Estimation of the Effect of 3D Grid Parameters on the Simulation of the Working Process of Axial Turbines

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Keywords: Component, Axial Turbine, CFD, Finite Volume Mesh, Settings, Simulation Accuracy, Error, Optimization.

Abstract: This article describes the second part of the global work done by the authors aimed at finding the best settings for a numerical model for calculations of axial uncooled turbines using the RANS approach. The authors studied more than 80 papers published over the past 5 years in the examined field. Their analysis did not allow to identify unified recommendations for the creation of numerical models. The selection of model parameters is usually motivated by general considerations of numerical simulation, which follow from the method. In none of the papers the selection of parameters is correlated with the structure of the flow in the turbine. Many specific simulation issues were not covered at all. For the research, more than 1000 models of full-size axial turbines (including multistage turbines) and their elements were created. They differed in the number, size, parameters of the elements of finite volume meshes, in turbulence models, in the degree of simplification. The results were compared with the experimental data. As a result, the following was obtained: 1. A method for developing and optimizing the working process of turbines using numerical simulation based on the RANS approach is proposed. The search for the optimal turbine configuration is carried out using light computational models, which are based on the simplified channel geometry and the finite volume mesh. Their application makes it possible to reliably find the optimal turbine configuration 2.8 times faster. The characteristics of the selected variants are verified with the help of verification models that consider the real geometry of the channels and have a minimum error. 2. Recommendations are given on the selection of parameters for finite volume meshes and the selection of turbulence models for numerical models of the working process of axial turbines designed to perform optimization and verification calculations.

NOMENCLATURE

GTU – gas turbine unit

GTE – gas turbine engine

LPT – Low pressure turbine

FT – free turbine

y+ – dimensionless distance

RANS - Reynolds-averaged Navier–Stokes equations

$ER_{FP} = \frac{y_{FP\,i}}{y_{FP\,i-1}}$ - cell expansion ratio of the finite volume mesh

$MR_{FP} = \frac{y_{FP\,max}}{y_{FP\,1}}$ - maximum cell aspect ratio of the finite volume mesh

y_{FP1} –size of the element of the finite volume mesh closest to the endwall.

y_{B2B1} - size of the element of the finite volume mesh closest to the blade surface

CIAM – Central Institute of Aviation Motors

ζ_{PR} – profile losses

λ – specific velocity

β_1 – inlet flow angle of the cascade, degree

β_2 – outlet flow angle of the cascade, degree

$\sigma^2_{\mathrm{res}}(\zeta_{PR})$ –residual dispersion

F – F-ratio test

qMSE – mean square error

$qMSE_{rel}(\zeta_{PR})$ – mean relative square errors

$\zeta_{EXP\ mean}$ – mean experimental value of profile losses

S – calculation speed up

η_{PR} – cascade efficiency

π^*_{T} - gas expansion ration in turbine

Popov, G., Matveev, V., Baturin, O., Novikova, I., Kolmakova, D. and Zubanov, V.
Estimation of the Effect of 3D Grid Parameters on the Simulation of the Working Process of Axial Turbines.
DOI: 10.5220/0006890203710377
In *Proceedings of 8th International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SIMULTECH 2018)*, pages 371-377
ISBN: 978-989-758-323-0

α_{OUT} – outlet flow angle of the turbine, degree

A^*_T - throughflow capacity of the turbine, $m^3 K^{-0.5} s^{-1}$

n – rotational speed, rpm

c^*_S - isentropic rate of gas expansion in a turbine, m/s

E – efficiency of parallelization of a computational task

B2B – two-dimensional blade passage

FV – finite volumes.

1 MOTIVATION AND STATEMENT OF THE RESEARCH PROBLEM

This paper is an integral part and a continuation of the paper (Popov, 2018) in which it was shown that axial uncooled turbine is widely used in aviation and industrial gas turbine propulsion engineering. Turbines are the components that significantly determine the reliability, efficiency and cost of gas turbine engines (Inozemcev, 2015). For this reason, the problem of increasing the efficiency of turbines is important and relevant. It is also important to develop methods for designing and developing such turbines, and primarily the methods for their numerical simulation that is the most advanced calculation method available to a modern engineer for evaluation of the characteristics.

