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Investigation of the Temperature Variations in Aeroderivative Gas Turbine Blade Cooling

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ABSTRACT

In order to improve performance and efficiency, modern-day gas turbines operate at high temperatures. It is essential to use suitable cooling techniques on the blade and other hot areas since the elevated temperatures might exceed the metal melting temperature of the turbine blades. This paper presents the numerical modelling of heat exchange in a cooled aerodrivative gas turbine blade depending on the Newton's law of cooling equation as governing equation, then integrating the heat transfer coefficient by convection into the alternating direction implicit (ADI) approach of computational fluid dynamics (CFD). Based on the chosen boundary conditions and the gas turbine's intended cooling characteristics, a model for the heat transfer problem was created. A MATLAB code was developed to ascertain the temperature variations inside a cooling blade for a half-hour in-service operation. This study found a temperature difference between the transient and final temperature values of roughly 25 to 300°C, demonstrating the heat transfer process between the hot gases and the coolant air. It inferred effective heat transmission from the blades to the cooling air because the temperature differential within the blades did not rise over the melting point of the blade material and it yielded an average blade temperature of 400°C. Thus, the ADI technique is appropriate for heat transfer design calculations for intricate devices such as the gas turbine engine.

1. Introduction

Aeroderivative gas turbines are rapidly gaining popularity for the production of energy due to their dependability, effectiveness, and adaptability, with up to 45% efficiency compared to up to 35%

for heavier gas turbines (GTs), they are significantly lighter, react quicker, and have a smaller footprint than their hefty industrial GT competitors. They make great choices for smaller-scale energy generation (up to 100 MW), [1]. To increase their efficacy and performance, modern GTs operate at exceptionally elevated temperatures. But, the high temperatures might melt some turbine blade metals, which would lead to the failure of vital internal parts in a number of engines in a gas turbine power plant. This would cause a power outage that would cause significant financial losses for both the electricity provider and the consumer. Consequently, gas turbine blades consist of several metals like nickel, titanium and aluminium, which have varying temperature in gas turbine engine blades [2]. Studies on nickel-based superalloy IN738LC gas turbine blades have shown that failure occurs not due to flaws in the material itself but rather due to surface oxidation caused by hot corrosion, overheating, and coating deterioration as a result of the high oxidation of the Al-Pt layer, which may not protect the base metal. Plate I shows the crack formation and corrosion on the leading and trailing edges of a GT blade [3].

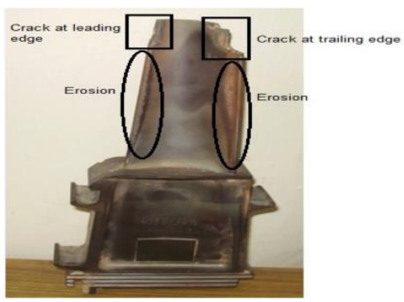

Plate I: Crack growth and Erosion at the leading and trailing edges
Source: [3]

Therefore, effective cooling technologies has to be developed to prolong the components' life and prevent early engine failures. It is on this backdrop that gas turbine designers need to analyse the operating conditions through appropriate modelling techniques with a view to assessing the effectiveness of design parameters used and possibility for improvement. It was opined that the cooling air measuring about 650^{o}C is obtained from the compressor and passed through the air foils, lowering the temperature of the turbine blades to around 1000°C, permitting reliable operation of the engine [4]. Figure 1 displays a schematic illustration of a typical GT blade that demonstrates popular cooling techniques.

