Faculty of Engineering
University of Nigeria, Nsukka
22nd- 25th June, 2021

Proceedings of the
2021 Sustainable Engineering and
Industrial Technology Conference

Modelling of the Temperature Distribution in a Cooled Aeroderivative Gas Turbine Blade with Cooling Holes

A.M. Orah, A. Nasir, A.B. Hassan, I. Bori

Department of Mechanical Engineering, Federal University of Technology, Minna, Niger State, Nigeria.
Tel: +234(0) 802 819 8356. ***Emails:*** *orahmohammed@yahoo.com (OMA), a.nasir@futminna.edu.ng (AN),*
abhassan@futminna.edu.ng (ABH), Ige.bori@futminna.edu.ng. (IB)

Abstract

Aero-derivative gas turbines have found extensive applications, as mechanical drives and medium sized utility power plants on offshore platforms and in petrochemical industries; because of its high operating temperature and pressure, it has a higher efficiency. The high operating conditions of the engine makes it necessary to adopt effective cooling techniques to achieve the required creep life and attain reliability. This makes the study of the heat transfer within the gas turbine blade essential. This study models the temperature distribution in a cooled aero-derivative gas turbine blade. A numerical model was developed from the interpolation of the Newton's law of cooling equation and the Alternating Direction Implicit (ADI) scheme. A MATLAB solver was generated for the heat transfer problem based on the selected boundary conditions and designed cooling parameters of model engine: GE PGT25+ aero-derivative gas turbine. It was found that there was effective heat transfer from the blades to the cooling air with a cooling effectiveness of 0.5, and the temperature gradient within the blade was within safe operating limits not exceeding the melting point of the blade material. It was deduced that the ADI strategy accurately compute temperature distributions within the blade, in time and space, thereby making it suitable for heat transfer design computations for complex thermodynamic systems like the gas turbine engine.

Keywords: blade, aeroderivative, model, temperature, distribution

1. INTRODUCTION

Aero-derivative gas turbines have found extensive applications, as mechanical drives and medium-sized utility power plants on offshore platforms and in petrochemical industries; because of its high operating temperature and pressure, it has a higher efficiency over other industrial gas turbines. The high operating conditions of the engine make it necessary to adopt effective cooling techniques to achieve the required creep life and attain reliability. Their compactness, lightweight, and multiple fuel application make aero-derivative gas turbine a natural power plant for offshore platforms [1]. During gas turbine operations, the components in the hot section are subjected to very high temperatures often require cooling [2]. As a result of these temperatures, the blade material melting temperature may be exceeded [3]. It makes the study of the heat transfer within the gas turbine blade essential. This study models the temperature distribution in a cooled aero-derivative gas turbine blade with cooling holes. The study developed a numerical model from the interpolation of Newton's law of cooling equation and the Alternating Direction Implicit (ADI) scheme of Computational Fluid Dynamics. A MATLAB solver was generated for the heat transfer problem based on the selected boundary conditions and designed cooling parameters of the model engine: GE PGT25+ aero-derivative gas turbine. It obtained the temperature distribution within the cooled blade for 30 minutes in-service and examined the heat transfer. The results showed effective heat transfer from the blades to the cooling air with cooling effectiveness of 0.5, and the temperature gradient within the blade was within safe operating limits, not exceeding the melting point of the blade material. It deduced that the ADI strategy accurately computes temperature distributions within the blade, in time and space, thereby making it suitable for heat transfer design computations for complex thermodynamic systems like the gas turbine engine.

2. METHOD

The research used the Alternating-Direction Implicit (ADI) scheme to study the temperature distribution in the cooled aero-derivative gas turbine blade with holes, considering the convective heat transfer rate governed by Newton's law of cooling in Eq. (1) [4]:

$$\mathrm{q}_{\mathrm{S}}'' = h(\mathrm{T}_{\mathrm{S}} - \mathrm{T}_{\infty}) \tag{1}$$

Where $\mathrm{q}_{\mathrm{S}}''$ is the surface flux, T_{S} is the surface temperature, T_{∞} is fluid temperature away from the surface and h is the heat transfer coefficient.