It was shown in (Popov, 2018) that the available publications do not contain universal recommendations for numerical modeling of turbines. In (Popov, 2018), an approach was suggested, according to which the selection of finite volume mesh should be differentiated in accordance with the flow structure in the blade row.

The selection of the values for 2D mesh parameters must be carried out by the profile losses determined during the simulation for individual blade rows or by integral parameters of the turbines. The paper (Popov, 2018) contains the results of the study to substantiate this choice. Secondary losses have a complex distribution along the height of the blade and have effect only near the end surfaces of the flow path. Therefore, when selecting the values of ER_{FP} and MR_{FP}, it is necessary to evaluate the distribution of the flow parameters (for example, loss coefficients, flow angle, total pressure) along the height of the flow path. Below the development of recommendations for the selection of the distribution of parameters along the height of the turbine cascade and the results of testing the received recommendations during the simulation are described.

2 INVESTIGATION OF EFFECT OF THE DISTRIBUTION OF FINITE-VOLUME MESH ELEMENTS ALONG THE HEIGHT OF THE FLOW PART TO THE SIMULATION EFFICIENCY OF THE WORKING PROCESS OF TURBINE CASCADES

In the framework of the research, 9 meshes were created for each cascade, the values of ER_{FP} and MR_{FP} parameters in which ranged from 1.2 to 1.7 and from 250 to 4000, respectively. Each mesh was simulated using 6 turbulence models. In total, 216 numerical models were created.

ER_{FP} and MR_{FP} parameters have a qualitative and quantitative effect on the calculated distribution of secondary losses along the height of the flow part $\zeta_{SEC} = f(h)$. The increase in the ER_{FP} and MR_{FP} parameters leads to a decrease in the characteristic loss peak on the distribution of secondary losses along the height of the flow part (Figure 1), which is also confirmed by the patterns of the flow structure in the blade passages (Figure 2).

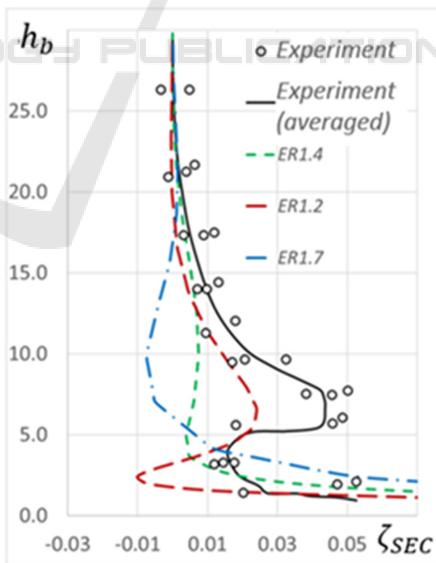
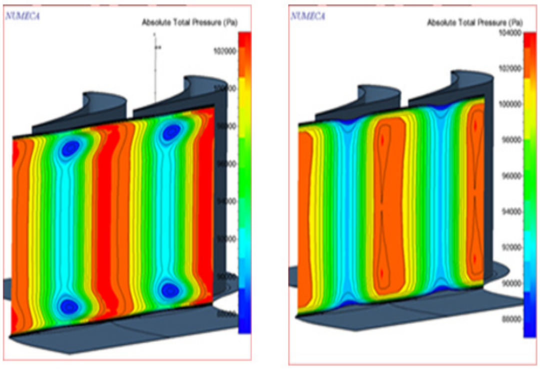


Figure 1: Influence of the MR_{FP} parameter at $ER_{FP} = 1.2$ on the simulation of secondary losses (on the example of cascade No. 34 (Venediktov, 1990).



a) $ER_{FP} = 1.2$; $MR_{FP} = 250$ b) $ER_{FP} = 1.7$; $MR_{FP} = 4000$

Figure 2: Influence of the ER_{FP} and MR_{FP} parameters on the computed fields of turbulent viscosity at the outlet from the cascade No. 34 (Venediktov etc., 1990).