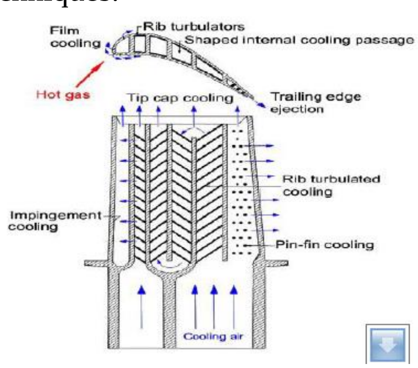

Figure 1. Diagram of a contemporary GT blade applying simple cooling methods
Source: [4]

The Conjugate Heat Transfer (CHT) method was able to achieve a conduction thermal model calibration, which makes the CHT approach a useful design tool, despite the temperature accuracy not meeting the Thermo-Mechanical Fatigue (TMF) life prediction requirement. [5] The computer simulation, using THERMOFLEX software, of a GE 7001 EA gas turbine engine applying cooled air data gotten previously from various experiments revealed that the greatest increase in the net power output was around 5.8 6 and 12%; and the highest percentage increase in efficiency is about 0.9, 1.3 and 2.5 respectively [6]. Also, a converged coolant temperature was gotten by mixing at every span location the corresponding gas and coolant, when the blade's film cooling effectiveness was modelled, through a modified gas temperature input. However, there was a limitation at the point where the film and blade temperatures crossed arising from a steep temperature gradient [7].

Additionally, by applying the mass and energy balance equations under particular internal and external boundary conditions, a predictive model was developed to determine the variation of the coolant mass flow rate (MFR) and the turbine blade metal temperatures; it was able to predict temperature distributions reasonably accurately, particularly on the suction side (SS) [8]. Additionally, a CFD study and Finite Element study (FEA) modelling of high-speed GT blades using Fluent revealed that, after variations in the blades' temperatures, the lowered turbine blade's temperature ranged around 236 K, showing adequate cooling of the turbine blade; however, while adequate cooling of the blades might prolong their life expectancy, it could as well impair the engine's thermal efficiency [9]. Predicting the distribution of blade temperatures and other crucial blade performance parameters was made possible by an additional computational method designed for the rapid evaluation of the critical blade performance parameters, such as the coolant mass flow consumption and blade temperature distribution. [10]. The temperature distributions on the external and internal borders of the turbine blade were by applying an iterative technique, which also provided the difference in temperature between the porosity used and that determined from the inverse problem. The difference did not exceed 4 K [11]. The distribution of the blade temperature was predicted using simulation and experiment so as to establish the temperature and behaviour of stainless-steel during cooling as well as the impact of the thermal barrier coating on the thermal insulation. The findings demonstrated that the steel's temperature was lowered by roughly 433K for every turbine entry temperature when the thermal barrier coating and the cooling mechanism were used together; additionally, the cooling impact was quite great at the region [12]. This study involves the numerical modelling through the Crank-Nicolson based Alternating Direction Implicit (ADI) method of the heat transmitted in the cooling process of aero-derivative gas turbine blades. The ADI scheme is a numerical method involving directional splitting [13]. The ADI technique showed excellent stability properties, produced fast computed numerical flows, and is a great option for researching convergence to stationary solutions due to its constructive local error structure [14]. In the blade section, this study found a temperature difference between the transient and final temperature values of roughly 25 to 300oC, demonstrating the heat transfer process between the hot gases and the coolant air. The average blade temperature was 400°C, which is well within the range of the metal temperature for blades and indicates that the blade cooling operation was effective.

2. Model Development Concept

The ADI scheme of Computational Fluid Dynamics (CFD) constitutes the numerical model adopted for the temperature distribution predictions within the blade walls, and numerical codes for the solution generated by means of MATLAB software. The blade thickness is minimal and is assumed to be negligible. Therefore, considering the blade as a thin rectangular plate, the heat conduction equation applied to two dimensions would be used as the governing equation. The partial derivative is expressed in Equation (1) [15].

$$\frac{\delta T}{\delta t}=k\left(\frac{\delta^2 T}{\delta x^2}+\frac{\delta^2 T}{\delta y^2}\right) \tag{1}$$

Where k denotes the coefficient of thermal conductivity of the conductor from Fourier's law of conduction, T signifies the absolute temperature, t is the time-step intervals, and x and y are the 2D planes considered. Chapra and Canale [15] approximated the Peaceman-Rachford equations in two steps to give Equations (2) and (3) as the ADI equation for temperature distribution modelling.

