Fatigue Life Comparison of Gas Turbine Blade with and Without Cooling Effect

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ABSTRACT

Gas turbine has been an important and reliable power generation device which is being widely used in the field of power generation and has many other applications. With increased power requirement, power output as well as efficiency needs to be improved. So efforts are made to increase inlet temperature of turbine blade using branched holes cooling techniques taking care of fatigue failure which may occur with increased temperature. Therefore, estimation of the fatigue life becomes necessary concern which is done using Manson-Coffin approach and the comparison of fatigue life of blade with cooling and without cooling is made. Fatigue life is expected to increase which is proved by the study taken under this research.

Keywords*: Gas turbine, Fatigue Life, Manson-Coffin*

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1. INTRODUCTION

A gas turbine, also known as a combustion turbine, is a type of internal combustion engine. It has an upstream rotating compressor coupled to a downstream turbine. A combustion chamber is present in between. The basic operation of the gas turbine is same as that of the steam power plant. Only difference is that the air is used instead of water. Atmospheric air flows through a compressor that converts it to a higher pressure. Energy is added by spraying fuel into the air and igniting it so the combustion generates a high temperature flow. This high temperature and high pressure gas enters a gas turbine and then it expands to the pressure at an exhaust, producing a shaft work output. The turbine shaft work is used for driving the compressor and other devices like an electric generator that may be coupled to the shaft. The energy which is not used for shaft work comes in the exhaust gases, so these have either a high velocity or a high temperature. The purpose of the gas turbine determines the design so that the most desirable energy form is maximized. Gas turbines are used to power aircraft, trains, ships, electrical generators, and tanks. Nowadays, gas turbine engines operate at very high temperatures (1200-1500°C) to improve thermal efficiency and power output [1].

Due to increase in the gas temperature, the heat transfer to the blades will also increase considerably which results in their thermal fatigue failure [2]. Fatigue cracking is one of the dominant damage mechanisms of structural components. Cyclic stresses that are below the ultimate tensile stress or even the yield stress of the material results in fatigue cracking. Fatigue is based on the theory that a material fails at a stress level below the nominal strength of the material. Thus, calculation of the fatigue life of the turbine blades becomes necessary.

High cycle fatigue failure is very rare in gas turbine blade failures. Most commonly, low cycle fatigue failure is observed in gas turbine blades. For Low cycle fatigue analysis, strain life approach is used for calculating the fatigue life. The Strain Life (ε-N) method uses the total strain present at the critical location most likely to fail in

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determining the predicted life [3]. Masson-Coffin is used for estimation of the fatigue life in the low cycle fatigue range.

To increase inlet temperature without increasing chances of fatigue failure, advanced branched cooling methods are used which helps in reducing stresses on turbine blade profile [4].

1.1 Film Cooling Technique

Film cooling also known as branched holes cooling is most effective method of turbine blade cooling. Film cooling is the technique where the cold air taken through compressor is fed in turbine blade through hub and cooling passages which are made in turbine blades. Through the research since many years' various types of branched cooling holes were invented and effectiveness were checked. In 2008 NASA developed a new type cooling method i.e. Anti-Vortex cooling hole technique [4]. This hole consisted of a main hole and side branched holes at each side. The main advantage of this type of hole was the vortices formed by normal cylindrical hole were cancelled by these anti vortex holes. Due to this the cool film remains attached to the blade surface and we get more cooling effectiveness than the other cooling methods [5].

As this advanced cooling method has proved effective it becomes necessary to test its effect and how it has affected the life of blade [1].

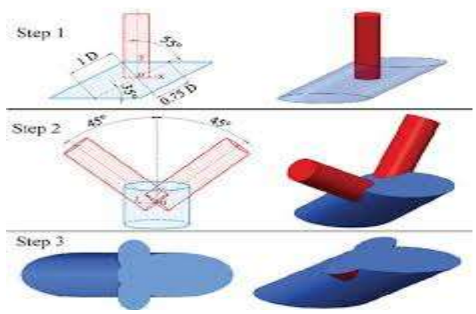

Fig-1: Steps involved in cooling

2. DESIGN OF GAS TURBINE BLADE

The blade profile was generated with key points and extruded to get solid structure using design software [6].

