Rational Settings of a Numerical Model to Simulate the Working Process of an Axial-Film-Cooled Turbine Blade

Andrei Volkov, Vasilii Zubanov, Valery Matveev, Oleg Baturin, and Grigorii Popov
Samara National Research University, Samara, Russia
oleg.v.baturin@gmail.com

Abstract—**Today, film cooling is widely used in axial turbines of aircraft gas turbine engines. Typically, a turbine blade has a large number of holes, and finding their optimal configuration and location is a difficult task, where it is necessary to search for the optimal combination of a huge number of factors depending on many conditions. For this reason, the experimental study of film cooling is difficult. Here modern methods of numerical simulation come to the aid of the researcher. In this paper, a study is carried out aimed at finding the optimal settings for numerical models of the working process in film-cooled turbines using conjugated 3D models of the working process, which take into account the flow in the blade and internal channels, as well as the thermal state of the blades. The stationary nozzle blades of the first stage of a high-temperature turbine, for which there are experimental data, was taken as the object of study. As a result of the research, optimal settings of numerical models were found, which allow simulating the workflow in cooled film-cooled turbines accurately and at a reduced cost. The use of these recommendations will make it possible to obtain results close to the real ones while reducing the required time and computational costs.**

Index Terms—**axial turbine, cooling, nozzle blade, film cooling, numerical modelling, verification**

I. INTRODUCTION

The temperature of the gases at the turbine inlet of modern gas turbine engines can reach up to 1800-2000K. This temperature exceeds the melting point of the construction material. For these reasons, the blades and other components have to be cooled intensively by blowing air, the temperature of which is considerably lower than the temperature of the gases. The coolant exits into the flow path and mixes with the main flow, which significantly affects both the gas dynamic processes and the heat exchange between the blades and the flow [1]. Therefore, when modelling the turbine processes, it is important to consider both the interaction of the main flow with the coolant and the heat release into the blade body. This will significantly improve the accuracy of the simulation and allow to assess not only the turbine efficiency, but also the thermal and stress state of the blades simultaneously. Modern computational fluid dynamics (CFD) simulation programs make it possible to carry out such simulation and in available scientific publications one can find a lot of examples of coupled simulation of turbine processes [2-9, 11-15]. In these tasks, numerical process models have one thing in common. They have a large number of elements (due to the modelling of flow, solid body and cooling channels) and consequently a large computational time and demands on the computational resources and skills of the calculator. However, this results in high validity of the outcomes. It is achieved because this mathematical model takes the geometry of the real object into account as much as possible. The dimensions of all elements are matched, the loss of accuracy from the data transfer is minimised.

However, after analysing the available publications, the authors were unable to find generally accepted recommendations for reliable modelling of cooled turbines with minimal use of computer resources and time. For these reasons, the aim of this paper is to find rational recommendations for the choice of settings of coupled numerical models of the cooled turbine working process, which will allow to obtain results close to the real flow and thermal state parameters, but requiring a reasonable solution time.

The study decided to focus only on those computational model settings (turbulence models and finite volume grid parameters) that can be changed by a practicing engineer who is not sufficiently qualified to make changes to algorithms and software codes.

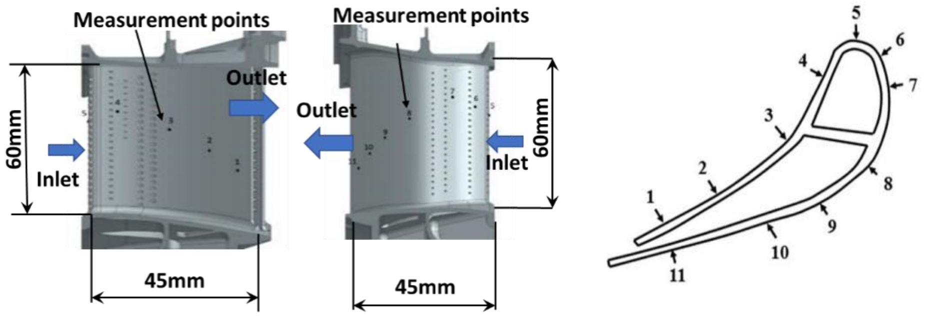
In this paper, the authors focused on modelling the blades with a film cooling system.

