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APPLICATION OF ADDITIVE LASER TECHNOLOGIES FOR FULL-SCALE MODELING IN THE DESIGN OF COOLED GAS TURBINE BLADES

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ABSTRACT

The methodology for designing gas turbine blades is outlined, based on the advanced verification of thermal and hydraulic models of their cooling system, by testing the prototype of a blade manufactured using selective laser melting technology. An experimental method for verifying the thermal model of blades with convective cooling systems is developed, based on a comparison of the density of heat fluxes obtained from the results of numerical simulation as well as of tests in a liquid-metal thermostat. The methods were tested in the development of a cooling system for the first stage blade of a high-pressure turbine.

Keywords: Gas Turbine, Cooled Blade, Cooling System, Thermal Hydraulic Model, Prototype, Verification.

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1. INTRODUCTION

Development of blades with an efficient cooling system is a complex and time-consuming process that includes selecting a circuit, designing the cooling path channels, calculations of gas-dynamic, thermal and strength, experimental tests, development of manufacturing technology and reliability assessment [1]. Numerical simulation of the temperature field of the cooled turbine blades is a mandatory element of the design process for the gas turbine engine. A reliable calculated data is required to ensure the modern level of efficiency and operating life of a gas turbine. Moreover, there is an urgent need for verification of the results of numerical calculations, which is usually carried out based on the results of testing a full-scale blade made using mass production technology [2, 3]. The discrepancies in the temperature of the blade feather surface and their calculated values identified during the tests may require changes in the cooling system, which leads to a significant additional cost and increase in the time for development of the cooled blade and the engine as a whole. The use of innovative technology of selective laser melting (SLM-technology) allows us to produce a prototype of a cooled blade without the development of design documentation [4, 5]. However, at the moment there are no methods that use the results of the prototype testing to confirm the thermal characteristics of the blade being designed.

2. THE THEORETICAL DESCRIPTION OF THE VERIFICATION METHODOLOGY

Thereby, the actual task is to develop a design methodology that allows for early verification of the thermal and hydraulic models of the blade according to the results obtained from testing of its prototype before the release of design documentation. A flow diagram of the stages of the proposed design methodology is shown in Figure 1.

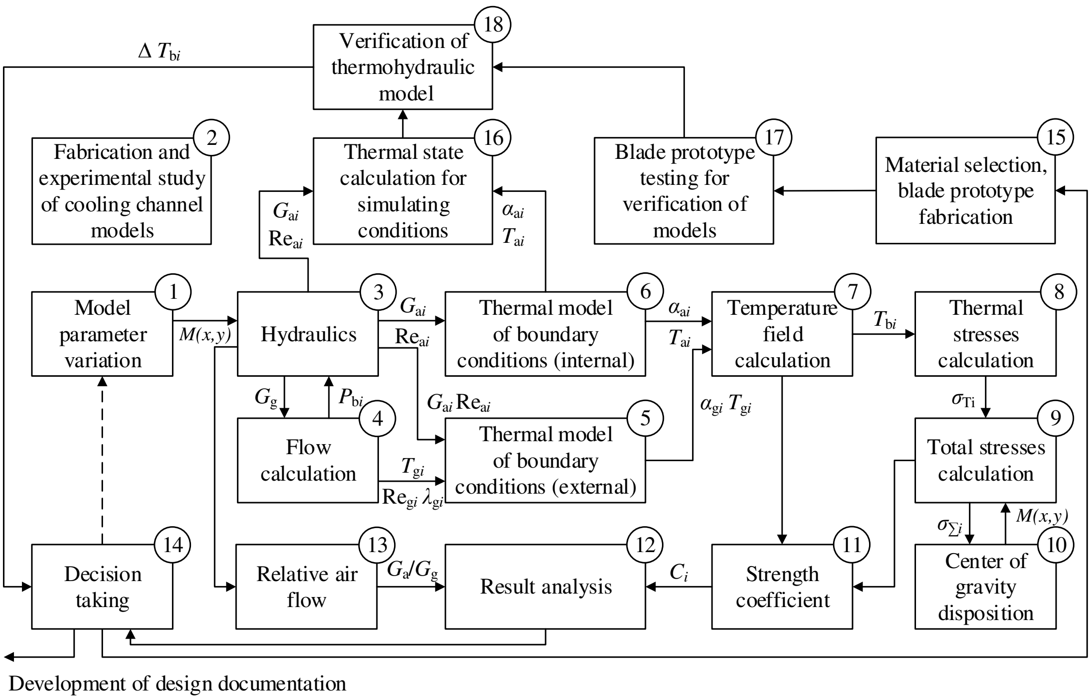

Figure 1 Flow diagram for the design of the blade with the advanced verification of thermal and hydraulic models