Acceptable combinations of the ER_{FP} and MR_{FP} parameters that allow to describe the distribution of secondary losses in blade height adequately to the experimental data are: $ER_{FP} = 1.2$, $MR_{FP} = 250 \ldots 2000$, and $ER_{FP} = 1.2 \ldots 1.7$, $MR_{FP} = 250$.

The ER_{FP} and MR_{FP} parameters have a negligible effect on the total loss coefficient ζ_{Total} in the cascades (the change in the calculated value of ζ_{Total} with changing ER_{FP} and MR_{FP} parameters in the indicated ranges does not exceed 0.002), but they significantly decrease the value of the speed up parameter S in the range of $ER_{FP} < 1.4$ and $MR_{FP} < 1000$, reaching the value S = 0.46 for $ER_{FP} < 1.2$ и $MR_{FP} = 250$.

Based on the performed studies, it was concluded that rational combinations of the parameters ER_{FP} and MR_{FP} for simulation of the secondary flows of turbine cascades are: $ER_{FP} = 1.2$, $MR_{FP} = 1000 \ldots 2000$.

Then, the influence of the turbulence model on the efficiency of simulation of the secondary losses in axial turbine cascades was studied. When conducting the mesh studies, it was found that the selection of the turbulence model has only a quantitative effect on the characteristics of the cascades in the form of $\zeta_{PR} = f(\lambda_{2S})$, and, consequently, on the error in determining the coefficients of profile losses and the efficiency of the cascades. The smallest errors in the calculation of the cascade characteristics are provided by using SST and k-ω turbulence models. It was also found that the selection of the turbulence model has a certain effect on the speed up of the calculations S. Figure 3 shows a histogram of the relative speed up averaged over all cascade and meshes $\overline{S_{\mathrm{Turb}\,j}}$. The relative speed up $\overline{S_{\mathrm{Turb}\,j}}$ was defined as the ratio of the calculation time of one iteration $t_{\mathrm{Mesh}\,i,SA}$ of the numerical model with the i-th mesh and the Spalart-Allmaras turbulence model to the time of calculation of one iteration $t_{\mathrm{Mesh}\,i,\mathrm{Turn}\,j}$ of the numerical model with the i-th mesh and the j-th turbulence model: $\overline{S_{\mathrm{Turb}\,j}} = t_{\mathrm{Mesh}\,i,SA}/t_{\mathrm{Mesh}\,i,\mathrm{Turn}\,j}$. The greatest value of speed up $\overline{S_{\mathrm{Turb}\,j}}$ is achieved using the Spalart-Allmaras turbulence model. Thus, to perform optimization calculations, it is advisable to use the Spalart-Allmaras model, and SST and k-ω turbulence models for the verification, since the least error in determining the losses is achieved.

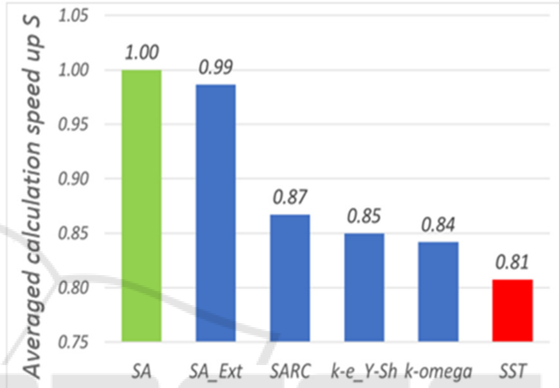


Figure 3: The averaged (over all meshes) calculation speed up for various turbulence models.

3 INVESTIGATION OF THE INFLUENCE OF VARIOUS PARAMETERS OF FINITE ELEMENT MESHES ON THE SIMULATION EFFICIENCY OF THE WORKING PROCESS OF FULL-SIZE GAS TURBINES

One of the features of numerical simulation of the working process of full-size axial uncooled turbines is the need to determine three characteristics for them: the dependences of throughflow capacity, efficiency and the flow angle in absolute motion at the outlet of the turbine from the expansion ratio to the total pressure ($A^*_{\mathrm{T}} = f(\pi^*_{\mathrm{T}})$, $\eta^*_{\mathrm{T}} = f(\pi^*_{\mathrm{T}})$ и $\alpha_{\mathrm{OUT}} = f(\pi^*_{\mathrm{T}})$, respectively). Other features of simulation of the working process of turbines is the variety of structural elements of stage, such as, for example, shroud platform, as well as the need to determine the characteristics for different modes of operation with respect to the $n/\sqrt{T^*_0}$ parameter.

