Estimation of Gas Turbine Blades Cooling Efficiency

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Abstract

This paper outlines the results of the evaluation of the most thermally stressed gas turbine elements, first stage power turbine blades, cooling efficiency. The calculations were implemented using a numerical simulation based on the Finite Element Method. The volume average temperature of the blade and the coefficient of heat transfer from the cooling medium to the cooling channel wall were chosen as the cooling efficiency criteria. A comparison of steam and air used as coolants was done, and the calculations were performed using ANSYS Fluent software.

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1. Introduction

There is a continuous desire to increase the thermal efficiency of gas turbines, which is realized mainly by increasing the turbine inlet temperature of the gases [1]. At the same time, gas temperature growth rate exceeds that of the heat resistance of alloys used in metallurgy [2]. Modern gas turbines operate at a turbine inlet temperature of more than 1600\textdegree C [3]. In order to provide the possibility of high temperature elements operation at such high parameters, it is necessary to use thermal barrier coatings [4,5] and advanced cooling systems [6].

Experimental tests to estimate the cooling efficiency of gas turbine elements are complicated. In recent years, it is more frequently used to perform the computer modeling of the thermal state of the cooling elements based on the finite element method. Whilst such an approach is significantly less expensive, the results have a good compliance with the experimental data.

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This paper evaluates the thermal state of the most stressed gas turbine elements: first stage blades. The influence of the cooling blade performance using a cooling medium with different parameters was estimated. In addition, a comparison of the cooling efficiency of steam and air was implemented. ANSYS software was used for the calculations.

2. Description of the computation model

2.1. Geometry model

Calculations were based on a geometry model of a gas turbine blade located in the gas flow. The blade and the surrounding gas flow were modeled on the application BladeGen ANSYS, and cooling channels within a blade were configured using the DesignModeler application. The prototype of the cooling channels, their locations, and their sizes were taken from the model described in [7]. For a comparison of the cooling efficiency, two cooling mediums were considered: air and water vapor. The above described model is presented in Fig. 1.

![Fig. 1. Geometry model of the gas turbine blade and gas flow.](image)

2.2. Physical properties of the blade material

The blade is made of an austenitic nickel-chromium superalloy Inconel-718. In calculations the following physical properties of the alloy were used: density $\rho = 8200 \text{kg/m}^3$, specific heat $c=435 \text{ J/(kg·K)}$, and coefficient of thermal conductivity $\lambda=11.4 \text{ W/(m·K)}$ [8].

2.3. Physical properties of air

In the calculations, the air used for cooling the turbine blade was considered with several values of pressure and temperature, with the former varying from 0.1 MPa to 8 MPa and the latter ranging from 373.15 K to 573.15 K. Air is considered to be an ideal gas with a molar mass of 28.966 g/mol [9]. Specific heat was considered as a polynomial function of temperature (1), and this relation is valid in the temperature range from 100 to 1500°C [10]. The coefficients of the polynomial are shown in Table 1.

$$c_p(T) = A_1 + A_2 \cdot T + A_3 \cdot T^2 + ... + A_n \cdot T^{n-1}$$

Table 1. The coefficients of the polynomial of the specific heat for air.
The coefficient of thermal conductivity for air was specified as a piecewise linear function of the temperature (2).

\[ \lambda(T) = \lambda_n + \frac{\lambda_{n+1} - \lambda_n}{T_{n+1} - T_n} \cdot (T - T_n) \]  

(2)

Table 2. The values of coefficients of thermal conductivity for air.

| Temperature, K | Coefficient of thermal conductivity, W/(m·K) |
|---------------|-----------------------------------------------|
| 300           | 0.0262                                        |
| 350           | 0.03                                          |
| 400           | 0.0338                                        |
| 460           | 0.038                                         |
| 560           | 0.0445                                        |
| 750           | 0.0549                                        |

To describe the viscosity dependence on temperature, the power relation (3) was used.

\[ \mu = \mu_0 \cdot \left(\frac{T}{T_0}\right)^n . \]  

(3)

2.4. Physical properties of gases

The pressure drop of gases for the blade was taken as equal to 0.1125 MPa, and the temperature as equal to 1173.15 K. To simplify calculations, other properties of gases have been taken such as in Section 2.3.

2.5. Physical properties of water vapor

As in Section 2.3, steam pressure varied from 0.1 MPa to 8 MPa and the temperature varied from 573.15 K to 773.15 K. Steam was established as an ideal gas with a molar mass of 18.01534 g/mol [9]. The specific heat of the water vapor was specified in the form of a polynomial function of temperature, and the coefficients of this polynomial are listed in Table 3.

