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Separation near the bushing of the flow in the outlet nozzle of the steam turbine at the low-flow rate modes

Oleksandr Shubenko
Department of Optimization of Processes and Designs of Turbomachines
Anatolii Pidhornyi Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine, Kharkiv, Ukraine
ORCID 0000-0001-9014-1357

Svitlana Alyokhina
Department of Optimization of Processes and Designs of Turbomachines
Anatolii Pidhornyi Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine, Kharkiv, Ukraine
ORCID 0000-0002-2967-0150

Volodymyr Goloshchapov
Department of Optimization of Processes and Designs of Turbomachines
Anatolii Pidhornyi Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine, Kharkiv, Ukraine
ORCID 0000-0002-2075-5326

Olga Kotulska
Department of Optimization of Processes and Designs of Turbomachines
Anatolii Pidhornyi Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine, Kharkiv, Ukraine
ORCID 0000-0002-5902-9313

Daria Senetska
Department of Optimization of Processes and Designs of Turbomachines
Anatolii Pidhornyi Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine, Kharkiv, Ukraine
ORCID 0000-0003-2527-4529

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Abstract: The paper considers the movement of steam flow from the working wheel of the last stage with a large fanning to the outlet nozzle of a steam turbine, considering the conditions for the formation of the separation near the bushing in a wide range of mode changes. An assessment was made of the initiation and development of the separation near the bushing in the space of the outlet nozzle of the steam turbine. To analyze the formation of the movement of the working medium in the free space of the outlet nozzle, an axisymmetric flow model is used, which is described by the equation of the hyperboloid of rotation.

Keywords: steam turbine, low-flow rate mode, outlet nozzle, separation near the bushing.

1. Object and subject of research

The object of the study is the output nozzle of a powerful steam turbine, and the subject of the study is the movement of the main flow in the space of the inlet part of the output nozzle of a powerful steam turbine.

2. Target of research

Since the last stages of cogeneration turbines are predominantly operated in the area of low-flow rate modes, the aim of this study is the theoretical and experimental representation of the movement of the main flow in the space of the inlet part (free from stiffening ribs) of the outlet nozzle of the cogeneration turbine.

3. Literature analysis

Steam removal after its exit from the last stage into the condenser is carried out by an outlet nozzle connecting the body of the low-pressure part to it. An analysis of the designs of the outlet nozzles of high-power turbines allows us to distinguish the following typical variants for their execution [1]:

– the outlet nozzle with a sudden expansion of the flow behind the working wheel of the last stage (Fig. 1, a). These design variants are used on turbines with a capacity of 100 MW or less (for example, T-100/120-130 turbine).

– the outlet nozzle with a small cylindrical visor with a length of at least 10 % of the rotor blade length, installed in the peripheral part over the riding ring (Fig. 1, b). There are design variants with a conical visor (taper approximately 30 – 35 °) installed in the peripheral part of the last stage with a length less than half the length of the rotor blade. Such a visor forms a small axial diffuser behind the last stage, which makes it possible to increase the heat drop generated in the last stage at the nominal operating mode of the stage (for example, the turbine T-250/300-240).

– the outlet nozzle with a radial diffuser with or without dividing blades. It is used in high power condensing type turbines, such as K-500-23.5, K-800-240, K-1000-60/1500 for nuclear power plants and the like (Fig. 1, c). These turbines are operated mainly in base mode.

– the outlet nozzle with a conical diffuser installed behind the last stage (Fig. 1, d) of the T-180/220-130 turbine.