The methodology consists of two interconnected modules – thermal and strength, each of which includes a number of units. Geometry and dimensions of cooling channels, the means of intensification of heat transfer and elements of the film cooling are the variable parameters. The geometry of the outer surface of the blade feather is determined by the calculation results of the three-dimensional flow process and the turbine cascade design, and does not change during the design of the cooling system. The thermal module consists of five units (*3*, *4*, *5*, *6* and *7*), each of which performs an independent function. The geometric parameters of heat transfer enhancers, which the designer selects from the heat transfer study materials based on his own experience, are the initial data for the thermal unit. The field simulation units are a distinctive feature of the proposed methodology. At the initial design stage (unit *1*), it is possible (if necessary), to conduct additional experimental studies for models of individual cooling channels (unit *2*). Channel models are manufactured using SLM-technology and fully comply with the geometry of the internal cavity of the investigated section of the blade cooling path. The obtained experimental results are used by the designer for a hydraulic (unit *3*) and thermal modeling (unit *6*) of the blade. This approach allows for the improvement of the quality of the created models [6–8].

Once a decision on the compliance of the developed blade with the specified criteria (the relative air consumption for cooling the blades and the safety margins in the design sections of the feather (unit *14*)) has been taken, that too, prior to the preparation of the design documentation, experimental studies can be performed to verify the hydraulic and thermal models. In accordance with the proposed methodology, a prototype blade is manufactured for thermal and hydraulic tests (unit *15*). A three-dimensional geometric model of the blade obtained based on the design results is used for the manufacture of a prototype using SLM technology. The prototype is made on a 1:1 scale. Depending on the method and program of testing, the prototype of the blade can be manufactured with the necessary elements, such as flanges for connecting the blade to the working section of the test bench, outlet manifolds, and etc. Moreover, it does not require the prototype preparation. The test results obtained in unit *17* and the calculation results (unit *16*) are compared in unit *18* to determine the efficacy of the thermal and hydraulic models.

As for the criteria for assessing the hydraulic model efficacy, it is reasonable to select parameters that are reliably measured in the process of the blade testing. As for such criteria, it is advisable to use: the total air flow through the blade G_a measured at isothermal conditions (the cooling air temperatureis equal to the blade temperature $T_a = T_b$–a cold air purge); the total air flow measured at heating conditions of G_{a_h} (the cooling air temperature is below the blade temperature$T_a < T_b$ – a hot air purge); static pressure value at the control points of the cooling path; the total pressure diagram throughout the height of the trailing edge slot. The measurement of the total pressure distribution throughout the height of the trailing edge slot can be used as an additional parameter to test the efficacy of the hydraulic model. The obtained distribution of total pressure is compared with the flow diagram at the branches simulating the trailing edge slot.

Verification of a thermal model of blades with convective cooling systems is based on a comparison of the distribution of the heat flux density qcal calculated from a verified thermal-hydraulic model, and the heat flux density qzinc determined from the test results of a blade prototype in a liquid metal thermostat [9–11]. The comparison of heat fluxes takes into account all the parameters of the thermal-hydraulic model from the side of the cooling medium affecting the blade thermal state.

In order to evaluate the permissible deviation of the parameter $(q_z/q_c)_p$ (1), which determines the thermal model efficacy, an analytical relationship was obtained that associates the blade cooling depth Θ under the gas flow conditions and the deviations of the heat flux density from the calculated value under the model conditions of the liquid- metal thermostat [12].

$$\left(\frac{q_z}{q_c}\right)_p = \frac{1}{\Theta \pm \Delta\Theta} \Big/ \frac{1}{\Theta - 1}, \Theta = \frac{T_g^* - T_b}{T_g^* - T_a^*}, \quad (1)$$

where T_g^* represents gas flow temperature, T_b represents temperature of the blade outside surface, T_a^* represents cooling air temperature, $\Delta\Theta$ represents cooling depth permissible deviation.

Having obtained the calculated value Θ for this feather section and the deviation $\Delta\Theta$, the permissible deviation $(q_z/q_c)_p$ can be determined. If the obtained value of the parameter $(q_z/q_c)_p$, then we can assume that the thermal model adequately describes the processes of internal heat exchange in this feather section.

3. EXPERIMENTAL TESTING OF THE VERIFICATION METHODOLOGY

In accordance with the proposed design methodology, an advanced verification of the thermal and hydraulic model for the turbine first-stage blade of the engine AL31-STN, developed by the design bureau named after A. Lyulka, was performed. The blade had a convective cooling system. The exit of the cooling air from the blade into the flow part of the turbine is carried out through the slot of the trailing edge and through three holes in the tip surface.