The coefficient of thermal conductivity is given as a polynomial of the form (1), and the coefficients of this polynomial are shown in Table 4. Viscosity is considered as a polynomial, and the values of this polynomial’s coefficients are presented in Table 5.
2.6. Meshing

The mesh for the finite element model was built using ANSYS ICEM CFD software. The mesh consists of 1,511,920 tetrahedral elements, with the minimum size of each element equal to 6.509·10⁻⁵ m, and the maximum size set to 1.3018·10⁻² m. The above described mesh is shown in Fig. 2.

| Coefficient | Value   |
|-------------|---------|
| $A_1$       | 1563.077 |
| $A_2$       | 1.603755 |
| $A_3$       | -0.002932784 |
| $A_4$       | 3.216101e-6 |
| $A_5$       | -1.156827e-9 |

Table 3. The coefficients of the polynomial of the specific heat for water vapor.

| Coefficient | Value   |
|-------------|---------|
| $A_1$       | -0.007967996 |
| $A_2$       | 6.881332e-5 |
| $A_3$       | 4.49046e-8 |
| $A_4$       | -9.099937e-12 |
| $A_5$       | 6.173314e-16 |

Table 4. The coefficients for the polynomial relation of the coefficient of thermal conductivity of the temperature for steam.

| Coefficient | Value   |
|-------------|---------|
| $A_1$       | -4.418944e-6 |
| $A_2$       | 4.687638e-8 |
| $A_3$       | -5.389431e-12 |
| $A_4$       | 3.202856e-16 |
| $A_5$       | 4.919179e-22 |

Table 5. The polynomial coefficients of viscosity in relation to steam.

3. Results

Calculations were implemented in FluidFlow (Fluent) software, with the aim to determine the heat transfer coefficient from the cooling channel wall to the coolant and the volume average temperature of the blade. Calculation results of the blade cooling by air are presented in Table 6 and 7.

The calculation results of cooling by steam are shown in Table 8 and 9.

The values obtained for the heat transfer coefficients with low pressure are in good agreement with the experimental data presented in [11] and with calculated values in [12-14].

To compare the efficiency using different cooling mediums and to estimate the influence of the coolant pressure, the two relations were built. The first relation is the dependence of the heat transfer coefficient between the cooling channel wall and coolant from the coolant pressure (Fig. 3a), whereas the second one is the average volume temperature of the blade from the coolant pressure (Fig. 3b). Both relations were determined at a constant coolant temperature of $T_{\text{coolant}}=573.15$ K.
Table 6. The average volume temperature of the blade cooling by air, K.

| Temperature, K | 373.15 | 473.15 | 573.15 |
|----------------|--------|--------|--------|
| Pressure, MPa  |        |        |        |
| 0.1            | 714    | 767    | 828    |
| 0.3            | 625    | 694    | 765    |
| 0.5            | 583    | 659    | 734    |
| 1              | 533    | 616    | 697    |
| 3              | 483    | 571    | 659    |
| 8              | 460    | 550    | 640    |

Table 7. The heat transfer coefficient from the cooling channel wall to the cooling air, W/(m²·K).

| Temperature, K | 373.15 | 473.15 | 573.15 |
|----------------|--------|--------|--------|
| Pressure, MPa  |        |        |        |
| 0.1            | 1526   | 1571   | 1537   |
| 0.3            | 2688   | 2681   | 2632   |
| 0.5            | 3765   | 3682   | 3617   |
| 1              | 6225   | 5997   | 5838   |
| 3              | 14459  | 13744  | 13120  |
| 8              | 32350  | 30572  | 29300  |
Table 8. The average volume temperature of the blade cooling by steam, K.

| Temperature, K | 573.15 | 673.15 | 773.15 |
|---------------|--------|--------|--------|
| Pressure, MPa |
| 0.1           | 801    | 862    | 922    |
| 0.3           | 744    | 814    | 885    |
| 0.5           | 717    | 792    | 867    |
| 1             | 684    | 766    | 847    |
| 3             | 651    | 738    | 825    |
| 8             | 636    | 726    | 815    |

Table 9. The heat transfer coefficient from the cooling channel wall to the cooling steam, W/(m²·K).

| Temperature, K | 573.15 | 673.15 | 773.15 |
|---------------|--------|--------|--------|
| Pressure, MPa |
| 0.1           | 1905   | 1917   | 1977   |
| 0.3           | 3250   | 3292   | 3359   |
| 0.5           | 4453   | 4520   | 4599   |
| 1             | 7257   | 7310   | 7407   |
| 3             | 16858  | 16839  | 16914  |
| 8             | 37729  | 37376  | 37415  |

Fig. 3. (a) the dependence of the heat transfer coefficient between cooling channel wall and coolant pressure; (b) the dependence of the average volume temperature of the blade from coolant pressure.

Fig. 3 shows that the heat transfer coefficient is much higher with steam cooling than air cooling. Moreover, the higher the pressure of the cooling medium, the greater the difference between the heat transfer coefficients for steam and air. Further, the influence of the coolant temperature on the cooling efficiency at the fixed coolant pressure was investigated. The results of the calculations are presented in Fig. 4.
4. Conclusions

The presented study estimated the cooling efficiency of the first stage turbine blade for different parameters of a cooling medium. For comparison, two types of cooling medium were considered: air and water vapor. The average volume temperature of the blade and the wall heat transfer coefficient were chosen as criteria of cooling efficiency. As shown in the study, steam is more efficient as a coolant than the air when analyzed using the same parameters (pressure and temperature). The average blade temperature is lowered by 20-30°C when steam is used, and the heat transfer coefficient from the cooling channel to the coolant for steam is higher by 10-30% than for air.

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