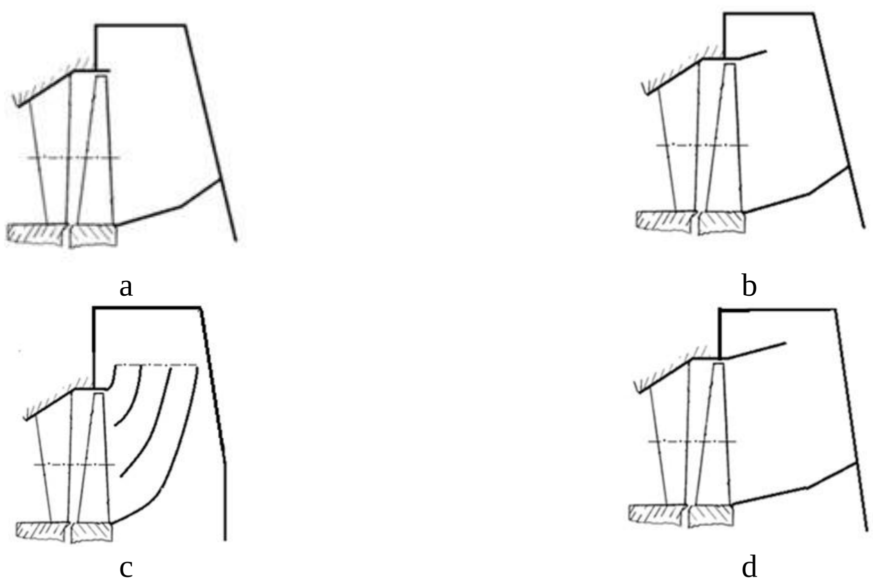
a b
c d

Fig.1. Designs of outlet nozzles of high-power turbines [1]

Outlet nozzles of different types are designed for operation of the turbine last stage in the nominal mode, in which the steam outlet from it has an axial direction at the middle diameter, and the deviation from it should be small, determined by the change in the law of swirling of the outlet angles of the flow along the radius working wheel. This should ensure maximum diffuser efficiency at the nominal operating mode of the last stage.

Stiffening ribs installed in the space of the outlet nozzle ensure minimal energy losses during axial flow out of the working wheel and significantly affect its structure and, as a result, the energy characteristics of the nozzle in low-flow rate modes under conditions of strong flow swirl at the outlet flow from the working wheel [2 – 4].

Publications [5 – 10] are devoted to the study of the outlet nozzles of wet-steam turbines of various design variations, in which the conditions for the flow in the outlet nozzle [6, 7], the causes of the occurrence of vortex flows [8], and the aerodynamics of the flow [11, 12, 13] are described. All results are obtained by calculation using CFD modeling.

4. Research methods

The variety of design variants for the outlet nozzles allows, at the first stage, to consider the movement of steam in two versions:

– the movement with a sudden expansion of the flow behind the working wheel in the outlet nozzle space free from stiffening ribs;

– the movement of the working medium in the annular space of great length behind the working wheel. The annular space is formed by an outer impenetrable contour and a bushing.

The working medium is considered as incompressible.

The axial flow at the outlet of the working wheel has a stable form of movement, i. e. at the nominal operating mode of the last stage. At point 0 of the root section of the rotor blades trailing edges, the flow separation is possible only if the bushing has a circumferential velocity component C_{2u}. The movement of the root stream of the working medium in the direction of the velocity vector $\bar{C}_2$ when $C_{2u} > 0$ leads to the flow separation from the bushing surface.

Interpreting the movement of the flow behind the working wheel as the movement of individual streams, the direction of which changes along the radius with a change in the angle β_2, we can assume that they are independent of each other.

Considering the movement of a rotating flow behind the guide vanes of a stage with a large rim clearance, in which the pressure is constant along the radius, I. I. Kirillov [9], based on the theory of helical flow, showed that this movement is linear within the axial clearance and can be described by an equation representing a hyperboloid of rotation. In this case, the streams, including boundary ones, in the meridional planes are hyperbolas. Their origin is located at the trailing edges of the rotor blades (Fig. 2, a).

