Determination of the velocity coefficient of a turbine nozzle diaphragm with partial blading of the runner

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Abstract. A method for determining the velocity coefficient of a nozzle diaphragm for a turbine with partial blading of the runner using the ANSYS software package is presented in the paper. The velocity coefficient of the nozzle diaphragm along the active arc length is distributed and plotted. The averaged values of the velocity coefficient of the nozzle diaphragm of the turbine with partial blading of the runner are determined. The dependences of the speed coefficients of the turbine nozzle diaphragm with partial blading of the runner in the range of \( \pi t \ 1,5 \div 2,5 \) and the degree of partiality in the range of \( 0,059 \div 1 \) are presented. The approximation resulted in an empirical dependence that takes into account the influence of the degree of partiality and the Mach number on velocity coefficients of the nozzle diaphragm with partial blading of the runner. The empirical dependence \( \varphi = f(M_1 t; \varepsilon) \) obtained in this work is essential for modeling variable modes and multi-mode optimization of low-flow turbines.

1. Introduction
Low-flow turbines (LFT) are reliable, productive, small-sized drives of various aggregates and devices. The experience of production and widespread usage of low-flow turbine stages determines the need to improve efficiency by simplifying and reducing the cost of manufacturing technology for blades and the stage as a whole. Improving the efficiency of low-flow turbines requires solving the problem of aerodynamic improvement of the flow part and calculating the optimal geometry and operating modes of low-flow turbines.

Today, theoretical and experimental material has been accumulated that allows us to summarize and formulate the general principles of the approach to the design of partial turbines. Turbines with partial blading of the runner occupy a special place. This turbine has a number of properties not previously seen in other LFT designs. In this regard, there is a need to study the processes occurring in the flow part of partial LFT with partial blading of the runner [1].

2. The goal of the work
The work’s purpose is to determine the velocity coefficient of the turbine nozzle diaphragm with partial blading of the runner by numerical simulation using the ANSYS CFX software package [2]. This will allow to consider each nozzle passage and determine its gas-dynamic characteristics. The total velocity
coefficient of the nozzle diaphragm averaged over the arc is possible to determine basing on the
determination of the coefficient \( \varphi \) in each nozzle passage.
The influence of the extreme channels does not allow to properly determine the value of the total
velocity coefficient of the nozzle diaphragm by the usual calculation method due to a large number of
influencing parameters and factors. Therefore, it is viable to create a model for determining the
coefficient \( \varphi \) by approximating the experimental data obtained on a simulation bench using the ANSYS
CFX software package. The empirical dependence should take into account the influence of the degree
of partiality and the Mach number, and the possibility of its using in modeling in multi-mode
optimization of low-flow turbines.

3. Formulation of the problem
A feature of the low-flow turbine with partial blading of the runner shown in Figure 1 is the design of
the runner. When the nozzle diaphragm with blades distributed along the arc of 360° is presented, the
blades are located only on a part of the circle of the runner, forming an active arc, and the solid body of
the metal disk occupies the inactive arc.

Figure 1. Examples of centripetal turbines: all-wheel drive and partial runner blading.

In such a stage, the working fluid is supplied to the nozzle passages around the entire circumference of
the nozzle device (ND), as in conventional turbines with a full admission. The flow is similar to the flow
in the nozzles of traditional turbines in the nozzle passages located opposite the active arc of the runner.
Moreover, the flow is limited by the minimum dimensions of axial and radial clearances in nozzles
located opposite the solid disk of the runner. Consequently, the movement of the working fluid in these
nozzles will be determined by its flow rate and the direction of leakage through the gaps. The more
commensurable the area of the nozzle exit section and the transverse annular gap between the crowns,
the more intensive the flow leaving the nozzles in the gaps or eject an inactive medium from them.
Clearances provide constant working fluid leakage in the inactive arc runner. These circumstances
should be taken into account when assessing the value of the suction of the working medium from
inactive to the active arc region.

The following initial parameters are known in a three-dimensional gas-dynamic calculation [3]: working
fluid pressure (air) at the inlet to the nozzle diaphragm \( P_0^* = 0.15 \div 0.25 \text{ MPa} \), working fluid temperature
at the inlet to the nozzle \( T_0^* = 293 \text{ K} \), the pressure of the working fluid at the exit of the wheel \( P_2 = 0.1 \text{ MPa} \),
the gas constant of the working fluid \( R = 287 \text{ J/kg \cdot K} \), the isentropic index of the working fluid \( k = 1.4 \),
the rotational speed of the runner \( 30 \ 000 \ \text{min}^{-1} \). The diameter of the runner \( D = 50 \text{ mm} \), the degree
of radiality - 0.55, the nozzle diaphragm has 27 blades. The main geometric parameters: the angle of
exit of the flow from the nozzle diaphragm \( \alpha_1 = 16.31^\circ \), the angle of entry of the flow into the runner
\( \beta_1 = 90^\circ \), the angle of exit of the flow from the runner \( \beta_2 = 42^\circ \). The most suitable turbulence model
for the selected model is SST (Shear Stress Transport). The SST model is a set of turbulence models: the
free flow is calculated by the k-epsilon equation and in the region near the walls by the k-omega equation.

