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KNOWLEDGE LACK IMPACT ASSESSMENT OF THE SOURCE DATE ON NUMERICAL SIMULATION RESULTS OF OPERATIONAL PROCESS IN AXIAL FLOW TURBINE BLADE ROW

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ABSTRACT

The assessment of impact of uncertainty of the geometric and physical variables on the operational process in the blade row of the turbomachine was performed using the example of the untwisted cascade of the nozzle diaphragm. The simulation of the flow in the nozzle diaphragm was performed in the dedicated software suite NUMECA. The calculations performed allowed providing a qualitative and quantitative assessment in respect of the issue under consideration as well as specifying directions for the further development.

Keywords: turbine, source data, characteristic, section, loss factor, boundary conditions, simulation model, tolerance, errors.

1. INTRODUCTION

Nowadays the numerical methods of the gas dynamics are widely used by design, adjustment and modernization of the various turbomachines. In the materials of any specialist conference or scientific and technical publication one may always find an article on this subject [1...3]. By comparing the results of the numerical research and experiments one may notice that despite the good qualitative description of the relevant physical processes the quantitative discrepancies remain significant.

This fact confirms that the available flow simulation models describe the relevant process to a certain tolerance. In order to bring the calculation results closer to the reality it is needed to explore from which components an error consists and having understood the essence thereof to suggest the methods for reducing it.

By analysis of the numerical simulation process one may distinguish the following error components [4...6]:

- error of the physical model (error by describing the reality with some equation on the basis of a physical law);
- discretization (sampling) error;
- error of the numerical solution convergence;
- error related to rounding;
- source data error;
- software code error;
- user error.

The most of errors may be reduced by the use of the most advanced physical models available as of today, application of the high-level discretization and qualitative dissection of the computational domain by the finite-element grid. The probability of the user and programmer error may be minimized by means of improving their skills and multiple control of the code and simulation model.

The analysis shows that the most difficult task is to reduce the source data error. Indeed, by construction of the computational domain a user shall set its principal dimensions: chord or radii of the leading or trailing edge. They may be obtained from the drawing or measured. However, it turns out by the detailed consideration that the actual object size may differ. This is related to the manufacturing or measurement error. The similar situation is about the flow parameters. The true value of a flow rate, for example, may differ from the actual one by the measurement error value that may make up to a few percent. Thus, by simulating the medium flow in a turbomachine a user has a rather rough idea both of the channel dimensions and of the flow parameters at the boundaries. He can safely say that this magnitude is approximately equal to one or another value. Taking into account a large number of such variables the error introduced into the aggregate result may be significant and may exceed other kinds of errors by several times.

As of today many researches have come to understanding of this problem, however, solid studies on this subject are still rare and, as a rule, consider the change of only 2-5 parameters that can be easily varied during simulation [7...9].

In view of the foregoing it seems to be topical to evaluate in which way the change of the basic blade dimensions and flow parameters within tolerance will affect the gas-and-dynamic characteristics of the blade rows.

2. SIMULATION MODEL

At the preparatory stage of the study the analysis of the Russian industry standards [10] for manufacturing of the turbomachines components and impeller machines drawings made at the different enterprises was performed. As the result the most relevant geometrical dimensions of the blade rows and standard tolerance value have been specified Figure-1, Table-1

Table-1. Standard tolerances for the geometrical blade parameters.

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Blade chord	**C**	**±0, 3 mm**
Stagger angle	γ	±20′
Radius of trailing edge	r_2	-0,1 mm
Blade height	H	±0,15 mm

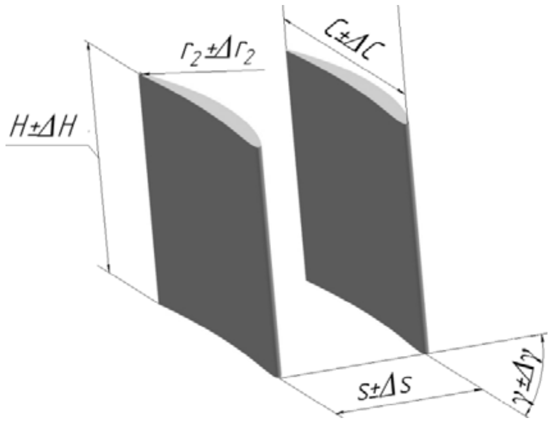

Figure-1. Design of the blade row with the most relevant dimensions.

The errors of physical quantities measurement by experimental study of the turbo machines were obtained through analysis of the measuring instruments used and the research data [11]:

Table-2. Limiting relative error of determination of the basic flow parameters by investigation of the cascades.

Flow pressure	p, pt	±0,4%
Flow temperature	Tt	±0,2%
Flow angle	α, β	±3%
Mass flow rate	$\dot{m}$	±2,4%

The assessment of impact of the geometric and physical variables uncertainty on the operational process in the blade row of an impeller machine was performed for a few essentially different from each other untwisted nozzle rows of the axial turbines of the constant cross-sectional height. Their complete geometry and comprehensive volume of the experimental data are presented in the atlas [12].

In order to perform the computational analysis a family of the computational models differing from each other through the dimensions indicated in the Figure-1. was constructed (the dimension difference does not exceed the range of the production tolerance or measurement error). Each computational domain consisted of the single blade passage with the periodic boundary conditions at the side walls.

The computational domain was divided into the finite elements by the hexahedral structural grid Figure-2. The total number of elements in all the models built made about 1, 5 million.

