Study of design and technology factors influencing gas turbine blade cooling

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Abstract. The knowledge of aerodynamic and thermal parameters of turbulators used in order to design an efficient blade cooling system. However, all experimental tests of the hydraulic and thermal characteristics of the turbulators were conducted on the rectangular shape channels with a strongly defined air flow direction. The actual blades have geometry of the channels that essentially differs from the rectangular shape. Specifically, the air flow in the back cavity of a blade with one and half-pass cooling channel changes its direction throughout the feather height. In most cases the ribs and pins are made with a tilt to the channel walls, which is determined by the moving element design of a mould for the ceramic rod element fabrication. All of the factors described above may result in the blade thermohydraulic model being developed failing to fully simulate the air flow and the heat exchange processes in some sections of the cooling path. Hence, the design temperature field will differ from the temperature field of an actual blade. This article studied the numerical data of design and technology factors influencing heat transfer in the cooling channels. The results obtained showed their substantial impact on the blade cooling efficiency.

1. Introduction

A precision investment casting is the main technological process in fabrication of blades for the high-temperature gas turbines. Cooling channels are formed with ceramic rods that are fabricated by moulding process using special moulds. This technological process limits the geometry of heat transfer turbulators in the cooling channels. Specifically, for blades of modern gas turbine engines the height of wall ribs is at least 0.3 mm, ribs and pins of vortex matrices have a tilt relatively to the feather walls and normal cross section of radial channels differs from rectangular shape. In addition, we must take into account an effect of standard deviations on the geometry of cooling turbulators.

In this article the numerical research was being conducted on the effects of several design and technological factors on the heat transfer rate in the turbine blade cooling channels. Software ANSYS CFX and $k-\omega$ turbulence model with the scalable wall function were used for simulation of the heat-mass exchange process in the cooling channels.

Verification of numerical method was carried out using a two-dimensional channel of the length 120 mm with channel cross-section of $2 \times 10$ mm on one of the wall at 50 mm distance from the inlet
of 0.5 mm width with an angle 90° to the flow direction. The relative height of a rib was 0.25, all rib edges were sharp. Distribution of the local heat transfer coefficients lengthwise of the channel was obtained based on the data of channel test conducted in a liquid-metal thermostat [1, 2] that was compared with the results of a numerical simulation performed for the test conditions including the geometry of a section of the air supply to the channel. The deviation of numerical heat transfer values from the experimental values of \( \frac{Nu}{Nu_0} \) is not more than 10% confirming the accuracy of selected parameters of the grid and turbulence model.

2. The influence of shape and incline of ribs on thermal and hydraulic characteristics of the radial channel of the leading edge

The radial channel of the leading edge with the heat transfer turbulators in the form of ribs was the first object of a numerical study [3, 4]. Geometrical parameters of the ribs are given in table 1. The channel hydraulic diameter \( d = 1.6 \text{ mm} \); length of a ribbed channel \( L = 48 \text{ mm} \); number of ribs – 17. The axial air flow was implemented in a channel. The channel wall temperature was 800°C, the air temperature at a channel inlet – 50°C, pressure – 16 bar.

| Parameter                        | Value |
|----------------------------------|-------|
| Rib height, mm                   | 0.3   |
| Rib width, mm                    | 0.3   |
| Ribs pitch, mm                   | 2.85  |
| Angle of the rib setting relatively to the flow direction, ° | 90    |

Three options of the rib design were studied: with the sharp edges of all rib surfaces (figure 1a), with the rounded end surfaces of the ribs (figure 1b) and with additional end rounding of the top and side rib surfaces (figure 1c). An option with ribs installed at an angle of 45° relatively to the flow direction (figure 1d) was studied additionally.

The results of solving the heat transfer problems for different options of the leading edge channel with the ribs perpendicular to the flow are given in figures 2, 3, 4 in the form of a relationship between Nusselt number \( Nu \) and Nusselt number calculated for a smooth channel with the same cross-section by the equation (1).

\[
Nu = 0.021Re^{0.8}Pr^{0.43},
\]

where \( Re \) – Reynolds number;
\( Pr \) – Prandtl number.

Data analysis shows that the ribs with sharp edges have maximum efficiency and the ribs with all rounded edges – minimum.
Figure 2. Distribution of the parameter value $\frac{Nu}{Nu_0}$ lengthwise the channel ($Re = 40000$).

Figure 3. Distribution of the parameter value $\frac{Nu}{Nu_0}$ lengthwise the channel ($Re = 70000$).

Figure 4. Distribution of the parameter value $\frac{Nu}{Nu_0}$ lengthwise the channel ($Re = 100000$).

As can be seen from the charts an influence of the rib geometry on the heat transfer rate is demonstrated at the distance of 15 hydraulic diameters from the inlet cross-section that is due to the initial flow turbulence. Rounding of all rib edges results in decreasing of $\frac{Nu}{Nu_0}$ by 15–20% ($Re = 40000, L/d = 20–27$). With increase of $Re$ number up to $10^5$ the intensification coefficient is not more than 1.5 throughout the channel length and the effect of rib geometry on the heat transfer is not observed. The edge rounding allows for reducing the channel hydraulic resistance in the number $Re$ range studied by 17–20% in comparison with a channel having all sharp edges.

