Visualization and PIV-study of the formation of a cooling film when flowing around the leading edge of the gas turbine nozzle blade

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Abstract. The results of particle image velocimetry near the perforated leading edge of the nozzle vane of gas turbine are presented. Visualization of the formation of cooling film on the surface of the blade with determination of its thickness is carried out. On the basis of the obtained results, the influence of the blown cooling air mass flow rate on the formation of the film is analyzed.

1. Introduction
One of the main problems of organization of effective cooling leading edges of nozzle blades of the first stages of gas turbines is providing a stable cooling film, which pushes the flow of hot gases from the surface of the blade. It is known that during film cooling, the behavior of the coolant jets significantly depends on such parameters as the blowing angle of the jet, its velocity and density. The last two parameters are taken into account by the blowing parameter $m$.

The real conditions of discrete blowing coolant through the rows of holes require preventing contact of the flow of high-temperature combustion products with the surface of the blade and escaping its burnout, therefore it is necessary to provide mixing of jets within the boundary layer and to avoid deep penetration of the coolant jets into the core of the blowing flow.

In case of cooling of a leading edge having the advanced perforation in the form of several rows of holes, the organization of effective blowing of the coolant is complicated by significant gradients of static pressure and gas velocity in regions of blowing the coolant. This is due to the peculiarities of the main flow on the blade. In this case, the holes in the adjacent rows are in significantly different conditions for the available pressure gradient and therefore the speeds of the coolant and the blowing parameters $m$ will be different. This problem can be solved by redistributing the flow of the coolant through the holes on the basis of varying the hydraulic resistance of the supply paths. This will provide the required values of the blowing parameter corresponding to the optimal range of effective film cooling.

Until recently, the main method of experimental study of the film cooling of the blades was thermal bench tests. However, the temperature conditions of the walls, as well as the presence of burnout, soot, etc., can be considered as practically the only criteria for the cooling efficiency of the blades according to the results of such tests. At the same time, the reasons of the defects are not always obvious, since
the thermal state of the blades is subject to changes due to non-stationary modes of operation of other engine elements, in particular the combustion chamber.

Possible solution of the problem of the formation of high-quality thermal protection of the blade surface is detailed study of the flow structure near the leading edge of the blade with determination of velocity vectors and visualization of the convective film in different modes by the blowing parameter \( m \). Such studies cannot be carried out by traditional gas-dynamic measurement methods based on direct contact of sensors with the diagnosed flow since the introduction of even small sensors into the flow can completely change its structure. For this reason, these measurements should be carried out by non-contact optical methods, which have become widespread abroad, and in the last decade in Russia. The most famous among them are the methods of particle image velocimetry (PIV), particle tracking velocimetry (PTV), as well as high-speed video and optical visualization by inert impurities.

PIV method belongs to the class of non-contact optical methods for measuring velocity in flows [1, 2]. Among other tools for the study of the flow structure, it occupies a special place due to the ability to record instantaneous spatial velocity distributions. This advantage is particularly important in the study of flows containing large-scale vortex structures, information about which is partially lost when using single-point diagnostic methods.

The study of gas-dynamic parameters of flow in turbines using PIV has been actively developing since the early 2000s. At the initial stage, non-contact measurements of the velocity vectors were carried out during the flow around the blade models. However, the full advantages of non-contact measurements were revealed in the study of eddy formation in edge traces, the structure of secondary flows and features of interaction with the coolant jets.

A sufficiently large number of PIV studies have been performed to study stator-rotor interaction in turbine stages [3-5]. These papers contain the results of measurements of instantaneous and averaged velocities, as well as the parameters of the vortex created by the separation of the flow from the trailing edge of a blade. Some papers [6, 7] show the possibility of applying PIV to identify the secondary flow in the interblade channels. The measurements of the velocity allow to estimate intensity of secondary flows and their influence on aerodynamic losses. The paper [8] presents fairly detailed results of PIV studies of the formation of coherent vortex structures in the boundary layer on the surface of a low-pressure turbine blade.

Detailed PIV measurements of the velocity near the model of the trailing edge of the blade with film cooling for the purpose of studying the mechanism of generating aerodynamic losses are given in studies [9-11]. It should be noted that almost all such studies are limited to the use of 2D PIV, and measurements are carried out on scaled models of blades to facilitate the formulation.

In the experimental study [12], which is closest to the subject of this paper, the local velocity field for a package of nozzle blades of a high-pressure turbine with film cooling was analyzed using the methods of flow visualization and PIV measurements. The visualization was performed near the flow deceleration point of the leading edge of the blade for a more detailed understanding of the flow structure, while the PIV method was used to measure the velocity field of the coolant jets at the outlet of the perforation holes in the 2D vertical plane.

This paper deals with an experimental study of flowing around the leading edge of the nozzle blade of a high-pressure turbine with an advanced perforation of film holes at different flow rates of the coolant. The main purpose of the work is to identify the structure of the main flow in terms of its interaction with the coolant jets blown through the film holes in the leading edge of the blade, and determine the thickness of the cooling film at the surface of the blade.