II. NUMERICAL MODEL OF A NOZZLE BLADE WITH FILM COOLING

The research was carried out on the example of an annular fixed nozzle blade of the high pressure turbine (HPT) first stage of one of Kuznetsov engines (Fig. 1). This blade has a large number of film cooling holes near the leading edge. The air is supplied to them through the deflectors. This blade has 2 coolant inlet cavities.

Manuscript received October 1, 2022; revised November 11, 2022.

doi: 10.18178/ijmerr.11.12.901-907



(a) (b) (c)

Figure 1. View of Kuznetsov blade from pressure side (a) and suction side (b) with thermocouple arrangement diagram in experiment (c).

For this nozzle blade (NB) of the first turbine stage, the results of its thermal condition evaluation are available on the model bench. Blade height – 0.06m, width -0.045m. The NB sector was purged with hot air with an inlet temperature of 1120K and overpressure of 70kPa. The static pressure at the NB sector outlet corresponded to atmospheric pressure. The Mach number at the NB outlet was equal to 0.92, Reynolds criterion $3.5{\cdot}10^6$. Cooling air temperature at the inlet to the front cavity of the blade was 650K, overpressure 74kPa. In the experiment, the rear cavity of the coolant was closed, and cold air was blown out only near the leading edge.

During the tests, the surface temperatures of the middle blades of the three NB units were measured at 11 points, as shown in Fig. 1. The temperature of the blade surface was measured by thermocouples on three different blades in the same places. All thermocouples, except for those that failed, showed close results. The temperature difference was no more than 1%. During the tests, calibrated measuring instruments were used and all metrological requirements for such measurements were met. Since the information was provided by PJSC Kuznetsov, we have exactly the data that is given in the test report. Unfortunately, they are not available in the public domain. We are not aware of the presence of other similar experimental data in open publications.

A 3D conjugate thermal and gas dynamic calculation was carried out in the work.

The main goal of the work is to find the best settings of numerical models for accurate simulation of film cooling with minimal computational resources. For this reason, the study is aimed specifically at the issues of heat transfer and aerodynamics of blade and internal channels. The study does not address the issues of strength and resource of the blade airfoil. Strength studies were also not carried out due to the fact that the flow in a stationary nozzle blade is being investigated, for which the strength issues are not as acute as for the working blade, but it is important to provide thermal protection. In addition, a model problem of heat transfer in a blade with disabled convective cooling was studied. Those. The cooling system of the considered blade is far from real and its strength calculation will not give adequate results.

The non-stationarity of the flow is not taken into account here due to the fact that for a given blade it comes from the combustion chamber and is of a complex nature.

A numerical model of the blade working process was created in the Ansys CFX software package (Fig. 2) and included the main flow area, the front cavity of the coolant and the blade body.

The initial grid model of the NB process consisted of 30.3 million tetrahedral elements with prismatic wall layers (Fig. 3).

The following settings were used to build the mesh model [10], which were derived from experience in building mesh models of uncooled turbine blades:

– maximum global dimension – 0.002m;

– near wall layer of the coolant cavity elements - 20 layers with first element height of 1 µm and growth coefficient of 1.2;

– near-wall layer of the blade passage - 40 layers with first element height of 1 µm and growth coefficient of 1.2 (calculated height of the last element of the near-wall layer is 0.00147 m, total thickness of the near-wall layer is up to 0.008m).

The value of the dimensionless parameter y+ for the calculated model does not exceed 0.4 over the entire external surface of the blade.

