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Application of innovative solutions to improve the efficiency of the LPC flow part of the 220 MW NPP steam turbine

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Abstract The results of the gas-dynamic calculation of the low-pressure cylinder flow part of the K-220-44 type steam turbine intended for operation at nuclear power plants are presented. The ways of the flow part improvement were determined. Some of those ways include the use of innovative approaches that were not previously used in steam turbines. The design of the new flow part was carried out on the basis of a comprehensive methodology implemented in the IPMFlow software package. The methodology includes gas-dynamic calculations of various levels of complexity, as well as methods for analytical construction of the spatial shape of the blade tracts based on a limited number of parameterized values. The real thermodynamic properties of water and steam were taken into account in 3D calculations of turbulent flows. At the final step, end-to-end 3D calculations of the low-pressure cylinder that consists of 5 stages were performed. The technology of parallel computing was applied in those calculations. It is shown that due to the application of innovative solutions, a significant increase in efficiency can be achieved in the developed low-pressure cylinder.

Keywords: Steam turbine; Low-pressure cylinder; Flow part; Meridional contours; Spatial flow; Computational investigations

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Nomenclature

C_3	–	absolute speed, m/s
D_{av}	–	average diameter, m
D/L	–	blade fanning (ratio of the mean diameter to the height of the blade)
L	–	blade height, m
NPP	–	new nuclear power plants
P_c	–	pressure in the condenser, Pa
LPC	–	low-pressure cylinder
RB	–	rotor blade
SB	–	stator blade
u/c_0	–	velocity ratio (loading of stage)
y^+	–	dimensionless distance from the wall
Z	–	distance along the rotor blade height

Greek symbols

η	–	efficiency, %
ξ_v	–	losses with outlet velocity, %
ρ	–	degree of reactivity

1 Introduction

In the early 2000s, the whole world talked about the revival of nuclear energy and the massive building of new nuclear power plants (NPP). There were intentions to build about 160 more new nuclear power units by 2020 [1]: 53 of them in China and 35 in the USA, as well as some in South Korea and Russia. After the second-largest accident at the Fukushima NPP in 2011, the world nuclear power policy was fundamentally changed [2]. Many countries of the European Union (EU) have decided on the mass liquidation of NPPs. In addition, the EU has adopted a package of proposals "Fit for 55" from the European Commission, which provides for the reduction of greenhouse gas emissions by at least 55% (compared to 1990) by 2030 [3]. To implement this package, it is necessary to switch to "green" fuels with a simultaneous reduction in the use of hydrocarbons [4], including the almost complete rejection of coal-fired thermal power plants (TPP) [5]. That is, the aim is to achieve an increase in electricity generation with the use of renewable energy sources (RES). Today, renewable energy sources does not have sufficient capacity to generate electricity [6]. For example, in 2018, only 28% of electricity produced in the EU was generated using renewable energy sources, 12% of which came from hydroelectric power plants [7]. This indicates that renewable energy sources cannot exist without traditional power plants. NPPs are one of the types of such power plants. In 2018, 10.1% of the world's electricity was produced at NPPs; in the EU this part was 26%, in Ukraine – 51% [8]. The main advantages of the NPP are the absence of greenhouse gas emissions into the atmosphere [9] (which conforms to EU policy) and the low cost of electricity production. It is worth noting that not all countries supported the refusal to use NPPs. The United States, China, South Korea, other Asian countries, as well as some EU countries, adhere to the policy laid down in the 2000s and continue to massively modernize existing NPP units and build new ones. It is planned to build 5 more nuclear power units in Ukraine within the next 10–15 years [10], and more than 10 power units in China [11]. In addition, there is a significant increase in electricity consumption in the modern world. For example, in 2018, the world used 23,398 million GWh of electricity, which is by 4% more than in 2017 (22,486 million GWh) [12]. To satisfy the increased electricity consumption, in addition to building of new NPP power units, it is necessary to modernize the existing ones with the use of modern technologies and innovative approaches [13].

JSC "Ukrainian Energy Machines" (formerly PJSC "Turboatom") is one of the world's largest manufacturing plants of turbines for NPPs. Turbines of this enterprise are operated at NPPs in Ukraine, Russia, Finland, Hungary, Bulgaria and other countries [14]. For many of these turbines, options for their modernization and reconstruction have been developed [15, 16].

The paper presents a version of a new low-pressure cylinder (LPC) flow part of the turbine with a capacity of 220 MW. The new flow part was designed in such a way that it can be accommodated within the dimensions of the existing turbine. When creating a new flow part, some innovative solutions were applied, including those that were not previously used in the world practice of steam turbine construction, namely, a special form of meridional contours. The design was carried out using a comprehensive methodology implemented in the IPMFlow software package. The methodology includes gas-dynamic calculations of various levels of complexity, as well as methods for the construction of spatial shape of the blade tracts based on a limited number of parameterized values. It is shown that in the developed LPC, due to the use of stages with modern smooth profiles and a special shape of meridional contours, a significant increase in efficiency and power has been achieved.

2 Method for calculation and analytical profiling of axial type flow parts

The numerical study of the three-dimensional steam flow and the design of the steam turbine flow part were carried out using the IPMFlow software package, which is the development of earlier software packages FlowER and FlowER-U [17]. The mathematical model of the package is based on the numerical integration of the Reynolds-averaged unsteady Navier-Stokes equations with the use of an implicit quasi-monotonic essentially non-oscillatory scheme ENO-scheme of increased accuracy and Menter's k-ω SST (shear stress transport) two-equation turbulence model [18]. To take into account the thermodynamic properties of steam, the method of interpolation-analytical approximation of the IAPWS-95 equations was used [19, 20]. The results obtained with the use of IPMFlow software package have the necessary reliability both by the qualitative structure of the flow and by quantitative assessment of the characteristics of an isolated turbine stage and flow parts of turbomachines as a whole [21].

To speed up the time of calculations in the IPMFlow software package, an original technology of parallel computing [22] has been introduced. The technology has the following main characteristics:

- it is used for computers with shared RAM,
- it weakly depends on the operating system because each parallel process is an executable module,
- no less than one blade row (minimal geometric object) should be considered in one parallel process,
- the number of parallel processes does not exceed the number of blade rows,
- the number of parallel processes may not equal the number of cores (threads),
- acceleration of calculations is almost linearly dependent on the number of parallel processes.

For example, the parallelization of the calculation process of the flow part consisting of 18 stages for 9 processes when using a computer with 8 cores (threads) gave an acceleration of the calculation time by 7.1 with the maximum theoretically possible acceleration of 8.

To construct the geometry of the blade row of the axial flow part, the method of analytical profiling [23], in which the blade is defined by an arbitrary set of flat profiles described by curves of the 4th and 5th orders, was used. As the initial data, we used a limited number of parameterized values such as profile width, number of blades, inflow angle, effective outflow angle from the row, etc. The meaning of these values, in most cases, is generally accepted in turbine engineering. The method allows to obtain full three-dimensional geometric characteristics of a wide class of axial turbines' flow parts very fast, which makes it convenient and effective when it is needed to solve the problems of gas-dynamic design and during the improvement of turbomachines.

