Software Analyses

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Abstract

In the gas turbine, the power is generated at higher temperature and large magnitude, the results of which it generates lots of heat, so the cooling of turbine blade is very much required. Geometrical changes in the gas turbine blade as well as the changes in designs of turbine, which may be in the form of perforations, are required for the optimization and efficient cooling. In the present work, effects of perforations on the turbine blade have been studied for small jet engine gas turbine manufactured by Williams International for CJ1 (Cessna Citation Jet) Model 525 engine by improving its geometry using the software called CATIA and also analyses at different boundary conditions by the analysis software called as ANSYS 14.0 workbench. Material of the turbine blade has also been optimized to improve performance of the gas turbine. After analyses, maximum temperature at tip i.e. 1050°C and minimum heat flux i.e. 509.99 W/m^2 have been found for INCONEL-718 blade material without holes but the minimum temperature at tip i.e. 971°C and maximum heat flux i.e. 575.73 W/m^2 have been achieved for NIMONIC-115 with holes which are good for gas turbine blade. In this research work NIMONIC-115 has been recommended as blade material and hole in the blade geometry has been suggested as improvement in the design of blade.

***Keywords**: Gas turbine blade; Perforation; Temperature at tip; Heat flux; CATIA V5R12 software; ANSYS 14.0 software*

LIST OF NOMENCLATURE

A = Cross section of the blade in m^2,
h = Heat transfer coefficient in W/m^{2}K,
K = Thermal conductivity of the blade material in W/mK,
P = Perimeter of the blade in meter,
Q = Heat flux or heat dissipation for the blade in W/m^2

INTRODUCTION

From the last few decades, numbers of the researchers are using the various power generation sources like solar energy, wind energy and many natural and non-conventional sources of energy. In the gas turbine, power is generated by the use of energy of the working medium, i.e., gases which strikes over the blades to get the mechanical work and then turn in the form of electrical energy as output. The level of air pressure in this area of research has been reached its peak from the year 1930 accordingly the new technologies have to be developed to increase the performance of the aircraft engines with higher velocities and higher thrust which in turn decreases the weight and reduces engine size. The military aircraft engines have to perform in a better way to achieve the desired performances. The increase in the turbine inlet temperature will give rise to the increase in the turbine efficiency of the cycle and the turbine work/power output. There are number of techniques employed for the purpose of cooling, it may include like increase the overall flow rate of the coolant around the gas turbine casing or providing the cooling holes which may differ in sizes and shapes according to the gas turbine applications. Flow of boundary layer over the passage of the blade is shown in Fig. 1 (Ganeshan, 2010; Soares, 2014; Han, Dutta and Ekkad, 2012). The material is the most important constraint choosing for the turbine blades, the material must be light in weight, low cost, easy available and high erosion-corrosion resistant with optimum and reliable services.