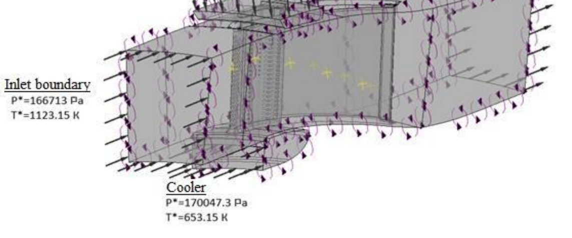


Figure 2. Numerical model geometry for working process calculation taking into account film cooling of the Kuznetsov nozzle blade.

Figure 3. Basic grid model appearance of the Kuznetsov NB with internal cavity at the leading edge.

The following boundary conditions have been adopted for the calculation (Fig. 2):

– the working fluid is an ideal gas, with temperature-dependent values of heat capacity and viscosity; – turbulence model - SST;

– at the inlet boundary for the main flow in the turbine, the following boundary conditions p*=166713 Pa, T*=1123 K were set;

– at the outlet boundary - p=98067 Pa;

– boundary conditions for the coolant entering the cooling system channels p*=70047 Pa, T*=653 K

Also, at the inlet boundary of the NB and the inlet boundaries of the coolant a turbulence intensity of 5% was set.

As a result of the base model calculation, the temperature values at the locations where the thermocouples were located in the experiment (points on the profile surface in Fig. 4) were determined. For the obtained temperature values the film cooling efficiency coefficient was calculated by the formula:

$$\theta = \frac{T^*{}_g - T_{blade}}{T_g - T^*{}_{colant}},$$

where $T^*{}_g$ is the main flow temperature at the NB inlet;

T_{blade} is flow temperature at the blade surface;

$T^*{}_{colant}$ is coolant temperature.

Fig. 4 compares the calculated distribution of the film cooling efficiency around the blade perimeter with the experimental data.

Analysis of the data in Fig. 4 shows that:

1) the calculation results differ qualitatively and quantitatively from the experimental data. Qualitative coincidence is observed only in points 8 ... 11, located on the suction side of the profile;

2) significant discrepancy with the experimental data is observed at the pressure side in the throat area (points 1-2), which requires further research;

3) the discrepancy at points 4 ... 6 on the leading edge is explained by the presence in this area of holes for the coolant blow-out, which disturb the flow, thereby making it difficult to determine the correct temperature values;

4) the calculation results coincide with the experimental data only at points 3, 7, which are a short distance away from the coolant blowout points.

The difference between calculated and experimental values of cooling efficiency factor reaches 25%.

Analysis of results of basic calculation shows that application of settings obtained from open sources (especially for uncooled turbines) does not lead to qualitative results when modelling operation process of cooled turbines with coupled heat exchange. As it was mentioned earlier there is no information in open publications about settings of calculation models for investigation of coupled processes in cooled turbines with film cooling. For this reason, it seems topical to conduct research aimed at finding such recommendations.

III. FILM COOLING SIMULATION RESULTS

In order to investigate the influence of the parameter y+ on the results of numerical simulation of the coupled working process in a film-cooled axial turbine, several numerical models were created. The value of parameter y+ in them varied from 0.1 to 2 over the entire surface of the blade. The results are shown in Fig. 5. It can be seen that the change of parameter y+ in the considered range does not significantly influence the results of calculation of cooling efficiency.

Several numerical models have been created to investigate the influence of the number of elements in the near-wall layer of the finite volume grid on the numerical simulation results of the coupled working process in an axial-film-cooled turbine. The number of elements in the near-wall layer varied from 0 to 40. The value of parameter y+ in all models was equal to 0.4. The results are shown in Fig. 6. The following conclusions can be drawn from comparison of the results of these calculations with each other and with experimental data.

1. Increase of layer number in near wall layer over 30 does not lead to significant change of calculated efficiency values for points 1-3, 5, 7-11. Probably, for the number of layers 30 and more with the chosen grid model parameters grid convergence is established, i.e. increase of number of elements in the near wall layer does not lead to significant change of calculation results. The exceptions are points 4 and 6, located in the area of the hole rows.

