Finding Recommendations for Selecting Numerical Model Settings for Efficient Simulation of the Working Process of an Axial Turbine Blade with Convective Cooling

Andrei Volkov, Valery Matveev, Oleg Baturin, Ivan Kudryashov, and Sergei Melnikov

Abstract At present, when modeling the working process of axial cooled turbines, models have been used that include the flow area in the main flow channels, the blade body and the internal channels of the cooling system. It requires significant resources for calculation and high qualification of the engineer. An attempt to simplify the model reduces the reliability of the results obtained. Unfortunately, the available technical publications do not contain recommendations for setting up such calculation models. The present paper presents the results of a study aimed at finding optimal settings for numerical models that allow accurate and low-cost modeling of the coupled workflow in cooled turbines with convective cooling. As a result, practical recommendations were obtained on the choice of mesh parameters and turbulence models for such problems. Recommendations have been formulated for setting up numerical models of the working process of turbine blades with convective cooling in a two-dimensional formula.

Keywords Axial turbine · CFD modelling · Verification · Coupled model · Convective cooling

Nomenclature

Blade	Related to blade
C3X	Investigated blade
GTE	Gas turbine engine
HTC	Heat transfer coefficient
Mark II	Investigated blade

A. Volkov · V. Matveev · O. Baturin (✉) · I. Kudryashov · S. Melnikov
Samara National Research University, Samara, Russia
e-mail: oleg.v.baturin@gmail.com

J. P. T. Mo (ed.), *Proceedings of the 8th International Conference on Mechanical, Automotive and Materials Engineering*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-99-3672-4_4

NB	Nozzle blade
PJSC	Public joint-stock company

1 Introduction

The temperature of the gases at the turbine inlet of modern gas turbine engines can reach up to 1800–2000 K. 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 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 [2–11]. 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 convective cooling system.

2 Numerical Model of a Turbine Row with Convective Cooling

The coupled operation of three cooled nozzle grids, for which sufficient experimental data are available, has been simulated to reveal the influence of computational model settings on the results obtained. The objects of the study were: (1) Nozzle grid MarkII [12]; (2) Nozzle grid C3X [12].

The MarkII and C3X nozzle grids are widely known and have been used as test cases by many researchers. There is a large amount of experimental data in the open access source [12] for them. These are flat grids with a constant height cross section.

In order to investigate the influence of the numerical model parameters on the results of calculating the temperature of a convectively cooled blade, 2D models of working processes in the MarkII and C3X grids have been created. Hereinafter, the 2D calculation model is understood as an infinitesimal thickness model (one cell of finite volume thickness) in which the parameters vary only in circumferential and axial directions (Fig. 1).

Mesh models for the investigated blade geometries have been created in the Ansys CFX 18.2 software package.

As boundary conditions for the main flow at the inlet boundary the total pressure and the total flow temperature were set. At the outlet boundary the static pressure was set. The values of these parameters for Mark II and C3X models are presented in Table 1.

The finite volume grid was constructed so that the size of the near-wall layer is 0.003 mm, the number of near-wall layers is 40, and the cell growth factor when moving away from the wall is 1.2. The total number of elements in Mark II mesh is 169893 and in C3X mesh is 185170.

The SST turbulence model with Eddy Diffusivity option was used as the turbulence model. The laminar-turbulence transition was also taken into account using the Gamma Theta Model.

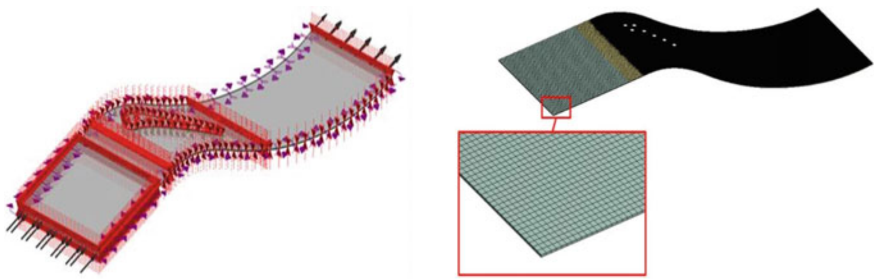


Fig. 1 Geometric and grid models for numerical simulation of blade cooling system with convective heat transfer

Table 1 Boundary conditions for the main flow [12]

No	Parameter name	Designation	Dimension	Mark II	C3X
1	Total pressure at the inlet to the calculation area	p_{in}^{*}	Pa	337,145	408,105
2	Total temperature at the inlet to the calculation area	T_{in}^{*}	K	788	815
3	Static pressure at the outlet of the calculation area	p_{out}	Pa	175,713	240,000

The boundary conditions on the walls of the cooling system channels were set in the form of heat transfer coefficient α and coolant temperature T_{cool}, taken from experimental data [12].

The numerical model results obtained were compared with experimental data of Mark II (experiment number 5411 in [12]) and C3X (experiment number 4511 in [12]) (Figs. 2 and 3). The relative temperature distribution over the profile was used for comparison, which was determined as follows:

$$T_{rel} = T_{blade}/811,$$

where T_{blade} is metal surface temperature of the blade.

Such a formula was adopted because it was the one used in processing the results of the experiment.