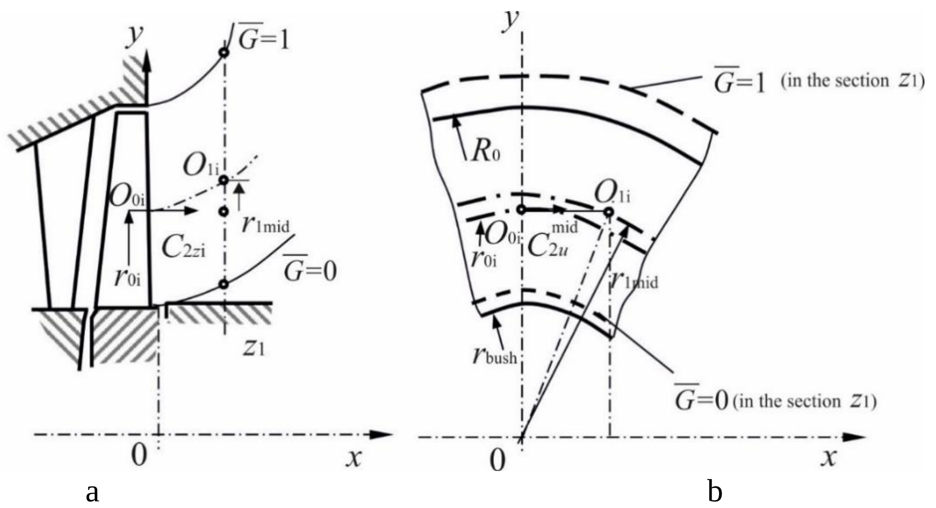

Fig. 2. The movement of the rotating flow in the space behind the working wheel:
a – in the meridional plane; b – in Oxy plane at a distance z_1 from the trailing edges of the rotor blades.

Since the movement of each stream after leaving the working wheel is linear in the direction of the velocity vector $\bar{C}_2$ and, neglecting the losses from their mutual influence, the movement of the flow in free space can be assumed to be linear, described by the hyperboloid equation [14]

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}-\frac{z^2}{c^2}=1, \tag{1}$$

where a, b, c are constants.

For the section $z=0$, located on the trailing edges of the working wheel, equation (1) takes the form

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}=1 \tag{2}$$

and the boundary conditions for each stream will take the form: the parameter $y=b=r_0$ at $x_0=0$; the parameter $x_0=a=r_0$ at $y_0=0$, and the equation (2) for each stream at a radius r_{0_i} is a circle

$$x_0^2+y_0^2=r_0^2.$$

To determine the constant c in the equation (1), its solution for the average flow stream in the section z_1, remote from the trailing edges, is found taking into account the movement of the stream element that flows from the working at a radius r_{0_i} in Oxz plane perpendicular to the radius (Fig. 2, b), in time τ: $z_1=C_{2z_i}\cdot\tau$, $x_1=C_{2u_i}\cdot\tau$. In this case, the coordinate $y_1=y_0$ remains constant. In time τ, the stream will move from a circle with radius r_{0_i} to a circle with radius r_{1_i} in a plane located in section z_1 (from point M_0 to point M_1, Fig. 2, b).

The stream radius r_1 in the section z_1 is equal to

$$\frac{x_1^2+y_1^2}{r_0^2}-\frac{z_1^2}{c^2}=1$$

or

$$\frac{\left(C_{2u_i}\cdot\tau\right)^2+r_0^2}{r_0^2}-\frac{\left(C_{2z_i}\cdot\tau\right)^2}{c^2}=1.$$

Hence the constant c is equal to

$$c^2=\left(\frac{C_{2z_i}}{C_{2u_i}}\right)^2\cdot r_0^2.$$

Substituting the values a, b, c into (1) and considering that $x_i^2+y_i^2=r_i^2$, we obtain to determine the radius of the streamlines in the section z

$$r_i^2=r_{0_i}^2+z^2\cdot\left(\frac{C_{2u}}{C_{2z}}\right)_i^2. \tag{3}$$

The ratio $\left(\frac{C_{2u}}{C_{2z}}\right)_i$ for the i-th stream of the main flow is a function of the angle α_{2_i}, which is equal to 90 ° at the nominal mode.

