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Application of innovative solutions to improve the efficiency of the low-pressure cylinder flow part of a 1000 MW steam turbine for nuclear power plant

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Abstract

The outcomes of gas-dynamic computations for the low-pressure cylinder component of the K-1000-60/1500-2M type low-speed steam turbine intended for use in nuclear power plants are presented in the paper. Various strategies for enhancing the low-pressure cylinder, incorporating a novel approach, which was not previously employed in low-speed high-power steam turbines, have been identified. The flow part redesign has been carried out through the comprehensive methodology and software implemented in the IPMFlow package. This methodology encompasses gas-dynamic computations of varying complexities and analytical profiling methods for spatial blade row shapes based on a limited set of parameterized values. Real thermodynamic properties of water and steam were considered in 3D turbulent flow calculations. The final stage involved end-to-end 3D computations of the 7-stage low-pressure cylinder, employing parallel computing technology. The results indicate that the innovative solutions incorporated in the developed low-pressure cylinder led to a substantial increase in both efficiency and power.

Keywords: Flow part; Low-pressure cylinder; Meridional contours; Low-speed steam turbine; Spatial flow

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1. Introduction

Nowadays, the world pays a lot of attention to low-carbon [1] forms of energy sources, such as organic Rankine cycle (ORC) [2–4], but all of them are low-power ones [5–7]. Despite the existing risks, nuclear energy, just like a low-carbon one [8], is a promising source to achieve the climate policy goals stipulated by the Paris Climate Agreement [9].

In the European Union (EU), the Green Deal [10] presented in December 2019 allows nuclear energy usage by EU members as part of their national energy balance. Many developing countries have considered the construction of nuclear power plants that can provide relatively cheap electricity, which is an important factor for economies with growing energy consumption [11]. In addition, on February 2, 2022, the European Commission at the summit in Brussels proposed to classify both gas and nuclear power plants as „green energy sources" [12].

According to data from the World Nuclear Association, as of September, 2020 [13], the number of nuclear power plants operating worldwide was 439, with a total capacity equal to 391.7 GW. Currently, 52 reactors are under construction [14], and 12 of those reactors are located in China, 6 in India and 4 in South Korea. In Ukraine, it was planned to put 5 or more nuclear power plants into operation within the next 5–10 years [15], and by 2040, it is planned to have 14 nuclear power units in launch.

Nomenclature

C_3 – absolute speed, m/s
D_{av} – average diameter, m
D/L – blade fanning (ratio of the mid-diameter to the blade height)
L – blade height, m
Pk – pressure in the condenser, Pa
u/C_0– velocity ratio (loading of stage)
y^+ – dimensionless distance from the wall

Greek symbols

η – efficiency, %
ξ_{ov} – losses with the outlet velocity, %
ρ – degree of reactivity

Abbreviations and Acronyms

HIPC– high-intermediate-pressure cylinder
HPC – high-pressure cylinder
IPC – intermediate-pressure cylinder
LPC – low-pressure cylinder
NPP – nuclear power plant
RB – rotor blade
SB – stator blade

In total, 106 more nuclear reactors are planned to be launched (with a total capacity of 113.8 GW), including in countries where there were no NPPs before, such as Turkey [16] and Uzbekistan [17]. The possibility of building nuclear power plants is also being considered in other countries [18], including Kazakhstan, Poland and Saudi Arabia.

The International Energy Association predicts a 75% increase in electricity generation at NPPs by 2050 [19].

One of the largest worldwide turbine manufacturers of nuclear power plants is JSC "Ukrainian Energy Machines" (former JSC "Turboatom"). The turbines made by JSC "Ukrainian Energy Machines" are operated at NPPs in Finland, Ukraine, Bulgaria, Hungary and other countries [20]. The modernization and reconstruction techniques have been developed in [21–23] for many produced turbines.

