Thermal Analysis of a Cooled Turbine Blade

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Abstract. Using Computational Fluid Dynamic (CFD), a gas turbine with an air-cooled blade was analyzed thermally. In terms of design, the domain was divided into three regions. The first region is the blade to blade passage (external flow) governed by a quasi-3-D Euler equation in a conservative form. Mac-Cormack's technique algorithm based on the finite differences, was used for this region. The second region involves the coolant passage (internal flow). This region involved the use of 2-D axi-symmetric Navier Stokes equations (Finite volume with staggered grids). A 3-D Laplace heat transfer equation was applied for the third region which involves a blade metal, where the solution algorithm was based on the finite difference technique. Consequently, to achieve temperature distribution through blade metal, the three regions have been coupled via the external and internal boundaries. Six different cases were examined in same blade geometry. The effect of gas heat transfer coefficient was analyzed in cases 1 and 2. With regards to cases 3, 4, 5, and 6, gas and coolant temperatures were changed. The computational results showed that the blade surface (metal) temperature is cooler than the surrounding gases (external hot gases) by about 100-500 oC, depending on boundary condition. An increase in gas temperature by 100 oC resulted in 50-100 oC increase in metal temperature, while, an increase in coolant temperature by 100 oC resulted in an average 50 oC increase in blade temperature. The results also show a temperature difference in blade metal of 250 - 450 oC between the leading and trailing edges.

1. Introduction:
Gas turbine engines provide a reliable and efficient production of power for both power plant applications and aircraft propulsion. Improvement in gas turbine engines performance is still the most important aim in the design and production of gas turbine engines [1]. The improvement of gas turbine engines performance requires operation of the gas turbine cycle at high turbine inlet temperatures. Turbine inlet temperature can exceed, by more than 500 degrees, the maximum blade metal alloy temperature; therefore, only through the use of effective cooling methods can the blades survive [2]. The universal method of blade cooling is through air bled from compressor flowing through the internal passages in the blades.

Research in this area has been done by [3-5] wherein Computational fluid dynamics (CFD) tools have been typically applied for the prediction of heat and flow transfer in cooling passages of turbine blades. Various numerical, experimental, and theoretical approaches have been implemented for the study of blade temperatures and heat transfer [6-11]. Wang and Chiou [12] found through calculating the expected benefits from the inclusion of the inlet cooling feature that there would be about 12% increase in power output and 5.16% increase in efficiency when the ambient temperature is cooled from 305 to 283 K. Moreover, investigations conducted by [13-16]...
have also been carried out in the field of inlet air cooling of gas turbine. Chandrakant [17] attempted to computationally analyze, using innovative cooling passages within the blade, the coupled conjugate analysis of HP stage turbine blade for effective cooling. Other researchers in this area have been done by [18-21]. More recent work on thermal design is [22-24].

In the present work, all the three modes of heat transfer from gases through blade material to the coolant flow will be considered. The hope in doing so is to achieve an air cooled blade with a thermal design employing computational fluid dynamics (CFD) analysis [finite difference and finite volume formulation with transformation and grid generation theories]. Initial conditions and practical data as boundary were noted for the blade of the 1st stage of the engine used in Al-Dorah power station (one of Iraqi power stations).

2. Grid Generation Technique
In this research, algebraic grid generation is employed to generate the grid through the passage of blade to blade at five sections in the span direction of the blade (Tip z=1 to Hup z=0). While, in the case of uniform physical domain, the grid generation with uniform spacing is a simple exercise. This type of grid is used to generate the grid point through the cooling passage of blade. An elliptic grid is used to generate grid points through the blade metal at five sections.

