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Numerical and Thermal Finite Element Analysis (FEA) of Idealized Gas Turbine Engine Blade

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ABSTRACT

The turbine blades are responsible for extracting energy from the high temperature gas produced from the combustor of a gas turbine. To obtain a better efficiency and maximum work output from the gas turbine, it is operated at elevated temperature. The blades are required to withstand elevated temperature. The need for the blades to operate effectively and survive in an aggressive environment without failure required an exotic material for the design of the blades. In this paper, the blade under study is made of titanium and it was subjected to a temperature of 1200°c to 1650°c. The thermal finite thermal element analysis was done with the aid of ABAQUS software. A 3- dimensional model of the blade was developed by the software and also to predict the thermal behavior of the blade at different elevated temperature with an interval of 50°c. The simulation result shows that the temperature gradient along the blade length is 49°c/mm.

General Terms

Finite Element Analysis

Keywords

Combustion, FEA, Propulsion, Thermal, Turbine.

1. INTRODUCTION

Thermal finite element analysis (TFEA) required the differential and variational equations that govern the thermal conditions. These equations provide the basis for the finite element analysis formulation and the solution of the thermal problems.

It is a known fact from the gas turbine cycle analysis that higher turbine inlet temperature produce large amount of work per unit mass flow and also improve the power to weight ratio of the gas turbine engine. The major problem that is associated in achieving this increase in performance is the availability of material that can withstand such high temperature and combined stress due to temperature, rotation and aerodynamic loading [1-10].

The need for higher turbine inlet temperature for aircraft gas turbine, lead to the relationship of temperature and the two paramater of specific thrust and thrust specific fuel consumption.

$$\frac{T}{\dot{m}_0} = V_0\left[\left[\left(\frac{\tau_t}{\tau_0\tau_c} - 1\right)\left(\frac{\tau_t}{\tau_0\tau_c} - 1\right)(\tau_c - 1) + \frac{\tau_t}{\tau_0\tau_c}\right]^{0.5} - 1\right] \quad (1)$$

$$\frac{\dot{m}_f}{T} = \frac{C_p(\tau_t - \tau_0\tau_c)T_1}{CV(\frac{T}{\dot{m}_0})} \quad (2)$$

Heat are transfer in gas turbine blade through conduction and convection modes. Conduction is the mode of heat transfer due to temperature difference in a solid or any phase of material where the mass is contiguous and in thermal contact. Microscopically this mode of energy transfer is attributed to free electron flow from higher to lower energy levels, lattice vibration and molecular collision [11-19].

This is mode of heat transfer occurs in the blade of gas turbine. Heat transfer occurring through the intervening matter without bulk motion of the matter. The outside surface, which is exposed to the hot gases from combustor, is at higher temperature than the inside surface, which has cooling air next to it. The level of the wall temperature is critical for a turbine blade.

For one –dimensional plane heat conduction, Fourier's law is apply.

$$\dot{q} = -k\frac{dT}{dx} \quad (3)$$

The rate of heat transfer by conduction from a body is related with equation (3). The amount of heat conducted per unit time per unit area per unit negative temperature gradient is the thermal conductivity (K) of the material. Conduction is an intermolecular diffusion, and its process can be predicted easily as long the accurate value of K is known [3].

A high value for thermal conductivity indicates that the material is a good heat conductor, and a low value indicates that the material is a poor heat conductor or insulator.

For three-dimensional heat transfer in a Cartesian coordinate, the conduction equation is shown in equation (4)

$$k\begin{vmatrix}1 & 0 & 0\\0 & 1 & 0\\0 & 0 & 1\end{vmatrix}\begin{vmatrix}\frac{\delta^2 T}{\delta x^2}\\\frac{\delta^2 T}{\delta y^2}\\\frac{\delta^2 T}{\delta z^2}\end{vmatrix} + q = \frac{\rho C_p \delta T}{\delta\tau} \quad (4)$$

$$\alpha = \frac{k}{\rho C_p} \quad (5)$$

Heat is transfer from the hot gas to the blade, across the blade from external surface to internal surface and heat transfer from the inner surface of the blade to the coolant. This will involve simultaneous calculations. With the help of ABAQUS software, the analysis is made easy and simple. The temperature of within the blade can be determined by giving solution to the Laplace equation.