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

And

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

A Matlab code was written to solve the ADI scheme, thereby obtaining the unknown temperatures at the left-hand part of the equation. The flow diagram for the temperature distribution model is in Figure 2. The governing equation for the heat convection problem is the Newton's Law of cooling equation indicated in Equation (4) [16].

$$q=h_g A(T_g-T_w) \tag{4}$$

Therefore, the convective heat transfer coefficient is expressed in Equation (5).

$$h_g=\frac{q}{A(T_g-T_W)} \tag{5}$$

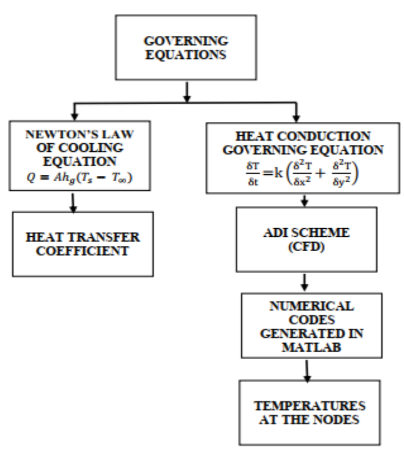

Figure 2. Flow Diagram for the Temperature Distribution Model

However, the heat transfer characteristic from accepted correlations of heat transfer in turbulent flows is given by the Nusselt number in Equation (6) [17].

$$Nu = 0.023Re^{0.8}Pr^{0.4} \tag{6}$$

Where Nu signifies the Nusselt number, Re represents the Reynolds number and Pr represents the Prandtl number. But the Nusselt number is also given by Equation (7):

$$Nu = \frac{hD}{k} \tag{7}$$

Therefore, the heat transfer coefficient *h* could now be expressed as indicated in Equation (8)

$$h = 0.023Re^{0.8}Pr^{0.4}\frac{k}{D} \tag{8}$$

Where k denotes the thermal conductivity of the blade metal (W/m.K) and D signifies the hole diameter (m).

3. Development of the MATLAB Solver

The algorithm for the solution of the temperature distributions is illustrated by the flowchart displayed in Figure 3. The algorithm shall be implemented in MATLAB. It would require the blade to be divided into several grids to determine the nodal points within the blade. Grid sensitivity test was performed for a selected number of nodes, 6, 10, 15 and 20 in the x and y directions. It was done by running each number of nodes in the Matlab program and comparing the results until there was no change in the results. In order to get 100 nodes within the rectangular grid area for the numerical solutions, a rectangular grid with 10 x 10 nodes in the x and y axes was chosen as the best value.

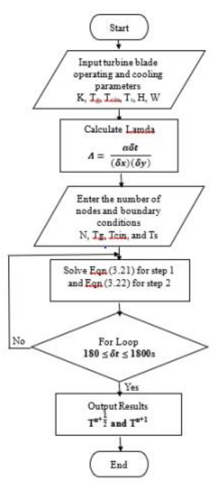

Figure 3. Flowchart illustrating the program algorithm

The rectangular grid area of 64.5 x 82.6 mm dimension (with 7.17 x 9.18 mm spacing) was used, resulting in grids totalling 100 nodal points at $t = 0$, as shown in Figure 4. The temperature T is assumed by the Dirichlet boundary conditions to be the ambient temperature (288.15K) at time t = 0. The time step used for the numerical solution is $\delta t = 180s$, incremental at 180s for a duration of 1800s. The unknown temperatures at the nodal points within the blade metal at the different time steps are obtained for the boundary conditions.