With a decrease in $\overline{Gv}_2$, its value changes in accordance with a change in the value of the radius of the separation near the bushing at the trailing edges of the working wheel (from r_{bush} at $\overline{Gv}_2$ = 0.9·R_{out} to 0.95·R_{out} at $\overline{Gv}_2$ = 0.04) [15]. The moment of the appearance of flow separation from the flow bushing in the root section of the blades is designated as $\overline{Gv}_{2z=0}$.

The ratio of the components $\left(\frac{C_{2z}}{C_{2u}}\right)_i$ of the velocity $\bar{C}_2$ on the middle line of the main flow at the outlet of the working wheel was obtained for the group of studied models of large fanning stages with geometric characteristics:

$\bar{r}_{\text{bush}}$ is the relative radius of the bushing, takes values $\bar{r}_{\text{bush}}$ = 0.442 ÷ 0.647;

$\beta_{2\text{eff}}$ is the effective exit angle of the flow from the working wheel, $\beta_{2\text{eff}}$ = 22°53′ ÷ 28°30′;

γ_{incl} is the angle of inclination of the meridional bypass in the guide vanes, γ_{incl} = 0° ÷ 50° [16], depending on $\overline{Gv}_2$ and is represented as a function $\left(\frac{C_{2z}}{C_{2u}}\right)_{\text{mid}} = f(\overline{Gv}_2)$ in Fig. 3.

Equation (3) makes it possible to determine the structure of the flow with known characteristics of its movement at the low-flow rate modes, namely:

– the change in the position of the boundary line $\bar{G}$ = 0 (the inner boundary of the rotating flow separating the separation near the bushing from the main flow), the beginning of which at the trailing edges of the rotor blades corresponds to the radius r_{0_A};

– the relative volumetric flow rate $\overline{Gv}_{2_{z_A=0}}$, corresponding to the moment of initiation of the separation near the bushing in the root section of trailing edges of rotor blades;

– the distribution of the ratio of the components (C_2z/C_2u)~f(r) for the main flow at the formed separation near the bushing.

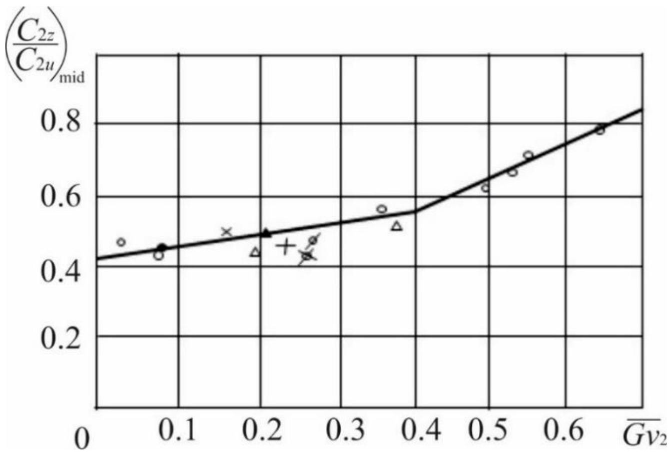

Fig. 3. Change in the ratio $\left(\frac{C_{2z}}{C_{2u}}\right)_{\text{mid}}$ at the output of the working wheel stages with a small bushing ratio at the low-flow rate modes:

stage I: $\frac{D_{\text{mid}}}{l}$ = 2.58; $\beta_{2\text{eff}}$ = 22.9; γ_{incl} = 0°; ○ – n = 5000 rpm; ● – n = 6500 rpm;

stage Ik: $\frac{D_{\text{mid}}}{l}$ = 2.58; $\beta_{2\text{eff}}$ = 22.9; γ_{incl} = 0°; ¤ – n = 8000 rpm; ¤ – n = 6500 rpm;

stage II: $\frac{D_{\text{mid}}}{l}$ = 2.87; $\beta_{2\text{eff}}$ = 24.5; γ_{incl} = 30°; Δ – n = 5000 rpm;

stage IIk: $\frac{D_{\text{mid}}}{l}$ = 2.87; $\beta_{2\text{eff}}$ = 24.5; γ_{incl} = 50°; ▲ – n = 5000 rpm;

stage III: $\frac{D_{\text{mid}}}{l}$ = 3.24; $\beta_{2\text{eff}}$ = 26.0; γ_{incl} = 0°; + – n = 5000 rpm;

stage IV: $\frac{D_{\text{mid}}}{l}$ = 4.57; $\beta_{2\text{eff}}$ = 28.5; γ_{incl} = 0°; × – n = 5000 rpm