In this paper, options for a new LPC of a low-speed turbine (1500 rpm) of the K-1000 series are presented. The new flow part is designed to ensure the possibility of its placement within the existing turbine framework. During the development of the new flow part, the innovative solutions, implemented for the first time in the K-220-44-3 series steam turbine [24], namely, meridional contours of the special form, are involved. The advanced methodology implemented in the IPMFlow software has been used during the design stage. This methodology includes gas-dynamic evaluations with various complexity levels, as well as methods for the spatial blade rows shape construction based on a limited number of parameters. The newly developed LPC, due to the usage of blades with modern smooth profiles and the special form of meridional contours has demonstrated a significant increase in efficiency and power.

2. Computational methods and axial flow parts analytical profiling

The three-dimensional steam flow calculation as well as the steam turbine flow part design have been provided using the IPMFlow software [25]. The unsteady Reynolds-averaged Navier-Stokes equations are the basis of the software package mathematical model. The numerical integration is accomplished using the implicit quasi-monotonic ENO-scheme of high accuracy. The Menter two-equations $k–\omega$ SST turbulence model [26] is involved in calculations. The steam thermodynamic properties are incorporated by applying the interpolation-analytical approximation method to the IAPWS-95 equations [27]. The results obtained by the IPMFlow software package have the necessary trustworthiness for the qualitative flow structure analysis as well as for the quantitative estimations of isolated turbine stages [28,29] and entire flow paths of turbomachines [30–32].

The original parallel computing technology is implemented to speed up the calculation time of the IPMFlow software [33].

The effective analytical profiling method for the blade row of the axial flow turbine geometry [34] is used.

3. Research object

Steam turbines of the K-1000-60/1500 series are low-speed condensing-type steam turbines developed by JSC „Ukrainian Energy Machines".

These mentioned turbines have the following modifications:

- K-1000-60/1500-1. A 57.4 m long turbine unit (without a generator its length is 50.7 m) with HPC, IPC and three LPCs, with a single-pass condenser is considered. The rated and maximum power is 1030 MW [35];
- K-1000-60/1500-2. The length is reduced to 52.2 m due to the combination of HPC and IPC into one double-flow HIPC [36]; the weight with a condenser is lower by 350 tons. It is capable of generating the power up to 1100 MW;
- K-1000-60/1500-2m. Slightly different from the previous one.

In total, 17 turbines of such type were installed in the 1980–1990s, 8 of them were installed in Ukraine and 2 in Bulgaria (Kozloduy NPP) [37].

The K-1000-60/1500-1 modification, according to the studies at the South Ukraine NPP, showed the best economic results [38]. Despite this, due to the large size and cost, it was abandoned.

As an object of research, an LPC flow of the latest K-1000 series turbine with 7 stages (Fig. 1) is considered in the paper. This flow part has four regenerative steam extractions (behind 1st, 2nd, 4th and 6th stages).

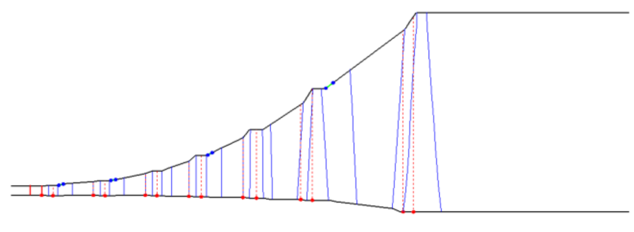


Fig. 1. Longitudinal section of K-1000-60/1500 series turbine LPC.

The following parameters are used as initial data for the flow part calculations: the inlet total pressure is 1.069 MPa, the inlet total temperature is 249.5°C, the outlet static pressure is 3.825 kPa; steam extractions: behind the first stage the value is 8.595 kg/s, behind the second stage the value is 12.588 kg/s, behind the fourth stage the value is 9.723 kg/s, behind the sixth stage the value is 7.824 kg/s.

The first five stages SBs and the first three stages RBs are of constant cross-sections, and the rest have variable cross-sections as shown in Fig. 2.