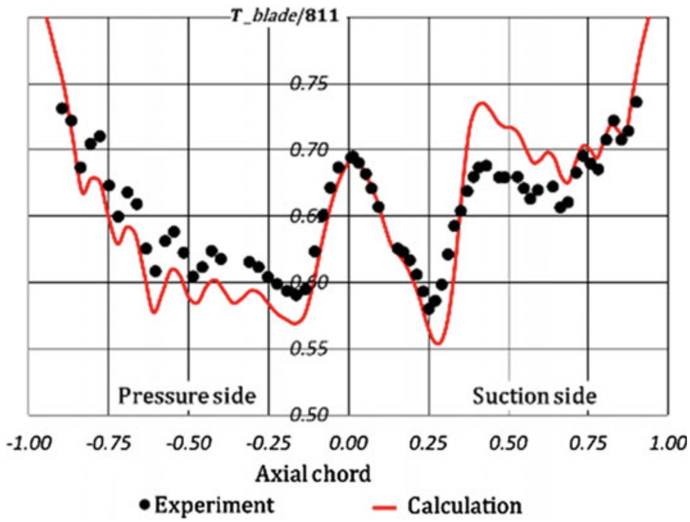


Fig. 2 Comparison of calculated and experimental relative temperature distributions over the Mark II blade profile

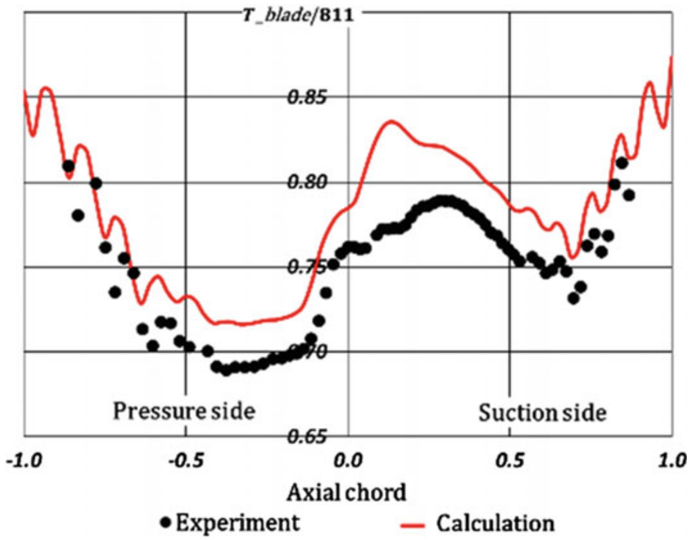


Fig. 3 Comparison of calculated and experimental relative temperature distributions along the blade profile C3X

Figures 2 and 3 show that the calculation results are in good agreement with the experimental data qualitatively and quantitatively. The difference in relative temperature does not exceed 5%.

Fields of temperature distribution in the blade passage and in the blade are shown in Figs. 4 and 5. It can be seen that the most heated part of the blade is the trailing edge, which corresponds to the available experimental data [12].

In convective cooling of turbine blades, the heat transfer calculation results are strongly influenced by the correctness profile of the flow temperature in the boundary layer. Therefore, it is to be expected that in a mesh model of a cooled blade, the finite volume mesh parameters characterising the boundary layer have a paramount influence on the calculation results:

- size of the first element from the blade wall;
- number of elements in the near wall layer;
- cell growth factor.

The choice of turbulence model will also have a significant influence on the calculation results, as it determines the distribution of flow parameters in the boundary layer.

Based on the above, a computational research plan has been formed to investigate the influence of numerical model parameters of the cooled turbine blade with convective cooling system on the simulation results:

- study of the influence of the size of the first element from the wall of the blade finite volume grid;

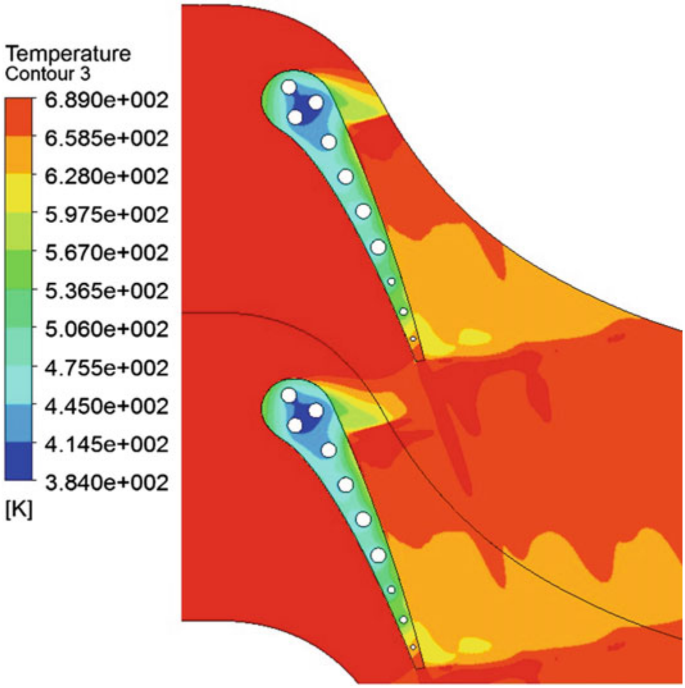


Fig. 4 Temperature distribution in the blade passage and the Mark II blade body obtained by calculation

– study of influence of number of elements in the near wall layer;
– study of influence of growth coefficient of finite volume grid cells in the near wall layer; study of turbulence model influence.

3 Convective Heat Transfer Simulation Results

To investigate the effect of the size of the first element from the wall of the finite volume grid on the calculation results, 10 different models were created. They differed in the size of the first element. The size ranged from 0.00003 to 0.00216 m (0.02 … 0.15% of blade chord).

The results of the calculation of the relative flow temperature distribution for the two nozzle grids are shown in Figs. 6 and 7.

Figures 8 and 9 show the dependence of the effect of the size of the first element of the finite volume grid in the near-wall layer on the calculation results for the average integral value of temperature along the blade profile, as derived from the analysis of the data obtained.