In turbomachinery and aerospace applications, the transfer of heat in a fluid occurs through conduction and convection through the movement of the fluid. The overall heat transfer in a moving media, both convection and conduction is called convective heat transfer. In convective heat transfer, temperature and velocity field always interact. The velocity field affects temperature distribution. In some situation where velocity is high and temperature is small, the velocity field influences the temperature, but the velocity field is mildly affected by the temperature. Gas turbine has both high velocity and temperature and the flow of heat is influence by external forces. This is to say that the flow of heat in gas turbine is a force flow.

For convective heat flow in the turbine blade, there is movement of heat from the hot gas to the surface of the blade. The interaction of the fluid (hot) gas and the surface of the blade viscous force at the boundary. The boundary tends to prevent the flow of heat. Due to the friction created by the media, it generates a layer. The boundary layer plays a very critical role in the heat transfer. The conditions and properties of the boundary layers determine the rate at which heat is transferred.

For three-dimensional flow, the heat transfer equation is; $\frac{\delta}{\delta t}(\rho \boldsymbol{T}) + \frac{\delta}{\delta x}(\rho \boldsymbol{uT}) + \frac{\delta}{\delta y}(\rho \boldsymbol{vT}) + \frac{\delta}{\delta z}(\rho \boldsymbol{wT}) =$

$$\frac{1}{PRR_e}\left[\frac{\delta^2 T}{\delta x^2} + \frac{\delta^2 T}{\delta y^2} + \frac{\delta^2 T}{\delta z^2}\right] E_c \qquad (6)$$

$$E_c = \frac{{V_\infty}^2}{C_p \Delta T_0} \qquad (7)$$

$$R_e = \frac{\rho_\infty V_\infty}{\mu_\infty} \qquad (8)$$

$$PR = \frac{\mu_\infty C_p}{K} \qquad (9)$$

2. MATERIAL AND METHODS

2.1 Thermal governing equations

The equations establishes in vector and differential form, shows the relationship between the time and space variation of temperature at any point of the gas turbine blade through which heat flow in three dimension by conduction takes place.

In finite element analysis, stress/deformation field in structure largely depends on temperature field, but the influence of stress/deformation field on the temperature field is negligible. For this heat transfer analysis not coupled with mechanical effect is considered.

The transient temperature field $T(x, y, z, t)$ throughout the domain was obtained by solving the three-dimensional heat conduction equations along with the appropriate initial and boundary conditions [20-28].

Using the vector operator ∇, equation 4 can be represented as

$$\nabla^2 t + {}^{q}/_{k} = {}^{\rho.\, c\delta t}/_{k\delta\tau} \qquad (10)$$

2.1.1 Unsteady state condition

This is the condition where there are no internal sources of heat generation $\left({}^{\delta t}/_{\delta\tau} \neq 0\right)$

$$\begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} \frac{\delta^2 T}{\delta x^2} \\ \frac{\delta^2 T}{\delta y^2} \\ \frac{\delta^2 T}{\delta z^2} \end{vmatrix} = \frac{\rho C_p \delta T}{k\delta\tau} \qquad (11)$$

2.1.2 Steady state condition

This is the condition when temperature does not depends on time $\left({}^{\delta t}/_{\delta\tau} = 0\right)$

$$\begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} {}^{\delta^2 T}/_{\delta x^2} \\ {}^{\delta^2 T}/_{\delta x^2} \\ {}^{\delta^2 T}/_{\delta x^2} \end{vmatrix} + {}^{q}/_{k} = \mathbf{0} \qquad (12)$$

The thermal analysis was done with the help of ABAQUS software. As shown in figure 1, a finite model of a gas turbine blade was built. The dimension under consideration is 200mm with a thickness of 50mm. In this study, the initial temperature was set 100°c, surface temperature was set to 500°C. Ten cases were simulated by varying the turbine inlet temperature from 1200°C - 1650°C. Table 3 shows the results obtained from the ten cases.