The selection of material for the manufacture of a prototype blade using SLM-technology was carried out according to the price-quality criterion. Iron-based (Fe) powder material was selected. The chemical composition also included Cr-14–15.5%, Ni-3.5–5.5%, Cu-2.4–4.5%; the remaining elements –constitute less than 1%. Powder size d = 5 μm. Previously, prototypes were made in advance using machine SLM 280HL in order to determine the surface roughness and thermal conductivity ratio λ of the obtained material. The sample maximum roughness: R_a =5.37 μm, R_z = 25.67 μm (as per GOST R 2789-73). It was established experimentally that in the temperature range from 373 to 723K, thermal conductivity varies from 12 to 19 W/(m·K). The experimental determination error was ±6%.

A three-dimensional geometric model was developed, according to which three identical prototype blades were manufactured. The prototype was designed and manufactured with manifolds for the supply and removal of cooling air required for testing in a liquid-metal thermostat. After testing, a prototype was cut on an EDM machine, followed by measuring the dimensions of the internal cavity elements. The results showed that the geometry of the cooling channels corresponds to the size of the geometric model. The photo of the prototype is shown in Figure 2.

The hydraulic model of the blade was verified by the criterion of the total flow rate of cooling air. Cooling air flow rates through the internal cavity of three prototypes (B1, B2 and B3) were measured for isothermal purge conditions – the wall temperature was equal to the purged air temperature. The test results are presented in Figure 3.

Figure 2 Prototype blades made by SLM-technology for testing in a liquid-metal thermostat

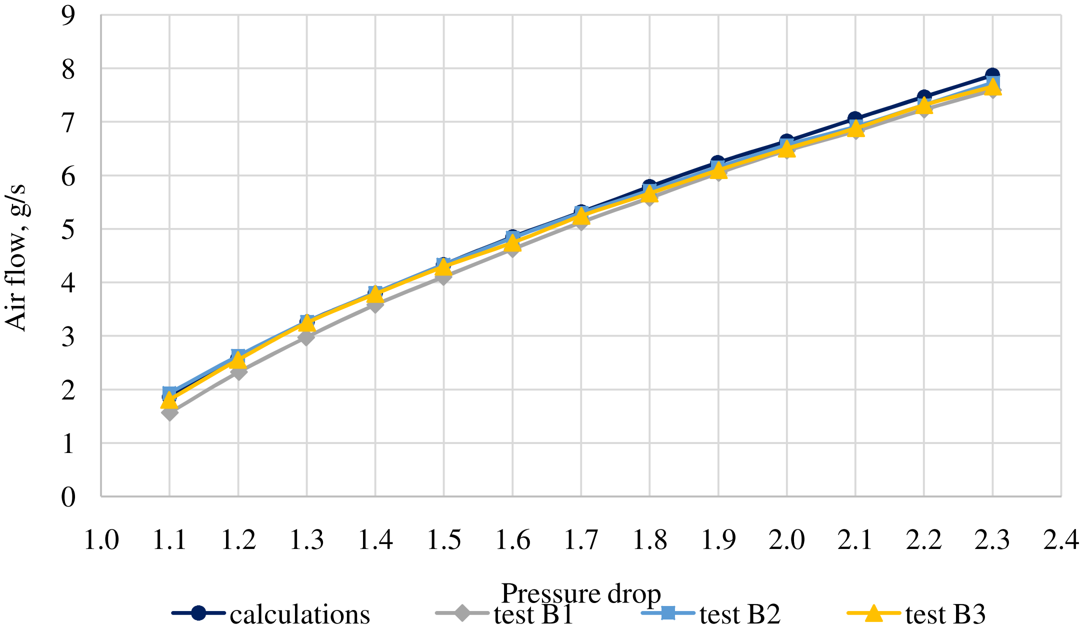

Figure 3 Flow characteristics of the prototypes B1, B2 and B3 obtained with isothermal purges

The graph shows the dependence of the physical air flow through the internal cavity of the prototypes, depending on the pressure drop P/P_0, where P – inlet pressure at the internal cavity, P_0 – atmosphere pressure.The flow characteristics of all three prototypes almost coincide. There are insignificant differences in flow rates (no more than 3%) at small pressure drops. The graph also shows the calculated dependence obtained using the hydraulic calculation model for experimental conditions, obtained taking into account the measured channel roughness. As we can see, the experimental and calculated flow characteristics almost coincide; the difference does not exceed 3%. This allows us to conclude about the adequacy of the calculated hydraulic model for the parameter of the total air flow and the stability of the technological process for manufacturing of prototypes.