Therefore, in addition to checking the results of studies for turbine cascades on the simulation efficiency of the turbine working process as a whole while varying the number of 2D B2B mesh elements, y^{+}_{B2B1}parameter, the ER_{FP} and MR_{FP} parameters, the turbulence models obtained earlier, additional studies on the effect of the accounting the parietal cavities over the shroud platforms on simulation efficiency, and also on the evaluation of the simulation efficiency for various values of the parameter $n/\sqrt{T^*_0}$ were carried out.

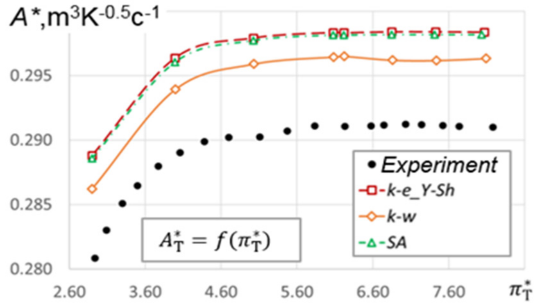
In total, ten uncooled axial turbines with aerodynamically long blades were examined. The number of stages in the selected turbines ranged from 1 to 4, the throughflow capacity A^*_{T} was in the range from 0.3 $\mathrm{m}^3 K^{-0.5} s^{-1}$ to 3.0 $\mathrm{m}^3 K^{-0.5} s^{-1}$, the value of the loading parameter u/c^*_S was up to 0.66.

In the beginning, the computational models of turbines were created using the parameters of the basic numerical models of the working process. They did not contain the parietal cavities. The simulation was performed using three turbulence models: Spalart-Allmaras, k -ε Low Re Yang-Shih and k-ω (in total 30 numerical models).

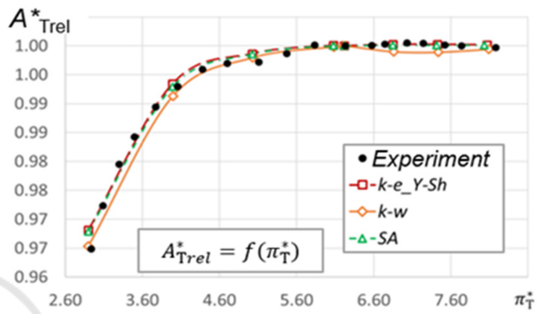
As a result of the conducted studies, it was established that all the obtained calculation characteristics are adequate to the available characteristics of turbines obtained experimentally or using verified mathematical models. At the same time, the discrepancy between the existing and the numerical values of the integral parameters of turbines at the design point reached 4% (abs.) (Figure 4, a). For this reason, the existing and resultant numerical simulation data were recalculated into a relative form: $Parameter_{rel} = f(\pi^*_{\mathrm{T}})$.. The relative values of the integral parameters of turbines A^*_{Trel}, η^*_{Trel} and α_{OUTrel} were determined using expression:

$$Parameter_{rel} = {}^{Parameter}/_{Parameter_{DP}},$$

where $Parameter$ is the parameter value at an arbitrary point of the characteristic curve, $Parameter_{DP}$ is the parameter value at the design point. All the relative characteristics obtained during numerical simulation are adequate to the available experimental characteristics (Figure 4, b). Thus, it was concluded that all the basic numerical models of the working process of turbines allow to determine the behavior of the characteristics of turbines.



a) absolute characteristics



b) relative characteristics

Figure 4: Comparison of the calculated and experimental characteristics of the NASA 4.5 turbine stage (Whitney, 1977), obtained using various turbulence models and basic meshes.