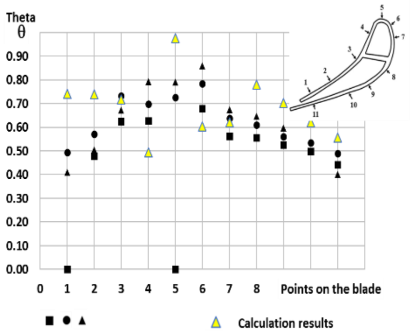


Figure 4. Comparison of results of film cooling efficiency calculation with experimental data.

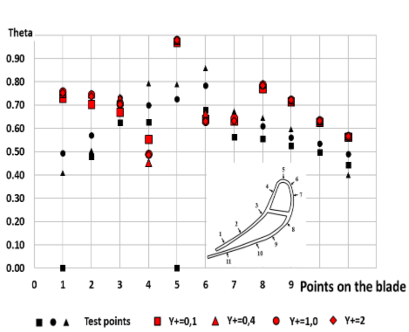


Figure 5. Comparison of the calculation results of the film cooling efficiency coefficient at different y+.

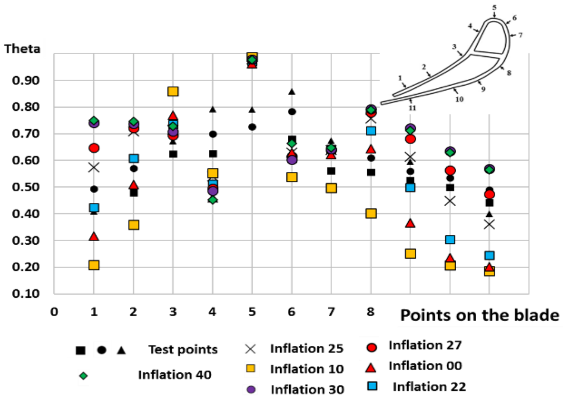


Figure 6. Results of calculating the efficiency factor for film cooling with different numbers of layers in the near-wall layer.

2. An increase in the number of layers from 10 to 30 leads to a significant change in the calculation results. The resulting effect can be explained by the different resolution of the mesh model for the areas of both coolant interaction with the main flow and coolant spreading. So, for example, when the number of elements in the near-wall layer is 10 the thickness of the near-wall layer is 0.0003 m, there is a blurring of the film curtain which leads to a high temperature on the blade surface.

3. A comparison of the total temperature distribution in the cross section behind the coolant discharge holes is shown in Fig. 7 and 8.

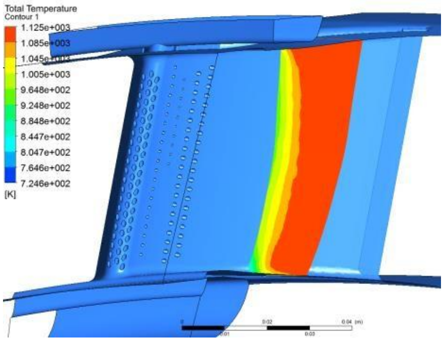


Figure 7. Distribution of braking flow temperature in the cross section behind the blow-out holes for the number of near wall layers: 10.

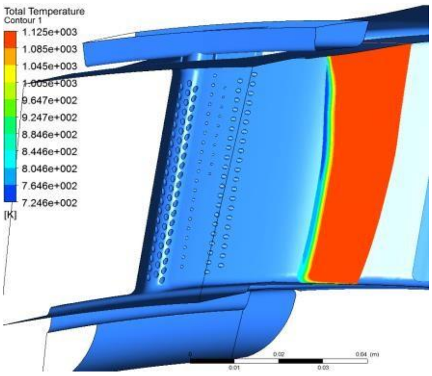


Figure 8. Distribution of braking flow temperature in the cross section behind the blow-out holes for the number of near wall layers: 40.