The change analysis $\left(\frac{C_{2z}}{C_{2u}}\right) \sim f(r)$ in the area of the main flow showed that at a relative volumetric flow rate $\overline{Gv}_2 < \overline{Gv}_2^R$, where $\overline{Gv}_2^R$ is the beginning of the nucleation of a vortex rotating in the rim clearance of a large fanning stage. The ratio $\left(\frac{C_{2z}}{C_{2u}}\right)_i \approx \mathrm{tg}\beta_{2i}$, since the outlet sections of the working wheel interblade channels in the area $r_i > r_{0_A} = r_{\mathrm{br}}$ are filled with the working medium without flow separation from blades. At the same time, in accordance with the law of rotation of the angle β_2 along the radius, the change in the values of $\mathrm{tg}\beta_{2i} \sim r_i$ is small and the value $\left(\frac{C_{2z}}{C_{2u}}\right)_i$ can be expressed as the averaged over the radius in the range of the change $r_{0_A} < \bar{r}_i < 1$, that is

$$\left(\frac{C_{2z}}{C_{2u}}\right)_i = \left(\frac{C_{2z}}{C_{2u}}\right)_{\mathrm{mid}} = \mathrm{const}.$$

The change in this value for the operating mode of the stage from $\overline{Gv}_2 = 0.4$ to $\overline{Gv}_2 = 0.65$ is shown in Fig. 3 and can be described by the dependence

$$\left(\frac{C_{2z}}{C_{2u}}\right)_{\mathrm{mid}} = 0.55 + (\overline{Gv}_2 - 0.40) = 0.15 + \overline{Gv}_2. \quad (4)$$

In the area of stage modes change ($\overline{Gv}_2 < 0.4$), in which the ratio $\left(\frac{C_{2z}}{C_{2u}}\right)_{\mathrm{mid}}$ is influenced by the vortex rotating in the rim clearance [11, 12], the dependence has a lower rate of change and is described by the equation

$$\left(\frac{C_{2z}}{C_{2u}}\right)_{\mathrm{mid}} = 0.40 + 0.375 \cdot \overline{Gv}_2, \quad (5)$$

where $\overline{Gv}_2$ changes from 0 to 0.4.

Using the equation (3) for the streamline $i = \overline{1, \dots, n}$, the dependencies describing the position of the boundary lines $\bar{G} = 1$ and $\bar{G} = 0$ have the form [14 – 16]:

– for the i-th streamline

$$r_i = r_{0_i} \cdot \sqrt{1 + \left(\frac{z}{r_{0_i}}\right)^2 \cdot \left(\frac{C_{2u}}{C_{2z}}\right)^2_{\mathrm{mid}}};$$

– for the outer flow boundary

$$R = R_0 \cdot \sqrt{1 + \left(\frac{z}{R_0}\right)^2 \cdot \left(\frac{C_{2u}}{C_{2z}}\right)^2_{\mathrm{mid}}}.$$

– for the inner boundary $\bar{G} = 0$, it is necessary to consider the position of the separation point A on the trailing edge of the working blade.