It modified the ADI scheme by introducing the convective heat transfer coefficient from Newton's law of cooling equation to give Eqs. (2) and (3), [5].

Table 1: Gas turbine Parameters used for the Development of the MATLAB Solver.

S/No.	Parameter	Symbol	Value
1.	Kinematic viscosity of the compressed air	ν	54.85×10^{-6} m^2/s
2.	Pressure ratio for the hot gas	P_g	21.5 × 105 Pa
3.	Heat Rate for the engine	q	2.43 kJ/kWs
4.	Diameter of cooling Passages	D	0.00125m
5.	Mass flow rate of cooling air	$_{d}otm$	435 kg/s
6.	Reynolds number	N_{RE}	60000

Source: [6, 7]

$$\frac{T_{i,j}^{n+\frac{1}{2}} - T_{i,j}^{n}}{\frac{\triangle t}{2}} = hg\left[\frac{T_{1+i,j}^{n} - 2T_{i,j}^{n} + T_{i-1,j}^{n}}{(\triangle x)^2} + \frac{T_{i,j+1}^{n+\frac{1}{2}} - 2T_{i,j}^{n+\frac{1}{2}} + T_{i,j-1}^{n+\frac{1}{2}}}{(\triangle y)^2}\right] \tag{2}$$

and

$$\frac{T_{i,j}^{n+1} - T_{i,j}^{n+\frac{1}{2}}}{\frac{\triangle t}{2}} = hg\left[\frac{T_{i+1,j}^{n+1} - 2T_{i,j}^{n+1} + T_{i-1,j}^{n+1}}{(\triangle x)^2} + \frac{T_{i,j+1}^{n+\frac{1}{2}} - 2T_{i,j}^{n+\frac{1}{2}} + T_{i,j-1}^{n+\frac{1}{2}}}{(\triangle y)^2}\right] \tag{3}$$

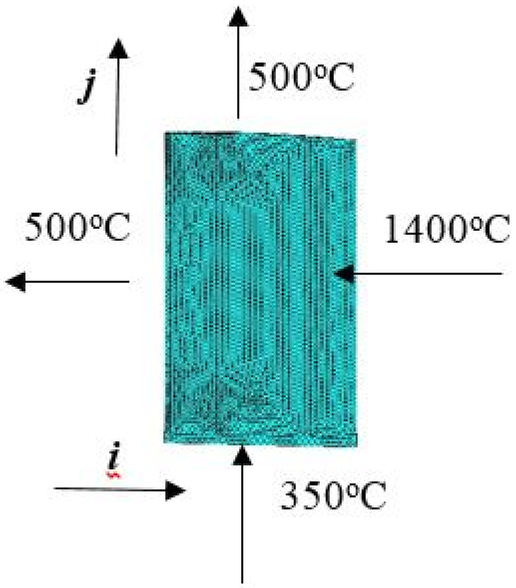

Figure 1: Meshed blades showing the temperatures at the boundary condition.

The research generated a MATLAB solver for a mesh grid with dimensions of 25 mm. it further examined the meshed section with six nodes at $\triangle t = 0$, as illustrated in Fig. 1. The boundary conditions considered with time increase were the turbine inlet temperature of 1,400°C, the temperature of the cooling air of 350°C, and the temperature of the cooled air exiting the blade of 500°C.

Other parameters considered for the development of the MATLAB solver were adapted from the GE PGT25+ engine as shown in Table 1.

3. FINDINGS AND DISCUSSIONS

The results for the MATLAB solver yielded the temperature distributions at the several nodal points in the turbine blade as shown in Table 2 to Table 4 for corresponding times of 10, 20, and 30 minutes respectively of the turbine blade in service.

Figure 2 shows the graphical representation of the temperatures obtained from the solver, where T_k represents the values of the intermediate temperatures at the first time step and T_g represents the final values of the temperature at the nodes in the gas turbine blade at the second time step. The figure shows the temperature profile for the nodal Points with time for a cooled gas turbine blade. The graph reveals a temperature difference of about 200 - 400°C between the intermediate and final temperature values within the blade section, yielding cooling effectiveness of 0.5, indicating the heat transfer process between the hot gas and the cooling air. The maximum temperature attained in the blade is 600°C, within the safe, operable limits of the blade metal temperature, signifying adequate cooling of the blades when the bled air passes through it considering the designed cooling parameters. This is in conformity with the results from the study by Zirakzadeh [8], who obtained temperatures around 1000°C within the turbine blade for safe operation, which was as a result of the high amount of injected coolant to the outer side at the stagnation point [8].