When tested in a liquid-metal thermostat, prototypes were purged at the same pressure drops P/P_0 = 1.49, 1.68, 1.78, 1.97, and 2.37. Five experiments were carried out in each mode. A comparison of calculated values of air temperature at the outlet of the trailing edge slot with values measured in experiments showed that the difference does not exceed 9%. This allows us to conclude that the thermal model accurately calculates the total heating of the air in the channels.

The distribution of the density of heat fluxes q_z along the outer surface perimeter was determined for five feather cross-sections according to the results of the experiments. In all sections, there is almost complete coincidence of q values along the entire section length between the models, the same coincidence of q values can be seen for all other studied sections. This allowed using the average value of the thermal flux obtained from the three prototypes for verification of the thermal-hydraulic model.

Figure 4 shows a graph of the averaged values of the density of heat fluxes along the outer surface in the studied sections for the working pressure drop P/P_0 = 1.68. The horizontal axis represents the length along the outer perimeter of the section, the sign (–) refers to the suction side, 0 corresponds to the critical point of the leading edge.

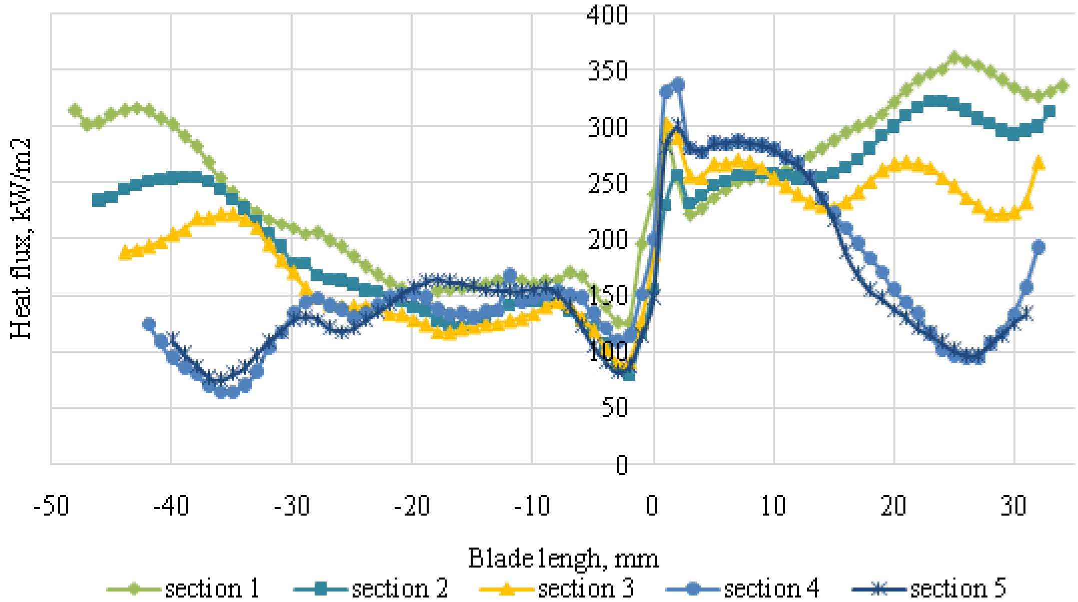

Figure 4 The heat flux density in the feather cross sections obtained by averagingover three prototypes, P/P_0 = 1.68

Using a verified thermal model of the blade, a calculation of the heat flux density distribution along the perimeter in five sections throughout the height was made for two pressure drops of 1.48 and 1.97 for the test conditions in the liquid metal thermostat. The boundary conditions of the first kind were given on the feather outer surface – the wall temperature was equal to the crystallization temperature of zinc $T_b = T_{cr}$ = 692.4. The calculated values q_c were compared with q_z, obtained from the test results in a liquid-metal thermostat.

Comparison of parameter q_z/q_c obtained at two pressure drops showed that the difference in all sections does not exceed 5%. This allows us to conclude that the exponent signs in the criteria equations of the thermal model taken equal to 0.8 correctly describe the features of heat transfer in the channels.

Since in some sections of the feather $q_z/q_c>(q_z/q_c)_p$, it was decided to refine the blade thermal model according to the test results in a liquid-metal thermostat, in accordance with the developed methodology.