3. Theory
3.1. External Flow
The flow analysis model used in the present work is based on time marching of time dependent Euler equations. The governing equations for an inviscid, compressible, two dimensional flow expressed in a conservative form is [25]:

- Continuity equation:
  \[ \Delta (\rho v) = \frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} = 0 \]

- The conservation of momentum equation is:
  \[ \frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2 + p)}{\partial x} + \frac{\partial (\rho uv)}{\partial y} = 0 \]
  \[ \frac{\partial (\rho v)}{\partial t} + \frac{\partial (\rho uv)}{\partial x} + \frac{\partial (\rho v^2 + p)}{\partial y} = 0 \]

- The conservation of energy equation is:
  \[ \frac{\partial (e_i)}{\partial t} + \frac{\partial [(\rho e_i + p)u]}{\partial x} + \frac{\partial [(\rho e_i + p)v]}{\partial y} = 0 \]

The Euler equation in Cartesian coordinates may be written in a vector form as:

\[ \frac{\partial U}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} = 0 \]

Where:
Euler equation is transformed to a computational domain where grid points spacing are uniform and the domain is rectangular.

\[
\frac{\partial \tilde{U}}{\partial t} + \frac{\partial \tilde{E}}{\partial \xi} + \frac{\partial \tilde{F}}{\partial \eta} = 0
\]

Where: \( \tilde{U}, \tilde{E} \) and \( \tilde{F} \) are a vector given by:

\[
\tilde{U} = \frac{U}{J}, \quad \tilde{E} = \frac{1}{J} [\xi_x E + \xi_y F] , \quad \tilde{F} = \frac{1}{J} [\eta_x E + \eta_y F]
\]

An explicit time dependent solution of the two dimensional Euler equations has been performed using MacCormack’s predictor-corrector finite difference technique. MacCormack's time-marching technique will be used to march down stream, effectively solving for flow properties in two spatial dimensions in the passage between two blades of turbine problem with march in time to steady state solution by solving the flow properties at every \((i,j)\) spatial location.

3.2. Internal Flow (cooling flow)

In the present work, the basic equations that describe the heat and flow are continuity, energy equations and momentum. These equations describe two-dimensional, turbulent and incompressible flow takes which the following forms [26]: -

(i) Continuity Equation

\[
\frac{\partial}{\partial z} (\rho u) + \frac{1}{r} \frac{\partial}{\partial r} (\rho rv) = 0
\]

(ii) Momentum equations

u-momentum (z-direction)

\[
\frac{1}{r} \left[ \frac{\partial}{\partial z} (\rho u u) + \frac{\partial}{\partial r} (\rho u v) \right] = -\frac{\partial p}{\partial z} + \frac{1}{r} \frac{\partial}{\partial z} \left( r \mu_{eff} \frac{\partial u}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \mu_{eff} \frac{\partial u}{\partial r} \right) + Su
\]

v-momentum (r-direction)

\[
\frac{1}{r} \left[ \frac{\partial}{\partial z} (\rho u v) + \frac{\partial}{\partial r} (\rho v v) \right] = -\frac{\partial p}{\partial z} + \frac{1}{r} \frac{\partial}{\partial z} \left( r \mu_{eff} \frac{\partial v}{\partial z} \right)
\]

(iii) Energy Equation
\[
\frac{1}{r} \left[ \frac{\partial}{\partial z} (\rho r u T) + \frac{\partial}{\partial r} (\rho r v T) \right] = \frac{1}{r} \left[ \frac{\partial}{\partial z} (r \Gamma_{\text{eff}} \frac{\partial T}{\partial z}) + \frac{\partial}{\partial r} (r \Gamma_{\text{eff}} \frac{\partial T}{\partial r}) \right] + S_r
\]

Where, \( Su \) and \( Sv \) are given by [27]

\[
Su = \frac{\partial}{\partial z} (\mu_{\text{eff}} \frac{\partial u}{\partial z}) + \frac{1}{r} \frac{\partial}{\partial r} (r \mu_{\text{eff}} \frac{\partial v}{\partial z})
\]

\[
Sv = \frac{\partial}{\partial z} (\mu_{\text{eff}} \frac{\partial u}{\partial r}) + \frac{1}{r} \frac{\partial}{\partial r} (r \mu_{\text{eff}} \frac{\partial v}{\partial r}) - \mu_{\text{eff}} \frac{v}{r^2}
\]

This effective viscosity coefficient \( \mu_{\text{eff}} \) is:

\[ \mu_{\text{eff}} = \mu + \mu_t \]