The study observed from figure 3 that there was no significant change in the temperature profiles across the nodal points in the 1800s (30 minutes) in service of the turbine blade. The temperatures within the blade were significantly constant throughout the operating time of the turbine blade, signifying the cooling of the blades when the bled air passes through it; the temperatures within the nodes varied between 90°C – 600°C inferring that heat transfer from the cooling air is effective as it maintains the temperatures within the blade to not more than 600°C.

4. CONCLUSION

This paper has presented the computation of the temperature distribution in a cooled aero-derivative gas turbine blade through a derived model equation

Table 2: Temperature distributions within the nodes after 10 minutes of Turbine blade in service.

At t = 600s						
	N1	**N2**	**N3**	**N4**	**N5**	**N6**
T1	285.965	202.304	175.811	180.038	223.439	346.127
T2	229.734	123.764	90.2052	95.5593	150.534	305.939
T3	218.846	107.298	71.9729	77.6088	135.477	299.061
T4	231.522	119.974	84.6489	90.2848	148.153	311.737
T5	293.115	187.144	153.586	158.94	213.915	369.319
T6	526.81	443.149	416.656	420.883	464.284	586.972

Table 3: Temperature distributions within the nodes after 20 minutes of Turbine blade in service.

At t = 1200s						
	N1	**N2**	**N3**	**N4**	**N5**	**N6**
T1	285.965	202.304	175.811	180.038	223.439	6.127
T2	229.734	123.764	90.2055	95.5596	150.534	305.939
T3	218.846	107.298	71.9731	77.609	135.477	299.061
T4	231.522	119.974	84.6492	90.2851	148.153	311.737
T5	293.115	187.144	153.586	158.94	213.915	369.32
T6	526.81	443.149	416.656	420.883	464.284	586.972

Table 4: Temperature distributions within the nodes after 30 minutes of Turbine blade in service.

At t = 1800s						
	N1	**N2**	**N3**	**N4**	**N5**	**N6**
T1	285.965	202.304	175.811	180.038	223.439	346.127
T2	229.735	123.764	90.2056	95.5597	150.535	305.939
T3	218.846	107.298	71.9732	77.6091	135.477	299.061
T4	231.522	119.974	84.6493	90.2852	148.153	311.737
T5	293.115	187.144	153.586	158.94	213.915	369.32
T6	526.81	443.15	416.656	420.883	464.284	586.972

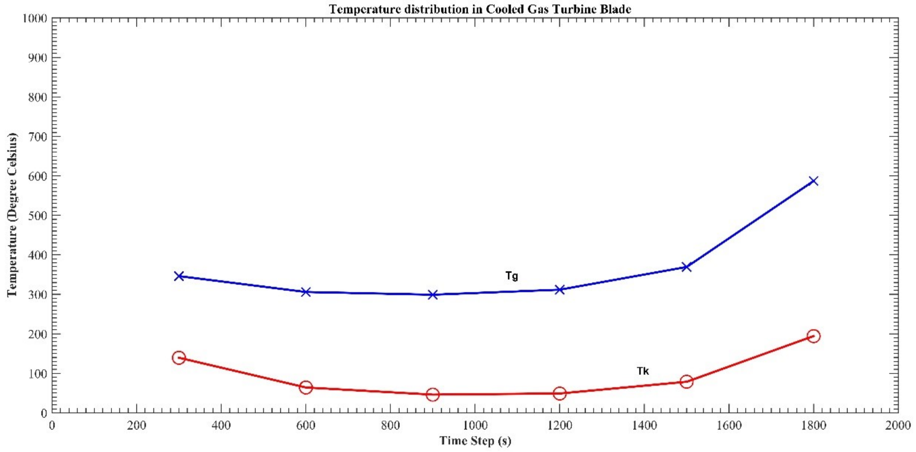

Figure 2: Temperature Profiles with respect to time for the Cooled Gas Turbine Blade at the Meshed Points.