The calculation model is a combination of flowing parts of the nozzle diaphragm, runner, radial and axial clearances with labyrinth seals. The runner has a different number of blades, depending on the degree of partiality - one, three, six, thirteen, and thirty-four blades. The computational grid generated for the turbine stage under study complies with all the main recommendations for ensuring the required reliability of the calculation results [4]. A thickening of the grid was created near the streamlined surfaces. This is necessary to increase the quality of the calculation of parameters in the boundary layer. The solution method is the Transient Rotor Stator unsteady task.

4. Results

Three-dimensional calculations of turbine stages with varying degrees of partiality made it possible to determine velocity fields at rotation frequencies of 30,000 min⁻¹. In order to average the velocity coefficient of the nozzle diaphragm φ, 10 positions of the runner were examined by the angle of rotation relative to the nozzle diaphragm when the wheel rotates counterclockwise to the left, Fig. 1. The value of the total velocity coefficient of the nozzle diaphragm φ at a specified time moment is determined by the averaged value of the velocity coefficients in each nozzle passage of the active arc. Averaging the total velocity coefficient of the nozzle diaphragm over 10 characteristic time instants determines the velocity coefficient of the nozzle diaphragm φ. Table 1 shows the values of the velocity coefficients of the nozzle passages and the nozzle diaphragm of the turbine with six blades on the runner. Parameters were averaged using the areaAve method (over the area). When the extreme left channel is opened up to 50%, five channels of the nozzle device are involved in the active arc. As one opens the extreme left channel, the right one will close. The value of the velocity coefficient of the middle nozzle passage is relatively constant. The value of the velocity coefficients of the extreme nozzle passages varies depending on the degree of openness. The total velocity coefficients of the nozzle diaphragm are determined at each time moment.

Table 1. The main results of a three-dimensional gas-dynamic calculation with six blades on the runner.

| Nozzle passage number, N | The degree of openness of the extreme left channel of the active arc, F |
|------------------------|--------------------------------------------------|
|                        | 10%     | 20%     | 30%     | 40%     | 50%     | 60%     | 70%     | 80%     | 90%     | 100%    |
| 1                      | P₀, MPa | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    |
|                        | c₁, m/s | 58.9    | 57.23   | 56.63   | 58.83   | 67.13   | 85.06   | 107.65  | 130.05  | 184.26  | 193.02  |
|                        | ζ      | 0.224   | 0.217   | 0.216   | 0.225   | 0.257   | 0.326   | 0.412   | 0.498   | 0.706   | 0.733   |
| 2                      | P₀, MPa | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    |
|                        | c₁, m/s | 209.2   | 225.86  | 238.39  | 242.45  | 237.86  | 232.35  | 223.88  | 221.07  | 229.83  | 237.48  |
|                        | ζ      | 0.795   | 0.858   | 0.909   | 0.926   | 0.861   | 0.890   | 0.857   | 0.847   | 0.880   | 0.902   |
| 3                      | P₀, MPa | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    |
|                        | c₁, m/s | 237.7   | 228.25  | 220.31  | 218.66  | 215.59  | 218.21  | 231.1   | 245.48  | 238.38  | 233.81  |
|                        | ζ      | 0.903   | 0.867   | 0.840   | 0.835   | 0.826   | 0.836   | 0.885   | 0.940   | 0.913   | 0.888   |
| 4                      | P₀, MPa | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    |
|                        | c₁, m/s | 231.4   | 232.12  | 225.86  | 225.90  | 238.12  | 250.10  | 250.34  | 240.55  | 231.83  | 234.95  |
|                        | ζ      | 0.879   | 0.882   | 0.861   | 0.862   | 0.912   | 0.958   | 0.959   | 0.921   | 0.888   | 0.892   |
| 5                      | P₀, MPa | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    |
|                        | c₁, m/s | 227.3   | 225.74  | 237.68  | 249.17  | 249.76  | 241.04  | 232.9   | 226.49  | 223.49  | 221.83  |
|                        | ζ      | 0.864   | 0.857   | 0.907   | 0.951   | 0.957   | 0.923   | 0.889   | 0.867   | 0.856   | 0.850   |
| 6                      | P₀, MPa | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    |
|                        | c₁, m/s | 228.7   | 238.49  | 239.35  | 232.24  | 221.82  | 206.86  | 210.45  | 213.72  | 216.82  | 224.57  |
|                        | ζ      | 0.869   | 0.906   | 0.913   | 0.887   | 0.850   | 0.792   | 0.806   | 0.819   | 0.830   | 0.853   |
| 7                      | P₀, MPa | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    | 0.13    |
|                        | c₁, m/s | 230.9   | 234.84  | 231.45  | 237.71  | 195.26  | 190.26  | 195.26  | 190.26  | 195.26  | 190.26  |
|                        | ζ      | 0.877   | 0.892   | 0.883   | 0.831   | 0.7478  | 0.502   | 0.467   | 0.432   | 0.406   | 0.380   |
Figures 2–5 show graphs of the breakdown of the velocity coefficient \( \phi \) of the nozzle diaphragm along the length of the active arc of the turbine with partial blading of the runner. The graph is divided into zones: the extreme left channel, the core of the flow and the extreme right channel. The red graph shows the value of the coefficient \( \phi \) in the nozzle passage. The value of the coefficient in the flow core is relatively constant and varies depending on the position of the inlet lump of the runner blades relative to the nozzle passages. As the extreme left channel opens, the coefficient \( \phi \) increases reaching a maximum at 100% opening. When the extreme right channel is closed (narrowing the passage section of the channel) to the size of the nozzle passage neck \( a_2 \), the coefficient \( \phi \) first increases. When the extreme right channel is closed further, the coefficient \( \phi \) decreases, since the expanded gas in the oblique section begins to pass through a narrower section than the neck of the nozzle passage \( a_2 \) that leads to a decrease in speed. The green line shows the average value of the total velocity coefficient of the nozzle diaphragm along the arc. The characteristic features in the extreme nozzle passages are the same in all stages of the turbine with partial runner blading. The difference in the geometry of the curve of the extreme right channel indicates a different relationship between the degree of openness of the extreme left and right channels with different runner blading. Figures 6 ... 8 show the velocity fields of turbine stages with one, three blades and a three-dimensional model of a turbine stage with current lines.