From Figs. 7 and 8 it can be seen that the pattern of distribution of braking flow temperature is qualitatively and quantitatively different for the considered variants. For the model with 10 near-wall layers the area of low flow temperature caused by coolant blowing out occupies a large part of the main flow, while for the model with 40 near-wall layers the coolant is localized near the blade wall. For the model with number of near-wall layers 40 a zone of low temperatures is observed in the area from the middle to the blade periphery, which is explained by coolant blowing out from the third row, which holes are located from the middle height to the blade periphery.

To quantify the results obtained, an absolute error analysis was performed for all points - qMSE (Fig. 9). To do this, first calculate the variance σ^2 (mean square of variance) using the following formula:

$$\sigma^2(\theta) = MSE(\theta) = \frac{1}{n-m}\sum_{i=1}^{n}(\theta_{\exp i} - \theta_i)^2,$$

i=1 where n is the number of points of the characteristic (calculated or experimental) lying within the range

m - number of terms in the regression equation (m=0).

The average value of cooling efficiency (both obtained in the experiment and by numerical model) was found according to the formula:

$$\theta_{exp\ ave} = \frac{1}{n}\sum_{i=1}^{n}\theta_{\exp i}$$

The so-called mean residual model qMSE, which characterises the mean deviation of the calculated data from the experimental data or the integral (over the whole characteristic) absolute error in determining the efficiency factor, was calculated according to the formula:

$$qMSE(\theta)\sqrt{MSE(\theta)}.$$

Fig. 9 shows that changing the number of layers in the near-wall layer from 10 to 40 has an effect on the integral error value of the film cooling coefficient, it changes by about 9%. The largest absolute error is obtained for the model with 10 layers and the smallest absolute error for the model with 25 layers. As the number of layers increases from 30 to 40, the absolute error of the film efficiency remains practically unchanged.

In order to investigate the influence of the distribution of elements in the near-wall layer of the finite volume grid on the numerical simulation results of the coupled working process in an axial-film-cooled turbine, 7 numerical models have been created. All of them had 40 near-wall layer elements but different near-wall layer growth coefficients (ratio of thicknesses of neighbouring elements when moving towards the wall). The growth coefficient for the models considered varied from 1.05 to 1.5. The calculation results are shown in the Fig. 10.

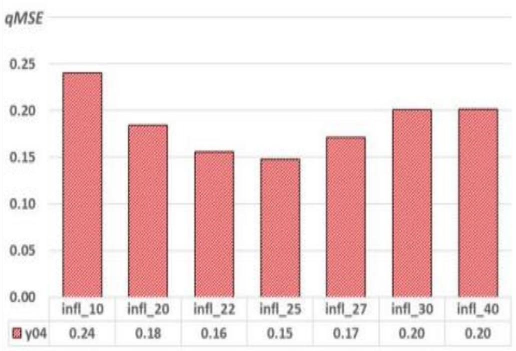


Figure 9. Comparison of absolute errors in determining the efficiency factor of film cooling.

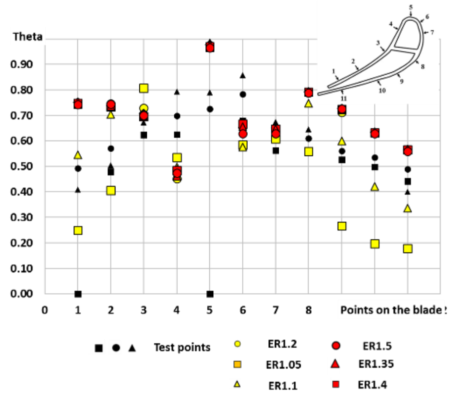


Figure 10. Calculation results for film cooling efficiency at different values of the growth coefficient in the near-wall layer.