3 Research object

The first steam turbine of the K-220 series with a rated power of 220 MW, designed for operation at NPPs with inlet steam parameters of 4.31 MPa, 241°C and with reheating of steam, was manufactured by JSC "Turboatom" in 1969 [24]. Thirty-four turbines of this type have been supplied to NPPs in Ukraine, Russia, Armenia and Hungary. In 1976, the first one out of four turbines of the second modification was produced for the Loviisa NPP in Finland. These turbines differed from the turbines of the first modification by increased power with the same inlet steam mass flow, which was ensured by the use of a more modern last stage of the LPC with a rotor blade of 1030 mm. Since 1979, 10 turbines of the third modification have been supplied to the Paks and Kola NPPs. Their efficiency has been increased due to the use of a modified first stage of the high-pressure cylinder. These turbines also differed from the previous modifications by the lateral steam supply to the LPC. 220 MW turbines of all three modifications worked flawlessly [25, 26]. Warranty thermal tests of turbines of various modifications carried out at the Novovoronezh, Kozloduy, Loviisa and Kola power plants have confirmed their high efficiency. It turned out to be by 1.5–1.6% higher than the initially guaranteed [27, 28].

The turbine of the K-220 series is a single-shaft, three-cylinder unit that consists of one low-pressure cylinder (HPC) and two two-flow symmetric low-pressure cylinders (LPCs). As an object of research, the article considers one flow of the LPC of the latest modification of the K-220 series turbines that consists of 5 stages (Fig. 1). This flow part has three regenerative steam extractions (behind 1, 2 and 3 stages).

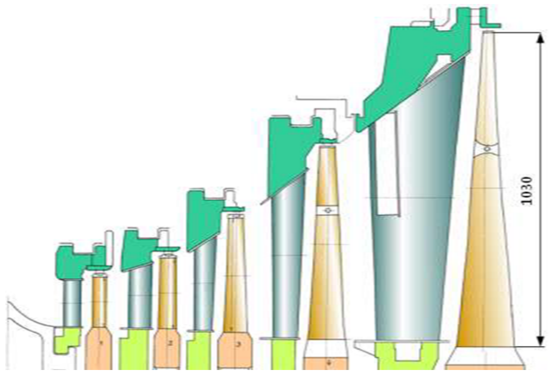
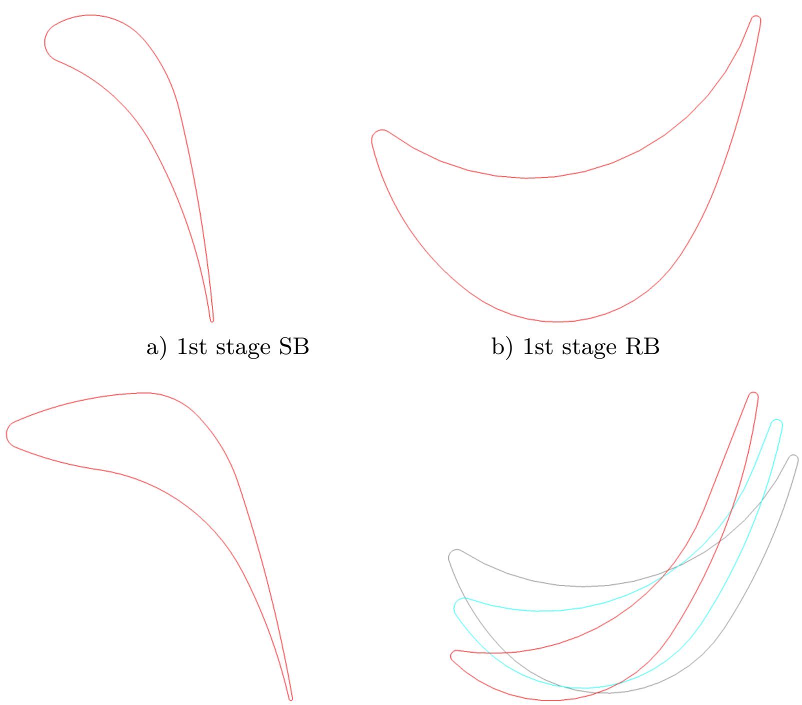


Figure 1: Longitudinal section of the low-pressure cylinder (LPC) of the K-220-44-3 series turbine.

Stator blades of the first two stages and rotor blades of the first stage have constant cross-sections spanwise, the rest are of variable cross-section (Fig. 2)



a) 1st stage SB b) 1st stage RB

c) 2nd stage SB d) 2nd stage RB

Figures 2 a)–d). For caption see next page.