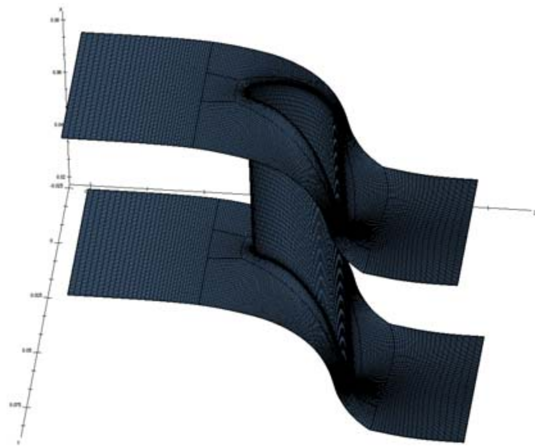

Figure-2. The computational domain with the finite-element grid applied.

The computational analysis was performed with the use of the software suite NUMECA [13]. During the analysis the following boundary conditions were applied: at the inlet the total flow pressure, temperature and direction were set. At the outlet - the static pressure the value of which was calculated according to the value of given isentropic flow rate at the cascade outlet λ_{1s}.

The air obeying the perfect gas law was used as the medium. It was taken into account that its hat capacity and viscosity vary depending on the temperature. By the analysis the turbulence model *Spalart-Allmaras* was used. As the result of analysis for each cascade under consideration we have obtained the change dependences for the specific coefficient of the profile losses at the mean diameter $\overline{Y_p}$, specific mass flow parameter $\bar{A}$ and specific flow angle $\overline{\alpha_1}$ at the cascade outlet at mean diameter on the isentropic flow rate at the cascade outlet λ_{1s}.

The specific mass flow parameter equals to:

$$\bar{A}_i = \frac{A_i}{A_{cr\_base}} \tag{1}$$

Where,

A_i - is the mass flow parameter at the i-th computational point;

A_{cr_base} - the mass flow parameter of the base nozzle diaphragm at $\lambda_{1s} = 1$.

The mass flow parameter was calculated according to the following formula:

$$A = \frac{\dot{m}\sqrt{Tt_0}}{pt_0} \tag{2}$$

where,

$\dot{m}$ - Mass gas flow rate though the blade row under consideration, kg/s;

Tt_0 - Total gas temperature at the blade row inlet, K;

pt_0 - Total gas pressure at the blade row inlet, Pa.

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The specific profile losses coefficient equals to:

$$\overline{Y_p} = \frac{Y_{pi}}{Y_{p\,cr\_base}} \qquad (3)$$

Where,
Y_{pi} - Loss coefficient at the i-th computational point;
$Y_{p\,cr\_base}$ - Loss coefficient of the base nozzle diaphragm at $\lambda_{1s} = 1$.

The coefficient of profile losses at the mean diameter ζ is calculated as follows:

$$Y_p = 1 - \varphi^2 \qquad (4)$$

Where,
$\varphi = \frac{c_1}{c_{1s}}$ - rate coefficient;
c_1 - flow rate at the exit from the blade row under consideration, m/s;
c_{1s} - isentropic flow rate at the exit from the blade row under consideration:

$$c_{1s} = \sqrt{2c_p\left(1 - \left(\frac{p_1}{p_{10}}\right)^{\frac{k-1}{k}}\right)}$$

The specific angle of the flow exit equals to:

$$\overline{\alpha_1} = \frac{\alpha_i}{\alpha_{cr\_base}} \qquad (5)$$

Where,
α_i - angle of the flow exit at the i-th computational point;
α_{cr_base} - flow exit angle in the base nozzle diaphragm at $\lambda_{1s} = 1$.

The angle of the flow exit from the cascade is calculated on the basis of the measured values of the axial c_{1a} and tangent c_{1u} projections of the flow rate at the exit from the cascade:

$$\alpha_1 = \arctan\frac{c_{1a}}{c_{1u}} \qquad (6)$$

The results obtained for different cascades do not fundamentally differ from each other. For this reason further on the results for only one most common cascade will be provided for illustrative purposes.

As the result of calculations the complete information about all the flow parameters at each point within the computational domain as well as integral values of the physical parameters has been obtained. Thus, in particular, in the Figures 3, 5 the fields of variation of the static pressure, streamlines at the mid-section of the blade channel are presented.

The represented fields are completely in line with the existing physical ideas and do not contain areas that could not be explained in theoretical terms [14]. This fact indirectly confirms the adequacy of the created computational model.

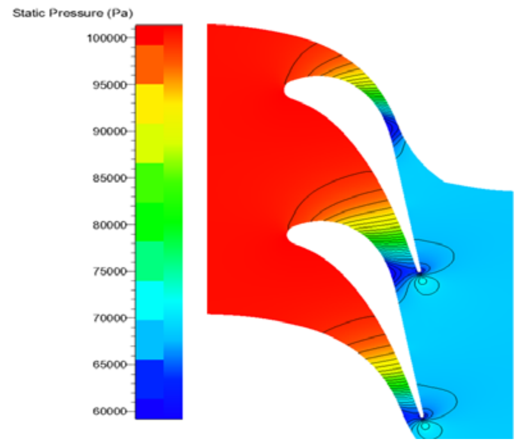

Figure-3. Field of static pressure at the mid-section of the nozzle diaphragm.