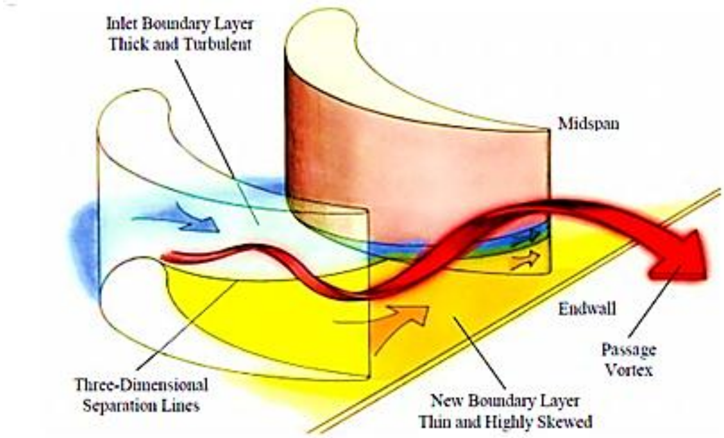

Figure 1: *Flow of boundary layer over the passage of the blade.*

Some of the important blade materials which are used conventionally are described as; (a) U-500: this material was used as a first stage (the most demanding stage) material in the 1960s, and is now used in less demanding stages. (b) Rene 77 and Rene N5: many times also employed for blade materials. (c) IN-738: GE used IN-738 as a first stage blade material from 1971 until 1984, when it was replaced by GTD-111. It is now used as a second stage material. It was specifically designed for land-based turbines rather than aircraft gas turbines. (d) GTD-111: blades made from directionally solidified GTD-111 are being used in many GE gas turbines in the first stage. Blades made from equiaxed GTD-111 are being used in later stages (Ganeshan, 2010; Soares, 2014; Han, Dutta and Ekkad, 2012). Some literature survey has been done on this field; Kliuev et al (2016) worked on the capacity and effectiveness of the materials used in gas turbine. Beghini et al., (2017) carried out the design of a new device that can evaluate the fatigue behaviour of the full gas turbine line based on finite element (FE) analysis of the blade reaction under thermo mechanical loads. Zhang et al., (2019) investigated the concept of an equivalent solid material for the mechanical properties of single-crystalline thin-walled nickel-based plates. Ajersch et al., (1995) conducted an experimental study in a slow wind tunnel on series of six rectangular nozzles injected at 900°C (main stream). Johnson et al., (2013) conducted an experimental study to examine the performance of the film cooling injection from a series of circular holes arranged laterally on a flat plate. Xue and Ng (2018) provided an overview of external cooling technologies for gas turbine blade tips and suggested the artificial intelligence techniques such as genetic algorithm which provides powerful alternative tools to optimize the end point cooling. Sen, Schmidt and Bogard (1994) studied that the heat transfer coefficient becomes particularly important variable for determining the overall power for injecting a compound angle at high momentum flux ratios. Andrews et al (1985) studied the influence of the size of the hole and blowing speed on the cooling of the discrete hole wall in gas turbine combustion chamber applications. Andrews et al., (1990) presented experimental measurements of total cooling efficiency for the cooling of discrete holes over the entire surface for a wide range of practical geometries and for a density ratio of 2.5 between the coolant and the flue gases. Lloyd and Brown (1985) described the results of an experimental study of velocity and turbulence fields and, to a lesser extent, heat transfer in the inlet areas of circular section tubes and a length/diameter ratio up to 20. In this research work, effects of perforations on the gas turbine blade have been analysed for the turbine which manufactured by Williams International for CJ1 (Cessna Citation Jet) Model 525 engine by CATIA software and also analysed by ANSYS 14.0 workbench software (Tickoo, 2010; Tickoo, 2013), and which material can be used for the turbine blade has also been suggested after this analytical work.

METHODOLOGY WITH MODELLING AND SIMULATION

As after studying the previous literature it has been found that there are various types of analyses have been done to meet the desired requirement. For the mentioned problem, some standard data from specific literature problem have been selected, the parameters are described with their values are; the temperature of the flowing fluid, T_∞ is $1200°C$, convection coefficient maintain between the surface of the blade and flowing fluid, h is $250\ W/m^2K$, thermal conductivity of the blade material INCONEL, K is $20\ W/mK$, length of the blade, l is 50 mm, cross sectional area of the blade profile, A is $6\times10^{-4}\ m^2$, perimeter of the blade, P is $110\ mm$ and temperature at the base of the blade, T_b is $300°C$. The mathematical relation between the surrounding temperature, maximum temperature and base temperature is given by (Cengel, 2003; Holman, 2009; Lienhard, 2008; Whitaker, 1983).

$$[(T_L - T_\infty) / (T_b - T_\infty)] = (1 / \cosh ml) \quad (1)$$

The formula by which the value of mathematical parameter m is to be calculated is given by (Cengel, 2003; Holman, 2009; Lienhard, 2008; Whitaker, 1983),

$$m^2 = (h P) / (K A) \quad (2)$$

And heat flux can be found by the following relation where the heat dissipates from a fin when the tip is insulated (Cengel, 2003; Holman, 2009; Lienhard, 2008; Whitaker, 1983),