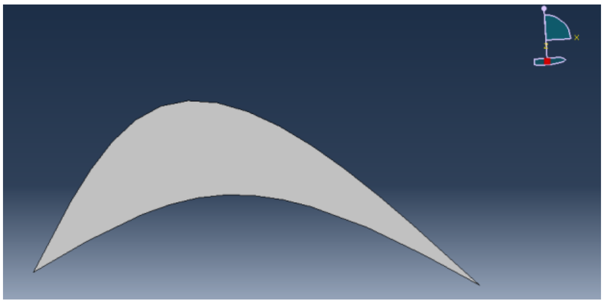


Figure 1 Blade Model Drawing

2.2 Material properties

The material selected for this study is Titanium. Temperature-dependent thermal physical properties of titanium, including density, specific heat, thermal conductivity and latent heat, were used as an input. The values of these properties are shown in table 1.

Table 1 Properties of Titanium

Properties	Value
Thermal Conductivity (W/mK)	21.9
Density (kg/m^3)	4400
Young Modulus (GPa)	116
Coefficient of Expansion	$8.6E-09$
Specific Heat (J/kgK)	544.284
Poisson ratio	0.32

2.3 Element selection

The type and size of elements used to approximate the domain were determined on the bases of computational accuracy. In heat transfer analysis under dynamic conditions, with second-order elements, there is a minimum required time increment [29-41].

$$\Delta t > {6c\Delta l^2}/{\rho k} \qquad (13)$$

If the time increment is smaller than this value, nonphysical oscillations may appear in the solution. Such oscillations are eliminated with first- order elements [30], but can lead to inaccurate solutions [23].

Fine meshes were used in the deposition zone, and the mesh gradually increased with distance from the deposits. In the region more separated from the heat affected zone, coarse meshes were utilized.as shown in figure 2, 14328 elements and 18612 nodes were created.

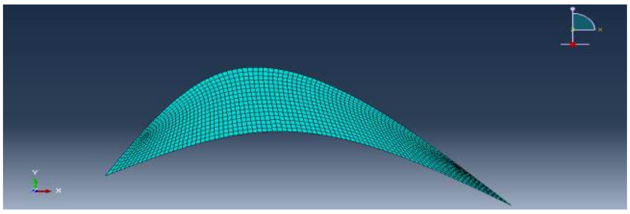
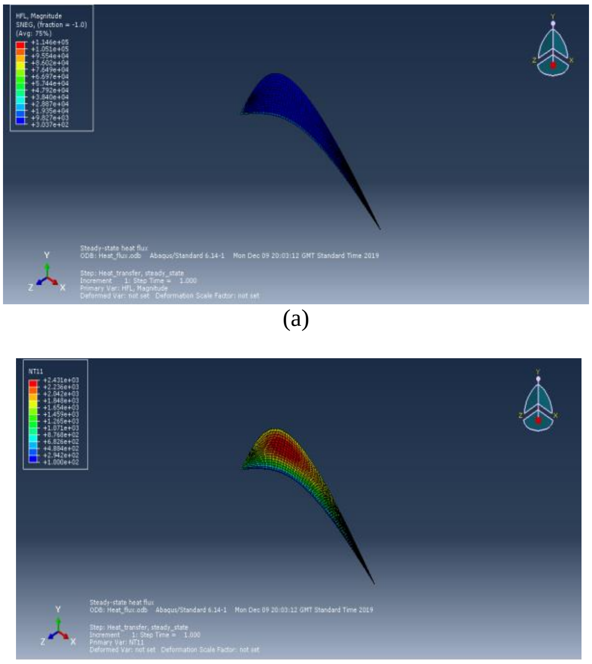


Figure 2 Meshing Scheme

In order to obtain reliable results from the thermal analysis, the maximum nodal temperature change in each increment was set to 50°C and the time increments were selected automatically by ABAQUS to ensure that the time value does not exceed any mode during any increment of the analysis [30].