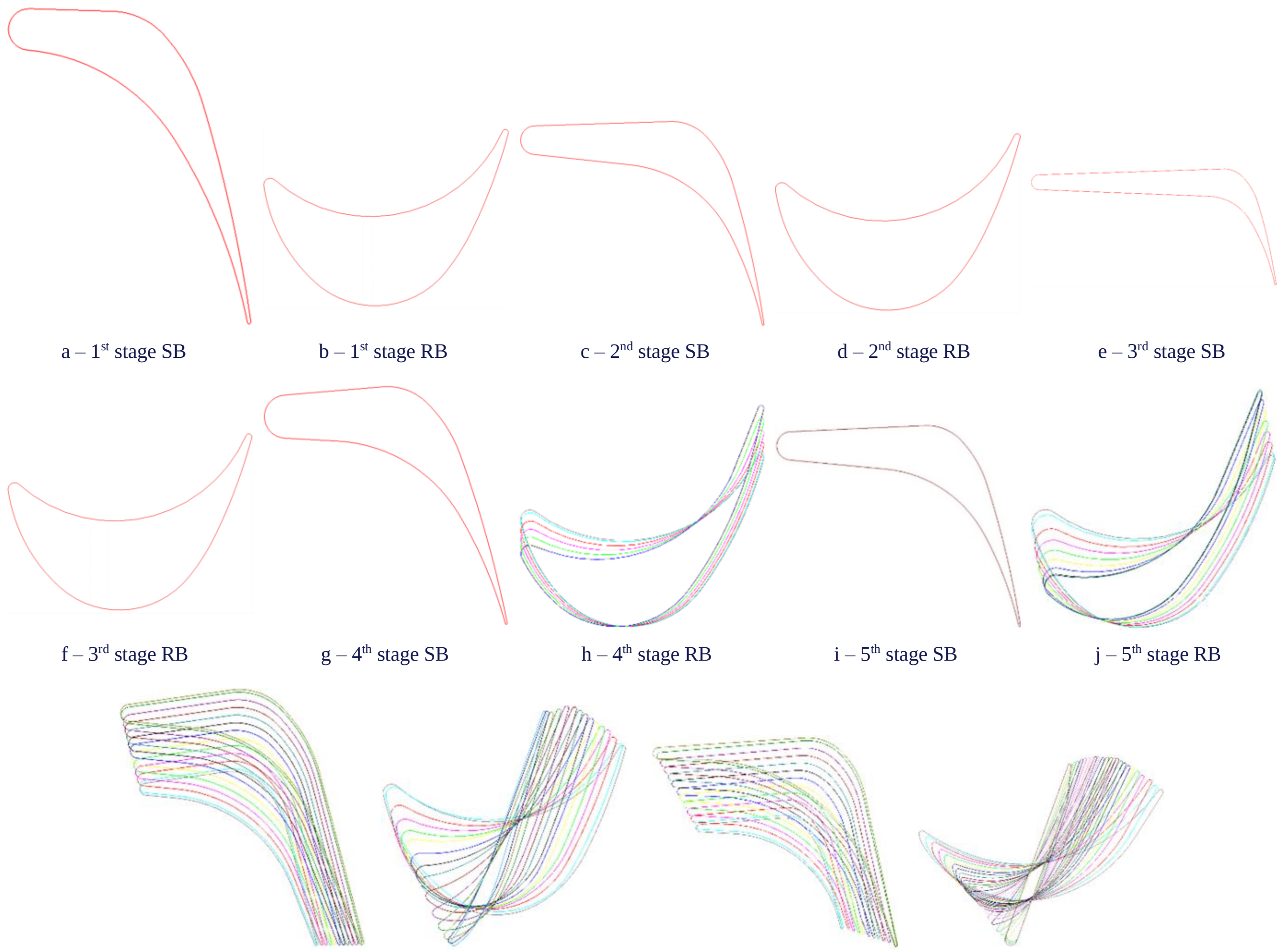


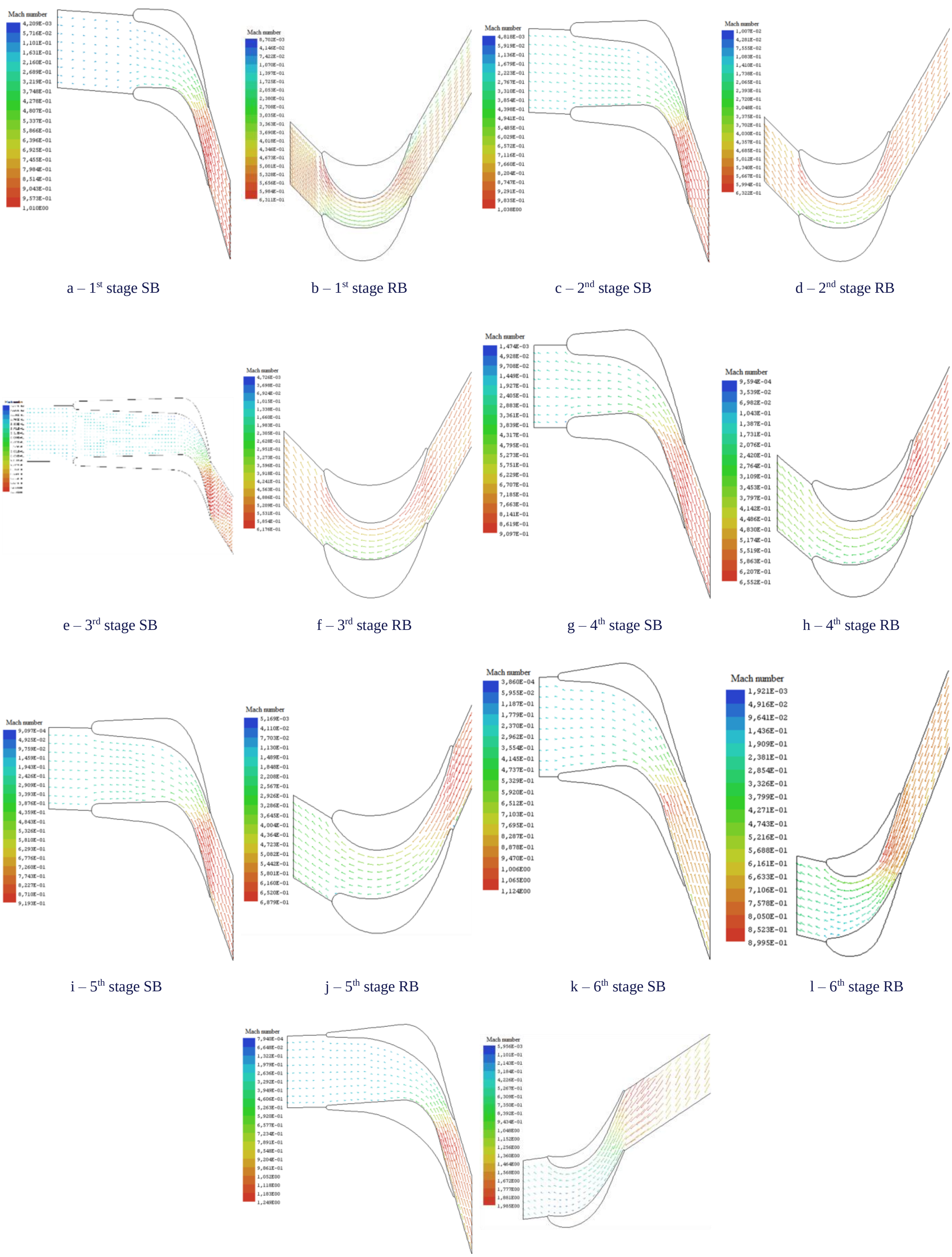
Fig. 2. View of the blades cross-sections.