$$Q = \sqrt{(h P K A)}\ dT \tanh (ml) \quad (3)$$

Where, h is the heat transfer coefficient in W/m^2K, K is thermal conductivity of the blade material as INCONEL in W/mK, P is perimeter of the blade in *meter*, Q is heat flux in W/m^2 and A is cross section of the blade in m^2. After calculations following results have been found – m is $47.87\ m^{-1}$, ml is 2.39, $\cosh mL$ is 5.51, T_L is $1200°C + (300\text{-}1200)/5.51 = 1037°C$ and the value of the heat flux is $507\ W/m^2$. Creations of the models of gas turbine blade in the CATIA software with and without cooling holes have been shown in Fig. 2 and 3. As per the given boundary conditions, gas turbine blades have been analysed by using three different materials namely INCONEL 718, NIMONIC 90 and NIMONIC 915, and the results have been obtained. These three materials, which have densities and melting points 8192 kg/m^3-1336°C, 8180 kg/m^3-1370^{0}C and 7850 kg/m^3-1304^{0}C respectively, are nothing but the super alloy materials with base material is nickel and chemical compositions of these blade materials have been tabulated in Table 1. The rest ingredients are chromium, iron, cobalt, molybdenum, tungsten, tantalum, aluminium, titanium, zirconium, niobium, yttrium, vanadium, carbon, boron and hafnium, and these materials are used for high temperature applications because of the creep and oxidation resistance as primary resistance. Temperature at tips and heat fluxes for two different geometries of the gas turbine blade have been shown in Fig. 4 and 15 using with and without holes vertically in the longitudinally direction of the turbine blade. The first six Fig. 4 to 9 represent without hole geometry for the analyses of three different super alloys namely INCONEL 718, NIMONIC90 and NIMONIC 115 representing both temperature and heat flux results respectively, similarly the next six Fig. 10 to 15 also represent seven equally spaced holes taking the same boundary conditions which were used previously for the three considered super alloy materials for observing the temperature at tip and heat flux respectively. Temperature and heat flux distributions for INCONEL-718 material without holes have been shown in Fig, 4 and 5 as, 1050, 966.67, 883.33, 800, 716.67, 633.33, 550, 466.67, 383.33 and 300°C, and 509.99, 453.32, 396.66, 339.99, 283.33, 226.66, 170, 113.33 and 56.667 W/m^2 from tip to base of the blade respectively. Temperature and heat flux distributions for NIMONIC-90 material without holes have been revealed in Fig. 6 and 7 as, 988, 894.17, 800.34, 706.52, 612.69, 518.86, 425.03, 331.2, 237.38 and 143.55°C, and 532.3, 473.15, 414.01, 354.87, 295.72, 177.43, 118.29 and 59.144 W/m^2 from tip to base of the blade respectively. Temperature and heat flux distributions for NIMONIC-115 material without holes have also been exposed in Fig. 8 and 9 as, 973, 875.03, 777.07, 679.1, 581.14, 483.17, 385.21, 287.24, 189.28 and 91.31°C, and 546.18, 485.49, 424.81, 364.12, 303.43, 242.75, 182.06, 121.37 and 60.686 W/m^2 from tip to base of the blade respectively. Similarly, temperature and heat flux distributions for INCONEL-718 material with seven equidistance holes have been shown in Fig. 10 and 11 as, 1006, 927.56, 849.11, 770.67, 692.22, 613.78, 535.33, 456.89, 378.44 and 300°C, and 510.83, 454.07, 397.31, 340.55, 283.79, 227.03, 170.28, 113.52 and 56.759 W/m^2 from tip to base of the blade respectively. Temperature and heat flux distributions for NIMONIC-90 material with seven equidistance holes have been shown in Fig. 12 and 13 as, 973, 895.22, 817.44, 739.67, 661.89, 584.11, 506.33, 428.56, 350.78 and 273°C, and 549.4, 488.36, 427.31, 366.27, 305.22, 244.18, 183.13, 122.09 and 61.044 W/m^2 from tip to base of the blade respectively and finally, temperature and heat flux distributions for NIMONIC-115 material with seven equidistance holes have been publicized in Fig. 14 and 15 as, 971, 884.97, 798.93, 712.9, 626.86, 540.83, 454.79, 368.76, 282.72 and 196.69°C, and 575.73, 511.77, 447.82, 383.87, 319.92, 255.96, 192.01, 128.06 and 64.107 W/m^2 from tip to base of the blade respectively. From these figures, it has been observed that distributions of temperature and heat flux decrease from the tip to the base of the blade for each blade material and blade geometry which are obvious.

Table 1: *Chemical compositions of INCONEL 718, NIMONIC90, NIMONIC 115 materials.*

INCONEL 718 as blade material		**NIMONIC90 as blade material**		**NIMONIC 115 as blade material**	
Elements	**Composition (%)**	**Elements**	**Composition (%)**	**Elements**	**Composition (%)**
Columbium, Co	4.75-5.50	Cr	18-21	Ni	54
Titanium, Ti	0.65-1.15	Co	15-21	Cr	14-16
Aluminum, Al	0.20-0.80	Ti	2-3	Co	13-15.5
Cobalt, Co	1.00 max	Al	1-2	Al	4.5-5.5
Boron, B	0.006 max	C	0.2 max	Mo	3.0-5.0
Copper, Cu	0.30 max	Si	1.0 max	Ti	3.5-4.5
Tantalum, Ta	0.05 max	Cu	0.2 max	Fe	1.0 max
Molybdenum, Mo	2.80-3.30	Fe	1.5 max	Mn	1.0 max
Elements	Composition (%)	Mn	1.0 max	Si	1.0 max
Nickel, Ni	50-55	B	0.02 max	Cu	0.2 max
Carbon, C	0.08 max	S	0.015 max	Zr	0.15 max
Manganese, Mn	0.35 max	Zr	0.15 max	C	0.2 max
Phosphorus, P	0.015 max	Pb	0.002 max	S	0.015 max
Sulfur, S	0.015 max				
Silicon, Si	0.35 max	Ni	Balance	B	0.015-0.02
Chromium, Cr	17-21				