The maximum temperature for this study is 1650°c, while the lowest temperature is 100°c. This small temperature differences and small geometrical dimension cause a very small temperature gradient.

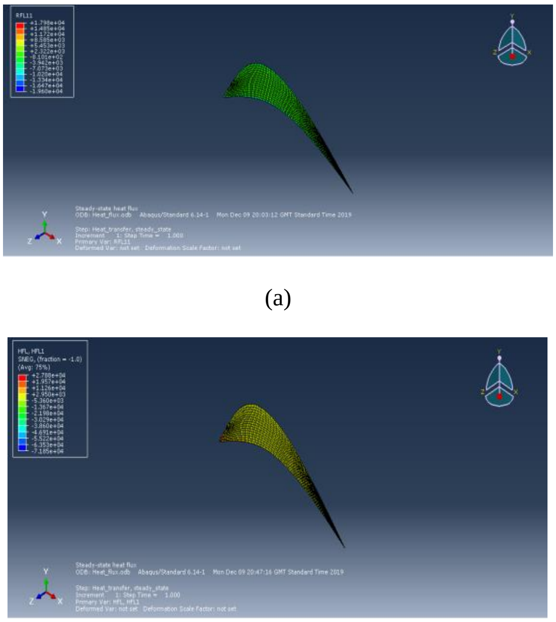


(a)

(b)

Figure 3 (a) Heat Flux Magnitude

(b) Nodal Temperature Magnitude



(a)

(b)

Figure 4 (a) Reaction Flux Magnitude (b) Heat Flux 1 Magnitude

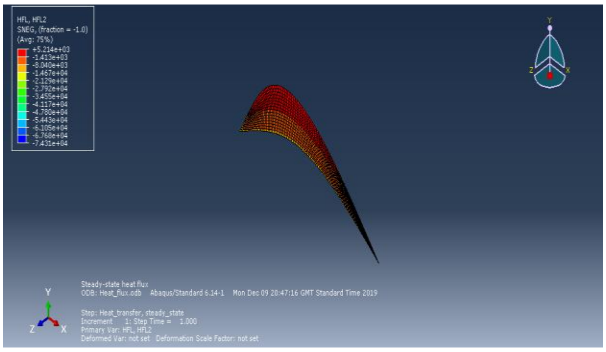


Figure 5 Heat Flux 2 Magnitude

3. CONCLUSION

The simulations results of temperature field are influenced by process parameter, material properties and boundary conditions. Among material properties, the thermal conductivity has some effect on the temperature field. The effect of material density and specific heat on temperature field can be neglected.

The results revealed the characteristics of temperature distribution on the blade. Table 2 shows the results obtained from the simulation of the model.

The output obtained was used to plot graph against the maximum temperature the blade was subjected, at each case. Figure 6 shows the graph of NT11 versus Maximum temperature at each case. From the graph, it is deduced that the behavior of NT11 is directly proportional to the maximum temperature the blade was subjected.