The change in the position of point A of the boundary line $\bar{G} = 0$ of the main flow, which separates it from the vortex structure of the separation near the bushing at the trailing edges of the rotor blades, is linear (Fig. 4), which can be described by the equation

$$\bar{r}_{0_A} = 1 - \frac{1 - \bar{r}_{\mathrm{bush}}}{\overline{Gv}_{2_{z_A=0}}} \cdot \overline{Gv}_2. \quad (6)$$

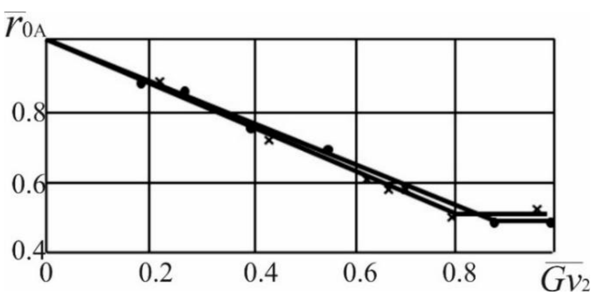

Fig. 4. The position of the flow separation radius at the trailing edges of the rotor blades of K-100-90 turbine (●) and VKT-100 (×).

As follows from the equation (6), to determine the inner boundary of the main flow, it is necessary to know the value of the relative volumetric flow rate at the initiation of the separation near the bushing from the trailing edges of the rotor blades in the root section $\overline{Gv}_{2_{z_A=0}}$.

The line of development of the separation near the bushing in the free space of the outlet nozzle in this case can be represented by the equation

$$\bar{r}_{\mathrm{br}} = \bar{r}_{0_A} \cdot \sqrt{1 + \left(\frac{z}{\bar{r}_{0_A}}\right)^2 \cdot \left(\frac{C_{2u}}{C_{2z}}\right)^2_{\mathrm{mid}}},$$

where $\left(\frac{C_{2z}}{C_{2u}}\right)_{\mathrm{mid}}$ is taken according to equations (4) and (5) depending on the considered mode $\overline{Gv}_2$ of the stage operation.

The choice of the value of the relative volumetric flow rate $\overline{Gv}_2$ of the bushing cylindrical or conical surface of the outlet nozzle is made based on the following considerations.

Let us assume that for the optimal stage in the bushing area there is an axial exit of the steam flow (α_2 = 90°) for the nominal operating mode. The flow separation from the trailing edges of the last stage occurs at a certain value $\overline{Gv}_2 < \overline{Gv}_{2\mathrm{nom}}$. For the nominal operating mode of the stage, the output velocity $C_2 = C_{2z} = u\,\mathrm{tg}\,\beta_2$.

With a relatively small change in the turbine operating mode, the pressure in the condenser P_{cond} and the specific volume of steam remain constant, the value of the axial velocity component C_2 will be proportional to the change in mass flow

$$\frac{C_{2z}}{C_{2z\mathrm{nom}}} = \frac{G}{G_{\mathrm{nom}}} = \frac{Gv_2}{Gv_{2\mathrm{nom}}} = \overline{Gv}_2. \tag{7}$$

At the same time, while maintaining the circumferential velocity of the working wheel $u = w_2 \cdot r_{\mathrm{cond}}$, the value w_2 will decrease and the circumferential component C_{2u} of the output velocity $\bar{C}_2$ will be formed (Fig. 5).

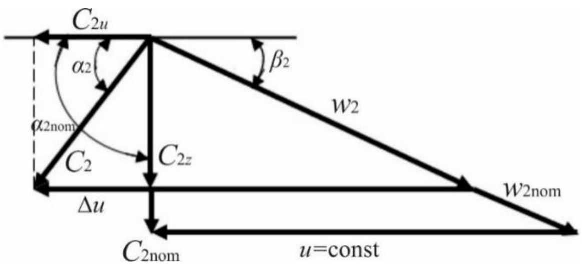

Fig. 5. Changes in the output triangle of velocities of the optimal stage in the bushing area.

The decrease in the consumption component C_{2z} and the formation of $C_{2u} = \Delta u$ at $\overline{Gv}_2 < \overline{Gv}_{2\mathrm{nom}}$ allows us to write from the aspect ratio of the output triangle

$$\mathrm{tg}\,\beta_2 = \frac{C_{2z\mathrm{nom}}}{u} = \frac{C_{2z}}{u - \Delta u} = \frac{C_{2z}}{u - C_{2u}}$$

or

$$\frac{C_{2z}}{C_{2z\mathrm{nom}}} = 1 - \frac{C_{2u}}{u}. \tag{8}$$

Considering (7), the equation (8) is transformed to the form

$$\overline{Gv}_{2_{z=0}} = 1 - \frac{C_{2u}}{u}, \tag{9}$$

in which the ratio $\frac{C_{2u}}{u}$ determines the moment of occurrence of the separation near the bushing from the trailing edges of the working blades root section, characterized by the mode $\overline{Gv}_{2_{z=0}}$.