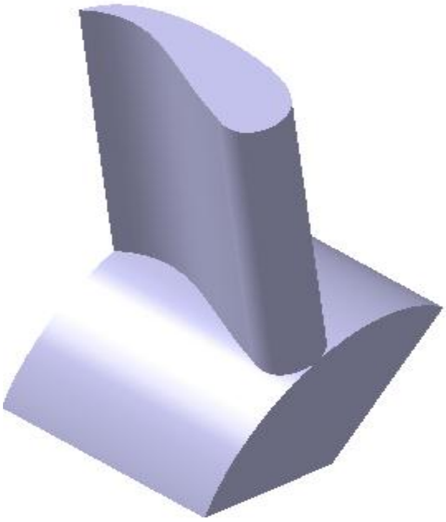

Figure 2: *Three dimensional model of turbine blade.*

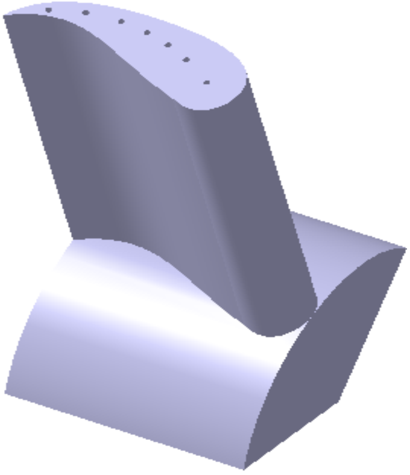

Figure 3: *Three dimensional model of turbine blade with seven holes.*

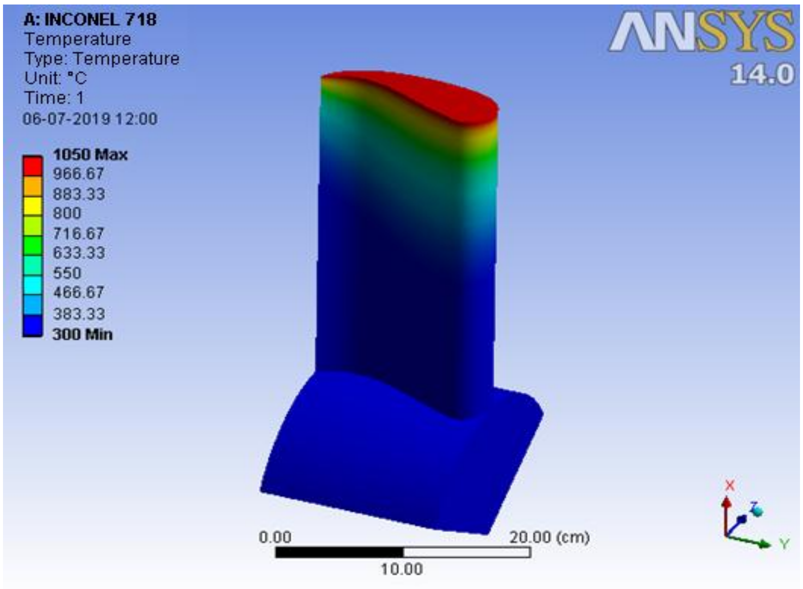

Figure 4: *Temperature at tip and distribution for INCONEL-718 material without holes.*