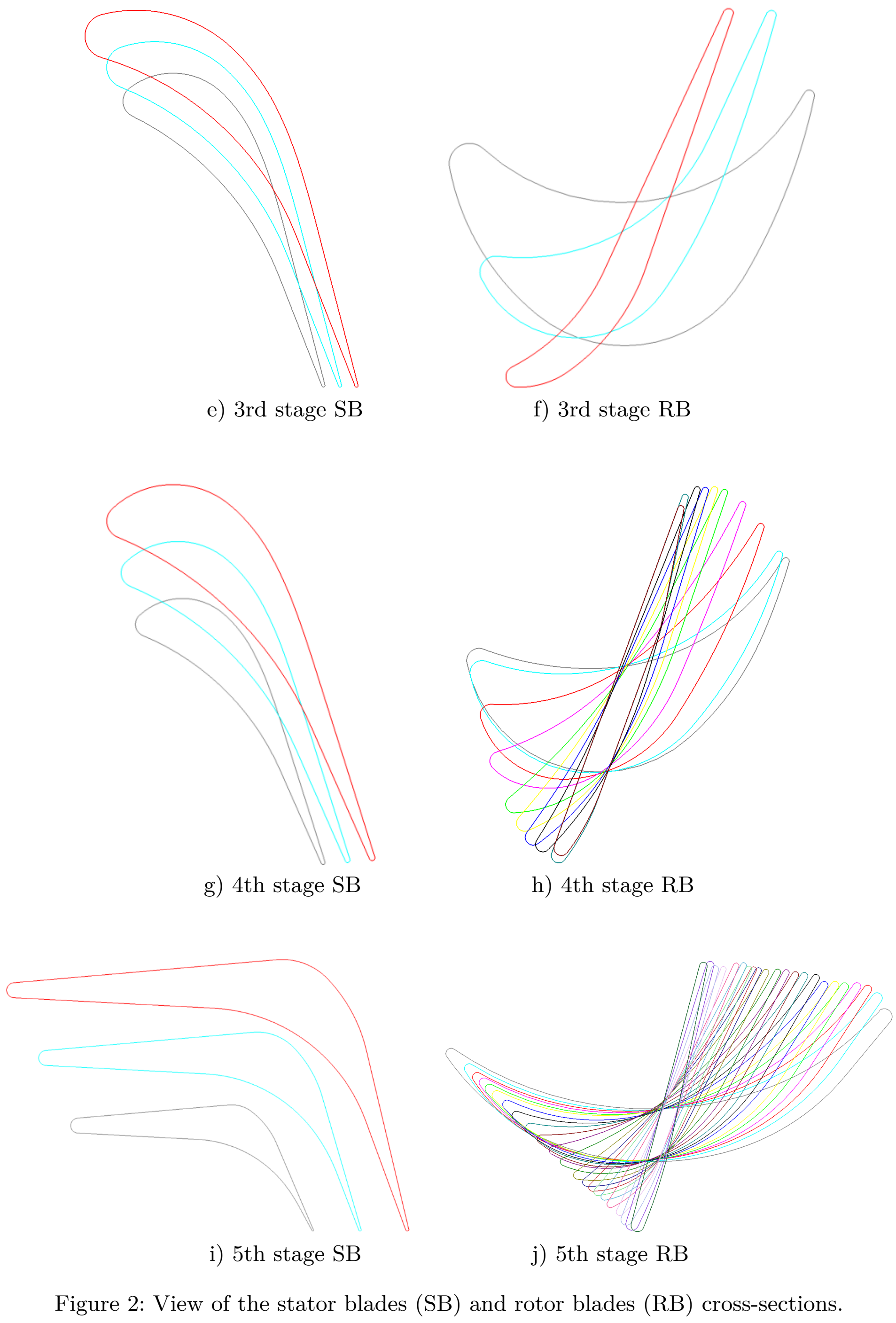
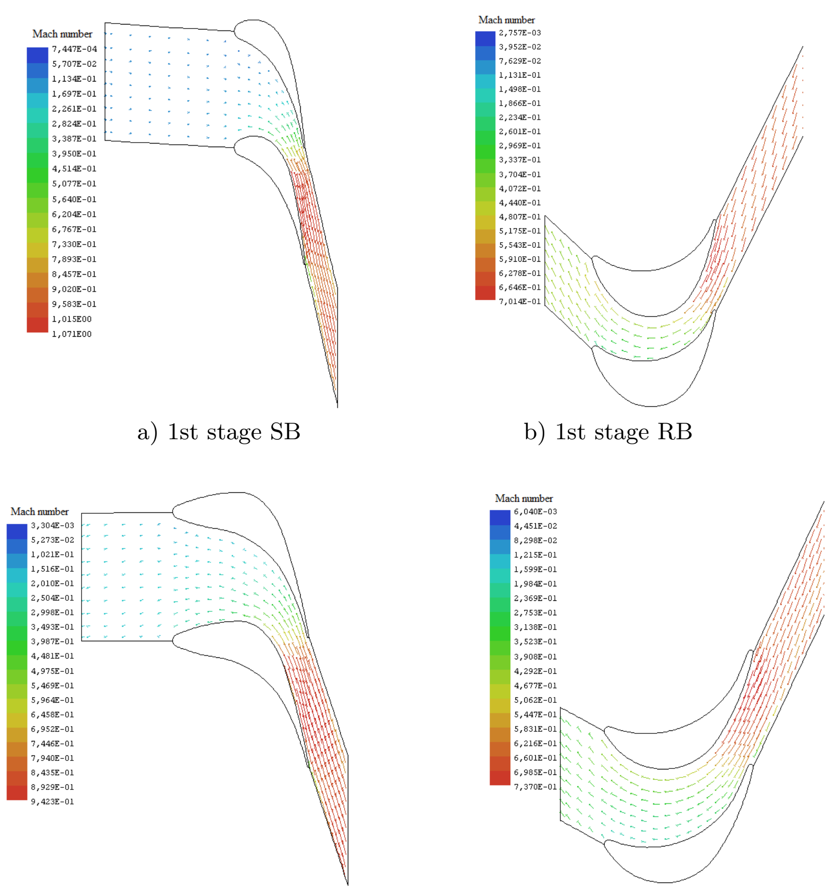


Figure 2: View of the stator blades (SB) and rotor blades (RB) cross-sections.

4 Analysis of the initial flow part and selection of modernization directions

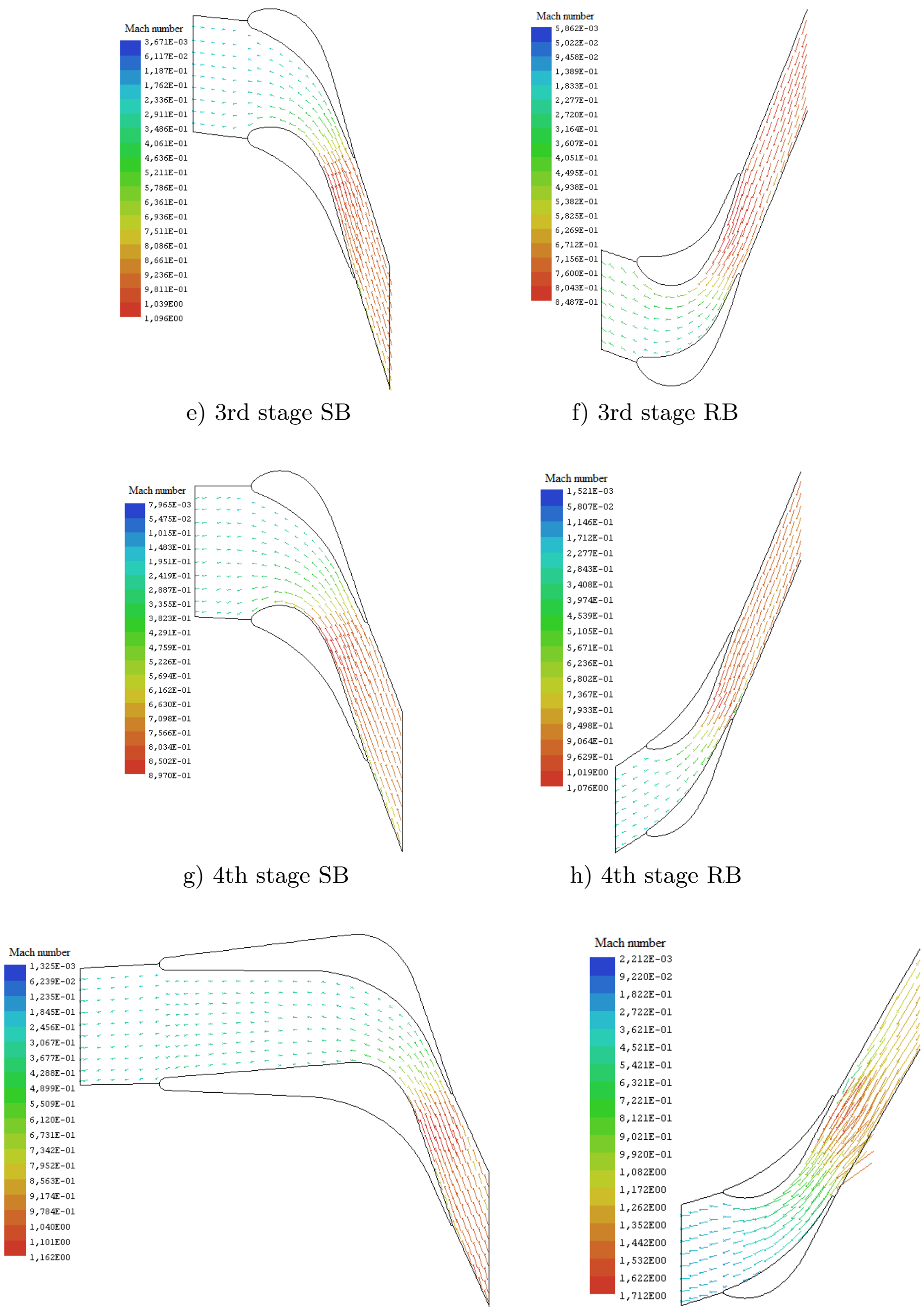
To determine the directions of modernization, calculations and analysis of the three-dimensional steam flow in the original flow part of the turbine were performed. End-to-end LPC calculations (5 stages) were performed on h-type difference grids with a total number of cells of about 5 million. Refinement of the computational grid near solid surfaces corresponds to $y^+ < 5$. Figure 3 shows the visualization of the flow in the flow part and Fig. 4 shows graphs of pressure distribution over blade surfaces. Table 1 shows the main integral characteristics of the investigated flow part.



a) 1st stage SB b) 1st stage RB

c) 2nd stage SB d) 2nd stage RB

Figures 3 a)–d). For caption see next page.