The results of the calculations of air flow distribution for experimental conditions were used in order to determine the local heat transfer coefficients. The error in determining the heat transfer coefficients by the calorimetric study in a liquid-metal thermostat did not exceed ±10%. The values of the Nusselt criterion Nu_i were calculated in the *i*-th points of the internal surface of the cooling channels using the obtained values of heat transfer coefficients for each test mode. Further, dependencies $Nu_i = A_iRe_i^{0.8}$ were constructed using the least squares method. The coefficients of heat transfer intensification were also calculated by the dependence $Nu_i/0{,}018 \cdot Re_i^{0.8}$.

Comparison of the flow characteristics of the blade and the prototype when purging in the zinc melt showed that the blade capacity is higher than that of the prototype. However, the maximum flow difference does not exceed 5% at maximum pressure drops. This difference is due to the smoother surface of the cooling channels of the cast blade.

Testing of the blade and its prototype were carried out in two modes at equal cooling air flow and inlet temperature to the feather. The first mode corresponded to the flow rate of cooling air of 3 g/s, the second mode – 6 g/s. This allowed us to compare the field of heat fluxes of the prototype and the blade at Re = idem.

Figure 5 shows a comparison of the densities of heat fluxes obtained by testing the cast blade and the prototype with the same cooling air flow.

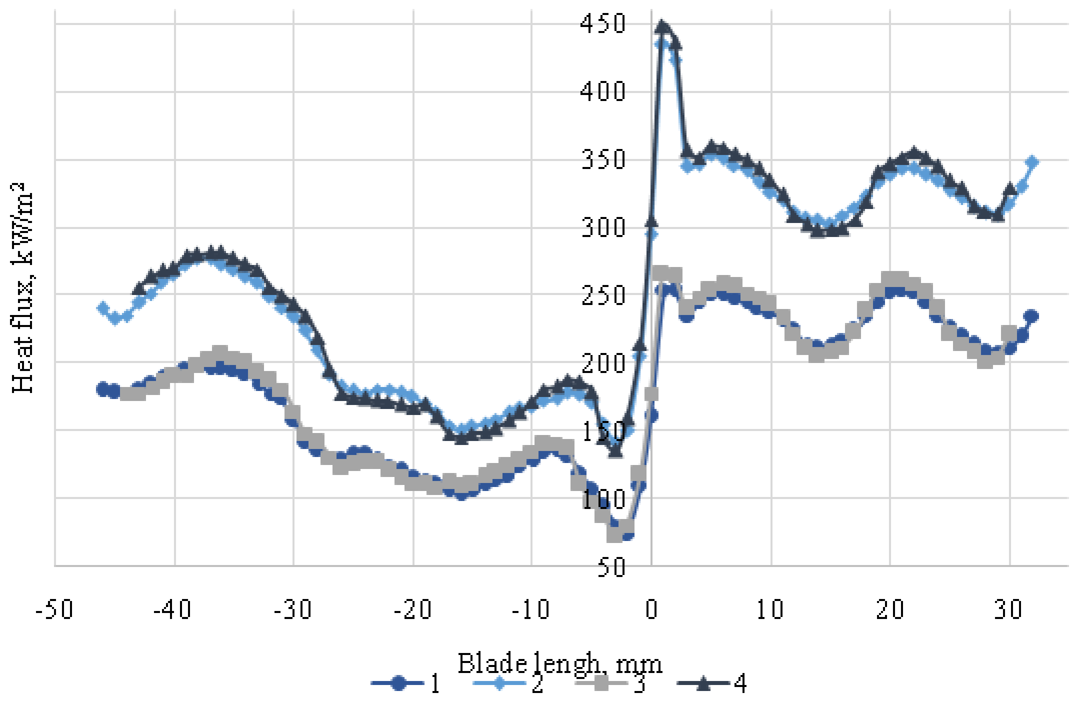

Figure 5 Comparison of the density of heat fluxes in the section 3:

1, 3 – G_a = 3 g/s; 2, 4 – G_a = 6 g/s; 1, 3 – prototype; 2, 4 – blade

As can be seen from the graphs, the heat flux values, obtained from the prototype and the blade, almost coincide, the difference in all parts of the section surface does not exceed 5%. Large differences are observed in the section of the trailing edge slot. This is due to the presence of a blade collector for air exhaust connected to the blade by soldering. Herein, the trailing edge of the blade is embedded into the collector.

The good coincidence of the heat flux density in the control sections confirmed the possibility of verifying the thermal and hydraulic model for the blade cooling system on its prototype manufactured using SLM-technology.

4. CONCLUSIONS

The design methodology for cooled gas turbine blades has been improved, a distinctive feature of which is the experimental verification of a thermal and hydraulic model in the early design stages by means of testing a prototype blade made using SLM-technology. The methodology allows us to obtain an experimentally tested version of the blade and eliminate its experimental refinement after the start of serial production.

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