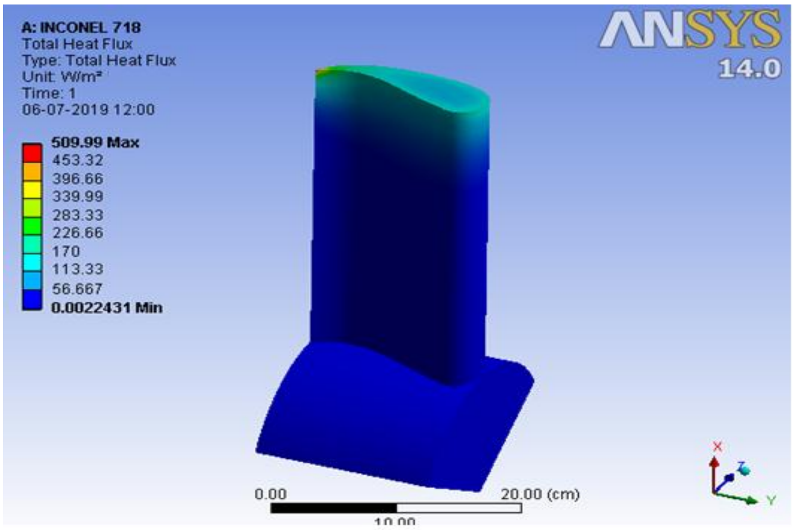

Figure 5: *Heat flux for INCONEL 718 material without holes.*

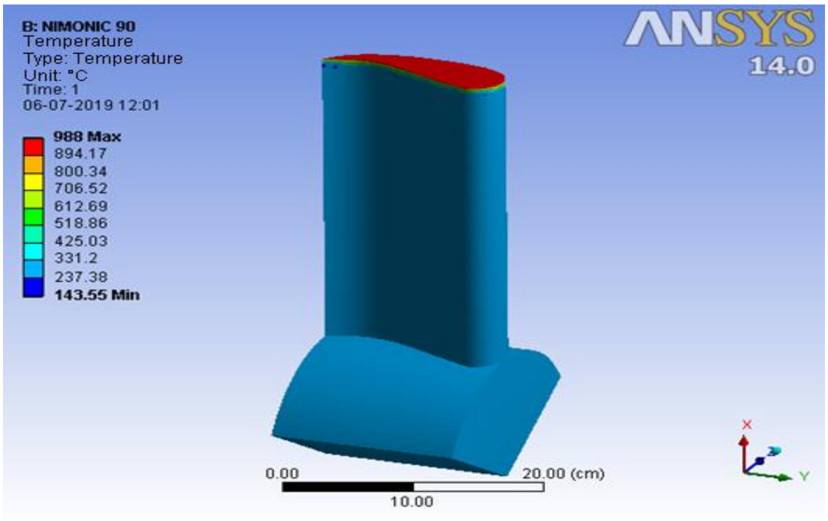

Figure 6: *Temperature at tip and distribution for NIMONIC-90 material without holes.*

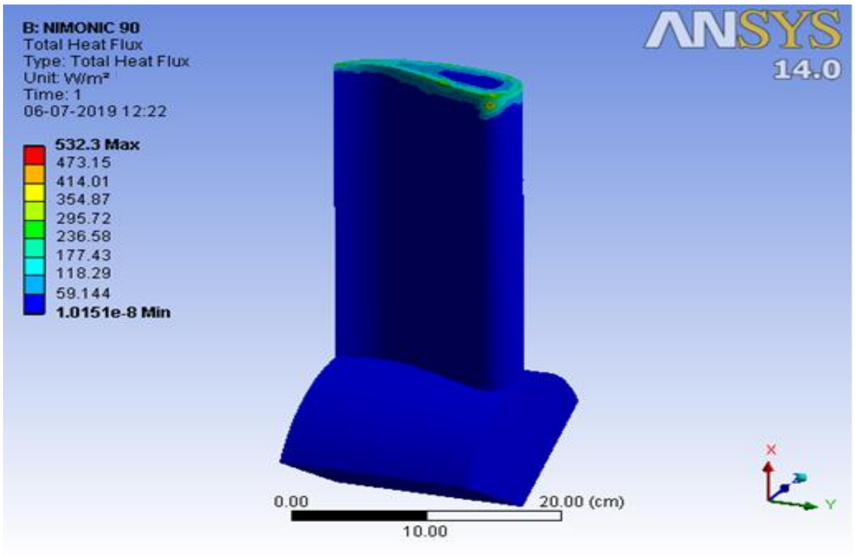

Figure 7: *Heat flux for NIMONIC-90 material without holes.*

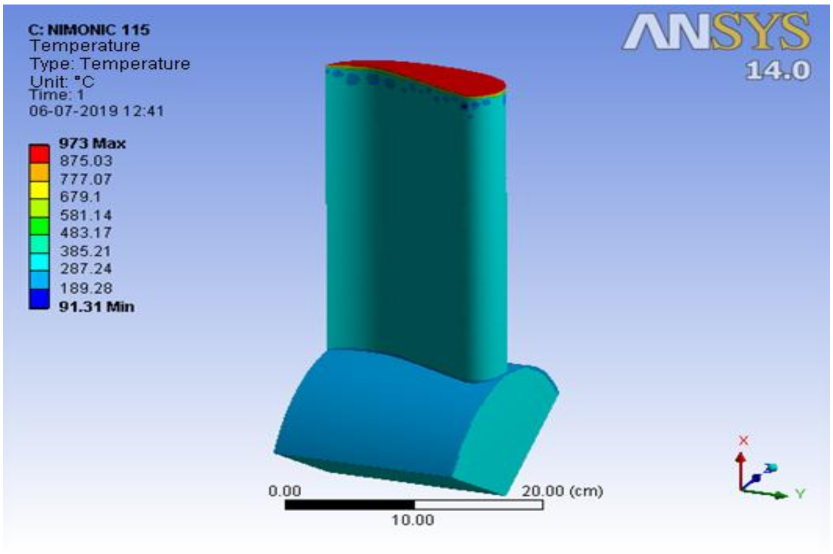

Figure 8: Temperature at tip and distribution for NIMONIC-115 material without holes.