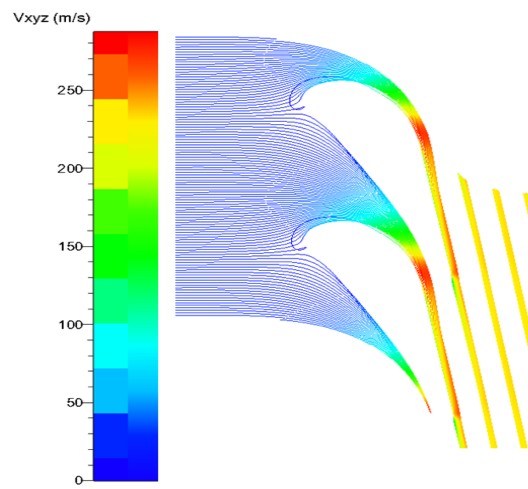

Figure-4. Streamlines at the mid-section of the nozzle diaphragm.

The results of comparison of the estimated and experimental dependences of change of the reduced coefficient of specific profile losses at the average diameter $\overline{Y_p}$ on isentropic flow rate at the cascade outlet λ_{1s} are presented in the Figure-6. As we can see, the experimental approximating curve [12] completely repeats the computational dependence trend which confirms the adequacy of the created computational models. At this point one should pay attention to the existing quantitative difference between the theoretical and experimental data. Such a large difference can be explained by the fact that the source of the experimental data [12] suggests an ambiguous interpretation of the information obtained. The test rig geometry is misunderstood, particularly with regard to the blades height.

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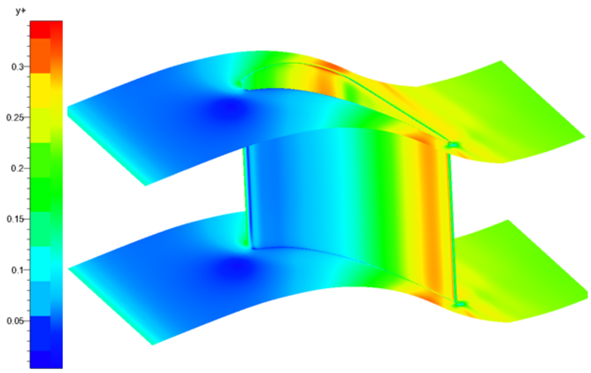


Figure-5. Distribution of the y+ parameter over the blade (c).

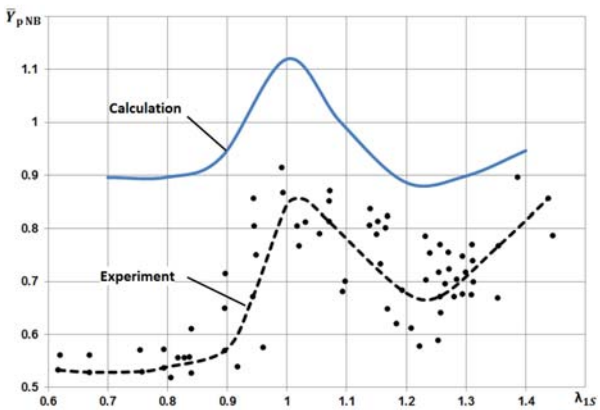


Figure-6. Dependence of the specific profile losses on the isentropic flow rate at the cascade outlet.

3. THE STUDY OF IMPACT OF the DEVIATION OF THE GEOMETRICAL DIMENSIONS ON THE GAS-DYNAMIC PERFORMANCE OF THE BLADE ROW

At the following stage the study of impact of deviation the basic blade row geometrical dimensions (chord, stagger angle, the trailing edge radius and height of the blade) on the estimated gas-dynamic characteristics was performed. For this purpose the assessment of impact of each geometrical parameter in particular on the estimated characteristics of the blade row under consideration was carried out.

It should be mentioned that changing of the nominal chord size, stagger angle and blade row height was performed with account for both the upper and lower maximum deviation Figure-1. As a rule, only the lower maximum deviation is indicated for the trailing edge radius, i.e., the trailing edge radius may be only lesser than the rated value. The reduction in radius results on the change of the blade section configuration at the trailing edge. It may be carried out in different ways:

- The suction side configuration is changed and the pressure side retains its shape Figure-7a In the further Figures this model is designated as (PS);
- The pressure side configuration is changed, the suction side is retained Figure-7б. In the further Figures this model is designated as (SS);
- The suction side and pressure side are changed but the shape of the camber line is retained Figure-7в. In the further Figures this model is designated as (CL).

Note. In all the Figure-7 the basic blade profile is shown as a dashed line.

Thus, in order to study the impact of the trailing edge radius on the blade gas-dynamic behavior in terms of each cascade under consideration the three computational models have been constructed.