4. The initial flow part analysis and choosing the directions of modernization

Numerical simulations of the three-dimensional steam flow through the original turbine flow part are provided to determine the modernization areas. End-to-end LPC computations of 7 stages are accomplished on h-type difference grids with a total number of cells of about 7 million. The computational grid refinement near rigid surfaces corresponds to $y^+ < 5$. Figure 3 visualizes the flow in the flow part, whereas Fig. 4 demonstrates the pressure distribution across the blade surfaces. The basic integral characteristics of the flow part under consideration are shown in Table 1.

The flow visualization results (Fig. 3), demonstrate the favourable flow picture. It should be noted that any flow separations or vortex flows are not observed here. However, the pressure on the blade surfaces is non-monotonic (Fig. 4). It usually leads to an increase in the kinetic energy losses. In the first six stages, a relatively low reactivity degree is observed (compared with the desired value of 0.5). The increased load (small value of u/C_0) is recognized in the first five stages (Table 1). The loading in the seventh stage is high (small value of $u/C_0 = 0.48$), with a high value of reactivity. Such a ratio of loading and reactivity is uncharacteristic and can be explained by the high supersonic flow velocity in the interblade channel (Fig. 3: m, n).

Relatively long cylindrical blades with a constant profile (small D/L) are used for the first stage blades, which leads to deterioration in the picture of flow along the blade height. Also, as it can be concluded from the graphs (Fig. 4), the pressure distributions on the blade surfaces are not monotonous. In all stages, the significant underload of the inlet stator blade is observed from the pressure distribution graphs (Fig. 4: a, c, e, g, i, k, m). It is caused by the blade extension there (Fig. 2i). Such a profile has been created using the strength conditions, but it is not optimal from the gas dynamics point of view.



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
i – 5th stage SB
j – 5th stage RB
k – 6th stage SB
l – 6th stage RB
m – 7th stage SB
n – 7th stage RB

Fig. 3. Vectors of velocity in the mid-span blade-to-blade section.