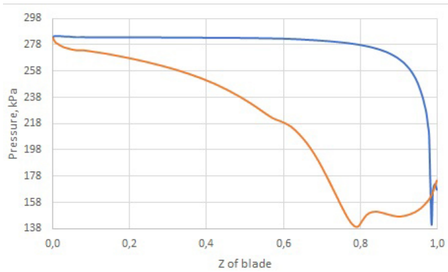


e) 3rd stage SB f) 3rd stage RB

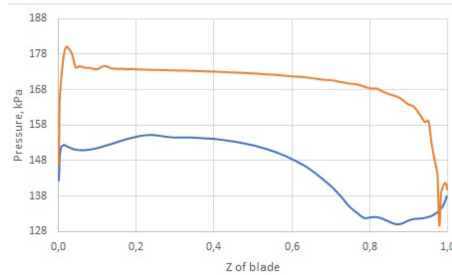
g) 4th stage SB h) 4th stage RB

i) 5th stage SB j) 5th stage RB

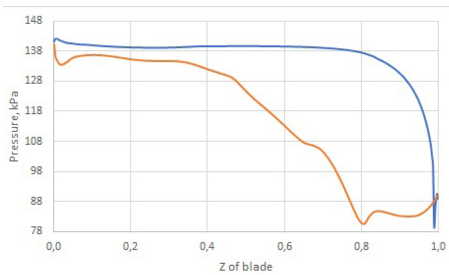
Figure 3: Velocity vectors in the mid-span blade-to-blade section.



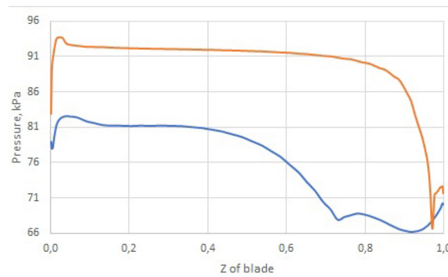
a) 1st stage SB



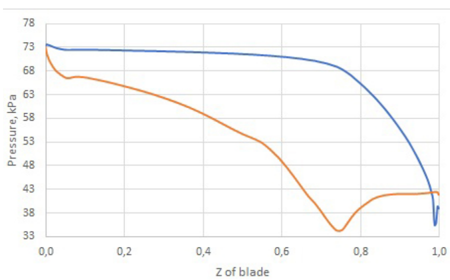
b) 1st stage RB



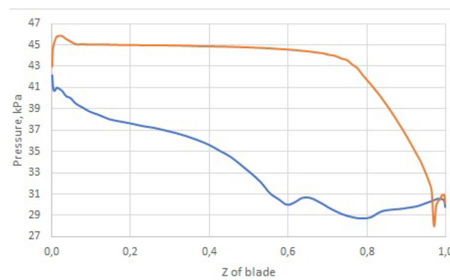
c) 2nd stage SB



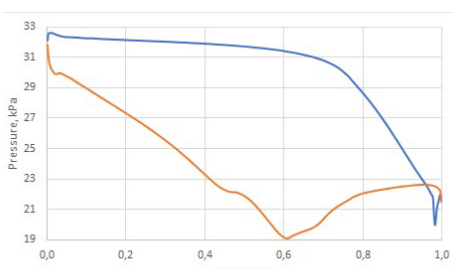
d) 2nd stage RB



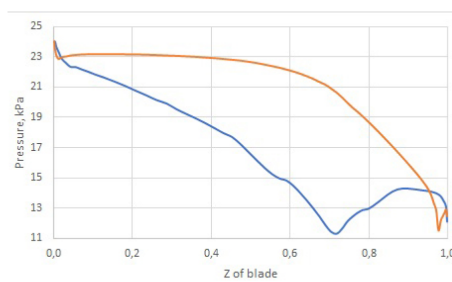
e) 3rd stage SB



f) 3rd stage RB

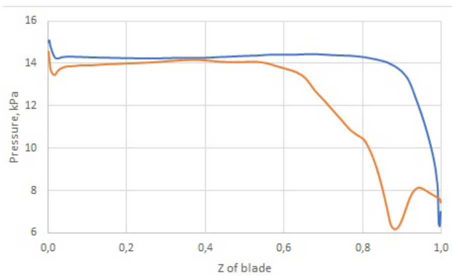


g) 4th stage SB

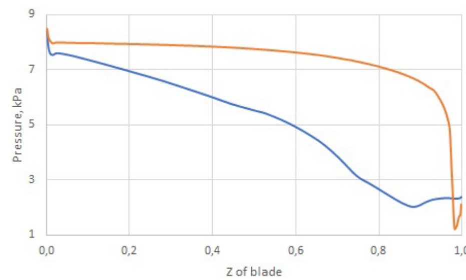


h) 4th stage RB

Figures 4 a)–h). For caption see next page.



i) 5th stage SB



j) 5th stage RB

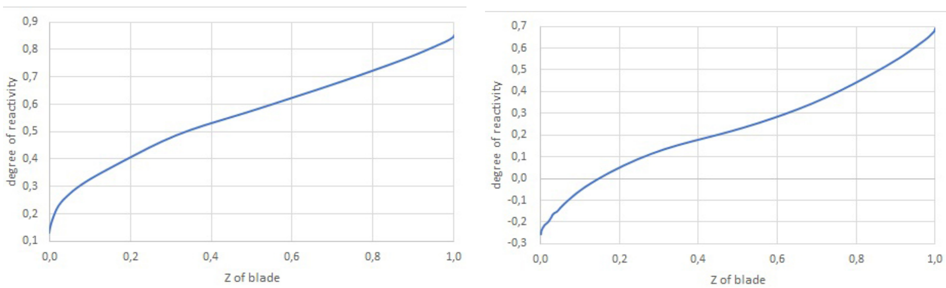
Figure 4: Graphs of pressure distribution over the blade surface in the middle-radius section.

Table 1: Basic geometric and integral gas-dynamic characteristics of the flow part.