Figures 8 and 9 show that when the size of the first element from the wall changes by 0.2 mm, the value of the relative integral temperature along the blade profile

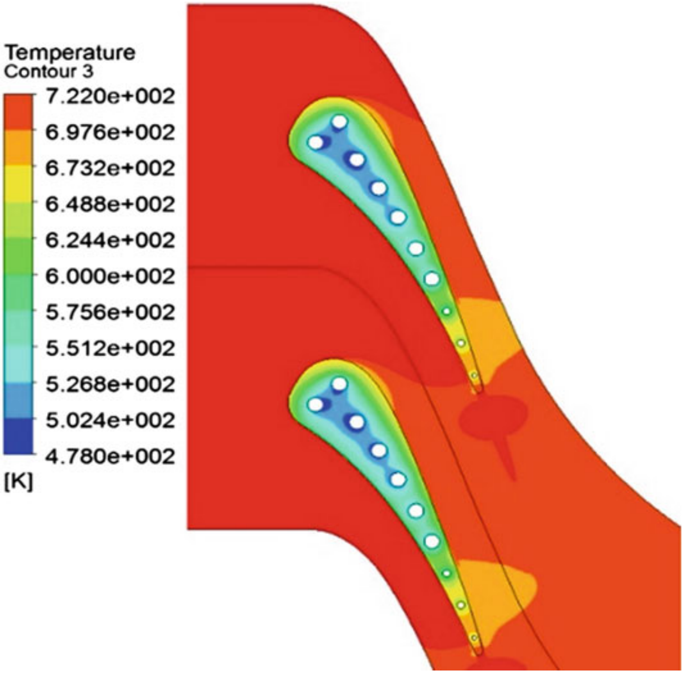


Fig. 5 Temperature distribution in the blade passage and C3X blade body obtained by calculation

changes by the value of 6 K. Consequently, the integral value of the blade temperature is weakly influenced by the size of the first element in the range under consideration.

In order to investigate the effect of the number of elements in the near-wall layer, 12 computational models were created which differed in the number of finite volume grid elements in the near-wall layer. The number of elements in the wall layer varied from 0 to 40.

The results of the relative flow temperature distribution are shown in Figs. 10 and 11.

Figures 12 and 13 show the results of the analysis of the effect of the number of elements in the structured near-wall layer on the calculation of the average integral temperature over the blade surface. It can be seen that when the number of elements in the walled layer changes from 0 to 40, the value of the integral relative temperature of the blade profile changes by about 25 K. And the biggest change is observed in case of small number of elements in the near wall layer. It is seen that with increase of number of elements in the layer from 0 to 5 the mean integral value of temperature at the blade surface increases, then decreases and after 10 elements it changes weakly. This is explained by the fact that with small number of elements in the near wall accepted layer turbulence model uses special empirical function—addition, which calculates the change of parameters near the wall with some approximation. With a large number of grid elements in the near wall zone, the processes in the boundary

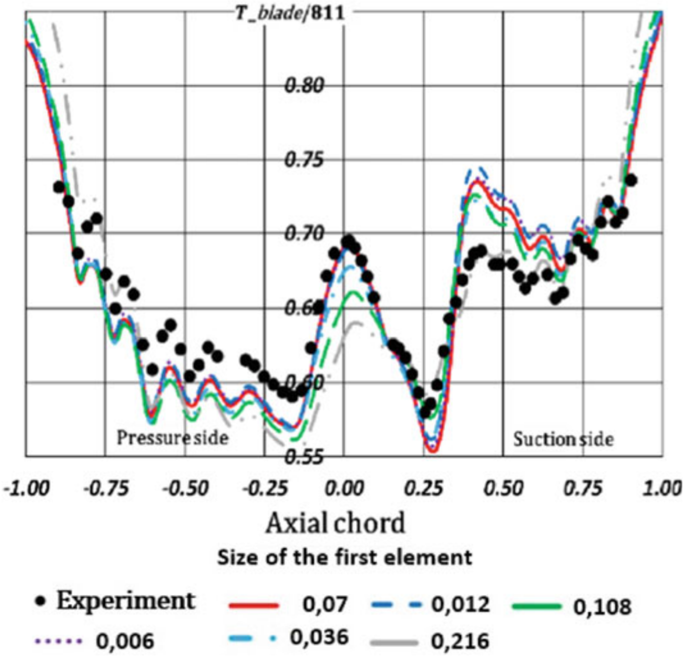


Fig. 6 Relative temperature distribution across the Mark II blade profile at different values of the first element size

layer are calculated directly using the turbulence model. Once a certain number of elements is reached (10 in this case) their further increase has little effect on the integral temperature value along the blade profile.

In order to investigate the effect of the growth coefficient of the elements in the near wall layer, 10 numerical models were created which differed by the growth coefficient of the cells in the near wall area of the finite volume mesh. This coefficient represents the ratio between the thickness of two neighbouring layers in the near-wall layer of the mesh when moving away from the wall. In this study, the cell growth coefficient in the near-wall layer varied from 1.05 to 1.4.

The results of the relative flow temperature distribution are shown in Figs. 14 and 15.

Figures 16 and 17 show the result of the analysis of the results as a function of the effect of the finite-volume mesh growth factor in the near-wall layer on the calculation of the average integral temperature over the blade surface.

Figures 16 and 17 show that changing the finite volume mesh growth factor in the range from 1.05 to 1.4 leads to a change of the integral relative temperature across the blade profile by less than 3 K. Based on this it was concluded that the mesh growth coefficient has little effect on the integral value of the relative temperature across the blade profile.