Then, a study of the effect of the number of 2D B2B mesh elements on the simulation efficiency of the working process of axial uncooled turbines was performed. Within the framework of the research based on the basic meshes, 3 additional computational meshes were created for each turbine with 2D meshes B2B-2, B2B1 and B2B2, the number of B2B elements varied from 6000 to 34000. The calculation of each mesh was carried out using three turbulence models. In total, 120 numerical models were created. The studies confirmed the conclusions made for the cascades about only the quantitative influence of the number of B2B elements on the calculation absolute characteristics; about a small quantitative effect on the calculated parameters for the number of elements $B2B > 21000$ (2D mesh B2B1); about the insignificant influence of the number of B2B elements on the absolute and relative errors in determining the integral parameters of turbines (Figure 5), as well as on increasing the calculation speed up S to 2, while reducing the number of 2D mesh elements to 6000 (corresponds to B2B0 mesh). At the same time, the relative characteristics of turbines when changing the number of B2B elements practically do not change and are adequate to the available relative characteristics.

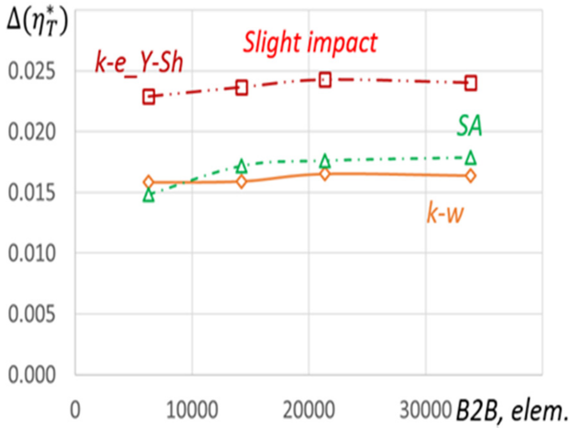


Figure 5: The influence of the number of 2D mesh elements on the absolute error in determining the efficiency of the turbine.

Investigations on the effect of the y_{B2B1}^{+} parameter on the simulation efficiency performed in the range of y_{B2B1}^{+} from 0.2 to 5.0 using three turbulence models also confirmed the conclusions drawn for the cascades. The change in the y_{B2B1}^{+} parameter does not change the behavior of the calculation absolute characteristics of turbines and only shifts them along the ordinate axis. For $y_{B2B1}^{+} \leq 1$, the influence of the parameter on the calculated values of the integral parameters of the turbines and on the error of their determination is extremely insignificant. At the same time, the relative characteristics of turbines with a change in the y_{B2B1}^{+} parameter practically do not change and are adequate to the available relative characteristics.

The next step was to investigate the effect of the ER_{FP} and MR_{FP} parameters on the simulation efficiency of the turbine workflow. The range of parameters during the study was: $ER_{FP} = 1.2 \dots 1.7$, $MR_{FP} = 1000 \dots 4000$.. Also, as for cascades, the increase in ER_{FP} and MR_{FP} parameters lead to the flattening of peaks due to secondary losses on the loss distribution over the height of the flow part (Figure 6). At the same time, permissible combinations of the ER_{FP} and MR_{FP} parameters allow adequately describing the distribution of losses along the blade height: $ER_{FP} \leq 1.4$, $MR_{FP} \leq 2000$. ER_{FP} and MR_{FP} parameters in the permissible range have practically no effect on the absolute and relative characteristics of the turbines. At the same time, the calculation speed up S significantly decreases with decreasing the ER_{FP} and MR_{FP} parameters, reaching the value S = 0.67 for $ER_{FP} \leq 1.4$, $MR_{FP} \leq 2000$.

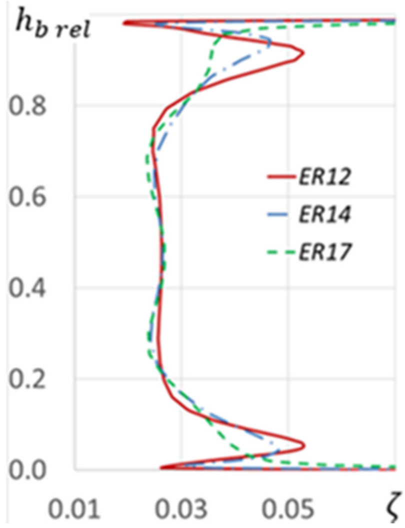


Figure 6: The effect of the ER_{FP} parameter at $MR_{FP} = 1000$ on the simulated distribution of losses along the blade height in a section behind first nozzle block of the NASA turbine (Whitney, 1977).