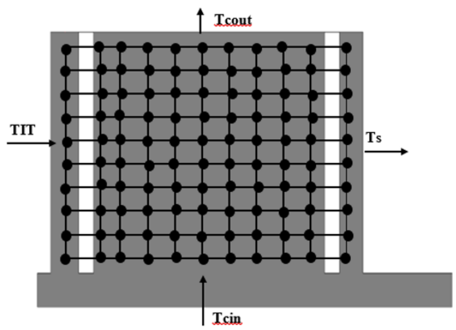

Figure 4. Rectangular grid illustrating 100 nodes on a 2D blade section.

Applying the GasTurb programme, the off-design point (ODP) modelling of a two-shaft turbofan engine yielded the parameters used in the development of the MATLAB codes for the temperature distributions. Table 1 displays the parameter values.

Table 1. Gas turbine Engine Operating Parameters for the Numerical solution

Parameter	**Value**	**Unit**
Boundary Conditions		
Turbine Inlet Temperature (TIT)	1673	K
Cooling air Temperature (Tcin)	721.5	K
Static Temperature (Ts)	1273	K
Thermal Conductivity (k)	0.05426	W/m.K
Operating Parameters		
Engine heat rate (Q)	3.405	kJ/kWs
Hydraulic Diameter (D)	0.004	M
Area of the blade(A)	1.438×10^{-3}	m^2
Velocity of cooling air (V)	113	m/s
Density of cooling air (ρ)	7.4229	Kg/m^3

4. Results and Discussion

The outcomes of the MATLAB solution that generated the temperature distributions at the turbine blade's nodal points for the final step of 1800s are shown in Table 2. The variation in temperature within the blade metal concerning time is shown in Figure 5. The convective heat transfer process yielded a mean blade metal temperature of about 400°C. This is within safe, operable temperature for the blade life sustainability, which is good since blade metal temperature must be maintained below 704°C, because blade metal temperatures exceeding 790°C are susceptible to high corrosion [18].

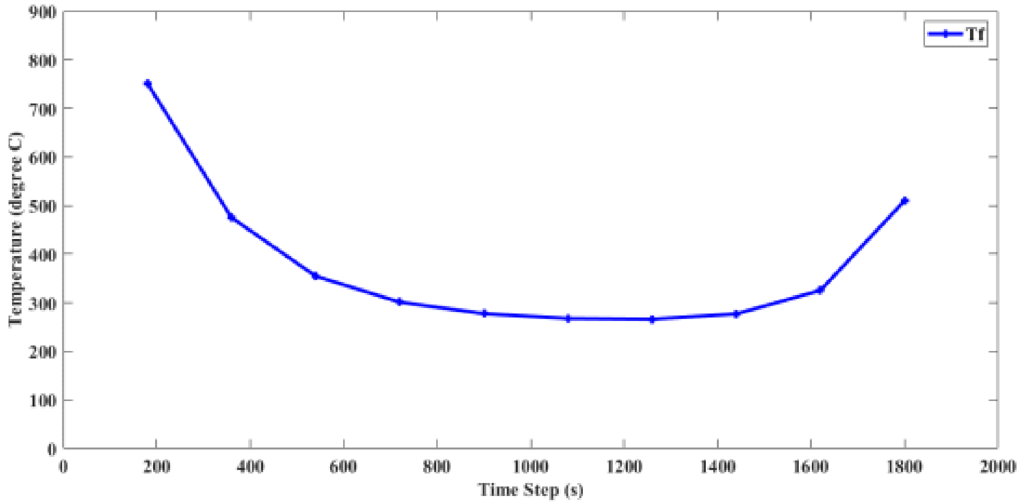

Figure 5. Temperature Distribution Curve for the Blade in relation to Time

The results for the 1800s duration are reported in Table 2 because the transient and final temperatures at the individual nodes were consistent, as determined by the Matlab programme for the time steps 180s to 1800s incremental at 180s. The temperature distribution successfully increases the turbine blade's useful life by accurately forecasting the cooling analysis within the blade metal [19]. Figure 6 indicates the temperature distribution across the nodes within the blade metal in variation with time.