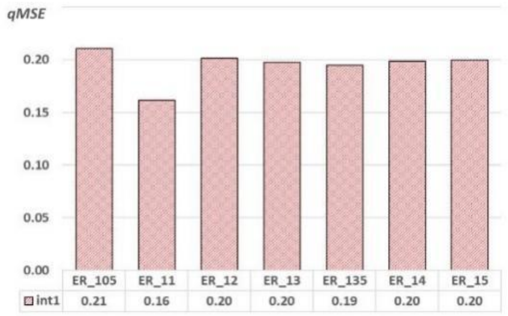


Figure 11. Comparison of absolute errors in film cooling efficiency coefficient.

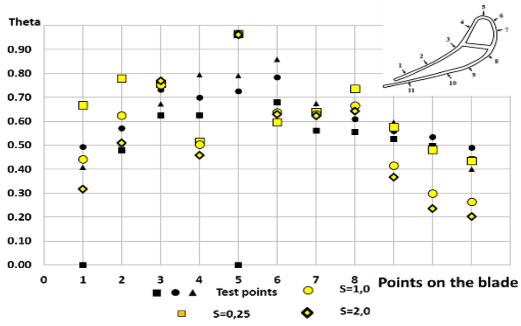


Figure 12. Results of film cooling efficiency calculation.

The following conclusions can be drawn from a comparison of the results of the calculations:

1. An increase in the growth coefficient in the near-wall layer greater than 1.2 does not result in a significant shift in the cooling efficiency for all the test points. Consequently, the calculation results are more significantly influenced by the thickness of the near-wall layer.

2. An increase in the growth coefficient from 1.05 to 1.2 leads to a significant change in the calculation results. The obtained effect can be explained by the difference in the resolution of the grid model for the areas of both coolant main flow interaction and coolant spreading.

To quantify the results obtained, an absolute error analysis was performed for all points - qMSE (Fig. 11).

Fig. 11 shows that changing the growth coefficient in the near-wall layer from 1.05 to 1.5 has an effect on the integral error value of the film efficiency, it changes approximately by 4%. The largest absolute error is obtained for the model with a growth factor of 1.1, the maximum relative error for the model with a growth factor of 1.105. Models with a growth factor of 1.2 and above have close values of the absolute error of the film efficiency.

In order to investigate the influence of the size of the first element in the near-wall layer of the finite volume grid on the numerical simulation results of the coupled working process in an axial-film-cooled turbine, 3 numerical models were created. They had the dimensions of the first element 0.25mm, 1mm, 2mm. Their numerical results are shown in Fig. 12.

The following conclusions can be drawn from an analysis of the results of the calculations:

1. Changing the size of the mesh element on the blade surface has a significant effect on the calculated coefficient of film cooling efficiency θ. Increasing the size of the element leads to a decrease in the calculated value of the film cooling efficiency. This is explained by the rarefaction of the near-wall layer of the mesh and, as a consequence, the blurring of the boundary layer, which leads to an increase in temperature and a decrease in the coefficient of efficiency of film cooling.

2. In the area of a leading edge there is practically no change which is explained by the peculiarity of mesh building: in the area of a leading edge the profile geometry of investigated grid has high value of curvature, therefore the given value of the element size on a blade surface does not lead to mesh change in the area of a leading edge.

To quantify the results obtained, an absolute error analysis was performed for all points - qMSE (Fig. 13).

It can be seen that the change in size of the first element in the range under consideration has a minimum in absolute error. This is due to the different effect of the element size on the pressure and suction sides of the profile.

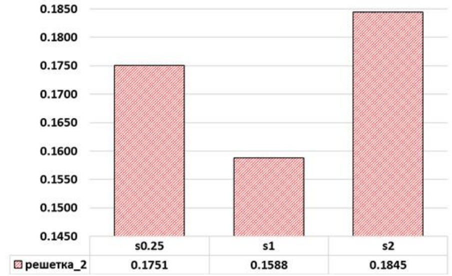


Figure 13. Comparison of absolute errors.

IV. CONCLUSIONS

In a summary of the results of a series of studies on the influence of the grid model settings of a cooled nozzle blade with film cooling on the calculation results, the following results were obtained:

1. Changing the number of layers while maintaining the near wall layer thickness has no effect on the calculation results when the number of layers is greater than 30. The recommended number of wall layers is at least 20 with a growth factor of at least 1.2.