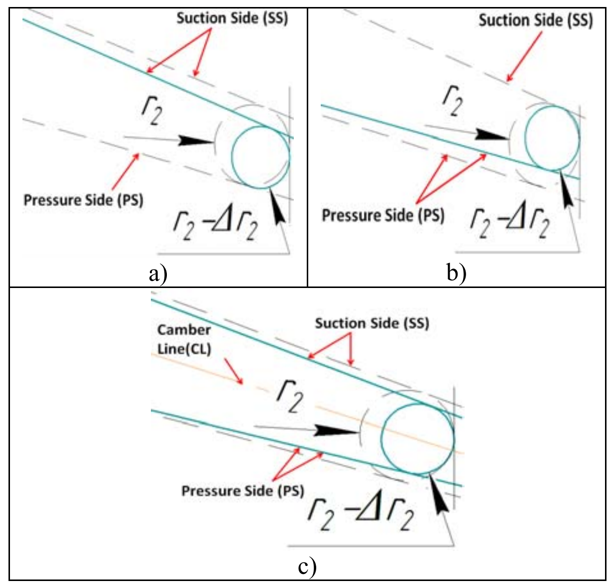
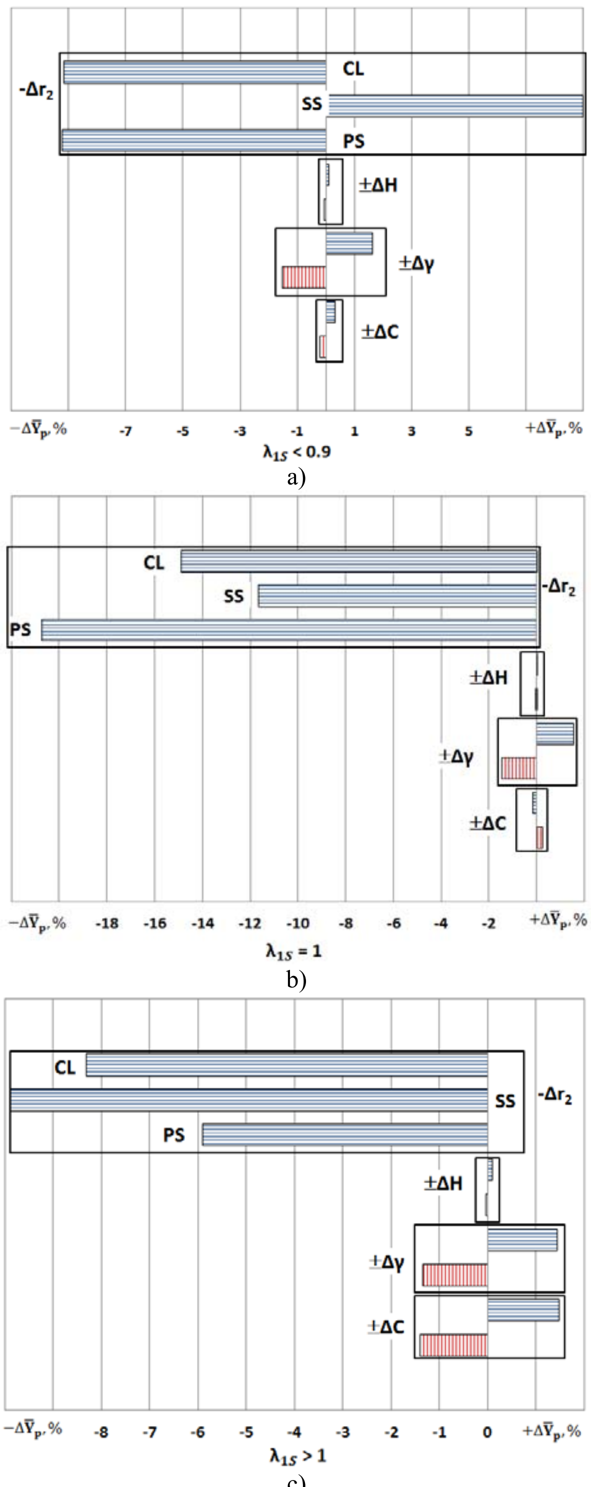


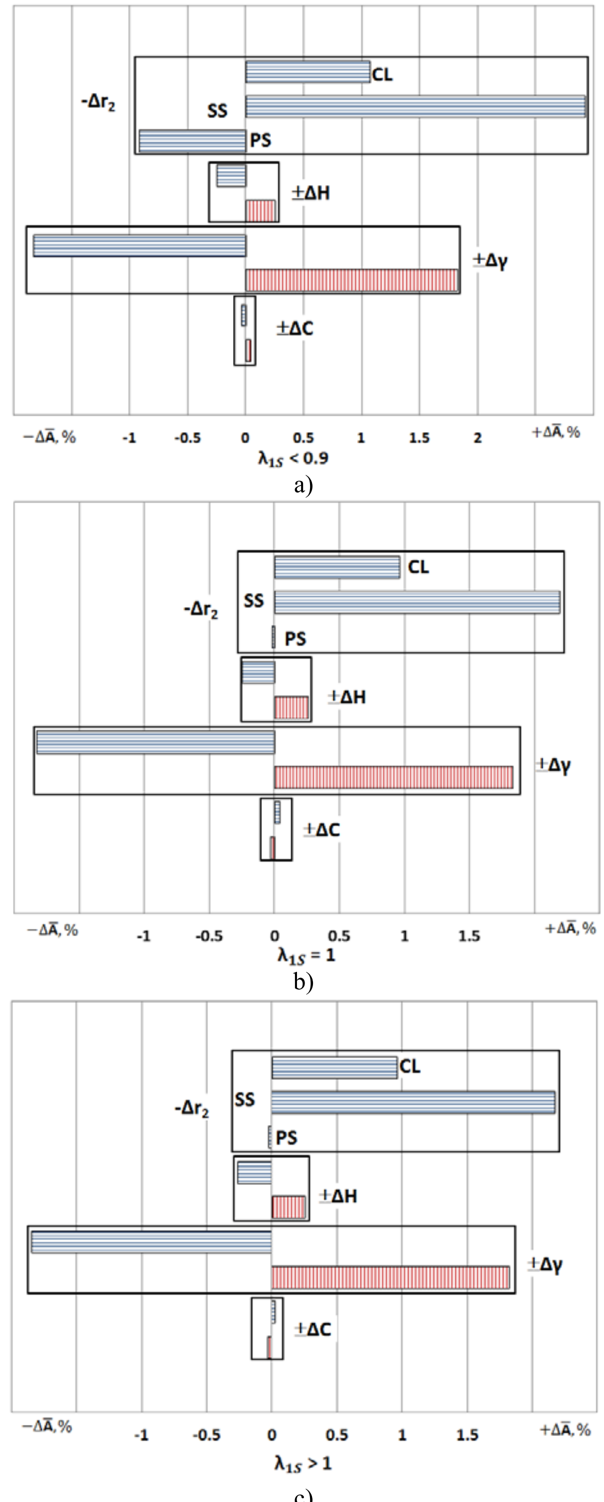
Figure-7. The variation of the trailing edge position aligned against the pressure side (a), suction side (b) and camber line (c) of the reference profil by the tolerance value.