The values of $\overline{Gv}_{2_{z=0}}$ for turbines of various types, considering the angles of flow exit from the working wheel channels, can be represented by the dependence

$$\overline{Gv}_{2_{z=0}} = 1.065 \cdot (1 - 0.369\mathrm{tg}\beta_2),$$

which allows to determine the mode of occurrence of the separation near the bushing in the turbine outlet nozzle behind the working wheel in the range of effective flow exit angle in the bushing area of the working wheel from β_2 = 24° to 34° for the optimally designed stages.

5. Research results

Let us consider the application of the proposed method for determining the area of the separation near the bushing behind the working wheel of the last stage of large fanning in the space of the outlet nozzle for operating high-power steam turbines.

The main geometrical parameter of the flow part of the turbine is the fanning of the last stage $\theta = \frac{l}{D_{\mathrm{mid}}}$. The length of the blade is limited, first, by the conditions of strength, including vibration strength, under variable operating conditions of the turbine. With an increase in the fanning, the structure of the flow also changes, and its spatial non-uniformity increases. The maximum value of the last stage fanning is today θ = 0.38 for the turbine K-300-240. For the most high-power turbines, it ranges from 0.35 (K-1000-60/1500) to 0.4 (K-1200-240-3).

The steam velocity behind the last stage C_{2z} usually does not exceed 250 ÷ 280 m/s, since at its high values, the losses in the outlet nozzle increase sharply. The value of the output speed C_2 determines the losses with the output velocity, which in modern machines reach 5 ÷ 8%.

To analyze the development of separation near the bushing, the following are accepted:

– the steam turbine K-300-240 with the last stage having a rotor blade length l = 960 mm, average stage diameter D_{mid} = 2550 mm, effective exit angle at the average diameter $\beta_{2\mathrm{eff}}^{\mathrm{mid}}$ = 25.6°, in the root section $\beta_{2\mathrm{ef}}^{\mathrm{root}}$ = 23.5°, the bushing ratio $\bar{r}_{\mathrm{bush}}$ = 0.457;

– the heating turbine T-250/300-240-3 with the last stage, which has the length of the working blade l = 940 mm, the average diameter of the stage D_{mid} = 2290 mm, the effective angle of the flow output in the average diameter $\beta_{2\mathrm{eff}}^{\mathrm{mid}}$ = 27.8°, in the root section $\beta_{2\mathrm{ef}}^{\mathrm{root}}$ = 27.8°, the bushing ratio $\bar{r}_{\mathrm{bush}}$ = 0.418.

The relative consumption $\overline{Gv_2}$ is adopted as a characteristic of the modes. The calculation results are given in table 1.

Table 1. The characteristics of the operating modes of the turbine of large fanning

Parameter		K-300-240	T-250/300-240-3
$\overline{Gv}_{2_{z=0}}$		0.8941	0.8578
$\overline{Gv}_2$ (accepted)	$\frac{C_{2z}}{C_{2u}}$	$\bar{r}_{0_A}$	$\bar{r}_{0_A}$
0.8	0.950	0.5141	0.4572
0.6	0.750	0.6356	0.5929
0.4	0.550	0.7571	0.7286
0.2	0.475	0.8785	0.8643

The value of $\bar{r}_{0_A}$ characterizes the rise of the current lines $\bar{G}$ = 0 of the main flow on the edge of the working blade, adopted as a boundary line separating the vortex flow that forms in the separation near a bushing and the main flow of steam passing through the stage.