Studies on the effect of accounting the cavities over the shroud platforms on the simulation efficiency showed that their presence does not qualitatively affect the behavior of the characteristics, but exerts a significant quantitative influence on them, shifting the efficiency along the ordinate axis by up to 1% (Figure 7), which leads to a significant reduction in the error in the calculation of the efficiency. At the same time, the calculation speed up S is also significantly reduced (up to 0.74) (J. Respondek, 2010).

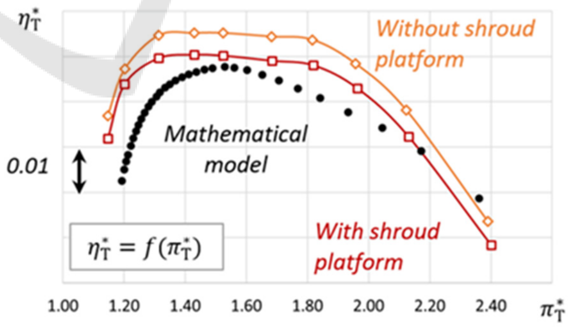


Figure 7: The influence of the accounting of the shroud platform on the calculation characteristics of the LPT.

Simulation of the turbine working process using different meshes, turbulence models for various values of the parameter $n/\sqrt{T_0^*}$ showed that all numerical models allow to estimate the characteristics at off-design modes by $n/\sqrt{T_0^*}$ in absolute and in a relative form without additional errors.

At the final stage, the effect of the selection of turbulence models on the simulation efficiency of the working process of axial turbines was generalized. All the described mesh studies for turbines were performed using only three turbulence models and allowed to establish that the selection of the turbulence model does not change the behavior of the characteristics, but only equidistantly shifts them along the ordinate axis. Thus, all turbulence models make it possible to evaluate trends in the turbine parameters. The simulated workflow of some of the turbines using the basic meshes and 7th turbulence models only confirmed these conclusions. The smallest errors in determining the integral parameters of turbines are provided by using k-ω turbulence model, and the greatest speed up S is when the Spalart-Allmaras turbulence model is used.

4 GENERALIZATION OF THE OBTAINED RESULTS: RECOMMENDATIONS FOR THE DEVELOPMENT OF NUMERICAL MODELS OF AXIAL UNCOOLED TURBINES

Based on the studies carried out, two methods were developed for the creation of rational numerical models for the working process of turbines with aerodynamic long blades, designed to perform optimization and verification calculations.

At the first stage of creating a rational numerical model designed to perform optimization calculations, the geometry of the computational domain is constructed.

Then a mesh of finite volumes is constructed. For optimization calculations it is necessary to use two-dimensional meshes B2B-2 (6000 elem.), in which the value of the dimensionless parameter y^{+}_{B2B1} is 1. The distribution of the elements along the height must be specified using the ER_{FP} and MR_{FP}. parameters. At the initial stages of optimization, it is advisable to use meshes in which $ER_{FP} < 1.4$, $MR_{FP} < 2000$. When optimizing with a more accurate account of secondary losses, meshes should be used in which $ER_{FP} < 1.2$, $MR_{FP} < 2000$.

At the third stage of adjusting the parameters of the numerical model, among other settings, it is necessary to select the Spalart-Allmaras turbulence model.

When configuring paralleling settings, it is advisable to adhere to the approach that involves running the maximum number of tasks simultaneously on all processors.

This method allows to create rational optimization numerical models that to estimate accurately the trends in the integral parameters of turbines and have high values of the speed up parameter up to 2.8.

The method of creating rational numerical models intended for verification calculations differs from the method for optimization models only by recommendations on the selection of values of model parameters.