This effective diffusion coefficient \( \Gamma_{\text{eff}} \) is:

\[ \Gamma_{\text{eff}} = \Gamma + \Gamma_t = \frac{\mu}{\sigma} + \frac{\mu_t}{\sigma_t} \quad \text{or} \quad \Gamma_{\text{eff}} = \frac{\mu_{\text{eff}}}{\sigma_{\text{eff}}} = \frac{\mu + \mu_t}{\sigma_{\text{eff}}} \]

Where \( \sigma_{\text{eff}} \) is the effective Prandtl number including the turbulent dynamic viscosity and turbulent diffusion coefficient.

To solve the governing equations, a mathematical expression for effective kinematics viscosity \( (\nu_{\text{eff}}) \) and effective diffusion coefficient \( \Gamma_{\text{eff}} \) will be required through the use of a turbulence model. The finite volume method (FVM) was employed to achieve a numerical solution of partial, non-linear differential equation. The staggered grid was used to solve the discretization equations, which were obtained by the (FVM). Two-equation models (k- \( \varepsilon \) ) were used for turbulence modeling.

3.3 Temperature Distribution within Blade Metal:

Fluid solutions for both internal and external flow are used as a boundary condition for the solid conduction problem, which gives a new temperature distribution along the blade metal. In this work, the temperature distribution on the blade metal will be computed, using steady-state heat equation. Finite difference formulation was used to discretize the conduction heat transfer with SOR iteration to determine the resulting blade temperature distribution. Laplace equation is the model form for elliptic partial differential equations. For steady-state conduction with no heat generation, constant thermal conductivity and for three-dimensional in Cartesian coordinates Laplace equation is [28].
\[
\frac{\partial^2 T}{\partial z^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0
\]

The transformed of Laplace equation in curvilinear coordinates:

\[
\frac{\partial T}{\partial \xi} (\xi_{xx} + \xi_{yy} + \xi_{zz}) + \frac{\partial T}{\partial \eta} (\eta_{xx} + \eta_{yy} + \eta_{zz}) + \frac{\partial T}{\partial \zeta} (\zeta_{xx} + \zeta_{yy} + \zeta_{zz})
\]

\[
+ \frac{\partial^2 T}{\partial \xi^2} (\xi_{xx} + \xi_{yy} + \xi_{zz}) + \frac{\partial^2 T}{\partial \eta^2} (\eta_{xx} + \eta_{yy} + \eta_{zz}) + \frac{\partial^2 T}{\partial \zeta^2} (\zeta_{xx} + \zeta_{yy} + \zeta_{zz})
\]

\[
+ 2\left(\frac{\partial^2 T}{\partial \xi \partial \eta}\right)[\xi_n \xi_x + \eta_n \eta_y + \zeta_n \zeta_z] + 2\left(\frac{\partial^2 T}{\partial \xi \partial \zeta}\right)[\xi_n \xi_z + \eta_n \eta_z + \zeta_n \zeta_z]
\]

\[
+ 2\left(\frac{\partial^2 T}{\partial \eta \partial \zeta}\right)[\zeta_n \eta_x + \eta_n \eta_y + \zeta_n \zeta_z] = 0
\]

The above equation is concerned with the internal nodes where the conduction mode takes place. These equations solved, using SOR iterative method with central differences for all derivatives except those at the boundary.

4. Thermal Analysis

Thermal analysis of internally air-cooled turbine blades requires the specification of external boundary condition on the blade surface in contact with hot gases (external) and of that in contact with coolant flow (internal), then determine the temperature distribution on both inner and outer blade surfaces. This solution procedure requires the specification of heat transfer coefficient distribution along outer and inner surfaces. The blade of interest will be analyzed according to different boundary conditions (internal, external) and in all these analyses the blade temperature distribution will be determined. The numerical procedure developed is presented for six cases. These cases were studied for different operating conditions and internal and/or external boundary conditions as shown in Table 1. It should be mentioned here that blade geometry was kept fixed in all cases.