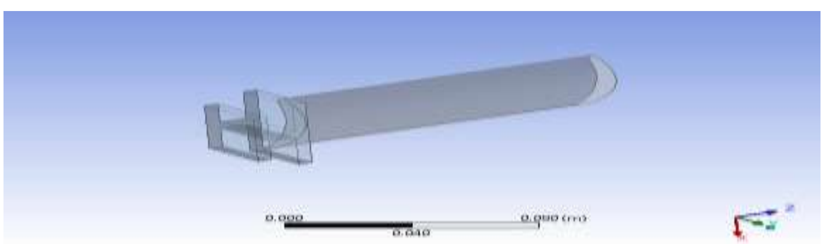

Fig-2: Gas turbine blade without cooling holes

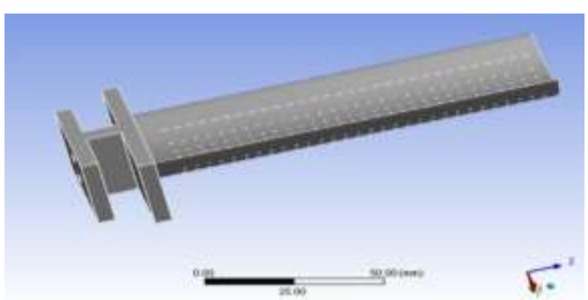

Fig-3: Gas turbine blade with cooling holes

3. COUPLED FIELD ANALYSIS OF GAS TURBINE BLADE

Gas turbine blade has been analyzed for structural as well as thermal using ANSYS 16.0 which is widely used for Finite Element Analysis. In the process, software is used to evaluate thermal stresses and temperature distribution of turbine blade [7]. From different materials, Inconel 718 has been considered for the analysis based on the previous research [8]. The geometric model of the blade profile is generated with key points and extruded to get a solid model.

3.1 Boundary conditions:

The blade was analysed first for the model [9] with the coupled field analysis with both thermal and mechanical loads acting both simultaneously. The boundary conditions for the analysis where as follows:

Sr. No.	Parameter	Value
1	Turbine Inlet Temperature	1123.15 K
2	Velocity of Hot Gas	265 m/s
3	Cold Air Temperature	523.15 K
4	Cold Air Velocity	530 m/s
5	Axial Force	3.82 N
6	Tangential Force	248.2 N
7	Centrifugal Force	38039 N
8	Speed	10800 rpm
9	Power	6 MW

Table-1: Boundary conditions

3.2 Results

3.2.1 Blade without holes

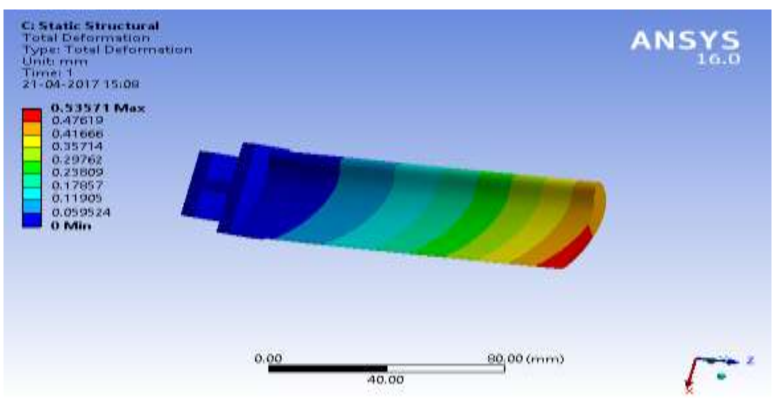

Fig-4: Total Deformation

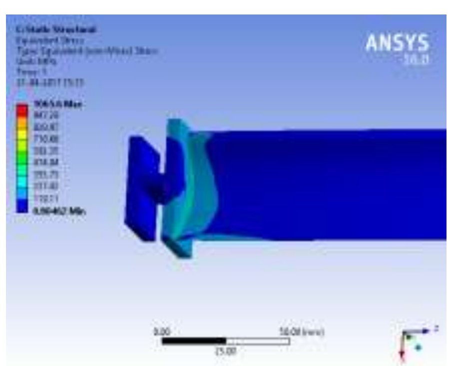

Fig-5: Equivalent stress

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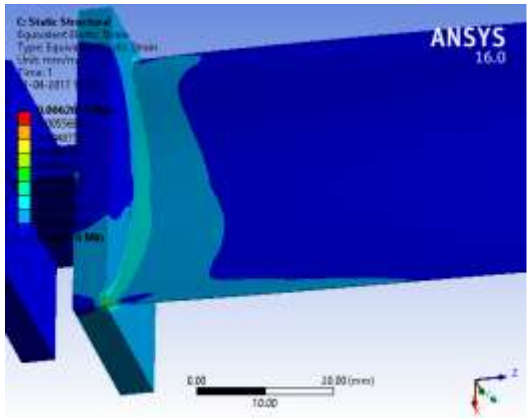