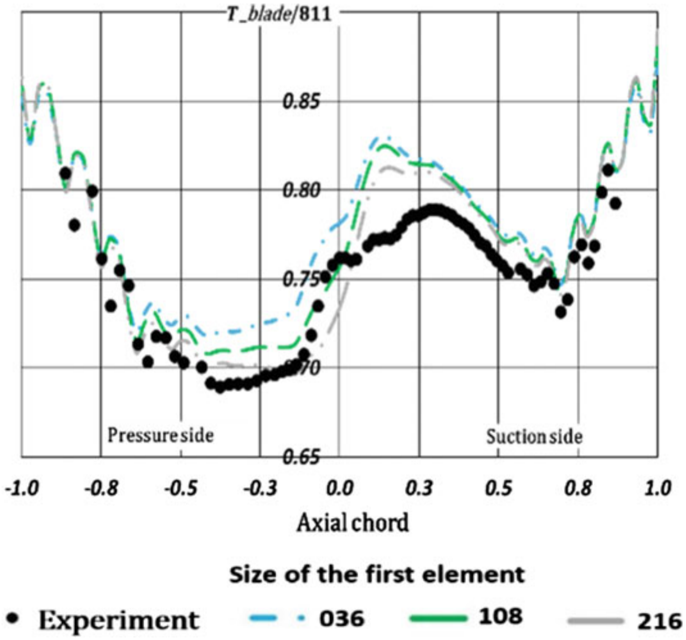
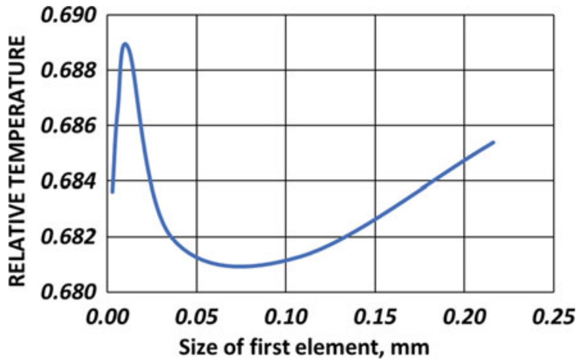


Fig. 7 Relative temperature distribution across the C3X blade profile at different values of the first element size

Fig. 8 Influence of first element size on the integral relative temperature value across the Mark II blade profile



In order to investigate the effect of the turbulence model on the calculation results, 14 calculation models were created, distinguished by the turbulence models adopted there.

To investigate the effect of turbulence, the following models, commonly used in modern calculation software, were chosen:

1. The k-ω model of turbulence (hereafter referred to as k-ω);
2. Omega Reynolds Stress and Baseline (BSL);

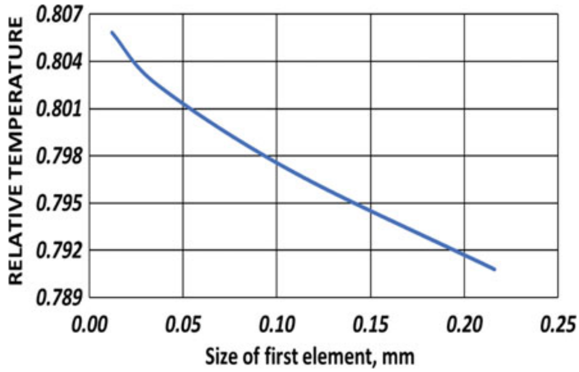


Fig. 9 Influence of first element size on the integral relative temperature value along the blade profile C3X

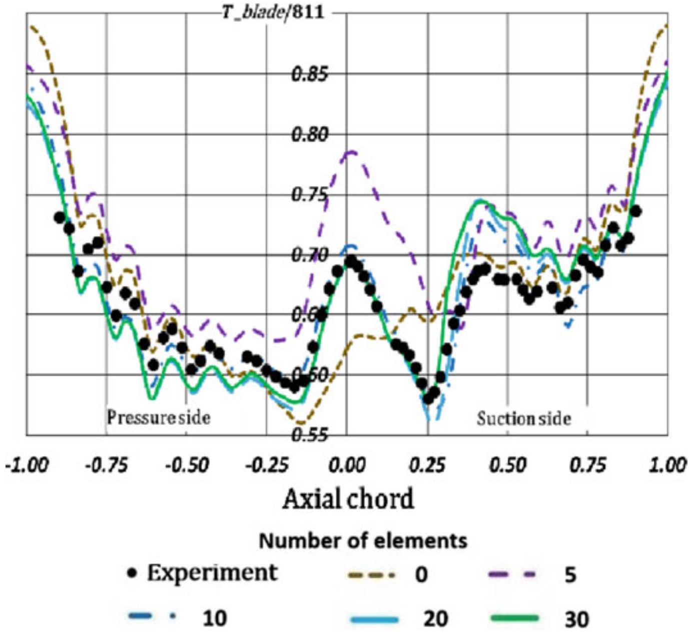


Fig. 10 Relative temperature distribution across the profile of the Mark II blade at different numbers of elements in the near wall layer

3. Shear Stress Transport (SST);
4. Shear Stress Transport with Eddy Diffusy option enabled (SST_ED);
5. Shear Stress Transport with Eddy Diffusy option enabled and Fully Turbulent laminar-turbulent transition (SST_ED_FT);
6. Shear Stress Transport with Eddy Diffusy option enabled and Gamma laminar-turbulent transition (SST_ED_G);