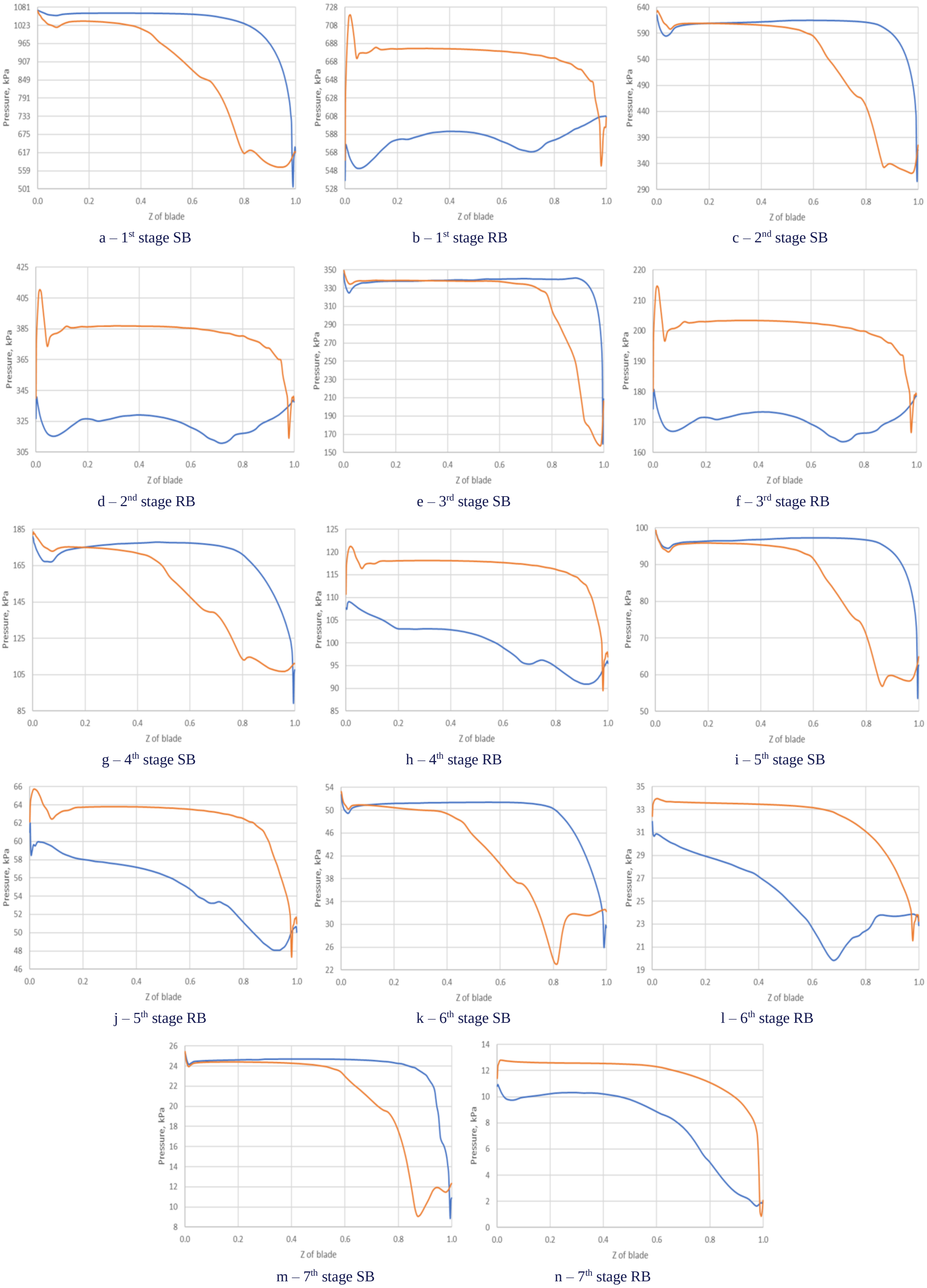


Fig. 4. Pressure distribution over the blade surfaces in the mid-span section.

Table 1. Main geometrical and integral gas-dynamical characteristics of the flow part.

Stage No.	*D/L*	u/C_0	*ρ*	*η*, %
1	40.68	0.48	0.0059	92.85
2	27.69	0.49	0.0584	97.56
3	17.40	0.51	0.0675	90.49
4	10.73	0.56	0.2399	94.03
5	6.80	0.59	0.3018	93.37
6	4.54	0.62	0.3614	92.92
7	2.86	0.48	0.5742	89.63

Figures 5 and 6 demonstrate some results concerning the last stage in the nominal mode. From the graph in Fig. 5, one can see that the value of reactivity degree at the hub is low.

From Fig. 6, it can be seen that there is an uneven distribution of parameters along the height. A supersonic flow is observed at the outlet of the blade row. It leads to a high value of losses with the outlet velocity (Table 2).

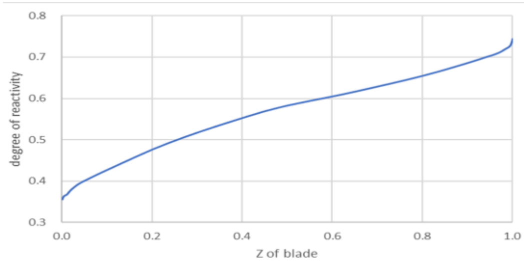


Fig. 5. Reactivity degree distribution along the rotor blade height in 7th stage.

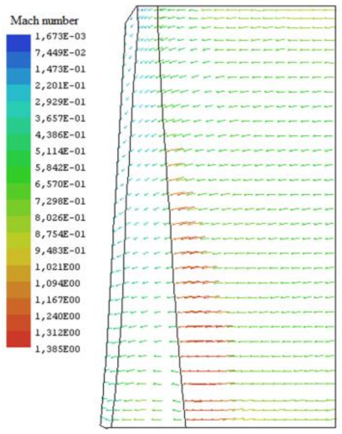


Fig. 6. Velocity vectors in 7th stage rotor at mid-meridional section.