Stage number	D/L	u/c_0	ρ	η, %
1	11.05	0.51	0.1989	90.94
2	8.26	0.57	0.2954	92.46
3	5.28	0.59	0.3534	93.20
4	3.47	0.67	0.5646	91.94
5	2.46	0.62	0.5744	86.72

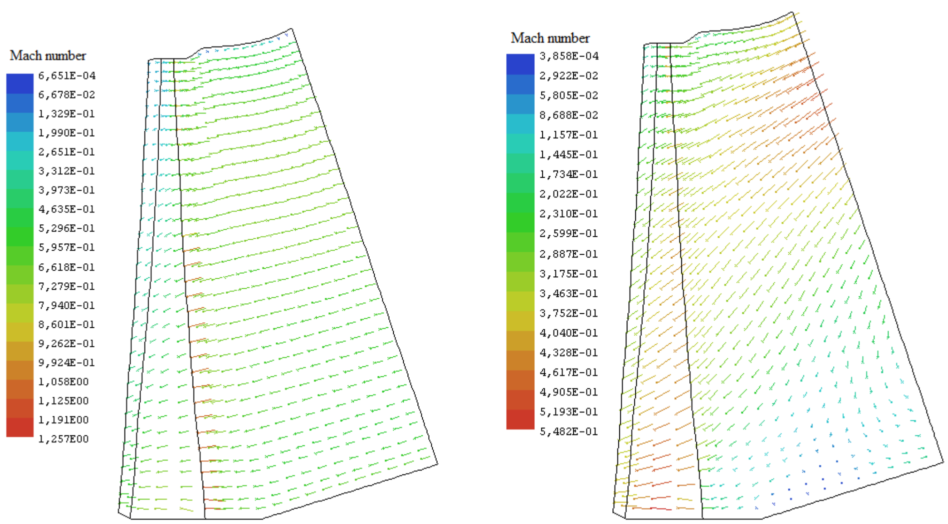
From the results of flow visualization (Fig. 3), a favourable flow picture can be seen, in which there are no flow separations and vortex flows observed. However, the pressure distributions on the blade surfaces are essentially non-monotonic (Fig. 4), which, as a rule, leads to an increase in kinetic energy losses. In the first three stages, a relatively low reactivity degree (desired value is 0.5) and an increased loading (small value u/c_0) are observed (Table 1). For stator blades of the first and second stages and rotor blades of the first stage, relatively long cylindrical blades with a constant profile shape were used (small D/L). This leads to a deterioration of the flow picture along the height of the blades. In the fourth stage, a favorable flow picture can be seen, but pressure distributions on the blade surfaces (Figs. 4g and 4h) are not monotonic. In the fifth stage, from the pressure distribution graph (Fig. 4i), a significant underloading of the inlet part of the blades can be seen. This is caused by the blade extension in this area (Fig. 2i). The profile shape was created from the strength conditions, but from the point of view of gas dynamics, such a shape is not optimal.

Figures 5 and 6 show the results related to the last stage for two operation modes: the first mode – nominal (P_c = 3200 Pa, pressure in the condenser) and the second – mode of “bad” vacuum ($P_c = 8000$ Pa). It can be seen from the given results that the negative reactivity degree is observed at the hub surface in the bad vacuum mode (Fig. 5b), which leads to the appearance of a hub surface separation of the flow (Fig. 6b).



a) $P_c = 3200$ Pa b) $P_c = 8000$ Pa

Figure 5: Distribution of reactivity degree along the rotor blade height in the 5th stage.



a) $P_c = 3200$ Pa b) $P_c = 8000$ Pa

Figure 6: Velocity vectors in the 5th stage rotor in the mid-meridian section.

Throughout the flow part, flow separations are observed in places of significant bending in the peripheral contour (overlap). Figure 7 shows an example of a similar flow separation that occurred between the 3rd and 4th stages.

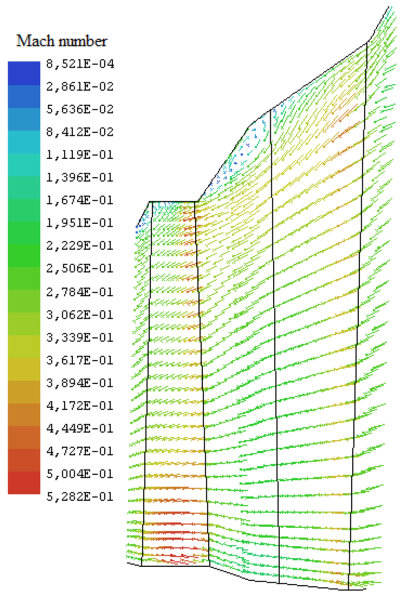


Figure 7: Velocity vectors in mid-meridian section between 3rd and 4th stages.

Table 2 shows some integral characteristics of the flow part as a whole and the value of the average velocity at the outlet. It can be seen that the efficiency of the flow part is relatively high, but the value of the outlet velocity and, accordingly, the losses with the outlet velocity are quite large.

Table 2: The main integral characteristics of the flow part.

C_3, m/s	ξ_v, %	η, %
244.3	4.23	87.15

Based on the obtained results and their analysis, a set of measures to improve the flow part was outlined. Table 3 lists the proposed measures and the expected impact of their implementation.

5 Modernized flow part and discussion

In accordance with the planned measures (Table 3), a new LPC flow part of a nuclear K-220 series turbine was designed. The condition that it would fit into the original dimensions was fulfilled. The view of the modernized flow

Table 3: Measures for the flow part modernization and the expected effect.

No.	Key solutions	Expected effect
1	Smooth meridian contours	Absence of flow separation in places of significant breaks of meridional contours
2	Development of blades with smooth (monotonic) surfaces	Absence of non-monotonicity (breaks) of pressure diagrams on the surfaces of blades
3	Development of blades, which are adjusted to the flow, with variable cross-sections along the height	The flow improvement around the blades
4	Re-profiling of meridional contours (used for steam turbine construction for the first time in the world practice)	Increase of average diameter (D_{av}) of the first 3 stages to reduce the loading of the stage (increase in u/c_0), increase of reactivity degree, more optimal distribution of thermal drops
5	Increase of the height of the last stage rotor blade	Reduction of losses with the outlet velocity
6	Development of a sabre-shaped last stage stator blade	More uniform distribution of parameters along the height, an increase in reactivity degree at the hub, the absence of hub separations in modes with a “bad” vacuum in the condenser

part is shown in Figs. 8 and 9. All blades are made with variable profiles along the height, in accordance with Paragraph 3 of Table 3.

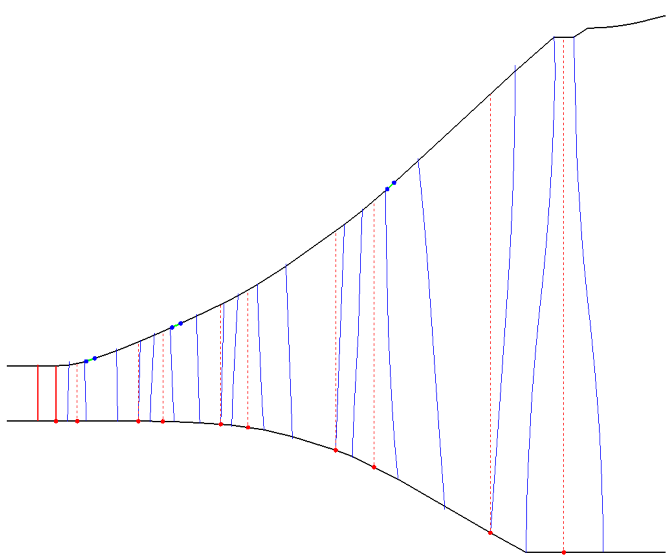
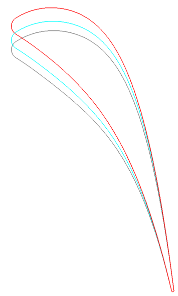
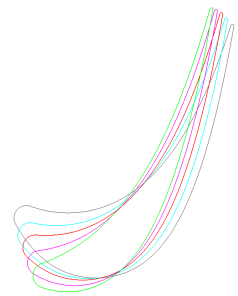


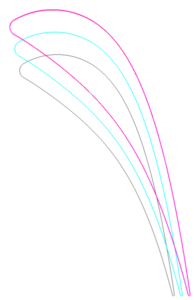
Figure 8: View of the new LPC flow part of the K-220-44 series turbine.