| Case No | \(g_m\) | \(p_g\) (bar) | \(T_g\) (°C) | \(T_c\) (°C) | \(h\) (W/m²°C) |
|---------|--------|---------------|--------------|--------------|---------------|
| 1       | 0.85   | 10.5          | 1000         | 177          | \(h_1\)       |
| 2       | 0.85   | 10.5          | 1000         | 177          | \(h_2\)       |
| 3       | 0.75   | 9.5           | 900          | 177          | \(h_1\)       |
| 4       | 0.75   | 9.5           | 900          | 277          | \(h_1\)       |
| 5       | 0.95   | 11.5          | 1100         | 177          | \(h_1\)       |
| 6       | 0.95   | 11.5          | 1100         | 77           | \(h_1\)       |
4.1 Boundary Conditions of Outer Surface
Two boundary heat transfer coefficient distribution were used. For case study No. 2, this heat transfer coefficient \( h_2 \) distribution is as shown in [29]. For all other cases the distribution of heat transfer coefficient \( h_1 \) are as shown in [30].

4.2 Boundary Conditions of Inner Surface
In this analysis, the same six case studies were used, in which the coolant temperature varied. While the heat transfer coefficient \( h_c \) was taken as in Table 2.

### Table 2. Heat Transfer Coefficient Value of Cooling Flow [30]

| Passage No | Diameter (mm) | Heat Transfer Coefficient (W/m\(^2\)C) |
|------------|---------------|--------------------------------------|
| 1-12       | 1.5           | 972                                  |
| 13-15      | 2.5           | 1033                                 |

4.3 Blade Temperature Calculations Procedure

Procedure steps:
- Step (1): The first step is to perform hot gas (external) flow calculations to determine temperature distribution in the blade-to-blade passage.
- Step (2): The second step is then to determine cooling passage temperature distribution from cool flow (inner) calculations.
- Step (3): determine surface blade temperature. For external surface, the external boundary condition for blade metal is as follows (Figure 1a):

\[
-k_b \frac{(T_b)_{i,j,k} - (T_b)_{i,j-1,k}}{S_\eta} = h_g [(T_g)_{i,j} - (T_g)_{i,j+1}]
\]

\[
(T_b)_{i,j,k} = \left[ -k_b \frac{(T_g)_{i,j} + (T_b)_{i,j-1,k}}{k_b S_\eta} \right] (1 + \frac{h_g S_\eta}{k_b})
\]

\[
(T_b)_{i,j} = (T_b)_{i,j,k}
\]

Step (4): transfer to coolant side to determine the inner boundary conditions for the blade metal as follows (Figure 1b):

\[
-k_b \frac{(T_b)_{i,j,k} - (T_b)_{i,j+1,k}}{S_\eta} = h_c [(T_c)_{i,j} - (T_c)_{i,j-1}]
\]
\[
(T_b)_{i,j,k} = \frac{h_c S_\eta}{k_b} (T_e)_{i,j-1} + (T_b)_{i,j+1,k} / (1 + \frac{h_c S_\eta}{k_b})
\]

\[
(T_e)_{i,j} = (T_b)_{i,j,k}
\]

Step (5): depending on the distributions predicted in steps (3) and (4), to determine the internal blade metal temperature distribution.

Step (6): Step (3) is then repeated to get a new boundary condition for the external surface which is used for external flow conditions.

Step (7): Step (4) is then repeated to get a new boundary condition for the inner surface which is used for inner flow calculations. This distribution is then averaged for the cooling hole circumference nodes.

Step (8): The same procedure is repeated for five sections from the root to tip. Blade metal temperature for blade nodes between sections is distributed linearly giving (21) nodes temperature with blade height.

Step (9): Steps (1-8) are then repeated until convergence is obtained.

5. Results and Discussion
The following paragraphs will offer a description of the numerical heat transfer analysis carried over the domain blade wherein parametric considerations are applied for each case. The solution is assumed to become converged once a suitable steady state condition is arrived.