As the result of the series of calculations performed there have been obtained the diagrams that graphically demonstrate the impact of change of all the geometrical dimensions within the tolerance ranges on the blade row behavior. The mentioned diagrams have been designed for specific profile loss coefficient $\overline{Y_p}$ at mean diameter, specific mass flow parameter $\overline{A}$, specific flow angle $\overline{\alpha_1}$ at the cascade outlet at mean diameter in three ranges: $\lambda_{1s} < 0,9$, $\lambda_{1s} = 1$, $\lambda_{1s} > 1$.



- plus tolerance; - minus tolerance

Figure-8. Impact of change of geometrical parameters of the blade row under consideration on the specific profile loss coefficient at λ1s.< 0,9 (a), λ1s = 1 (b), λ1s > 1 (c).



- plus tolerance; - minus tolerance

Figure-9. Impact of change of geometrical parameters of the blade row under consideration on the specific mass flow parameter at λ_{1s}.< 0,9 (a), λ_{1s} = 1 (b), λ_{1s} > 1 (c).

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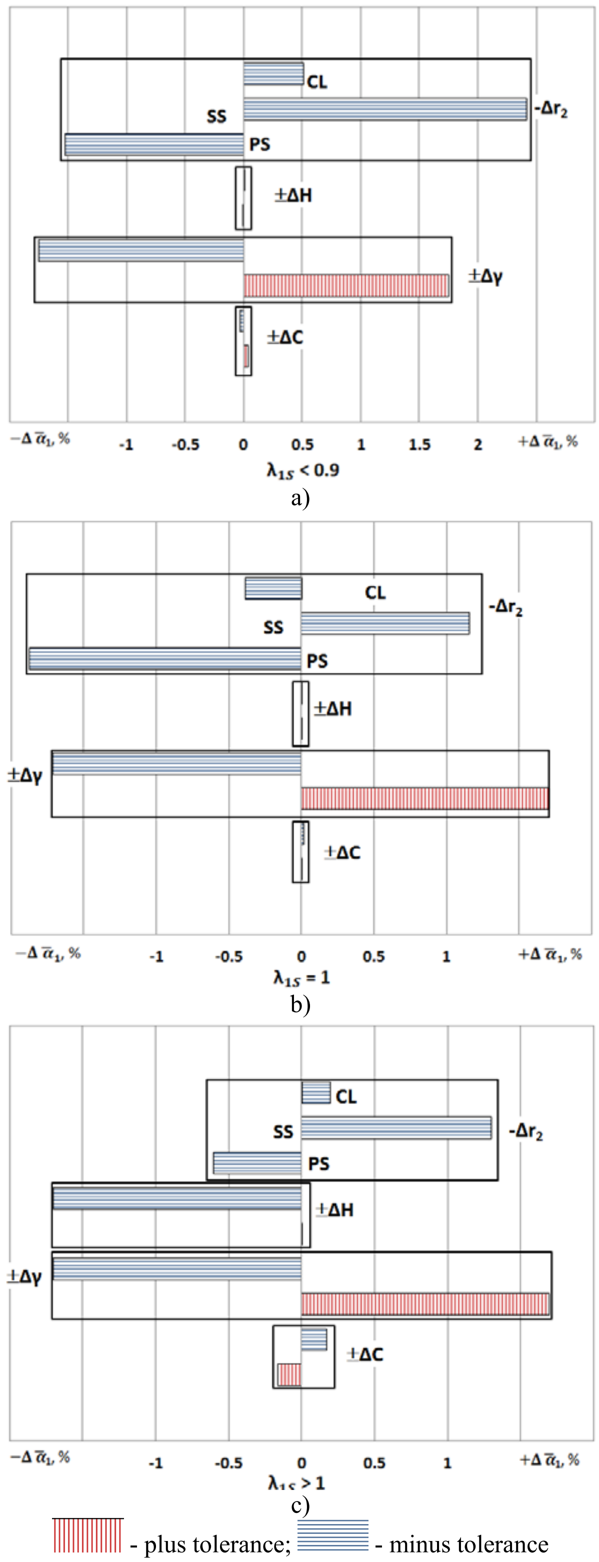

Figure-10. Impact of change of geometrical parameters of the blade row under consideration on the specific flow angle at λ_{1s}. < 0,9 (a), λ_{1s} = 1 (b), λ_{1s} > 1 (c).

As is seen from the figures provided the maximum impact on the blade row integral characteristics and its position is made by the railing edge radius, its position against the camber line and the stagger angle γ. The variation of the stagger angle γ within the tolerance range may result in the change of both mass flow parameter and the losses coefficient or angle of the flow exit by up to 3%. The impact of the trailing edge radius on the mass flow parameter and angle of the flow exit reaches about the same values. The trailing edge radius within the tolerance value has the most significant impact on the profile losses value. This value may be changed (reduced) by up to 20%. The loss reduction by the decrease in the trailing edge width is explained by the reduction of the edge losses that are directly proportional to its radius.