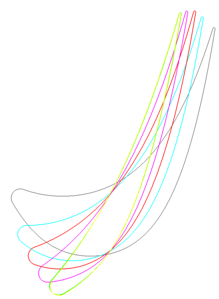
a) 1st stage SB



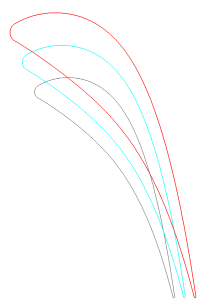
b) 1st stage RB



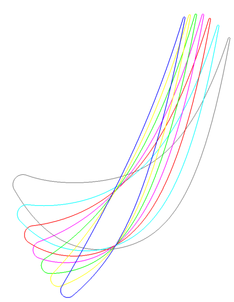
c) 2nd stage SB



d) 2nd stage RB

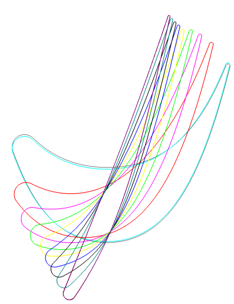


e) 3rd stage SB



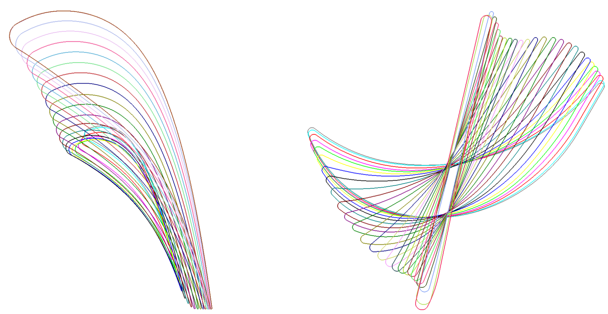
f) 3rd stage RB

g) 4th stage SB



h) 4th stage RB

Figures 9 a)–h). For caption see next page.



i) 5th stage SB j) 5th stage RB

Figure 9: View of the new blades.

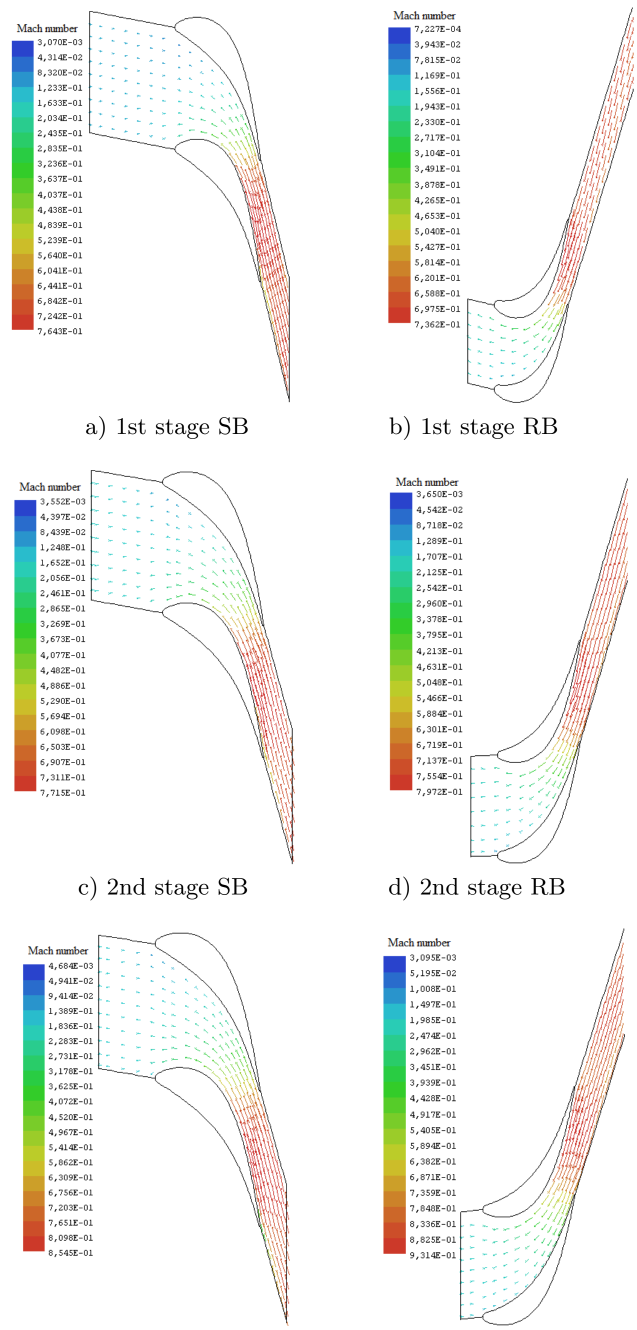
End-to-end calculations of the new LPC (5 stages) were carried out using h-type difference grids, similar to those of the original LPC, with a total number of cells of about 5 million. The computational grid refinement near solid surfaces corresponds to $y^+ < 5$.

Figure 10 shows the visualization of the flow in the new flow part and Fig. 11 shows graphs of pressure distribution over the surface of the blades. From the results presented in Fig. 10, a favourable flow pattern can be observed. Pressure distributions on the blades surfaces (Fig. 11) became much more monotonic compared to the original LPC (Fig. 4). This result is achieved by fulfilling Paragraph 2 of Table 3. The main integral characteristics of the new flow part are presented in Table 4.

Table 4: Basic geometric and integral characteristics of the flow part.

No. of stage	D/L	u/c_0	ρ	η, %
1	15.28	0.64	0.4467	94.13
2	10.05	0.69	0.4792	93.59
3	6.71	0.68	0.5046	95.87
4	3.53	0.69	0.5059	94.32
5	2.13	0.64	0.5693	90.36

Due to the implementation of Paragraph 4 of Table 3, an increase in the average diameters of the first three stages was achieved, which led to a number of positive effects in them (see Table 4): the relative height of the blades has decreased (D/L has increased), loading of stages became more optimal, the u/c_0 value became closer to 0.7 [29] and the reactivity degree of the stages has increased. It is expedient to say more about the innovativeness of