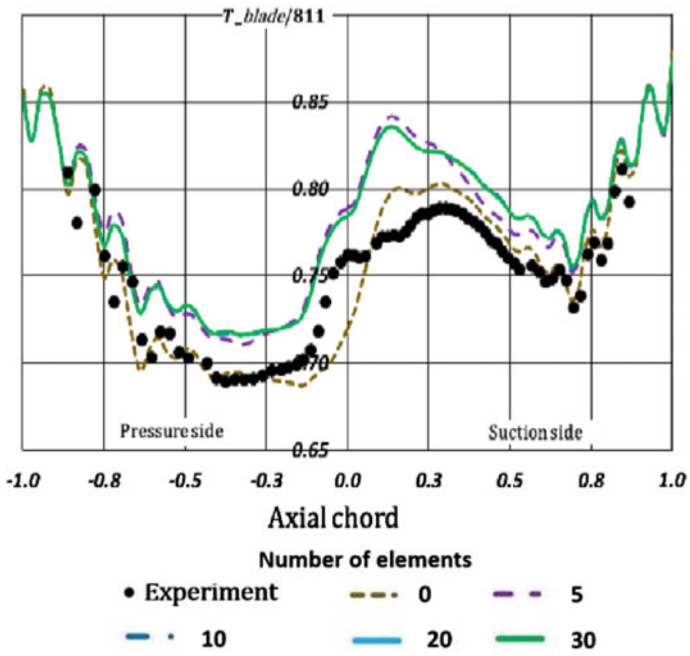


Fig. 11 Relative temperature distribution across the C3X blade profile at different numbers of elements in the near wall layer

Fig. 12 Influence of the number of elements in the near wall layer on the integral relative temperature value along the Mark II blade profile

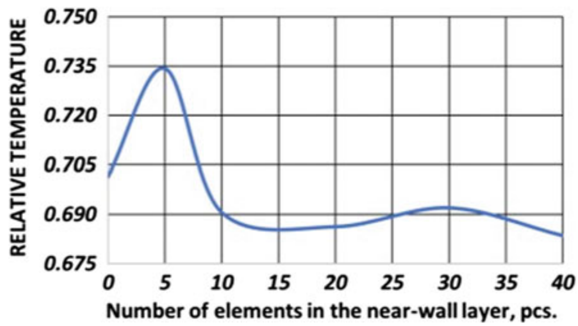
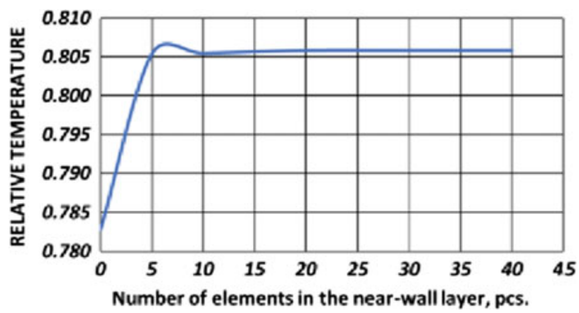


Fig. 13 Influence of the number of elements in the near wall layer on the integral relative temperature value along the C3X blade profile



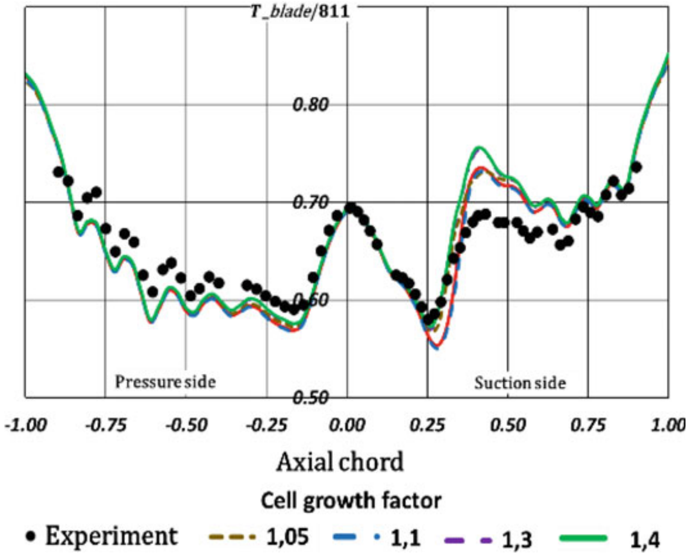


Fig. 14 Relative temperature distribution along the profile of the Mark II blade at different values of cell growth coefficient in the near-wall layer

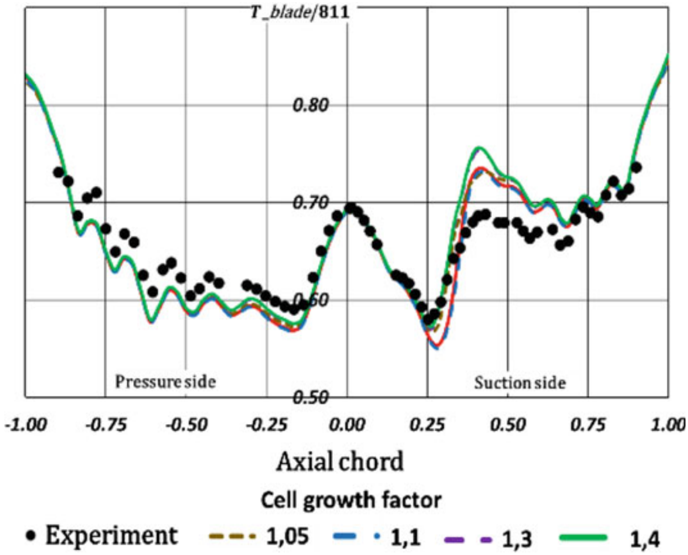


Fig. 15 Relative temperature distribution along the C3X blade profile at different values of cell growth coefficient in the near-wall layer