Fig-5: Equivalent strain

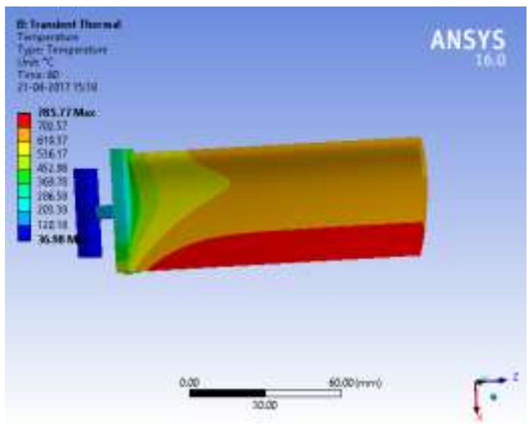

Fig-6: Temperature on blade profile

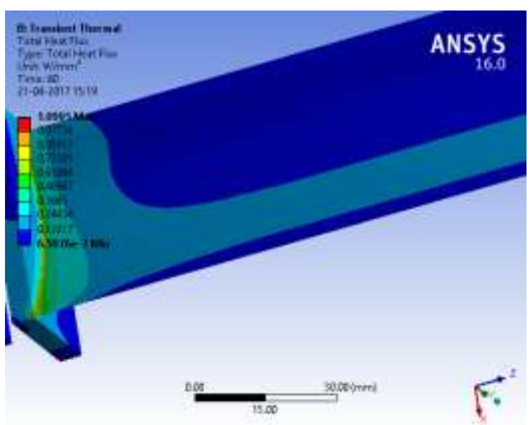

Fig-7: Total heat flux

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3.2.2 Blade with branched holes:

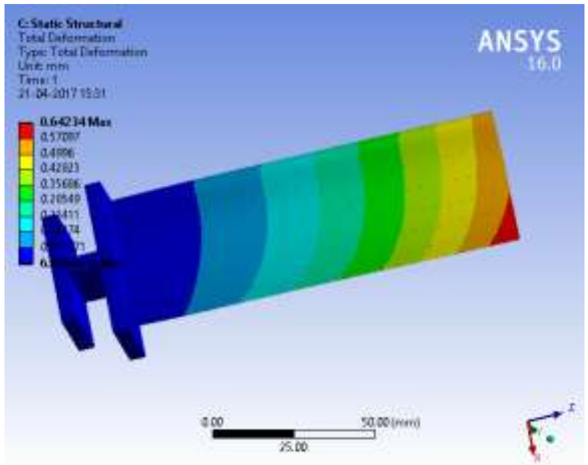

Fig-8: Total Deformation

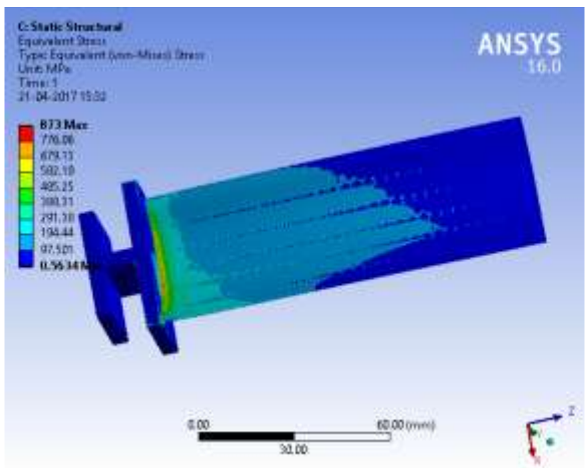

Fig-9: Equivalent stress

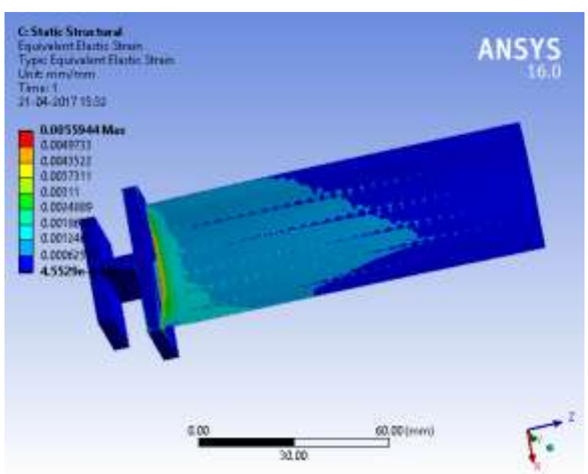

Fig-10: Equivalent strain

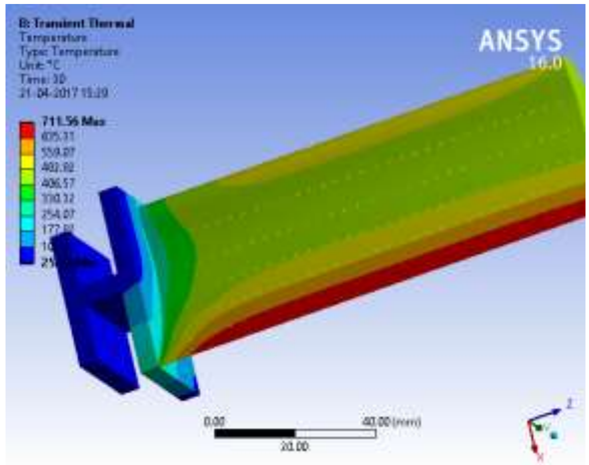

Fig-11: Temperature on blade profile

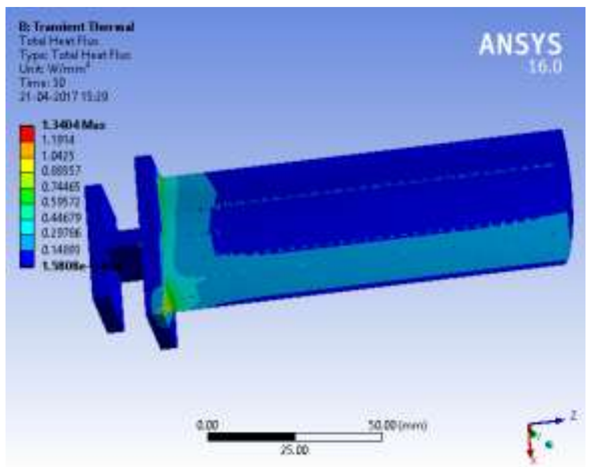

Fig-12: Total heat flux

4. FATIGUE LIFE ESTIMATION BY MANSON-COFFIN'S EQUATION

Masson-Coffin approach is used for estimation of the fatigue life in the low cycle fatigue range [10].This approach is accurate for crack initiation and damage. It involves more detailed analysis of the plastic deformation at localized regions where the stresses and strains are considered for life estimation. It is more complex since it involves many parameters to be considered. This approach generates accurate results in the low cycle fatigue range [11].

For Calculating Fatigue life,

By using the Manson-Coffin equation [12],

$$\Delta\epsilon_t = 3.4\left(\frac{S_u - S_m}{E}\right) N_f^{-0.12} + \epsilon_f^{-0.12} N_f^{-0.6}$$

where, $\Delta\epsilon_t$ = Strain range

N_f = Number of cycles to failure

S_u = Ultimate Tensile Strength

$S_m = \frac{\sigma}{2}$

4.1 Fatigue life of blade without holes

By using the Manson-Coffin equation,

$$\Delta\epsilon_t = 3.4\left(\frac{S_u - S_m}{E}\right) {N_f}^{-0.12} + {\epsilon_f}^{-0.12} {N_f}^{-0.6}$$

Where, $S_m = \frac{\sigma}{2} = \frac{1065}{2} = 532.5$ Mpa

$\Delta\epsilon_t = 0.0062610$, $S_u = 1240$ Mpa, $\epsilon_f = 0.7985$, E = 200000 Mpa and σ = 1065 Mpa

Substituting the values in the equation above we get,

$$0.0062610 = 3.4\left(\frac{1240 - 532.5}{200000}\right) {N_f}^{-0.12} + 0.8737{N_f}^{-0.6}$$

On simplification we get,

$$N_f = 17{,}050\ cycles$$

4.2 Fatigue life of blade with holes

By using the Manson-Coffin equation,

$$\Delta\epsilon_t = 3.4\left(\frac{S_u - S_m}{E}\right) {N_f}^{-0.12} + {\epsilon_f}^{-0.12} {N_f}^{-0.6}$$

Where, $S_m = \frac{\sigma}{2} = \frac{873}{2} = 436.5$ Mpa

$\Delta\epsilon_t = 0.0055898$, $S_u = 1240$ Mpa, $\epsilon_f = 0.7985$, E = 200000 Mpa and σ = 873 Mpa

Substituting the values in the equation above we get,

$$0.0055898 = 3.4\left(\frac{1240 - 436.5}{200000}\right) {N_f}^{-0.12} + 0.8737{N_f}^{-0.6}$$

On simplification we get,

$$N_f = 33{,}645\ cycles$$

5. RESULTS

Parameters	Blade with holes	Blade without holes
Temperature	711.56°C	785.71°C
Eq. Stress	873 Mpa	1065.6 Mpa
Total Heat Flux	1.3404 W/mm^2	1.0995 W/mm^2
Eq. Strain	0.005944	0.006265
Total Deformation	0.64234 mm	0.53571 mm
Fatigue Cycles	33,645	17,050

6. CONCLUSION

As previous study was based solely on structural analysis, the change in blade profile temperature as well as stresses can be distinguished as coupled field analysis takes into account the effect of thermal stresses. From the results it can be observed that the temperature on gas turbine blade are reduced significantly and hence the fatigue cycles of gas turbine blade is increased because of branched hole cooling. So it can be concluded that branched cooling holes in gas turbine blades help out to increase fatigue cycle of gas turbine blade and therefore fatigue life. This study also paves the way for further optimisation of turbine blade design and that of branched hole technique.

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