2. Changing the size of the near-wall element on the blade has a significant effect on the results of the film cooling coefficient calculation. Increasing the size of the element leads to a decrease in the calculated coefficient of film cooling efficiency.

3. It is found that the influence of the investigated parameters on the obtained values of film cooling efficiency coefficient θ pressure and suction sides of profiles is different. On a suction side it is recommended to reduce the size of the element on the surface by 4 times in comparison with the size of the element on the surface of a pressure side.

Recommendations for adjustment of numerical models of working process of turbine blades with film cooling in three-dimensional statement are formed:

- y+ value not exceeding 2;
- number of cells in the near wall layer: at least 20;
- cell growth factor in the near wall layer: not less than 1.2.

The use of these recommendations will make it possible to obtain results close to the real ones while reducing time and computational costs.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

This work was carried out under the general supervision of Professor Valery Matveev, a specialist in the field of turbomachines and the working process of gas turbine engines. The main driving force behind the work was Andrey Volkov. He created numerical models, performed calculations and analyzed data. Vasiliy Zubanov provided a great deal of assistance in creating numerical models, who performed most of their construction and debugging. Grigory Popov, relying on his experience in modeling uncooled turbines, provided significant assistance in developing the research algorithm. Baturin Oleg was involved in the analysis and synthesis of the results of the study, and he is also the final author of this text.

FUNDING

The research was supported by the Ministry of Science and Higher Education of the Russian Federation (Grant № 07772020-0015).

NOMENCLATURE

C3X	investigated blade;
GTE	gas turbine engine;
HTC	heat transfer coefficient;
Mark II	investigated blade;
NB	nozzle blade;
PJSC	Public joint-stock company.

REFERENCES

[1] M. P. Boyce, *Gas Turbine Engineering Handbook*, 10.1016/B978-0-7506-7846-9.X5000-7, 2006.

[2] K. S. Ho, J. S. Liu, T. Elliott, and B. Aguilar, "Conjugate heat transfer analysis for gas turbine film-cooled blade," in *Proc. the ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition*, vol. 5A: Heat Transfer. Seoul, V05AT10A003. ASME, GT2016-56688, 2016.

[3] Z. Ke and W. Jian-Hua, "Coupled heat transfer simulations of pulsed film cooling on an entire turbine vane," *Applied Thermal Engineering*, vol. 109, pp. 600-609, 2016.

[4] M. Insinna, D. Griffini, S. Salvadori, and F. Martelli, "Coupled heat transfer analysis of a film cooled highpressure turbine vane under realistic combustor exit flow conditions," in *Proc. the ASME Turbo Expo 2014: Turbine Technical Conference and Exposition*, vol. 5A: Heat Transfer. V05AT11A007. ASME, GT2014-25280, 2014.

[5] W. Wróblewski, "Numerical evaluation of the blade cooling for the supercritical steam turbine," *Applied Thermal Engineering*, vol. 51, pp. 953-962, 2013.

[6] A. Bonini, A. Andreini, C. Carcasci, B. Facchini, A. Ciani, and L. Innocenti, "Coupled heat transfer calculations on GT rotor blade for industrial applications: Part I—equivalent internal fluid network setup and procedure description," in *Proc. the ASME Turbo Expo 2012: Turbine Technical Conference and Exposition*, vol. 4: Heat Transfer, Parts A and B, ASME, GT2012-69846, 669-679, 2012.

[7] I. V. Shevchenko, N. Rogalev, A. Rogalev, A. Vegera, N. Bychkov, "Verification of thermal models of internally cooled gas turbine blades," *International Journal of Rotating Machinery*, vol. 110, 2018.

[8] D. Florent, A. Corpron, L. Pons, V. Moureau, F. Nicoud, and N. Poinsot, "Development and assessment of a coupled strategy for coupled heat transfer with large Eddy simulation: Application to a cooled turbine blade," *International Journal of Heat and Fluid Flow*, vol. 30, pp. 1129-1141, 2009.