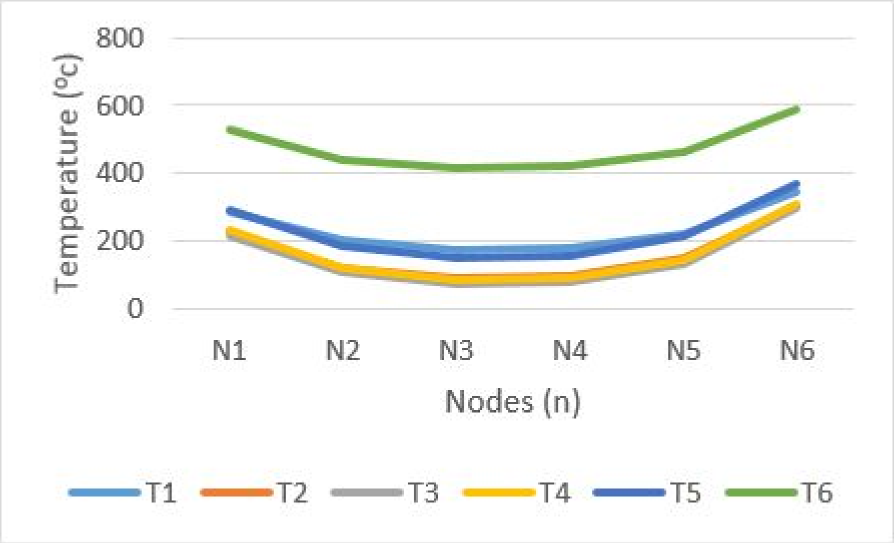

Figure 3: Temperature distributions within the nodes at 1800s in service.

based on the convective heat transfer process using the Alternating Direction Implicit (ADI) scheme from computational fluid dynamics (CFD). The design parameters and operating conditions for a High Pressure (HP) turbine blade were adopted. The model engine considered for the study was the GE PGT25+ gas turbine engine. A MATLAB solver accurately computed the temperature distribution within the meshed section of the blade model considering existing boundary conditions around it. The study found effective heat transfer from the blades to the cooling air, as the blade temperatures were maintained to acceptable limits not exceeding 600°C. It deduced that the ADI strategy accurately computes temperature distributions with the blade, spatially and periodically, thereby making it suitable for heat transfer design computations for complex thermodynamic systems like the gas turbine engine. The study aimed at proposing a method for the design of mechanical components, precisely gas turbine blades, based on numerical modelling using computational fluid dynamics with emphasis on the ADI scheme. The results obtained showed the promise of the proposed method suitable for predicting the heat transfer rate of the cooling process in the design of a gas turbine blade. Further research effort could apply this method to materials selection in designing the cooling system and turbine blade manufacture. There is also a need to investigate inputting additional design variables to allow for more complex design geometries.

References

[1] M.P. Boyce. *Gas Turbine Engineering Handbook*. Elsevier Inc, USA, 4th edition, 2012.

[2] T. Arnal, M. Precht, , and C. Sprunk. Fluid Structure Interaction makes for Cool gasTurbine Blades. *ANSYS Advantage*, 1(1):6–8, 2007.

[3] K. Balaji, C. Azhagesan, R. V. Pandian, N. M. Murugan, and N. Aravinth. Review of cooling effect on gas turbine blade. In *International Conference on Systems, Science, Control, Communication, Engineering and Technology*, pages 478–482, 2016.

[4] L.M. Jiji. *Heat convection*. Springer, Netherlands, 2006.

[5] S. C. Chapra and R. P. Canale. *Numerical methods for engineers*. McGraw-Hill Science/Engineering/Math, New York, 7th edition, 2015.

[6] Siemens. Gas turbines, 2019.

[7] P. V. Saravanamuttoo, H. I. H. Rogers, G. F. C. Cohen, H. Straznick, and Rogers G.F.C. Cohen, H. *Gas Turbine Theory*. Pearson Education Limited, England, 6th edition, 2009.

[8] H. Zirakzadeh. Numerical investigation of temperature distribution on a high pressure gas turbine blade. Texas A & M University, 2014.