The cooling rate of channel walls with ribs installed at angles of 90° and 45° were compared. The rib edges were sharp. The rib inclination tilt at an angle of 45° to the flow direction results in increasing of a heat transfer rate by 17–22% as compared with the transverse ribs. Apart from that the coefficient of linear hydraulic resistance increases by 2.3 times.
3. Effect of an angle of the coolant flow incidence on heat transfer on the inner surface of a cooling channel in area of the gas turbine blade trailing edge with pins installed

A convergent channel of the blade trailing edge with one and half-pass cooling channel was the second object of a numerical study [5]. Four rows of the staggered pins (cylindrical bars) were installed in the channel for the heat transfer intensification. A geometrical model of the trailing edge channel element is shown in figure 5. Pin diameter was set to $D = 2$ mm, longitudinal pin pitch to $S_1 = 5.2$ mm and transverse pin pitch – to $S_2 = 5.2$ mm.

![Figure 5. Geometric model of the trailing edge cooling channel.](image)

The stagnation pressure and temperature was set at the model entry according to Reynolds number at the channel entry equal to 50 000.

An effect of design features of the blade back cavity on the velocity vector of the flow incoming to the pin zone and, accordingly, on the heat transfer in the pin rows was simulated. Calculations of the heat transfer coefficients and Nu numbers were carried out for four values of an entry angle of the air flow in to the trailing edge channel: 0°, 15°, 30° and 45°.

A decrease in the heat transfer rate with an increase in an entry angle of the flow relatively to the basic option (0°) are caused by the fact that the array resembles in in-line arrangement. This is especially prominent in the first rows of pins. Starting from around third row the streamlines are straightened. At an angle of 45° the low-pressure areas in the “shadow” part of the pins was essentially increased, while the heat transfer rate at the last rows of pins was significantly reduced.

Figure 6 shows that the flow deviation from axis direction by 15° had almost no effect on the heat transfer level in the pin area, in other words the flow typical for staggered pin arrangement was retained. Nu values were decreased by 10% across all pin rows with increase in an inlet angle up to 30°. At the initial flow angle of 45° a local decrease of the heat transfer rate by 25% is shown in the area of third row of pins. This might be explained by the flow deflection at the segment of third row of pins as it’s clearly seen from the calculation data of streamlines (figure 7).

Different heat transfer rates from the suction and pressure sides due to difference in a wall shape (one is convex and other – concave) should also be noted.

Quantitative estimation of the effect of an angle of the coolant flow incidence on Nusselt number Nu for the staggered pin array is given in graphic form in figure 8. This characteristic might be used as a correction for the heat transfer values in the cooling channel in case of deflection of an angle of the flow incidence (for Re = 50 000).
Figure 6. Effect of an angle of the coolant flow incidence on distribution of Nu across the pin rows at Re = 50 000.

Figure 7. The coolant streamlines in a cooling channel with pins at an angle of the flow incidence of 45° and Re = 50 000.

Figure 8. Effect of an angle of the coolant flow incidence for the cooling channel at Re = 50 000.

4. A cross flow influence on thermal and hydraulic characteristics

A jet-stream blow across the main flow is one of the heat transfer intensification methods in a radial cooling channel of the leading edge [6]. A semicircular cross-section channel with the coolant radial flow, in which the air supply from a parallel collector channel was carried out through circular holes having diameter \( d \), was an object of research.

Static flow pressure (16 bar) and air temperature of 350°C was set at the model exit. Cooled surface of the leading edge was simulated by the viscous isothermal wall (temperature of 800°C). Other walls of the model were assumed viscous, adiabatic.
The model study was performed for three conditions: Re\textsubscript{hole} = 5\,000, Re\textsubscript{hole} = 10\,000, Re\textsubscript{hole} = 15\,000. Diameter of holes was used as a characteristic dimension.

Based on these data, we can conclude that the efficiency of jet cooling is sufficiently high especially for a condition with large Reynolds numbers: intensification is 3.2. Moreover, the hydraulic resistance of the considered cooling system is increased trice in comparison with the smooth radial channel, which is not critical.

For conditions of Re\textsubscript{hole} = 5\,000 and Re\textsubscript{hole} = 10\,000 the results are similar. However, the local and average values of Nu for Re\textsubscript{hole} = 10\,000 are greater: Nu = 38.20 (Re\textsubscript{hole} = 10\,000) in comparison with Nu = 23.21 (Re\textsubscript{hole} = 5\,000). An efficiency coefficient for both intensifications is 2.44.

Overall, a jet cooling system of the leading edge provides an essential heat transfer intensification with increase in hydraulic resistance by three times (in average). An efficiency coefficient of such system is more than two. However, it should be taken into account that in actual blade there will be the air heating in an entrance channel and consequently a decrease in amount of removed heat in the feather peripheral sections. This intensification method will be best utilized as a local in the blade sections with the maximum gas flow temperature.

5. Conclusion
1) Numerical study of the design and technological factors that influence the heat transfer in blade cooling channels of gas turbines was carried out.

2) It was shown that while calculation of the blade temperature conditions the 3-D models shall be used completely accounting all special features of an actual blade including tolerances on fabrication of the heat transfer turbulators, foundry radii, curvature of surfaces, etc.

3) Despite an essential complication of the design model and decrease in the grid elements this allows to increase efficacy of a thermohydraulic model of the blade.

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