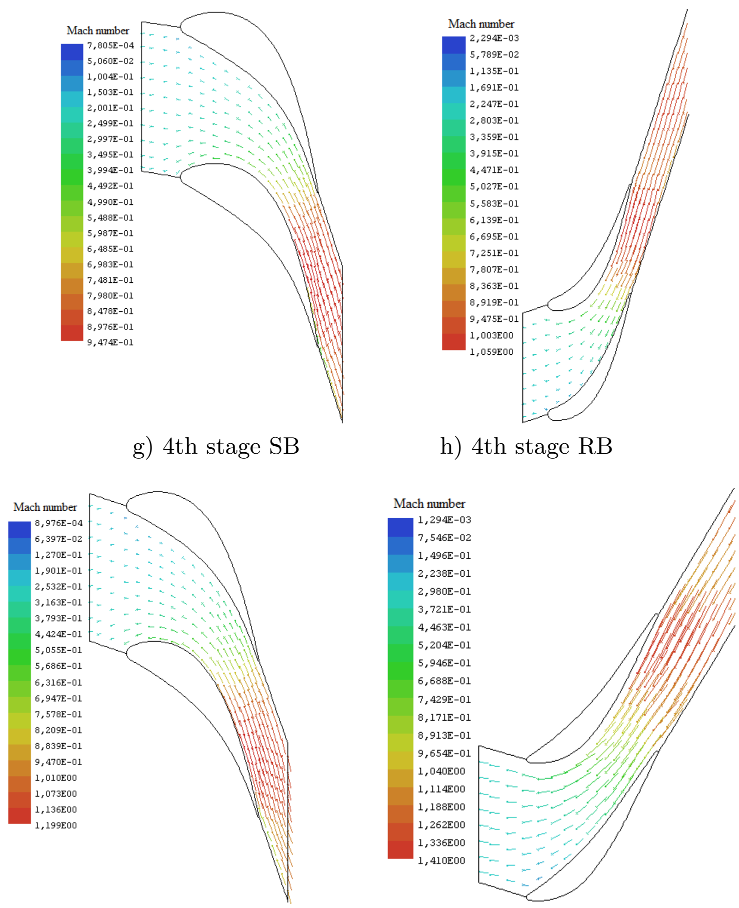


a) 1st stage SB b) 1st stage RB

c) 2nd stage SB d) 2nd stage RB

e) 3rd stage SB f) 3rd stage RB

Figures 10 a)–f). For caption see next page.



g) 4th stage SB

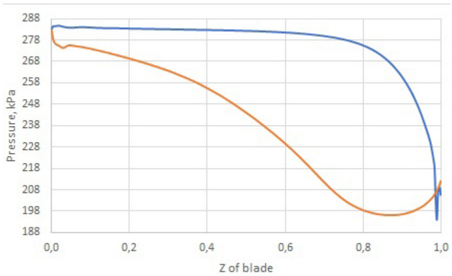
h) 4th stage RB

i) 5th stage SB

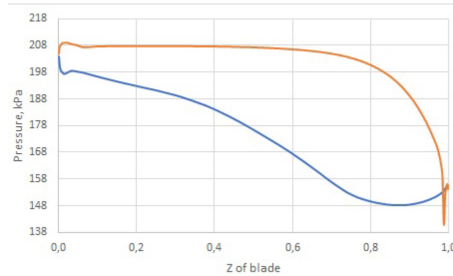
j) 5th stage RB

Figure 10: Velocity vectors in the mid-span section.

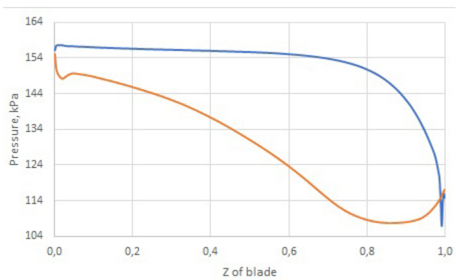
this solution. In the world practice of steam turbine construction, usually, the average diameter in LPC significantly increases from the first stages to the last ones, while the hub surface diameter remains approximately the same or also increases. The difference in average diameters between the stages in the proposed version has significantly decreased, and the hub surface diameter in the first stages significantly increased in comparison with the last stages and with the original version. This made it possible to achieve the described advantages. This approach was proposed for the first time and is planned for implementation by the JSC "Ukrainian Energy Machines". Previously, the implementation of such structures was not



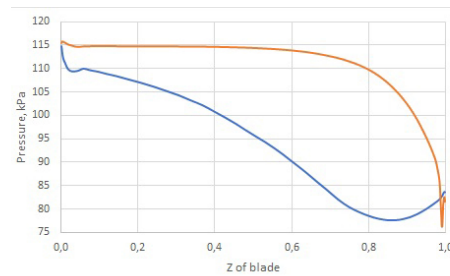
a) 1st stage SB



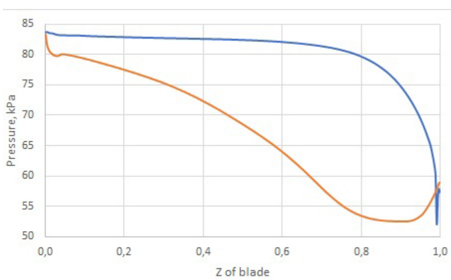
b) 1st stage RB



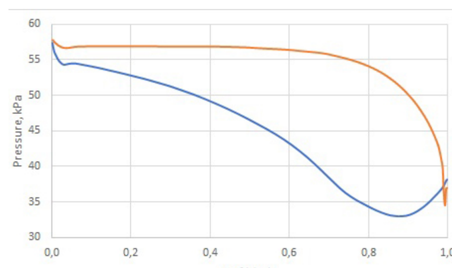
c) 2nd stage SB



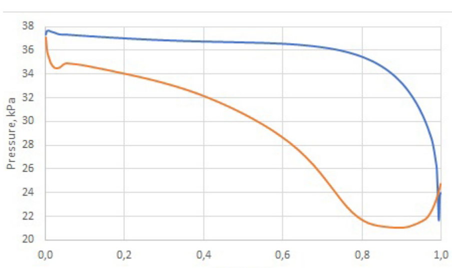
d) 2nd stage RB



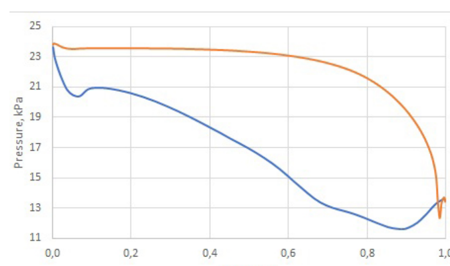
e) 3rd stage SB



f) 3rd stage RB

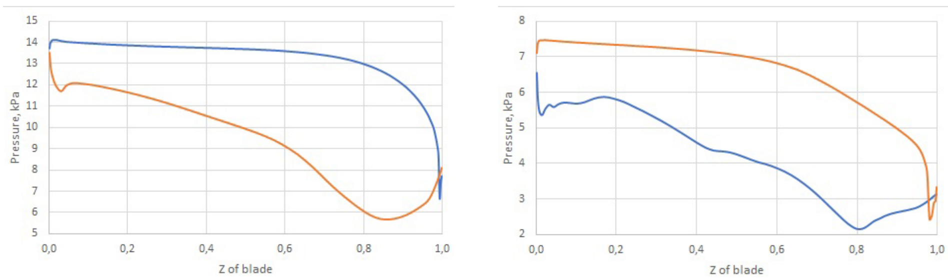


g) 4th stage SB



h) 4th stage RB

Figures 11 a)–h). For caption see next page.



i) 5th stage SB j) 5th stage RB

Figure 11: Graphs of pressure distribution over the blade surface in the middle-radius section.

carried out mainly due to technological problems, since the rotor in this case is significantly heavier. JSC "Ukrainian Energy Machines" solves this problem through the use of technology for the manufacture of welded rotors [30,31], which ensures their acceptable characteristics both in terms of weight and strength.