In order to assess the approximate aggregate impact of all the geometric parameters the computational models have been built on the basis of the analysis of diagrams in the Figures 8, 10. Totally, the two models have been built. The geometry of the “maximum model” was fitted in such a way that all the variable parameters took on the values increasing the mass flow parameter and reducing the losses coefficient. Another model - the “minimal” one - represented the opposite thereof. In it all the variables were selected to impair the row characteristics: they increased the losses coefficient and reduced the mass flow parameter. The results of comparison of the calculations according to the “maximum” and “minimum” models with the model all the dimensions of which corresponded to the design ones are presented in the Figure-11.

It is seen from the specified characteristic curves that by combination of the geometric parameters corresponding to the “maximum” model the estimated value of the losses coefficient differs from the losses coefficient computed for the geometry with nominal dimensions by more than 10%. The angle of the flow exit and the mass flow parameter - by 5%.

Also, the total change of losses has not reached the value of 20% which was reached by variation of the trailing edge radius only. This points to the fact that by the combined change of dimensions their impact shall be considered to be more complex and cannot be defined by simple summation only. Moreover, within certain combinations of the source data the same change (variation) may both impair and improve the row characteristics.

Thus, the designed “maximum” and “minimum” models are not the limiting cases and the difference between the deviations from the nominal values by accounting for the geometry change within the tolerance range may exceed the deviations in the Figure-11. Further on searching for the limit values of the blade row gas-dynamic characteristics shall be performed with involvement of the mathematical optimization techniques.

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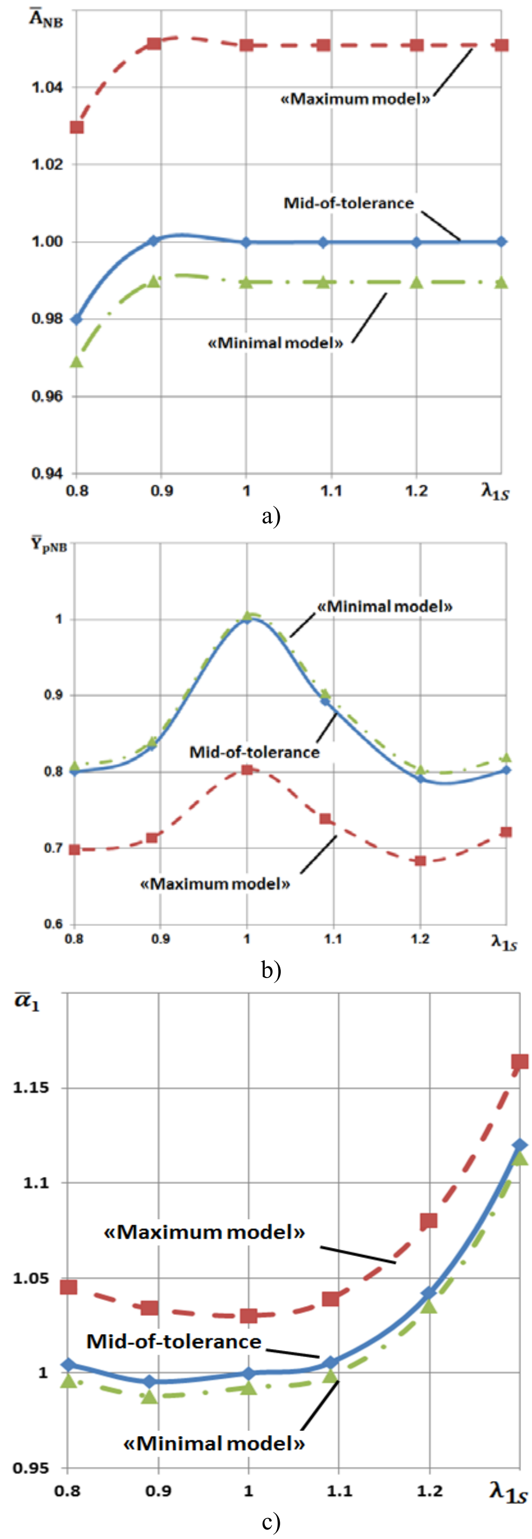

Figure-11. Dependence of the specific mass flow parameter (a), specific profile losses (b) and specific angle of the flow exit (c) on the isentropic flow rate at the cascade outlet for the “maximum”, “minimum” and "nominal model".

4. ANALYSIS OF IMPACT OF the FLOW PARAMETER DEVIATION FROM THE NOMINAL VALUE ON THE GAS-DYNAMIC BEHAVIOR OF the BLADE ROW

The analysis of the impact of deviation of the flow parameter value at the boundaries of the computational domains (total pressure pt and temperature Tt at the entry and static pressure p at the exit) on the design gas-dynamic characteristics of the blade rows was performed according to the procedure that is similar to the analysis of the geometry impact Figures 12, 14.

As is seen from the results presented the variation of the total temperature at the blade row inlet has little impact on its performance. The change of pressures at the entry and exit from the cascade exercises a more significant impact; however, even in this case the variation of the basic gas-dynamic characteristics does not exceed *0, 4%*. In the Figures 12, 14 you can find the diagrams of impact of the physical parameters variation within the measurement error range on the dependence of the specific profile losses coefficient at the average diameter$\overline{Y_p}$, specific mass flow parameter$\bar{A}$, and specific angle of the flow exit from CA $\overline{\alpha_1}$ at the average diameter on the isentropic flow rate at the cascade outlet. λ_{1s}.