As follows from the comparison of the results of the point A movement on the working blades output edge, an increase in the angle β_2ef^root in the root section slows down the appearance of the separation near a bushing. Table 2 shows the coordinates of the boundary position of the current lines G ̅= 1 and G ̅= 0 at the values of (Gv) ̅_2 corresponding to three operating modes of the last stage of the turbine K-300-240 (mode (Gv) ̅_2 ≤ 0.4 corresponds to the starting and is not used for long-term operation of the turbine).

Table 2. Coordinates of the position of the boundary lines $\bar{G}$ = 1 and $\bar{G}$ = 0 of the main flow in the output nozzle of the turbine K-300-240

$\overline{Gv}_2$	$\bar{G}$	Z, r, m	$\bar{Z}$								
			0	0.05	0.10	0.20	0.30	0.40	0.50	0.60	0.70
0.8941	1.0	Z_i	0	0.088	0.177	0.354	0.530	0.708	0.883	1.059	1.236
		r_i	1.765	1.767	1.773	1.798	1.838	1.893	1.961	2.041	2.132
	0	Z_i	0	0.088	0.177	0.354	0.530	0.708	0.883	1.059	1.236
		r_i	0.808	0.8095	0.823	0.875	0.954	1.057	1.174	1.303	1.440
0.6	1.0	Z_i	0	0.088	0.177	0.354	0.530	0.708	0.883	1.059	1.236
		r_i	1.765	1.769	1.781	1.827	1.901	2.002	2.122	2.260	2.415
	0	Z_i	0	0.088	0.177	0.354	0.530	0.708	0.883	1.059	1.236
		r_i	1.121	1.127	1.146	1.216	1.325	1.466	1.626	1.803	1.993
0.4	1.0	Z_i	0	0.088	0.177	0.354	0.530	0.708	0.883	1.059	1.236
		r_i	1.765	1.772	1.794	1.879	2.011	2.185	2.386	2.612	2.858
	0	Z_i	0	0.088	0.177	0.354	0.530	0.708	0.883	1.059	1.236
		r_i	1.536	1.544	1.569	1.665	1.813	2.004	2.222	2.463	2.722

The operating mode of the last stage (Gv)¯_2 = 0.8941 corresponds to the origin of the separation near the bushing and the mode (Gv)¯_2 = 0 corresponds to the turbine work at the end of the range of its use in variable mode.

For the heating turbine T-250/300-240, the origin and development of the separation near the bushing in the output nozzle is like the condensation turbine K-300-240. According to the characteristics given in table 1, the development of the separation near the bushing occurs less intensively in the modes to $\overline{Gv}_2 \approx 0.20$. In the area of the mode $\overline{Gv}_2 \leq 0.01$, the rate of change in the characteristics of the accommodation for both types of turbines become close.

6. Prospects for further research development

Thus, using the above methodology, it is possible to build the structure of the main flow moving in the outlet nozzle up to the stiffening ribs. In this case, the streamlines in the space between the boundary lines $\bar{G}$ = 1 and $\bar{G}$ = 0 are taken at the choice of their position on the trailing edges of the rotor blades, for which the coordinate $z = 0$.

7. Conclusions

The problem of the main flow movement of the working medium from the working wheel of the last stage of large fanning into the outlet nozzle of a steam turbine is considered, in view the conditions for the formation of the separation near the bushing in a wide range of mode changes, including low-flow rate ones.

To analyze the position of the main flow of the working medium in the free space of the outlet nozzle, a model describes the movement of the flow with a rotation hyperboloid.

The dependences obtained for determining both the boundary streamlines ($\bar{G}$ = 1 and $\bar{G}$ = 0) and the streamlines in the main flow allow us to estimate its movement in space from the rotor blades to the nozzle stiffening ribs.

An analysis of the initiation and development of separation near the bushing from the trailing edges of the rotor blades in the outlet nozzle space in a wide range of modes, including low-flow rate ones, was carried out.

A close dependence has been obtained to assess the mode of the occurrence of the separation near the bushing behind the large fanning stages of steam turbines.

A methodology for determining the boundaries position of the main flow behind the working blades of the last stage in the free space of the output nozzle is proposed.

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