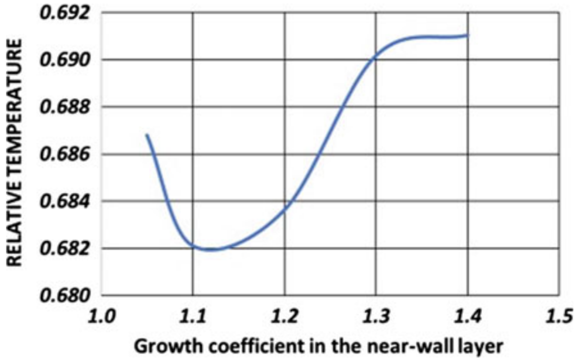


Fig. 16 Influence of the growth coefficient in the near-wall layer of the finite volume grid on the integral relative temperature value across the Mark II blade profile

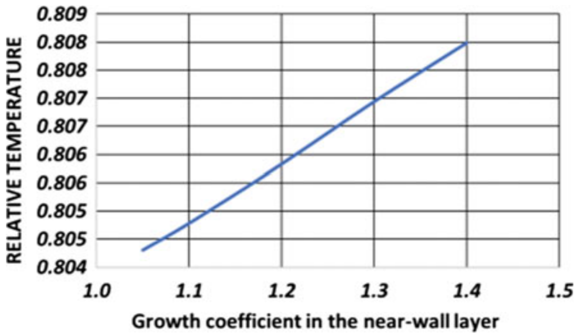


Fig. 17 Influence of the growth coefficient in the near-wall layer of the finite volume grid on the integral relative temperature value along the C3X blade profile

7. Shear Stress Transport with Eddy Diffusy option enabled and Gamma Theta laminar-turbulent transition (SST_ED_GT).

The results of calculating the relative flow temperature distribution are shown in Figs. 18 and 19.

Figures 20 and 21 show the effect of the turbulence model on the average blade surface integral temperature results. It can be seen that the turbulence model has a great influence on the blade integral temperature than the grid model parameters. When changing the turbulence model, the difference between the integral relative temperature values calculated with different turbulence models can reach 80 K. It should be noted that the character of change of relative temperature value over the blade surface depending on turbulence models is the same for the considered blades. But consideration of laminar-turbulent transition in C3X model leads to significant decrease of integral value of relative temperature along the blade profile, which requires further investigation. The k-ω and SST turbulence models show the best agreement with the experimental data.

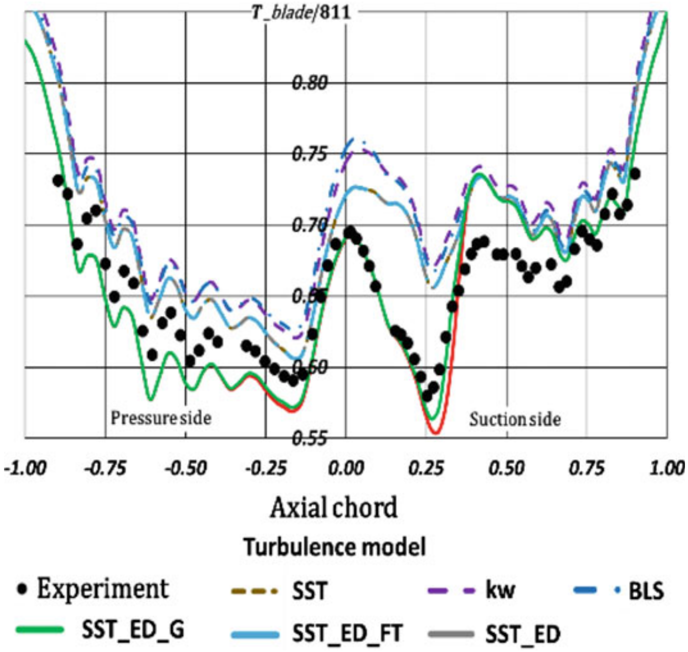


Fig. 18 Relative temperature distribution along the Mark II blade profile, obtained with different turbulence models

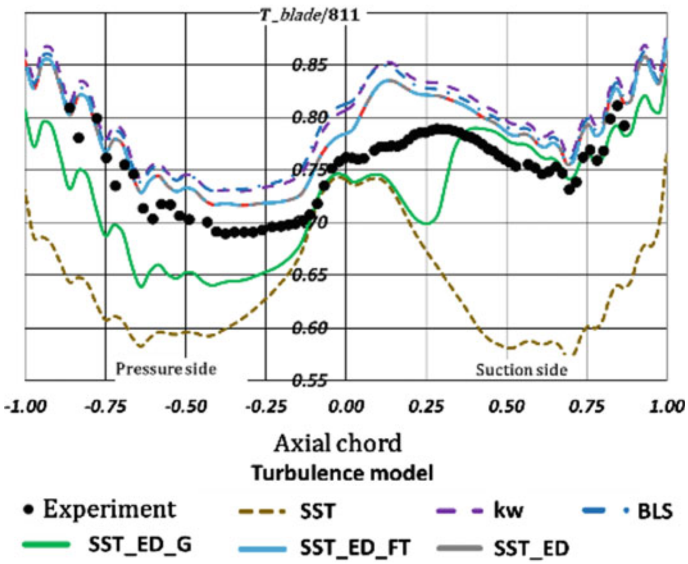


Fig. 19 Relative temperature distribution along the C3X blade profile, under different turbulence models