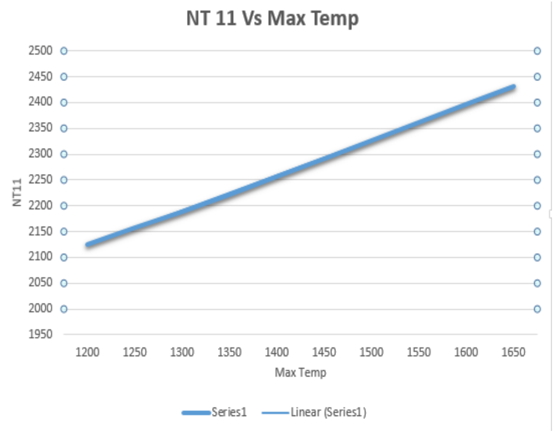


Figure 6 Relationship between Nodal temperature and Maximum temperature

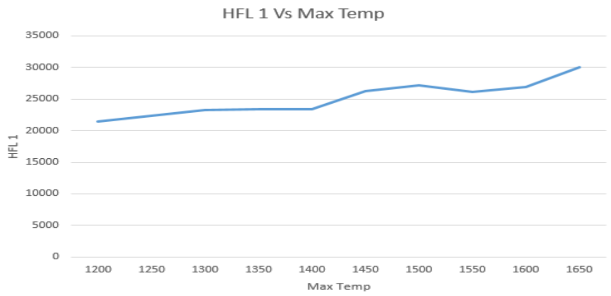


Figure 7 Relationship between Heat flux and maximum temperature

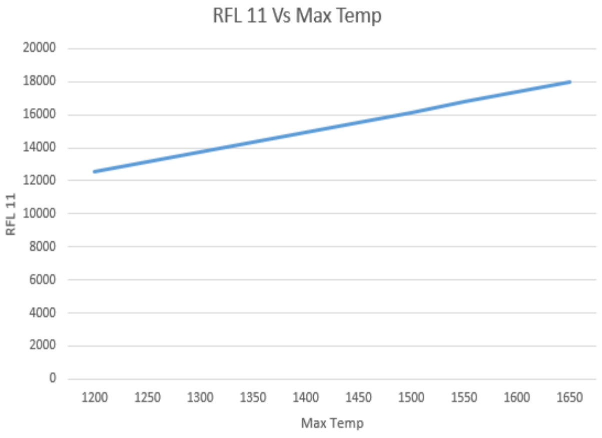


Figure 8 Relationship between RFL11 and Maximum Temperature

Nomenclature

Symbols

α	Thermal diffusivity
C_p	Specific heat capacity at constant pressure
CV	Calorific value
ρ	Density
$\dot{q}$	Heat flux
$\dot{m}_0$	Free stream mass flow
τ_t	Turbine temperature ratio
τ_c	Compressor temperature ratio
T_0	Ambient temperature
T	Thrust
V_0	Free stream velocity
∇	Vector operator
k	Thermal conductivity

Acronyms

FEA	Finite element analysis
HFL	Heat flux
RFL	Reaction flux
NT	Nodal temperature

4. REFERENCES

[1] Claire S., Gas Turbine: A handbook of land, sea and air application. Butterworth- Heinemann, UK.

[2] Mathur, M.L.and Sharma, R.P. (2014). Gas Turbines and Jet and Rocket Propulsion. 4th Ed. Nem Chand jain, Nai Sarak,Delhi.

[3] Lakshminarayana, B. (1996). Fluid Dynamics and Heat transfer of turbomachinery. John Wiley & sons, New York.

[4] Boyce, M.P. (2002). Gas Turbine Engineering Handbook" 2nd Ed. Butterworth- Heinemann, UK.

[5] Moran, M.J. (1999). Engineering Thermodynamics, Mechanical Engineering Handbook.

[6] Eswarprasad Thirunayukarasu. (2017) Modeling and Simulation Study of a Dynamic Gas Turbine System in a Virtual Test Bed Environment" University of South Carolina, USA.

[7] Mura F, De Doncker R W, Persigehl B, Jeschke P and Hameyer K. (2011). Analysis of a gearless Medium-voltage variable speed gas turbine, VGB PowerTech, vol. 91, No. 4, pp. 39-43.

[8] Rajput, R.K. (2007). Engineering Thermodynamics 3rd Ed. Laxmi publication Ltd, New Delhi.

[9] Saravanamuttoo, H.I.H.et al (2017) "Gas Turbine Theory" 7th Ed. Pearson Education Ltd, UK.

[10] Avwunuketa, A.A., Adamu, M.L. et al. (2019) Performance evaluation of axial flow compressor using stages characteristics. SSRG international Journal of thermal engineering Vol 5 1-7.

[11] Rahman, M.M. (2011). Thermodynamic Performance Analysis of Gas Turbine Power Plant International Journal of the Physical Sciences. Vol 6(14) 3539-3550.

[12] Harman, R.T.C., (1981) Gas Turbine Engineering, Applications, cycles and Characteristics1st Ed.