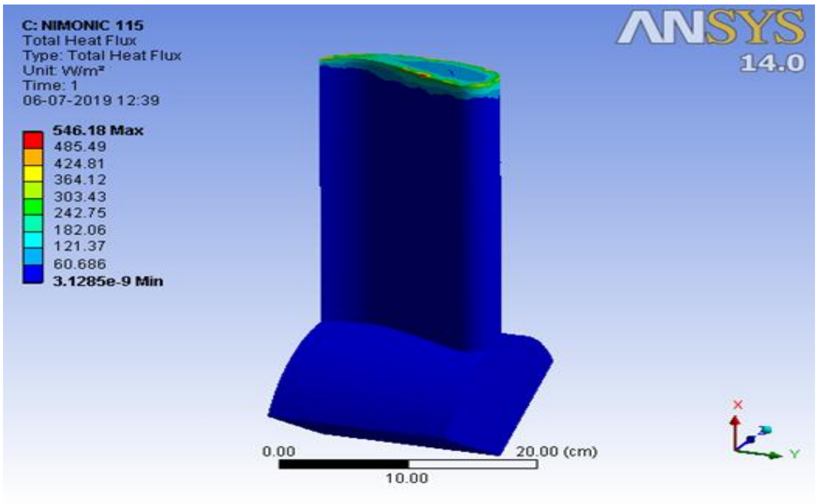

Figure 9: Heat flux for NIMONIC-115 material without holes.

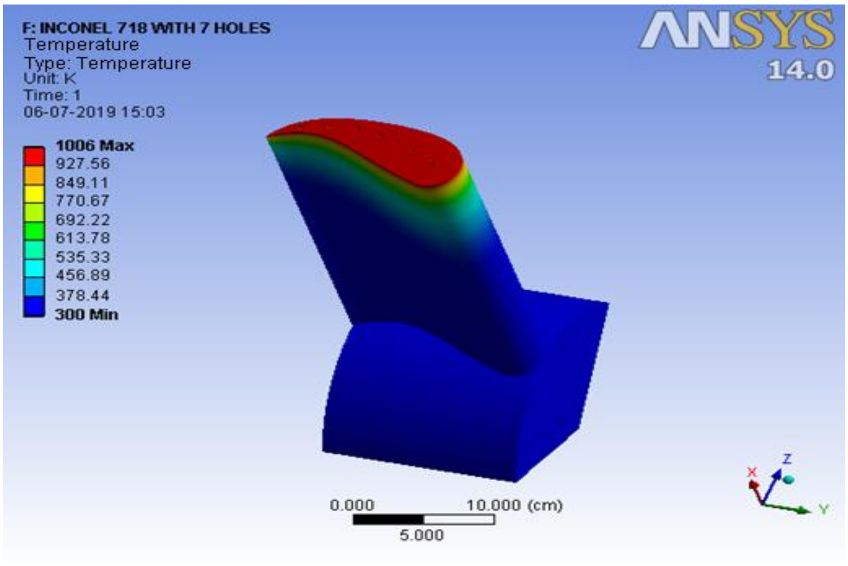

Figure 10: Temperature at tip and distribution for INCONEL-718 material with 7 holes.