Table 2. Matlab Results for the Temperature Distribution along the Nodes at the Transient and Final stages

dt = 1800(s)										
Ti	**N1**	**N2**	**N3**	**N4**	**N5**	**N6**	**N7**	**N8**	**N9**	**N10**
Ti1	632.61	356.935	249.845	205.728	186.77	178.377	174.581	172.839	172.03	171.651
Ti2	681.938	346.632	193.946	124.565	92.8504	78.2366	71.449	68.2744	66.781	66.0751
Ti3	695.143	347.653	179.307	98.5847	60.0677	41.7195	32.9781	28.8097	26.8196	25.8683
Ti4	698.634	348.836	175.63	90.4671	48.8356	28.5736	18.7439	13.9864	11.6877	10.5785
Ti5	699.394	349.056	174.376	87.6539	44.8076	23.7392	13.4239	8.3919	5.9449	4.7578
Ti6	698.94	347.996	172.819	85.7722	42.7411	21.5757	11.2123	6.1575	3.6998	2.5079
Ti7	696.367	343.989	168.902	82.6164	40.3845	19.8226	9.8496	5.0257	2.6968	1.574
Ti8	686.527	331.592	158.802	75.7913	36.1806	17.3302	8.3636	4.0956	2.0618	1.0915
Ti9	649.741	295.851	134.712	61.7473	28.5465	13.3177	6.2746	2.9932	1.4548	0.73
Ti10	512.435	202.072	84.1959	36.4858	16.2581	7.3939	3.4171	1.6026	0.7644	0.3736
Tf	**N1**	**N2**	**N3**	**N4**	**N5**	**N6**	**N7**	**N8**	**N9**	**N10**
Tf1	751.445	667.551	643.978	806.757	807.401	806.5	802.496	788.452	740.044	486.576
Tf2	475.341	447.212	427.342	432.489	432.029	430.241	424.518	407.701	361.213	220.687
Tf3	354.786	299.325	269.341	226.492	223.882	221.42	215.986	202.514	171.143	100.319
Tf4	301.359	215.995	175.067	119.796	115.052	112.16	107.807	98.7384	80.363	45.8789
Tf5	277.583	172.829	124.466	66.4523	60.0843	56.9512	53.6779	48.0765	38.0318	21.449
Tf6	267.625	152.929	101.131	41.138	33.7092	30.4522	27.983	24.6365	19.3256	11.3706
Tf7	266.179	149.686	98.5564	32.6409	24.6031	21.2957	19.348	17.3292	14.5464	10.7157
Tf8	277.143	169.787	124.664	43.0236	34.7472	31.4571	29.8333	28.5559	27.0793	25.2175
Tf9	325.618	248.224	216.328	102.252	94.2417	91.1151	89.7319	88.8756	88.0725	87.1613
Tf10	510.048	496.035	480.735	333.22	326.832	324.362	323.333	322.795	322.384	321.973