5. SUMMARY

By analyzing the results obtained from the study performed the following conclusions may be drawn:

- the change of the flow physical parameter used as the boundary conditions (p_t, T_t, p) within the specified tolerance does not exercise a significant impact on the behavior of the blade rows under consideration and just result in shifting of the points at the relevant curves;
- the change of the value of each geometric parameter considered in this paper within the tolerance range to different extents affects the computed value of the gas-dynamic criteria of performance of the blade rows under study;
- the minimum impact (<0, 5%) on the change of the complex gas-dynamic parameters of the blade rows is made by the inaccuracy of the profile chord setting *b*;
- the maximum impact on the values of the complex gas-dynamic parameters of the blade rows is made by the inaccuracy of stagger angle γ_{CA} (up to 4%), change of the trailing edge position as the result of the radius reduction (up to 20%);
- in general, the total impact of the change of all the geometric parameters under consideration on the design characteristics is in consistency with the nature and extent of impact of each parameter in particular and may reach 5%.

The data obtained have shown that the uncertainty of the boundary conditions in the CFD-analysis exercises a significant impact on the quantitative estimates obtained with the use thereof. The difference may exceed *10%*.

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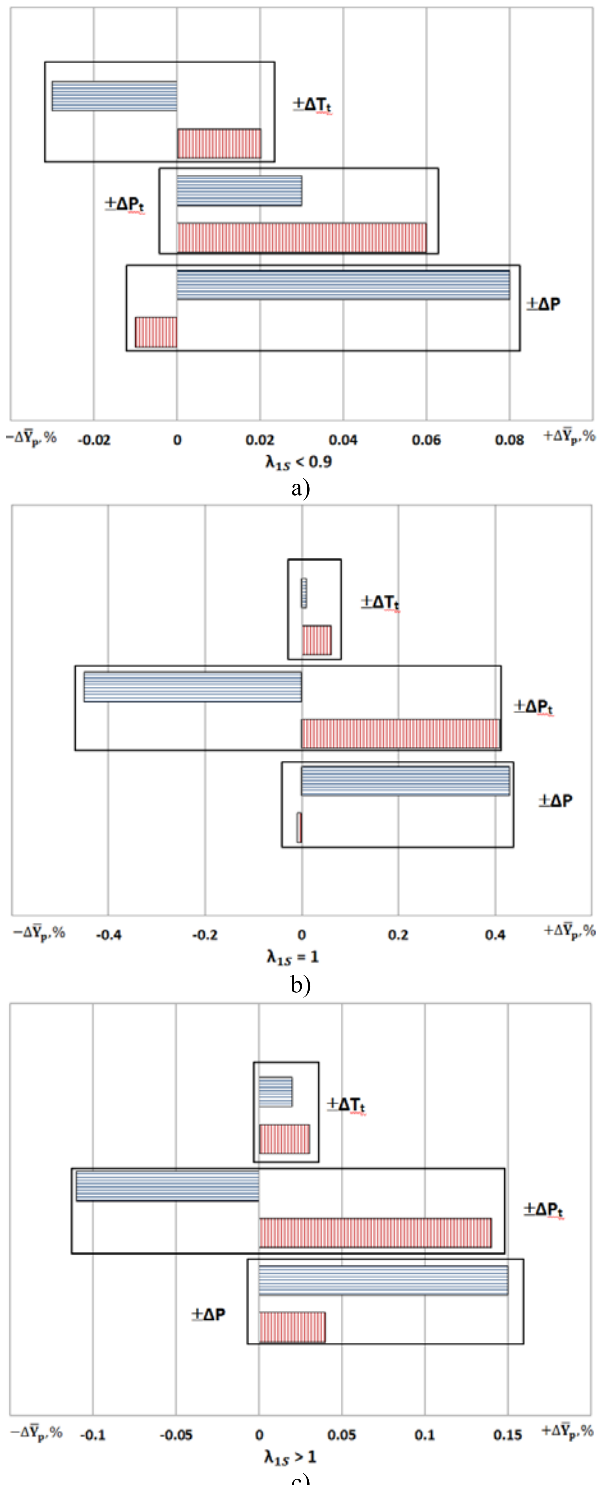
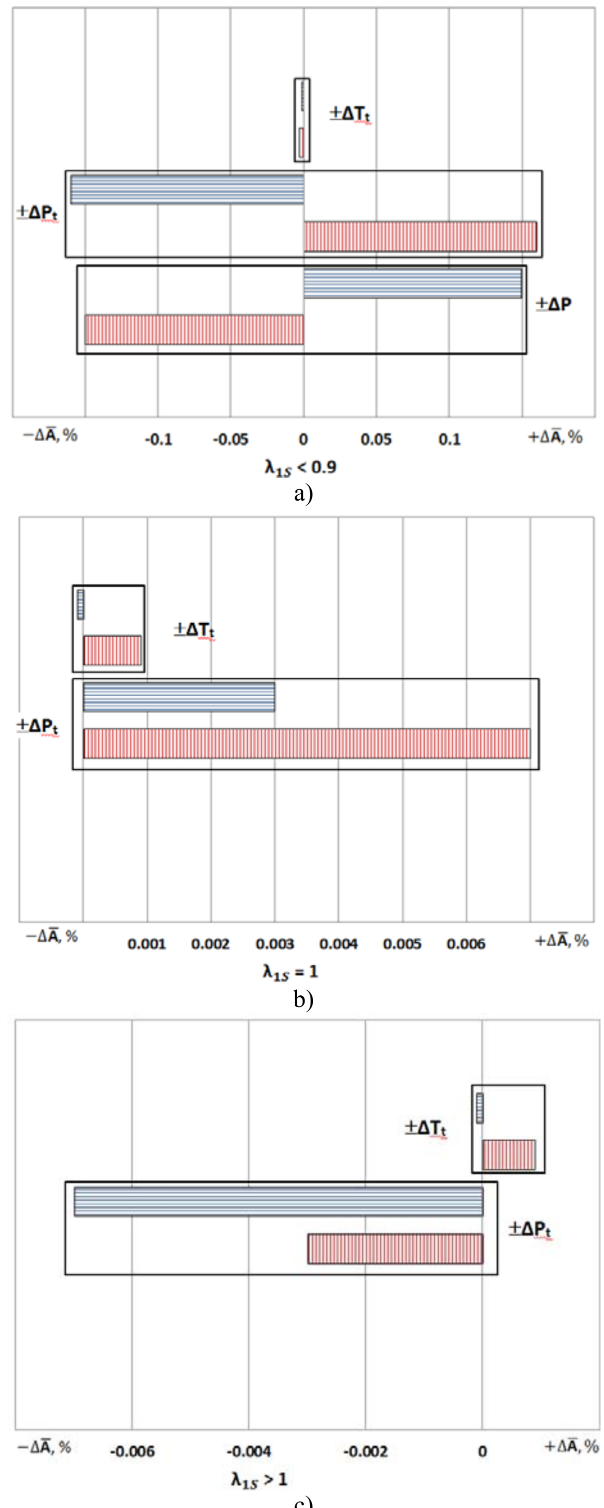