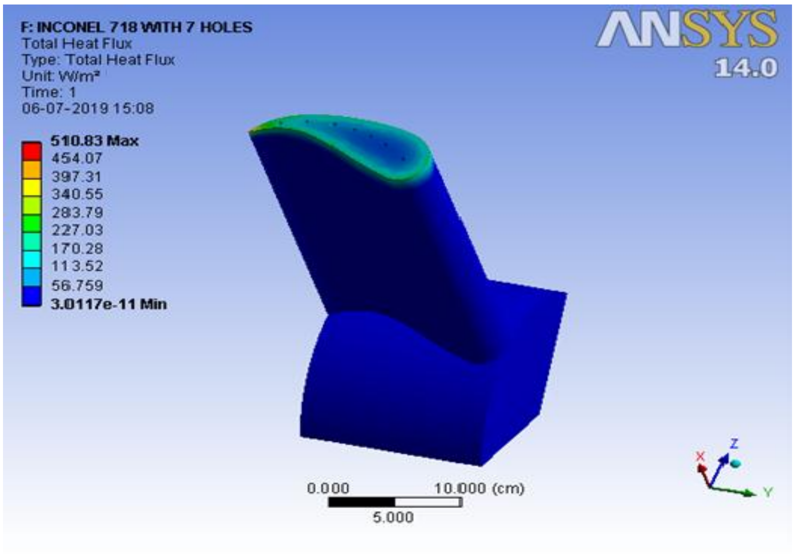

Figure 11: *Heat flux for INCONEL-718 material with 7 holes.*

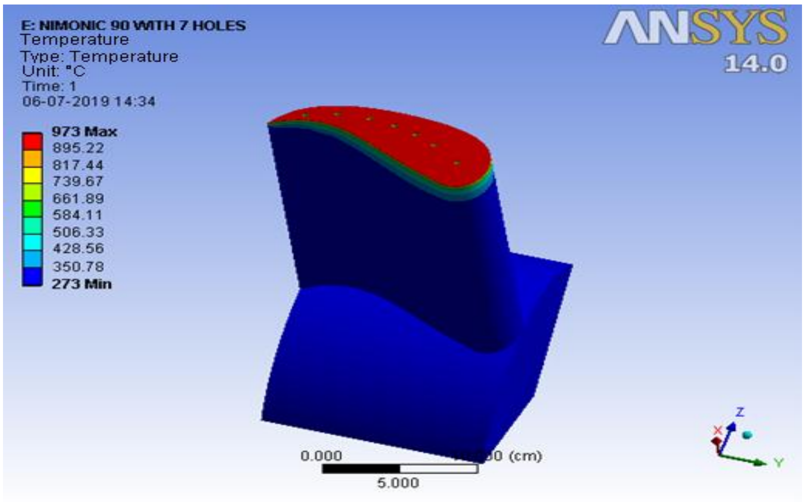

Figure 12: *Temperature at tip and distribution for NIMONIC-90 material with 7 holes.*

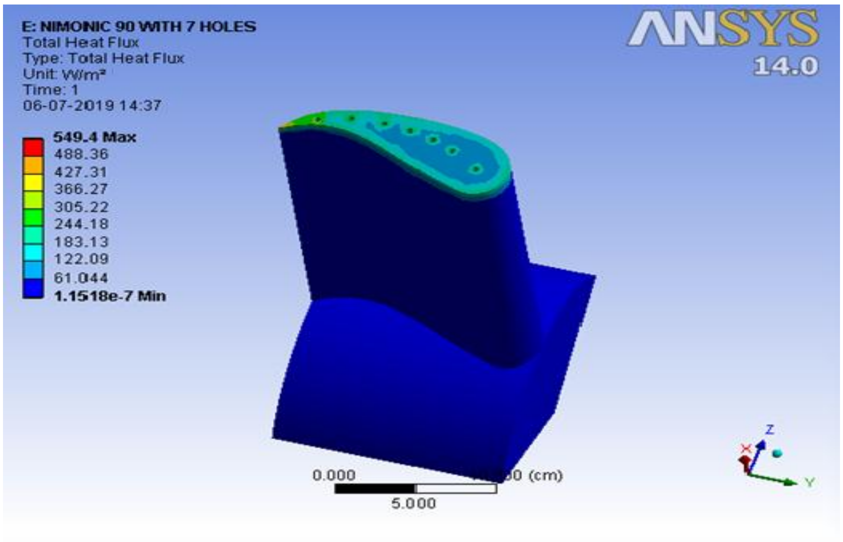

Figure 13: *Heat flux for NIMONIC-90 material with 7 holes.*

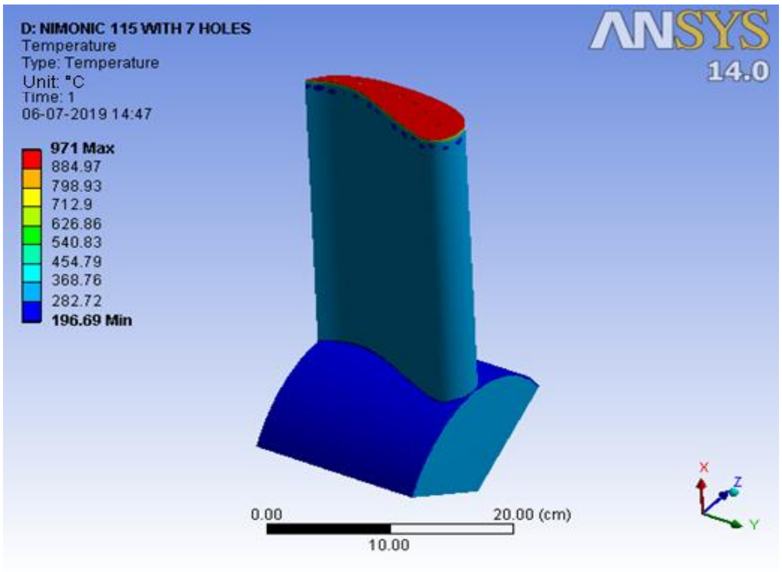

Figure 14: *Temperature at tip and distribution for NIMONIC-115 material with 7 holes.*