2. Experimental Stand and Object of Research

In order to carry out PIV research, experimental was developed (figure 1). This stand consists of a package of three blades (1), side channel blower SKS-1000 (2), controlled by a variable frequency drive (VFD). To illuminate the tracers a double pulse Nd:YAG laser Quantel Ever Green 70 was used. Registration of tracers was carried out by a cross-correlation 4MP digital camera Bobcat ImperX B2020. Synchronization of equipment during the experiment was provided by the processor "Polis" (5) using the software ActualFlow. The seeding particles were titanium dioxide powder and glycerin vapor.
Figure 1. Scheme of the experimental stand: 1 – package of three blades; 2 – side channel blower; 3 – double pulse Nd:YAG laser; 4 – cross-correlation 4MP digital camera; 5 – synchronizing processor "Polis"; 6 – PC.

The package of blades (figure 2 and 3) consists of an input diffuser, a flow stabilization section, a test object, and an output section. The test object is a curvilinear channel with optical access on three sides, in which a flat package of three blades is placed. The left and the right blades are made without internal cavities and designed to create conditions close to original flow around the central blade. The central blade is removable and has internal cavity for inserting the deflector. During the tests, metal deflector from full-scale blades was used. This deflector was slightly shortened for installation inside the internal cavity of the central blade. All the tested blades were manufactured using 3D printing from polyamide. After manufacturing, a consistent grinding of the surfaces of the blades and its platforms, as well as drifting of the film holes to the nominal diameter, were performed. The condition of the blade surface and the holes is shown in figure 4. A photo of the test stand is shown in figure 5.

The remaining elements of the stand are made by 3D printing of ABS plastic. Additionally, two deturbulating and balancing nylon nets are installed in front of the inlet diffuser and in front of the flow stabilization section.

Figure 2. Longitudinal section of the package of the blades.

Figure 3. General view of the package of the blades.

During the experiments, there were made measurements of temperature and pressure of surrounding air as well as the temperature of the main flow created by the blower, temperature,
pressure and mass flow rate of the air supplied into the internal cavity of the blade by a piston compressor. PIV measurements of the velocity field were carried out in sections shown in figure 6.

Figure 4. Photograph of the test blade from the leading edge after the grinding process.

Figure 5. Photograph of the test stand.

Figure 6. The layout of the control sections for PIV measurements and visualization.

3. Results and Discussion
The results of experimental PIV studies as well as visualization of the formation of the cooling film on the surface of the blade are shown in figures 7-14. These results correspond to the main modes with value of the relative coolant mass flow rate $G_c$ equal to 1.6%, 3.2%, 4.8% of the main air flow rate. It should be noted that due to the necessity to organize the laser plane as well as because of the geometric features of the experimental model, measurements were carried out only at the leading edge and part of the suction side of the central blade. The remaining areas in the figures are blacked out (in figure 13 – in blue), which corresponds to the absence of measurements.

For all three cross sections studied, increase in the blowing parameter $m$ in the range from 0.5 to 2.5 leads to an intense increase in the thickness of the cooling film. However, the rate and nature of the increase for different cases are different. In particular, it was found that in the studied range of $m$, the forming film is quite non-uniform. Operation modes with relative coolant mass flow rate $G_c > 4\%$ near the leading edge define deep penetration of cooling jets into the main stream. Drift of such jets by flowing air is observed only at a length of about 10..15 diameters of the perforation hole. This is
accompanied by the formation of a recirculation zone behind the jet, in which, obviously, an intensive mixing of the coolant with the main air occurs. Obviously, these modes should be avoided by setting the range for the blowing parameter from 1.0 to 1.5, which corresponds to the relative coolant mass flow rate 2.5..4.0%. Studies have shown that in this case a uniform cooling film can be formed on the surface of the blade.

Cooling film has the smallest thickness in the zone corresponding to the impingement point of the main air flow. At point 2 (figure 13), there is a deep penetration of cooling jets into the main flow observed practically for all the operation modes. This indicates a large value of the blowing parameter \( m \) for this row of holes. In this zone, the film can be detached from the surface of the blade with the formation of a suction zone behind the hole. It forms favorable conditions for potentially hot gases to flow from the main stream into this zone.

It is important to understand the formation of the cooling film on the surface of the blade is a significantly unsteady process. Analysis of flow structure in the central row of perforation holes (figure 14) indicates its high instability. This is realized in the form of alternate deflection of the jet to the pressure and suction sides.

Figure 7. Velocity vectors in section 1 for operation mode \( G_c = 1.6\% \).

Figure 8. Velocity vectors in section 2 for operation mode \( G_c = 1.6\% \).

Figure 9. Velocity vectors in section 1 for operation mode \( G_c = 3.2\% \).

Figure 10. Velocity vectors in section 2 for operation mode \( G_c = 3.2\% \).
4. Conclusion
The experimental stand for velocity measurement and flow visualization near leading edge of the blade under conditions of formation of cooling film is developed and made.

PIV study of the flow around the perforated surface of leading edge are carried out for 3 different sections and variable relative coolant mass flow rate blown through the film holes in the range from 1.6% to 6.2%. Based on the obtained velocity fields and the flow visualization, it is shown that at point 2 (figure 13) almost all operation leads to deep penetration of the cooling jets (from 3 mm to 4.2 mm) into the main air stream. This indicates a large value of the blowing parameter \( m \).

The analysis of the obtained results allowed to determine the most favorable operating range for the film cooling of the leading edge by the blowing parameter \( m \) from 1.0 to 1.5. These values correspond to relative coolant mass flow rate from 2.5% to 4.0%. Studies shown that in this case sufficiently uniform cooling film is formed on the surface of the blade.

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