The obtained results are discussed and contrasted to show the difference when compared to case 1 which represents the actual operating conditions taken from Al-Dorah station. Figure 2(a) presents Mach number contours for hot gases of external blade passage at three different blade sections (\(z = 0.075\), \(z = 0.05\) and \(z = 0.025\) m). These plots show that Mach number is increasing from the leading edge towards the trailing edge. This can be explained due to the nozzle shaped passage which allows acceleration to take place. Figure 2(b) shows the temperature distribution for external hot gases of blade passage at three different blade sections. It shows that the temperature drops towards the trailing edge is a result of pressure distribution and internal energy distribution.

Figure 3 shows the flow field velocity in cooling passages. It shows the effect of wall friction on the flow as reduction in velocity value at the wall. This effect diminishes towards the center of passage. On the other hand, Figure 4 shows the temperature contours with the radius and...
along the cooling passage. It shows that the cooling air temperature increases from the center line towards the blade's inner surface (wall). This is due to heat transfer by convection from the blade metal which also affects temperature distribution from blade root towards blade tip.

Figure 2. Mach number and Isothermal contours (case 1)
Figure 3. Flow field of 2D axi-symmetry cooling passage (Case 1)
Figure 4. Isotherm contours of air-cooling internal passage ($^\circ C$)(Case 1)

Figure 5 shows the blade metal temperature distribution for case (1) wherein the blade metal temperature drops towards the trailing edge. This is a consequence of the effect of gas temperature distribution around the blade. Figure 5 also shows the reduction in blade metal temperature towards the cooling holes because of the effect of coolant flow, and an average difference of $50^\circ C$ between outer surface and inner surface can be deduced.
Figure 5. Isotherm contours of blade (Case 1)

Figure 6 shows the blade metal temperature distribution for both case (1) and (2). Case (2) gave higher blade metal temperature. This is a clear result of the effect of higher heat transfer coefficient. Figure 7, a is a comparison between cases 3 and 4 for cooling passages 6 and 14. This shows that for both types of holes, case 4 gives higher coolant temperature distribution because the coolant (sink) inlet temperature is higher which leads to an increase in the coolant temperature distribution. Figure 6, b shows the coolant temperature distribution of cooling holes 6 and 14 for cases 5 and 6. It shows that the temperature distribution is lower for case 6 which is due to the coolant inlet temperature (sink) being lower.
Figure 6. Isotherm contours of blade. (case 1 & 2)

Figure 7. Bulk temperature of internal cooling air

a) Bulk temperature of internal cooling air (cases 3 & 4)

b) Bulk temperature of internal cooling air (cases 5 & 6)
6. Conclusion
CFD analysis of gas turbine blade is carried out with different operation conditions as mention in Table 1. An increase of 6% in the gas side heat transfer coefficient will lead to an increase of about 40 °C at the blade leading edge while the increase of 100% in the heat transfer coefficient will cause an increase of 100 °C in the blade trailing edge temperature. Increasing the gas temperature by 100 °C resulted in (50-100) °C increase in blade metal temperature. Increasing the coolant temperature by 100 °C resulted in 50 °C increase in blade metal temperature.

- **List of abbreviation**
  - P: pressure (N/m²)
  - h: heat transfer coefficient (W/m²°C)
  - k: Thermal conductivity (W m⁻¹ K⁻¹)
  - r: Polar coordinate (m)
  - T: Temperature (°C)
  - u: Velocity in x direction (m/s)
  - v: Velocity in y direction (m/s)
  - x: Coordinate (m)
  - y: Coordinate (m)
  - z: Coordinate (m)
  - $\xi, \eta, \zeta$: computation coordinate
  - $\Delta x, \Delta y$: spatial steps in physical domain (m)
  - $\Delta \xi, \Delta \eta, \Delta \zeta$: spatial steps in computation domain (m)
  - $\Delta t$: time steps (sec)
  - $\rho$: density of the fluid (kg/m³)
  - $\mu$: dynamic viscosity (kg/m s⁻²)
  - $\varepsilon$: rate of dissipation of kinetic energy (m²/s⁻³)
  - $\Gamma$: diffusion coefficient used in discretization equation.
  - b: blade
  - bu: bulk
  - c: cooling
  - eff: effective
  - g: hot gases
  - t: turbulent

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