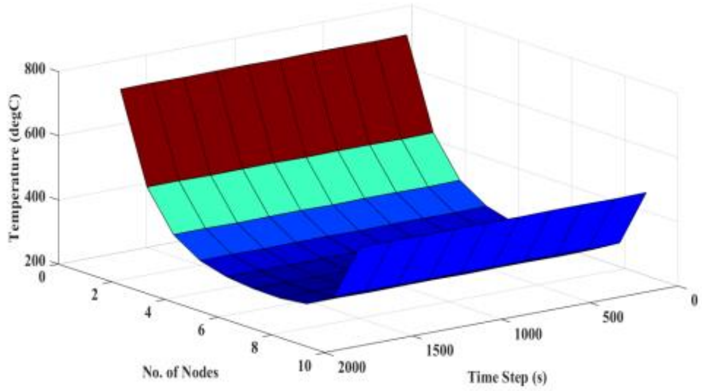

Figure 6. Temperature Distribution within the blade metal varying with time

The temperature distribution plot in Figure 6 reveals a higher temperature at the leading edge of about 800°C, represented by node 1. It is because of the influence of higher inlet temperature impinging on the blade at that point. Also, a temperature of 500°C is observed at the blade's trailing edge, represented by node 10. The differences observed in the temperature distributions at various points within the blade resulted from the difference in convection heat transfer as the cooling air flows through the blade [20]. Also, the non-uniform temperature distribution between the nodes is probably a result of the internal cooling effect of the coolant holes in the blade [19]. The outcomes also inferred that the temperature distribution at the nodes was consistently constant in each duration. It implies that the air cools convectively as it moves through the cooling channels. The coefficient of heat transfer for the convective process from the blade metal walls to the cooling air was determined as expressed in Equation (8). Table 3 summarises the result.

Table 3. Determination of heat transfer coefficient

Parameter	Value	Unit
Reynolds Number (Re)	28,751	
Prandtl Number (Pr)	0.71672	
Thermal Conductivity (k)	0.05266	W/m. K
Hydraulic Diameter (D)	0.004	m
Heat transfer Coefficient (h)	**195.54**	**W/m^2. K**

The heat transfer coefficient is often required to quantify the thermal load acting on the blade. The heat load on the blade walls is 991.25W resulting from the heat transfer coefficient of 195.54W/m^2. K.

The results obtained from the MATLAB solutions of the temperature distribution within the blade were validated with work from Literature. In addition, it was compared with the works of Zirakzadeh (2014), who numerically examined the temperature distribution within the turbine blade using the Finite element method (FEM), as indicated in Figure 7.

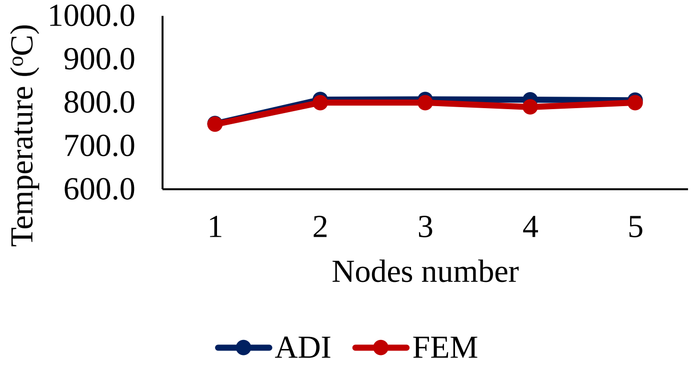

Figure 7. Validation of the blade temperature distribution between the ADI method and FEM method

A mean relative variation of 0.95% was observed between the values of the ADI method and those of the FEM method. Therefore, it means the ADI method showed close conformity with the results obtained from the FEM.

4. Conclusion

This study presented the numerical modelling of the temperature distribution in aero-derivative gas turbine blade cooling centred on the convective heat transfer process, through the alternating direction implicit (ADI) equations. The convective heat transfer coefficient of the cooling process was found using the governing equations, which include the heat conduction and Newton's law of cooling equations. Furthermore, Matlab was used to build numerical codes for the temperature distribution outcomes. To increase engine reliability and extend blade life, it is essential to forecast blade metal temperatures while the engine is operating. A mean blade metal temperature of 400^{o}C (673K) was derived from the outcomes, which is within the safe operating blade temperature limitations. Additionally, the heat transfer coefficient of 195.54W/m^2. K led to the determination of the heat load on the blade walls, which was 991.25W.

When designing a gas turbine blade, the suggested method, which placed a strong emphasis on the ADI scheme, demonstrated the potential to accurately forecast the temperature distributions and heat transfer rate of the cooling process. In order to allow for efficient generalisation on heat transfer for blade cooling designs, more research should be conducted to 3-D temperature distribution modelling while taking blade thickness into account. The study was restricted to 2-D heat transfer consideration.

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