All over the flow part, some flow separations have been observed near significant breaks in the peripheral contours, the so-called overlaps. Fig. 7 demonstrates an example of a similar separation, which occurred between the rotor and stator in the 5th stage.

Table 2 displays integral features of the entire flow part, encompassing average outlet velocity values. One can conclude

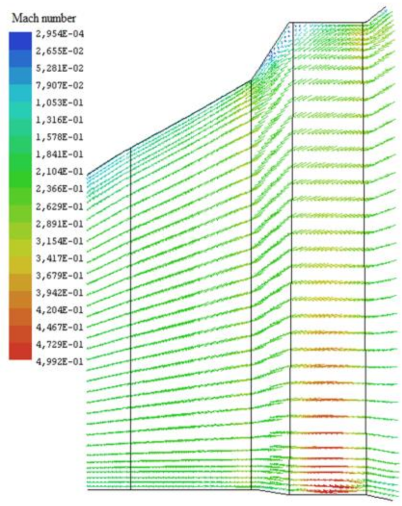


Fig. 7. Velocity vectors in 5th stage at mid-meridional section.

Table 2. The flow part main integral characteristics.

C_3, m/s	ξ_{ov}, %	*η*, %	Power (one flow), MW
285.7	4.74	88.60	134.095

that the flow part efficiency is relatively high, but the outlet velocity values, and so the corresponding losses, are quite large.

Based on the above shown results and their analysis, the following measures to improve the flow part are planned:

- The use of smooth meridional contours, which will ensure the absence of flow separations in the stator-rotor interspace overlap of meridional contours;
- Developing the blades with smooth (monotonic) surfaces, which will ensure the absence of non-monotonicity in the pressure diagrams on the blade surfaces;
- Developing the blades, adjusted along the flow, with variable cross-sections along the height, which will ensure the flow improvement around the blades;
- Redesigning the meridional contours (used for the low-speed steam turbine structure for the first time in the world practice), which will ensure an increase in D_{av} of the first stage, reducing the load of the stage (increase in u/C_0), increasing the reactivity degree, and more optimal distribution of thermal drops;
- Increasing the height of the last stage rotor blade, which will ensure the reduction of the outlet velocity losses;
- Developing the saber-shaped last stage stator blade, which will ensure more uniform distribution of parameters along the height and an increase in reactivity degree at the hub.

5. Modernized flow part and discussion

According to the measures described above, the new LPC flow part of the K-1000 nuclear turbine series was designed, whereas its fitting within the original framework has been reassured. The modernized flow part is shown in Figs. 8 and 9. Blades in the 3rd to 7th stages incorporate variable height profiles.