To reduce losses with the outlet velocity, the new rotor blade of the last stage is made of titanium alloy and has a height of 1200 mm instead of 1030 mm compared to the original one (Paragraph 5 of Table 3). However, an increase in the length of the scapula results in a decrease of D/L, which also leads to an additional decrease in the reactivity degree of the stages at the hub surface, especially in the modes of "bad" vacuum. To eliminate this negative phenomenon, a sabre-shaped stator blade for the last stage was developed (see Fig. 12).

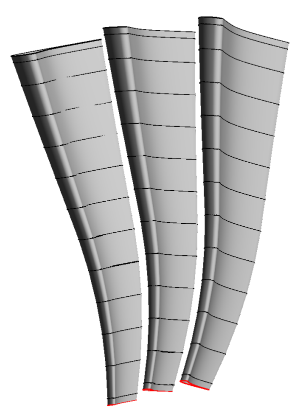
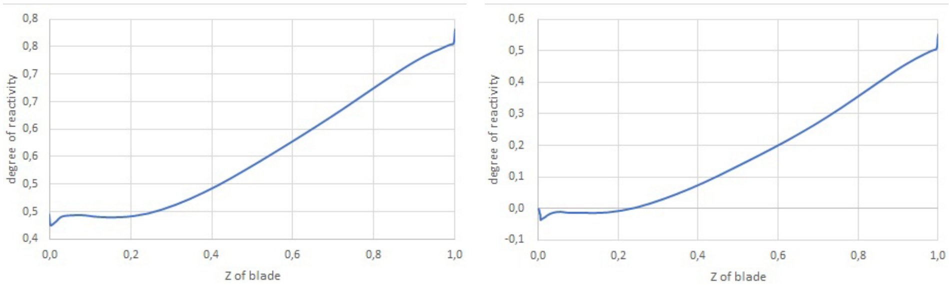


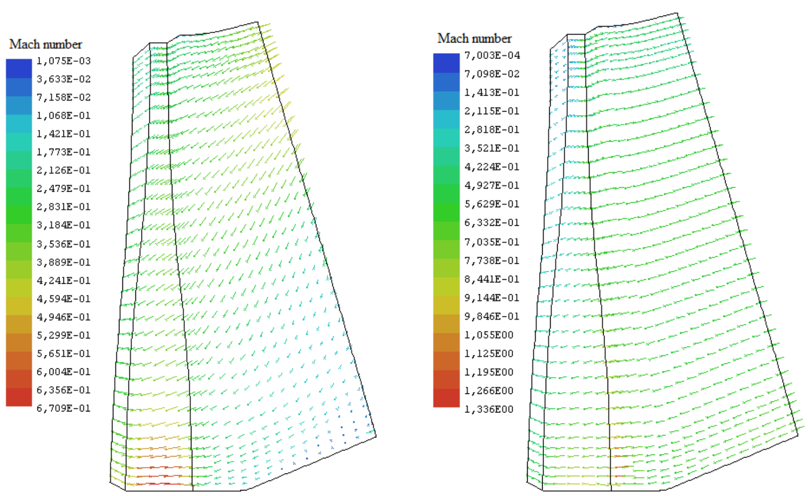
Figure 12: Three-dimensional view of the new last stage stator blade.

Figure 13 shows the value of the reactivity degree along the height of the blade and Figure 14 shows velocity vectors in the rotor of 5th stage in mid-meridian section for two operation modes.



a) $P_c = 3200$ Pa b) $P_c = 8000$ Pa

Figure 13: Distribution of reactivity degree along the rotor blade height in the 5th stage.



a) $P_c = 3200$ Pa b) $P_c = 8000$ Pa

Figure 14: Velocity vectors in the 5th stage rotor in the mid-meridian section.

From the given results it can be seen that due to the use of a sabre-shaped blade (Paragraph 6 of Table 3), the unevenness of the distribution of parameters along the height in the 5th stage has significantly decreased despite the large fanning. The reactivity degree at the hub surface (Fig. 13) increased as well, meanwhile flow separation in the "bad" vacuum modes was significantly reduced (Fig. 14b).

The new flow part also implements the recommendations according to Paragraph 1 of Table 3 (see Fig. 8), i.e. the meridional contours are smooth, without overlaps, which ensured the absence of flow separation in the areas of significant bending in the peripheral contour [32]. So, for example, Fig. 15 shows the visualization of the flow between stages 3 and 4. It can be seen that in contrast to the original design (see Fig. 7), the flow is continuous here. Table 5 shows the main integral characteristics of the flow part as a whole. It can be seen that the outlet velocity has significantly decreased and, accordingly, the losses with the outlet velocity are decreased too.

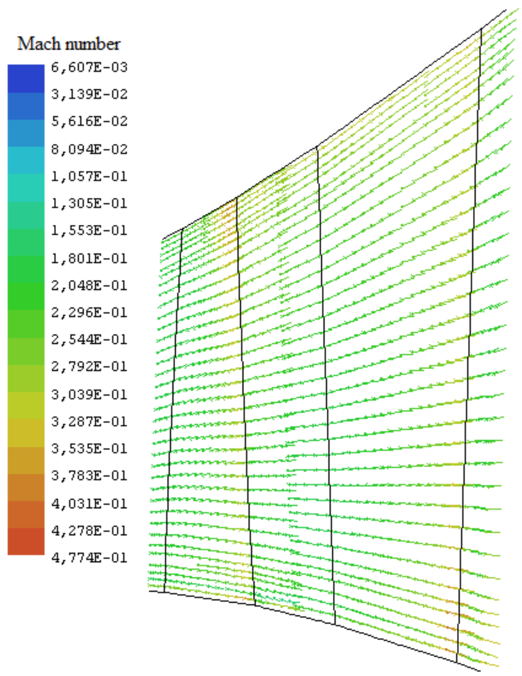


Figure 15: Velocity vectors in mid-meridian section between 3rd and 4th stages.

Table 5: Main integral characteristics of the flow part.

C_3, m/s	ξ_v, %	η, %
214.8	3.3	90.69

Due to the complexity of measures performed in the modernized flow part, the efficiency increased both in each individual stage (see Tables 1 and 4), and in the flow part as a whole (see Tables 2 and 5).

6 Conclusions

On the basis of calculations of three-dimensional turbulent steam flows of the initial design of the low-pressure cylinder (LPC) flow part of the K-220-44 turbine, the directions of its improvement were determined. The study was carried out using the methods and software systems for gas-dynamic calculation and flow parts designing developed at the A. Podgorny Institute for Mechanical Engineering Problems NAS of Ukraine.

The use of a number of innovative solutions, including those that were not previously used in the world practice of steam turbine construction (special shape of meridian contours), helped to achieve a significant increase in the efficiency of the low-pressure cylinder of the K-220-44 series steam turbine. The predicted total efficiency (obtained in 3D calculations) of the developed low-pressure cylinder flow part is 90.69%, which is 3.54% higher compared to the original flow part.

The results of the presented work are accepted by JSC "Ukrainian Energy Machines" for implementation at existing nuclear power plants in the world. The proposed approach and the gained experience can be used in the development and modernization of the low-pressure cylinder flow parts of other powerful steam turbines, which are operated or can be installed at thermal power plants and nuclear power plants both in Ukraine and in other countries.

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