[13]] Lefebvre, A.A., Ballal, D.R. (2010) Gas Turbine Combustion alternative fuels and emission 3rd Ed. CRC press New York.

[14] Kothandaraman, C.P. (2006). Fundamentals of Heat and Mass transfer 3rd Ed. New age international Ltd, new Delhi.

[15] El-Sayed, A.F. (2017). Aircraft Propulsion and Gas Turbine Engines 2nd Ed. Taylor & francis Group, LLC.

[16] Razak, A.M.Y. (2007). Industrial Gas Turbines Performance and Operability. Taylor & Francis Group, LLC.

[17] Avwunuketa, A.A., Bonet, M., et al. (2019). Performance, Characterization and evaluation of axial flow turbine engine, International Journal of advances in scientific Research and Engineering vol 5(10) 124-131

[18] Philip, H. and Carl, P. (1992). Mechanics and Thermodynamics of Propulsion 2nd Ed. Addison-Wesley Publishing Co, Reading.

[19] Mattingly, J.D. (2006). Elements of propulsion: Gas Turbines and Rockets 2nd Ed. AIAA Education series, Virgina, USA.

[20] Bathie, W.W. (1996). Fundamentals of Gas Turbines 2nd Ed. John Wiley & sons. Inc.

[21] Rajput, R.K. (2015). Heat and Mass Transfer 6th Ed. S. Chand & company PVT. Ltd. New Delhi.

[22] Reddy, J.N., Gartling, D.K. (2010).The Finite Element Method in Heat Transfer and Fluid Dynamics 3rd Ed.

[23] Ujjawal, A.J. (2013). Design and Analysis of Stator, Rotor and Blades of Axial Flow Compressor. International Journal of Engineering Development and Research.

[24] Boyce, M.P., Transonic Axial-Flow Compressor. ASME Paper No: 67-GT-47

[25] Turton, R.K. (1995).Principles of Turbomachinery. 2nd Ed. Chapman & Hall, London.

[26] Dixon, S.L. (1993). Fluid Mechanics and Thermodynamics of Turbomachinery. 4th Ed. Butterworth-Heinemann. UK.

[27] Enyia, J.D. et al. (2015). Industrial Gas Turbine On-Line Compressor Washing for Power Generation, International Journal of Engineering Research & Technology.

[28] Lebele-Alawa, B.T. (2008). Rotor Blade Profile Influence Gas Turbine Compressor Effectiveness. Applied Energy,

[29] Simulia, D. (2011). ABAQUS 6.11 Analysis User manual; pp.22-2.

[30] Oates, G.C. (1997). Aerothermodynamics of Gas Turbine and Rocket Propulsion 3Rd Ed. AIAA Education series, Ohio USA.

[31] Eastop, T.D., McConkey. (1998). A. Applied Thermodynamics for engineering Technologist 5th Ed.

[32] Ronald, H.A. (2003). Axial Flow Compressor 2nd Ed.

[33] Ganesan, V. (2010). Gas Turbine. 3rd Ed.

[34] Nicala, F. (208). Axial Flow Compressor Mean Line Design Master Thesis, Lund University, Sweden.

[35] Cumpsty, N.A. (2004). Compressor Aerodynamics Volume 10.

[36] Zienkiewicz, O.C., Taylor, R.L. (2011). The Finite Element Method"5th Ed. Butterworth- Heinemann, Oxford.

[37] Bergman, T.L. et al. (2011). Fundamentals of Heat and Mass Transfer" 7th Ed. John Wley & sons ,Inc, USA

[38] Lienhard, J.H. (2001). A Heat Transfer Book" 3rd Ed.

[39] Desmond, E. W. (1997). Advanced Thermodynamics for Engineers 1st Ed. Anold, London.

[40] Welsh, P.P, Fletcher, P. (2004). Gas Turbine Performance" 2nd Ed. Blackwel Sciences, UK.

[41] Avwunuketa, A.et al. (2019) Aircraft Auxiliary Power Unit (APU) Condition Monitoring, International journal of Aerospace and mechanical Engineering;, vol 6 5-8