![Figure 2](image1.png)

**Figure 2.** Dependence of the velocity coefficient of the nozzle diaphragm along the length of the active arc of the turbine with partial blading of the runner with one blade on the runner.

![Figure 3](image2.png)

**Figure 3.** Dependence of the velocity coefficient of the nozzle diaphragm along the length of the active arc of the turbine with partial blading of the runner with three blades on the runner.
Figure 4. Dependence of the velocity coefficient of the runner along the length of the active arc of the turbine with partial blading of the runner with six blades on the runner.

Figure 5. Dependence of the velocity coefficient of the runner along the length of the active arc of the turbine with partial blading of the runner with thirteen blades on the runner.

Figure 6. Turbine speed field with 1 blade on the runner.
The value of the velocity coefficient of the nozzle diaphragm is also determined by the variation range of $\pi t$ from 1.5 to 2.5 to determine the dependence on the Mach number. Figure 9 presents graphs of the dependence of the velocity coefficient of the nozzle diaphragm on the Mach number for various degrees of partiality. The value of the velocity coefficient of the nozzle diaphragm grows after increasing in the degree of partiality. The maximum value of the nozzle diaphragm velocity coefficient is achieved in the range of the Mach number 0.55 ÷ 0.60. In this area, the optimal value is located, where the value of profile losses is minimal. This is characterized by the presence of local supersonic zones on the convex surface of the profile and shock waves. [5].
The mathematical model for determining the coefficient \( \phi \) depending on the main determining factors \( \varepsilon \) and \( M_{1t} \) can be expressed: \( \phi = \varphi(\varepsilon, M_{1t}) \). To obtain this dependence, the values of the coefficient \( \phi \) are used in the range of \( \pi_t \) from 1.5 to 2.5 during the numerical experiment.

The two-parameter dependence \( \varphi = \varphi(\varepsilon, M_{1t}) \) shown in Figure 10 is approximated by a cubic polynomial:

\[
\varphi = 0.1502 + 0.2148 \cdot M_{1t} + 1.506 \cdot \varepsilon - 2.23 \times M_{1t}^2 - 2.035 \cdot \varepsilon \cdot M_{1t} - 1.486 \cdot \varepsilon^2 + 0.6226 \cdot M_{1t}^3 + 1.042 \cdot M_{1t}^2 \cdot \varepsilon + 0.5765 \cdot M_{1t} \cdot \varepsilon^2 + 0.6007 \cdot \varepsilon^3 \tag{1}
\]

A comparison of the data obtained during the numerical experiment with the calculation by formula (1) showed that the model presented in the work is adequate for determining the coefficient \( \varphi \) since the discrepancy between the calculation and the numerical experiment does not exceed 2.5\% in a wide range of the degree of partiality and mode parameter. Therefore, there is every reason to consider the created two-parameter dependence \( \varphi = \varphi(\varepsilon, M_{1t}) \) adequate to recommend it for practical use in modeling variable modes and multi-mode optimization of low-speed turbines.

5. Conclusion

Analysis of the results of three-dimensional modeling leads to the following conclusions:
- to determine the total velocity coefficient of the nozzle diaphragm, it is necessary to take into account the values of the velocity coefficient of each nozzle channel, as well as the influence of the extreme channels;
- averaging of the total velocity coefficient of the nozzle diaphragm at various degrees of partiality has to be carried out by the characteristic positions of the runner by the angle of rotation relative to the nozzle diaphragm;
- the obtained values of the velocity coefficient of the nozzle diaphragm at various degrees of partiality in the range of $\pi t$ from 1.5 to 2.5 are approximated by a cubic polynomial (1);
- A comparison of experimental data with the calculation according to formula (1) showed that the difference lies within the experimental error and does not exceed its value by more than 2.5%. This result can be considered satisfactory.

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