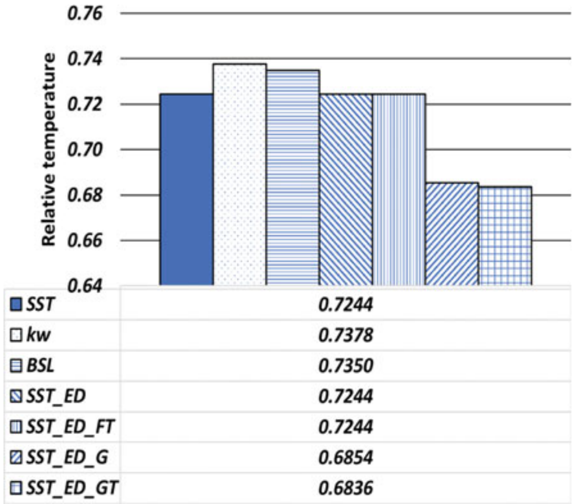


Fig. 20 Influence of turbulence model on Mark II blade mean integral temperature value

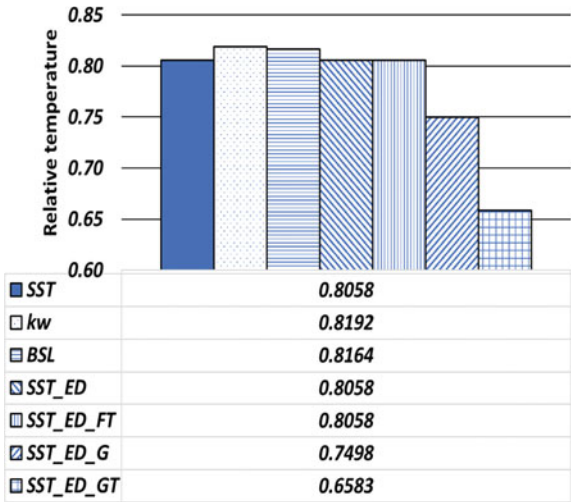


Fig. 21 Influence of turbulence model on average integral blade temperature C3X

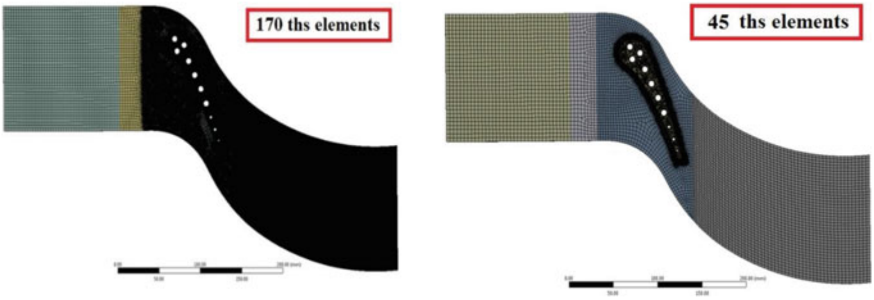
4 Summary of Numerical Simulation Studies of Convective Heat Transfer

For all performed calculations the analysis of influence of parameters of numerical model of working process in turbine blades with convective system of cooling on results of calculation was made. On the basis of the analysis the following recommendations were formed, which will allow modelling in such blades with the best accuracy while minimizing the number of elements in the mesh model.

1. The size of the first element affects the relative temperature distribution along the blade profile. The greatest influence is observed in the area of leading edge, as the size of the first element increases the value of the relative temperature along the blade profile shifts downwards along the abscissa axis. The integral value of the relative temperature along the blade profile is weakly influenced by the size of the first element. The recommended value for the size of the first element for a two-dimensional application is not more than 0.012 mm.
2. The number of elements in the near wall layer has a significant influence on the results of calculation of the relative temperature along the blade profile. When the number of elements in the near wall layer is less than 10, both qualitative and quantitative discrepancy of relative temperature distribution along the blade profile with the experimental data is observed. The integral value of the blade's relative temperature is also strongly influenced by the number of elements in the near wall layer which is observed in the range from 0 to 10 elements. With increasing of elements number in near wall layer the value of integral relative temperature on blade profile practically does not change. Recommended value for the number of elements in the near wall layer for a two-dimensional solution: at least 10 elements.
3. The growth coefficient of finite volume grid cells in the considered range, with a given number of elements in the near wall layer, has little influence on the calculation results (both on the temperature distribution along the profile and on its integral values). Recommended value of growth factor in two-dimensional calculations of blades of cooled turbines with convective cooling system with - no more than 1.2.

The choice of turbulence model has a significant influence on the calculation results of both the relative temperature distribution along the blade profile and the integral value of the relative blade temperature. Particular attention must be paid to the laminar-turbulence transition. For example, when calculating a Mark II blade with the laminar-turbulent transition option enabled, the relative temperature results are in good agreement with experimental data. But when calculating the C3X vane, enabling the laminar-turbulent transition option leads to a significant decrease in the calculated relative temperature of the blade, except for the leading edge area.

For the numerical model of the cooled Mark II blade working process [13], a numerical model was created according to the recommendations obtained earlier and described in the previous chapter (hereinafter this model is called "light"). The



"Heavy" mesh model "Light" mesh model

Fig. 22 Appearance of the basic and optimisation grid models of the Mark II blade

size of the first element was 0.003 mm, number of elements in the near wall layer was 20, cell growth factor in the near wall layer ER = 1.2, turbulence model SST_ED_GT considering laminar-turbulence transition. It is also worth noting that this model was distinguished by a reduced number of finite elements in the flow core relative to the models used in the studies described above (hereafter referred to as "heavy"). The total number of elements for the obtained numerical model is 44614, which is 3.8 times less than in the initial numerical model of the blade Mark II. The appearance of the initial and optimised Mark II grid model is shown in Fig. 22.

The results of calculating the relative temperature distribution along the axial chord of the blade of the original and optimised numerical models compared with the experimental data are shown in Fig. 23.