- plus tolerance; - minus tolerance

Figure-12. Impact of change of physical parameters of the blade row under consideration on the reduced profile losses coefficient at λ_{1s}.< 0,9 (a), $\lambda_{1s} = 1$ (b), $\lambda_{1s} > 1$ (c).



- plus tolerance; - minus tolerance

Figure-13. Impact of change of physical parameters of the blade row under consideration on the reduced flow rate parameter at λ_{1s}.< 0,9 (a), $\lambda_{1s} = 1$ (b), $\lambda_{1s} > 1$ (c).

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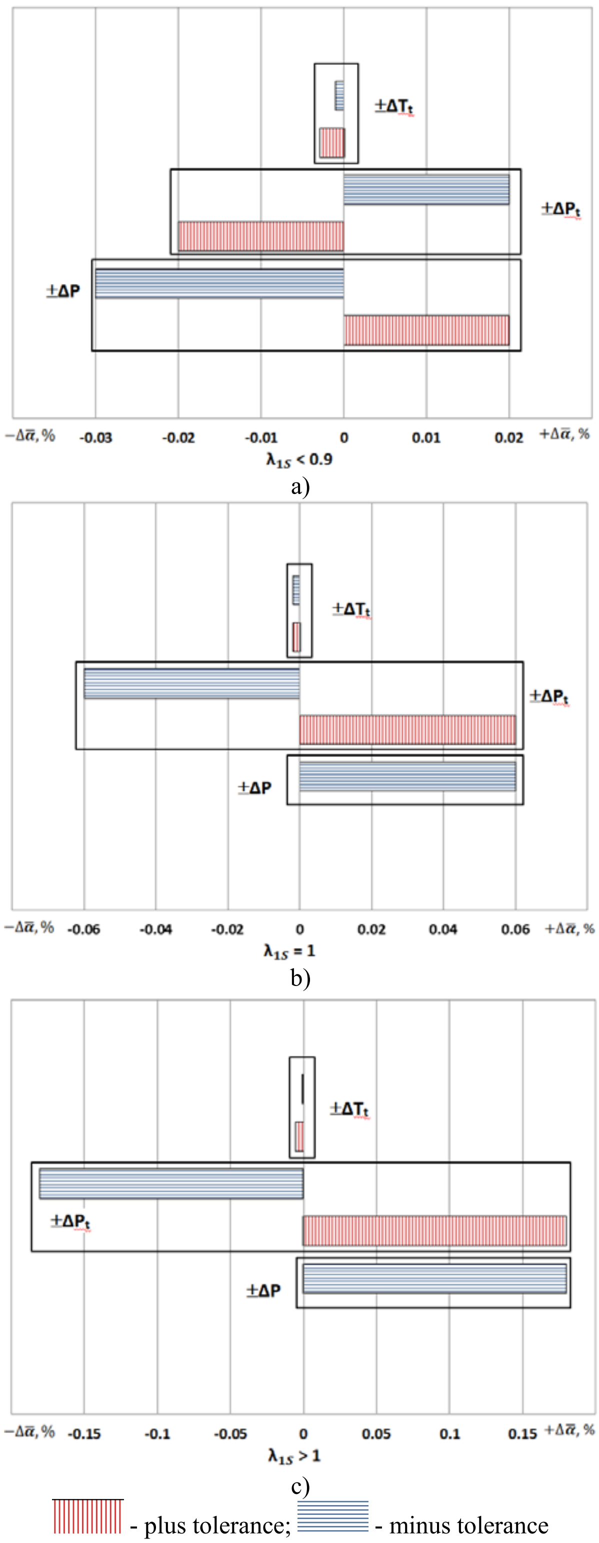

Figure-14. Impact of change of physical parameters of the blade row under consideration on the reduced angle of the flow exit from the grid at λ_{1s}.< 0,9 (a), λ_{1s} = 1 (б), λ_{1s} > 1(в).

The present paper is only the first step towards the solution of the specified task. In the future it is planned to develop the universal automatic algorithm that will allow by designing not to calculate the determined value of the required parameter but to specify the range within which it may fall. Such algorithm will allow improving the accuracy of estimation with the use of the CFD-techniques.

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CONFLICT OF INTEREST

The author confirms that this article content has no conflict of interest.

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