[9] L. D. Hylton, M. S. Mihelc, E. R. Turner, D. A. Nealy, NASA Technical Report: NASA-CR-168015, 1983.

[10] G. Popov, V. Matveev, O. Baturin, Y. Novikova, and A. Volkov, "Selection of parameters for Blade-Toblade finite-volume mesh for CFD simulation of axial turbines," in *Proc. MATEC Web of Conferences*, vol. 220, 2018.

[11] C. C. Easterby, J. D. Moore, and D. G. Bogard, "CFD evaluation of internal flow effects on turbine blade leading-edge film cooling with shaped hole geometries," in *Proc. the ASME Turbo Expo 2021: Turbomachinery Technical Conference and Exposition*, vol. 5A: Heat Transfer—Combustors*; Film Cooling*, Virtual, Online. June 7–11, 2021. V05AT12A023. ASME.

[12] H. Du, D. Xie, W. Chen, Z. Mei, and J. Zhang, "Overall cooling effectiveness on a gas turbine vane with swirl-film cooling," in *Proc. the ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition*. *Volume 5A: Heat Transfer*. Phoenix, Arizona, USA. June 17–21, 2019. V05AT10A006. ASME.

[13] L. Andrei, L. Innocenti, A. Andreini, B. Facchini, and L. Winchler, "Film cooling modeling for gas turbine nozzles and blades: Validation and application," *ASME. J. Turbomach*. vol. 139, no. 1, January 2017.

[14] J. Zhang, S. Zhang, C. Wang, et al. *Recent Advances in Film Cooling Enhancement: A Review Chin J Aeronaut*, vol. 33, no. 4, pp. 1119-1136, 2020.

[15] H. Zhang, Y. F. Li, Z. Y. Chen, et al. "Multi-fidelity model based optimization of shaped film cooling hole and experimental validation," *Int J Heat Mass Transf*, vol. 132, pp. 118-129, 2019.

Andrei Volkov is a PhD student. He is the employee of the Department of the Theory of Aircraft Engines of the Samara National Research University named after S.P. Koroleva (34, Moskovskoye shosse, Samara, 443086, Russia). Also the member of the same scientific group associated with the design and study of the working process of various types of turbomachines, CFD modeling and studying the working processes of gas turbine engines.

Grigory Popov is a PhD , associate professor Department of Engine Theory. He is the employee of the Department of the Theory of Aircraft Engines of the Samara National Research University named after S.P. Koroleva (34, Moskovskoye shosse, Samara, 443086, Russia). Also the member of the same scientific group associated with the design and study of the working process of various types of turbomachines, CFD modeling and studying the working processes of gas turbine engines.

Vasily Zubanov is a PhD , associate professor Department of Engine Theory. He is the employee of the Department of the Theory of Aircraft Engines of the Samara National Research University named after S.P. Koroleva (34, Moskovskoye shosse, Samara, 443086, Russia). Also the member of the same scientific group associated with the design and study of the working process of various types of turbomachines, CFD modeling and studying the working processes of gas turbine engines.

Valeriy Matveev is the professor of Department of Engine Theory. He is the employee of the Department of the Theory of Aircraft Engines of the Samara National Research University named after S.P. Koroleva (34, Moskovskoye shosse, Samara, 443086, Russia). Also the member of the same scientific group associated with the design and study of the working process of various types of turbomachines, CFD modeling and studying the working processes of gas turbine engines.

Oleg Baturin is PhD , associate professor Department of Engine Theory. He is the employee of the Department of the Theory of Aircraft Engines of the Samara National Research University named after S.P. Koroleva (34, Moskovskoye shosse, Samara, 443086, Russia). Also the member of the same scientific group associated with the design and study of the working process of various types of turbomachines, CFD modeling and studying the working processes of gas turbine engines.