Figure 23 shows that the calculation results for the 'heavy' and 'light' models do not differ much from each other. However, the amount of time required to calculate the "light" model is 2.3 times less than the "heavy" model.

5 Conclusions

In the presented work the results are presented aiming at finding optimal settings of numerical models which allow to simulate accurately and with reduced costs the coupled working process in convective cooled cooled turbines. As a result, practical recommendations for the selection of grid parameters and turbulence models for such problems have been obtained.

Recommendations for setting up numerical models for convectively cooled turbine blades in a two-dimensional setting are made:

- size of the first element: not more than 0.012;
- number of elements in the near wall layer: not less than 10;
- cell growth factor in the near wall layer: not more than 1.2;

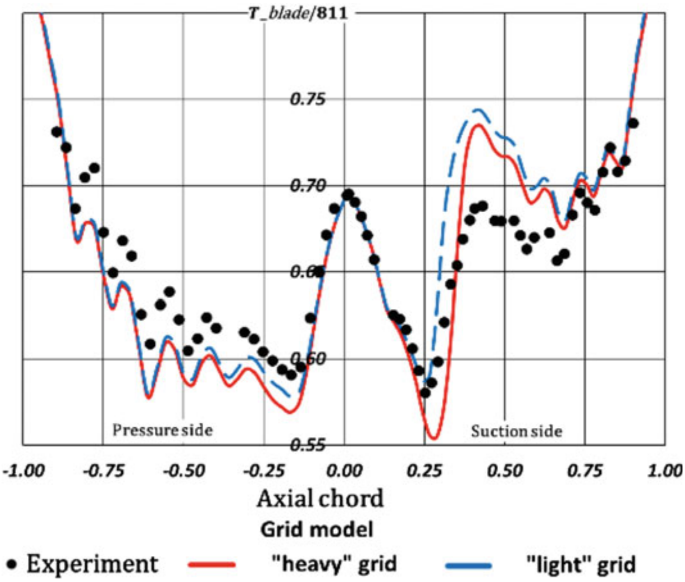


Fig. 23 Relative temperature distribution across the Mark II blade profile for models with different grid models

– turbulence model: further studies required.

It is shown that application of rarefied grid in the main flow core will allow to keep accuracy of coupled process modelling but reduce calculation time by 2.3 times.

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

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

References

1. Inozemcev AA, Nihamkin MA, Sandrackii VL (2008) Osnovy konstruirovanija aviacionnyh dvigatelej i jenergeticheskih ustanovok [Fundamentals of designing aircraft engines and power plants]. Mashinostroenie, Moscow
2. Ho K, Liu JS, Elliott T, Aguilar B (2016) Conjugate heat transfer analysis for gas turbine film-cooled blade. In: Proceedings of the ASME Turbo Expo 2016: turbomachinery technical conference and exposition. Volume 5A: heat transfer. Seoul, V05AT10A003. ASME, GT2016-56688
3. Ke Z, Jian-Hua W (2016) Coupled heat transfer simulations of pulsed film cooling on an entire turbine vane. Appl Therm Eng 109:600–609
4. Insinna M, Griffini D, Salvadori S, Martelli F (2014) Coupled heat transfer analysis of a film cooled high pressure turbine vane under realistic combustor exit flow conditions. In:

Proceedings of the ASME Turbo Expo 2014: turbine technical conference and exposition. Volume 5A: heat transfer. V05AT11A007. ASME, GT2014-25280
5. Wróblewski W (2013) Numerical evaluation of the blade cooling for the supercritical steam turbine. Appl Therm Eng 51:953–962
6. Bonini A, Andreini A, Carcasci C, Facchini B, Ciani A, Innocenti L (2012) Coupled heat transfer calculations on GT rotor blade for industrial applications: Part I—Equivalent internal fluid network setup and procedure description. In: Proceedings of the ASME Turbo Expo 2012: turbine technical conference and exposition. Volume 4: heat transfer, Parts A and B, ASME, GT2012-69846, pp 669–679
7. Shevchenko IV, Rogalev N, Rogalev A, Vegera A, Bychkov N (2018) Verification of thermal models of internally cooled gas turbine blades. Int J Rotat Mach 110
8. Florent D, Corpron A, Pons L, Moureau V, Nicoud F, Poinsot N (2009) Development and assessment of a coupled strategy for coupled heat transfer with large eddy simulation: application to a cooled turbine blade. Int J Heat Fluid Flow 30:1129–1141
9. Priyadarsini I (2019) Gas-turbine bladecooling using CFD gas-turbine bladecooling using CFD
10. Horiuchi T, Taniguchi T, Tanaka R, Ryu M, Kazari M (2018) Application of conjugate heat transfer analysis to improvement of cooled turbine vane and blade for industrial gas turbine. In: Proceedings of the ASME Turbo Expo 2018: turbomachinery technical conference and exposition. Volume 5A: heat transfer. Oslo, Norway. June 11–15, 2018. V05AT10A002. ASME
11. Wei L, Feng-bo W, Lei L, Tao C, Song-tao W (2018) Three-dimensional aerodynamic optimization of turbine blade profile considering heat transfer performance. In: Proceedings of the ASME Turbo Expo 2018: turbomachinery technical conference and exposition. Volume 2D: turbomachinery. Oslo, Norway. June 11–15, 2018. V02DT46A024. ASME
12. Hylton LD, Mihelc MS, Turner ER, Nealy DA (1983) NASA technical report: NASA-CR-168015
13. Popov G, Matveev V, Baturin O, Novikova Y, Volkov A (2018) Selection of parameters for blade-to-blade finite-volume mesh for CFD simulation of axial turbines. In: MATEC web of conferences, vol 220