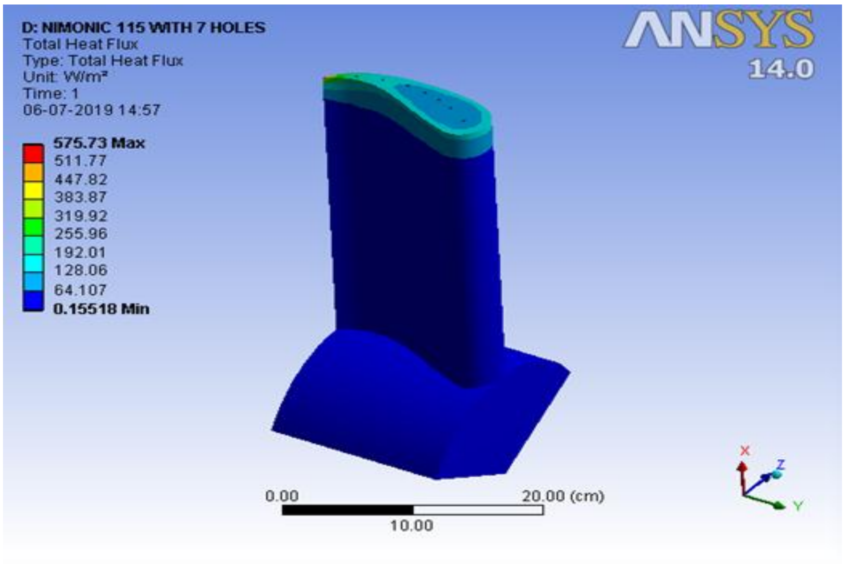

Figure 15: *Heat flux for NIMONIC-718 material with 7 holes.*

RESULTS

The effects of seven equally spaced perforated holes on the gas turbine blade with three different blade materials have been designed and analysed by CATIA and ANSYS 14.0 software respectively, and compared outputs by without holes in the turbine blade. The selected turbine was manufactured by Williams International for Cessna Citation Jet and materials which were selected for blade are super alloys; INCONEL 718, NIMONIC90 and NIMONIC 115. With these inputs, outputs have been tabulated in Table 2 to 5. The following observations have been drawn on the basis of the data obtained from the results; 1. The maximum temperature achieved in any case of the three materials is in the range from 970 to 1050°C. 2. The maximum heat flux achieved in any case of the three materials is in the range from 500 to 580 W/m^2. 3. It can be clearly observed that using NIMONIC alloy materials are being better in both temperatures at tip as well as heat transfer rate. 4. In case of NIMONIC materials both the alloys i.e., NIMONIC-90 and NIMONIC-115 are providing very similar results with respect to the obtained data from ANSYS workbench. 5. INCONEL-718 data value is justifying our numerical results and hence the analysis has been verified and can be considered for NIMONIC alloys too and 6. By observing the table keenly it has been found that the temperatures at tip and heat transfer rates are proportional to each other.

Table 2: *Temperature at tip and heat flux for three different super alloys using solid blade geometry.*

Sr. No	**Super Alloy Material**	**Temperature at tip in °C**	**Heat Flux In W/m^2**
1.	INCONEL-718	1050	509.99
2.	NIMONIC-90	988	532.3
3.	NIMONIC-115	973	546.18

Table 3: *Temperature at tip and heat flux for three different super alloys using blade using longitudinal equidistance holes geometry.*

Sr. No.	**Super Alloy Material**	**Temperature at tip in °C**	**Heat Flux in W/m^2**
1.	INCONEL-718	1006	510
2.	NIMONIC-90	973	549
3.	NIMONIC-115	971	575.73

Table 4: *Comparative results temperature at tip for three different super alloys using solid and geometry with longitudinal holes.*

Sr. No.	**Super Alloy Material**	**Temperature at tip in °C (for solid blade)**	**Temperature at tip in °C (for blade with holes)**	**% Difference**
1.	INCONEL-718	1050	1006	4.19
2.	NIMONIC-90	988	973	1.52
3.	NIMONIC-115	973	971	0.20

Table 5: *Comparative results heat flux for three different super alloys using solid and geometry with longitudinal holes.*

Sr. No.	**Super alloy material**	**Heat flux in W/m^2 (for solid blade)**	**Heat flux in W/m^2 (for blade with holes)**	**% Difference**
1.	INCONEL-718	509.99	510	0.0019
2.	NIMONIC-90	532.3	549	3.0418
3.	NIMONIC-115	546.18	575.73	4.7913

CONCLUSION

After analyses on gas turbine blades by computer software with different geometries and different blade materials the following conclusions can be done; 1. For both the geometries from the outputs, the temperature at tip is in decreasing order for INCONEL-718, NIMONIC-90 and NIMONIC-115 respectively. 2. For both the geometries, the heat flux is in increasing order for INCONEL-718, NIMONIC-90 and NIMONIC-115 respectively. 3. From both the above two points, it can be concluded that NIMONIC-115 is showing the best suitable material for gas turbine blade application for lower temperature at tip as well as high heat dissipation rate (i.e. heat flux). 4. The percentage deviations for temperature at tip in INCONEL material for solid and hollow geometries are considerably high and it is appreciable to use the geometry with holes for this category of the materials and 5. The percentage deviations of the heat flux or heat dissipation rate per unit area for

NIMONIC-115 as well as NIMONIC-90 provide the considerably high using gas turbine blade with equally spaced seven holes and can be considered for gas turbine application where it is really necessary to dissipate heat at higher rates. To improve the performance of the gas turbine blades, NIMONIC-115 as turbine blade material with perforated holes has been suggested.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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