For verification calculations, it is advisable to use two-dimensional meshes B2B1 (21000 elem.). The values of the parameters for the distribution of elements along the height of the flow part should be chosen from the interval: $ER_{FP} < 1.2$, $MR_{FP} = 1000 \ldots 2000$. When carrying out the verification calculations, it is necessary to consider the parietal cavities over the shroud platforms. For verifying calculations, the best results are shown by the k - ω turbulence model.

Parallelization should be performed on the maximum possible number of processors, but one processor should account for at least 200 thousand elements of the computational mesh.

This method allows the creation of rational numerical models designed for verification calculations, which determine the detailed flow structure, which have minimal errors in determining the integral parameters, but also a low value of the speed up S (approximately 0.27...0.30).

5 CONCLUSIONS

This paper together with (Popov, 2018) describes the main stages and results of the work aimed at increasing the simulation efficiency (increasing accuracy and reducing the calculation time) of the workflow of uncooled axial turbines of aircraft engines using the RANS approach.

To obtain the results, more than 80 papers by different authors published over the last 5 years related to numerical simulation of the working process of axial turbines were studied. More than 1000 numerical models of axial turbines and their elements were created, calculated and analyzed. The obtained results were compared with the results of experiments or calculations using verified methods. All the results obtained during the study were processed and generalized using the methods of mathematical statistics.

As a result of the work, the following results were obtained:

1. A method for studying, improving and optimizing the working process of axial turbines using numerical simulation based on the RANS approach is proposed. The essence of the method lies in the fact that the search for the optimal configuration of the turbine is carried out using light computational models that are based on a simplified channel geometry (neglecting the parasitic cavities, fillets, etc.) and a light mesh of finite volumes. The application of such models makes it possible to create a rational optimization numerical models that allow estimating the trends in the variation of the integral parameters of turbines and having high values of the speed up parameter (up to 2.8). The obtained results should be checked with the help of verification numerical models that consider the real geometry of the channels and allow to determine the detailed flow structure with minimal errors in calculating the integral parameters.

2. A universal complex of parameters describing the finite volume mesh of numerical models of axial air turbines and based on the features of the flow structure in the channels is proposed. The complex includes: the number of elements along the characteristic sides of 2D-mesh topological blocks; dimensionless parameter y^+_{B2B1}, which determines the values y_{B2B1} and y_{FP1}, the cell expansion ratio along the height of the flow part ER_{FP}, the maximum cell aspect ratio along the height of the flow part MR_{FP}.

3. An original approach to the search for the best parameters of a finite volume mesh was proposed and implemented. In particular, the selection of the values of the parameters of 2D mesh should be carried out according to the calculated profile losses for individual blade rows or by integral parameters of turbines. The selection of ER_{FP} and MR_{FP} parameter values must be performed based on the distribution of flow parameters along the height of the flow part.

4. Recommendations were received on the setting the parameters for finite volume meshes and the selection of turbulence models for numerical models of the working process of axial uncooled turbines designed to perform optimization calculations. The number of B2B mesh elements must contain more than 6000 elements, the value of the y^+_{B2B1} parameter is 1, the value of the MR_{FP} parameter is 2000, and the ER_{FP} parameter value is less than 1.4. Simulation should be performed using the Spalart-Allmaras turbulence model.

5. Recommendations were received on the setting the parameters for finite volume meshes and the selection of turbulence models for numerical models of the working process of axial uncooled turbines designed to perform verification calculations. For verification calculations it is advisable to use two-dimensional B2B meshes with the number of elements greater than 21000. The values of the parameters for the distribution of the elements along the height of the flow part should be chosen from the interval: $ER_{FP} < 1.2$, $MR_{FP} = 1000 \dots 2000$. When carrying out verification calculations, parietal cavities over the shroud platforms should be considered. Simulation should be performed using k-ω turbulence model.

ACKNOWLEDGEMENTS

This work was supported by the Ministry of Education and scenes of the Russian Federation in the framework of implementation of the Program of increasing the competitiveness of Samara University among the world's leading and educational centers for 2013-2020 years.

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