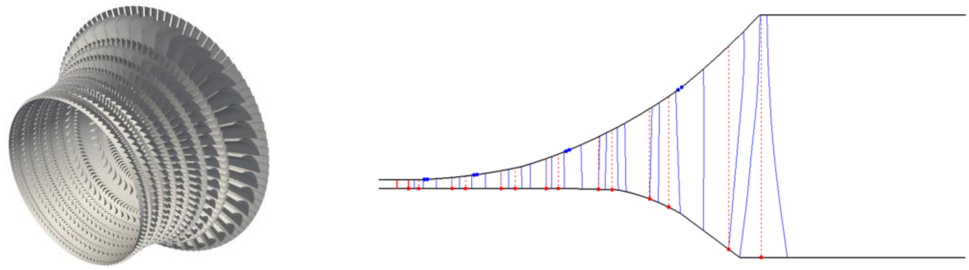
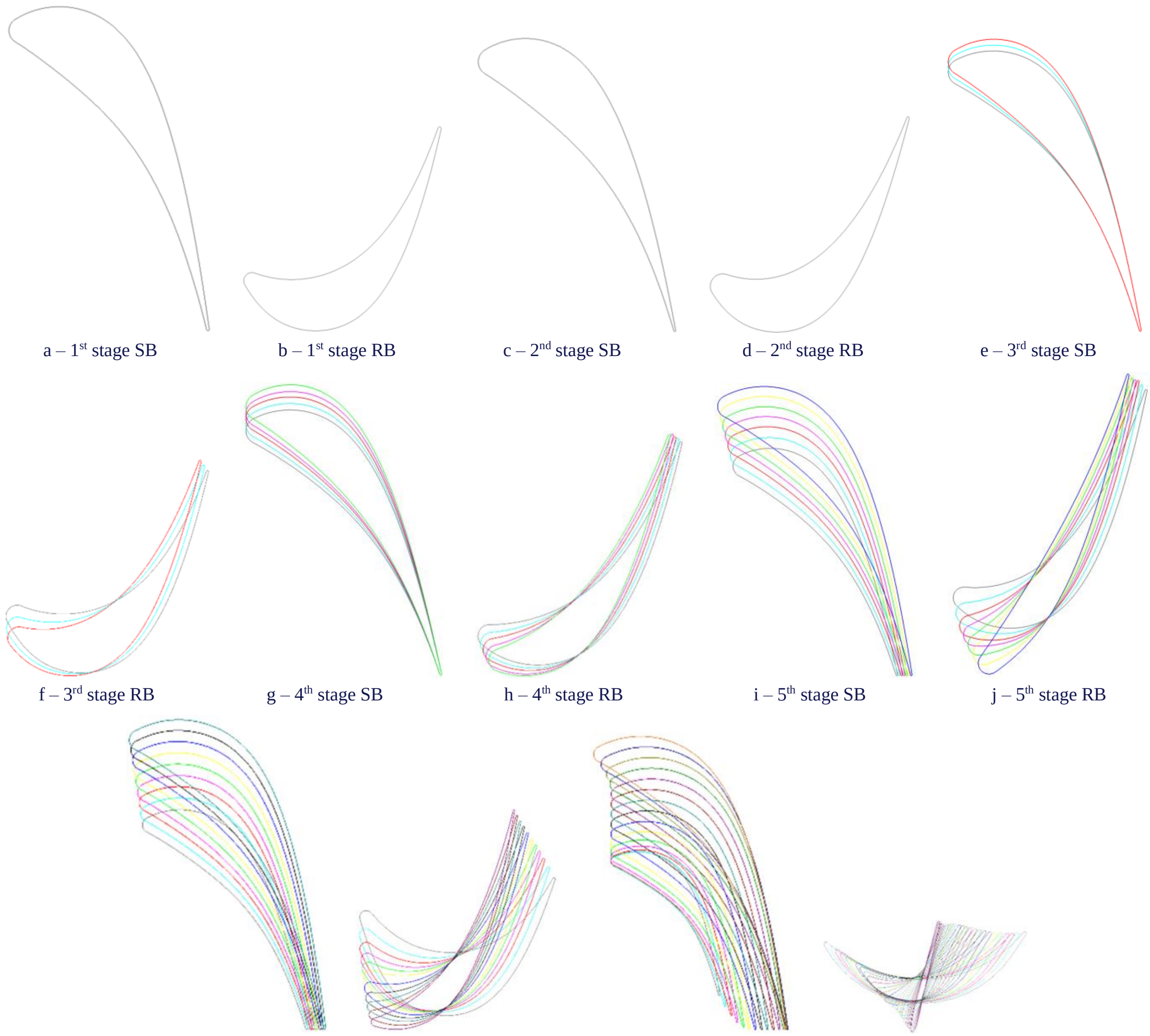


Fig. 8. Visualization of the redesigned flow part in the new LPC of K-1000-60/1500 turbine series.

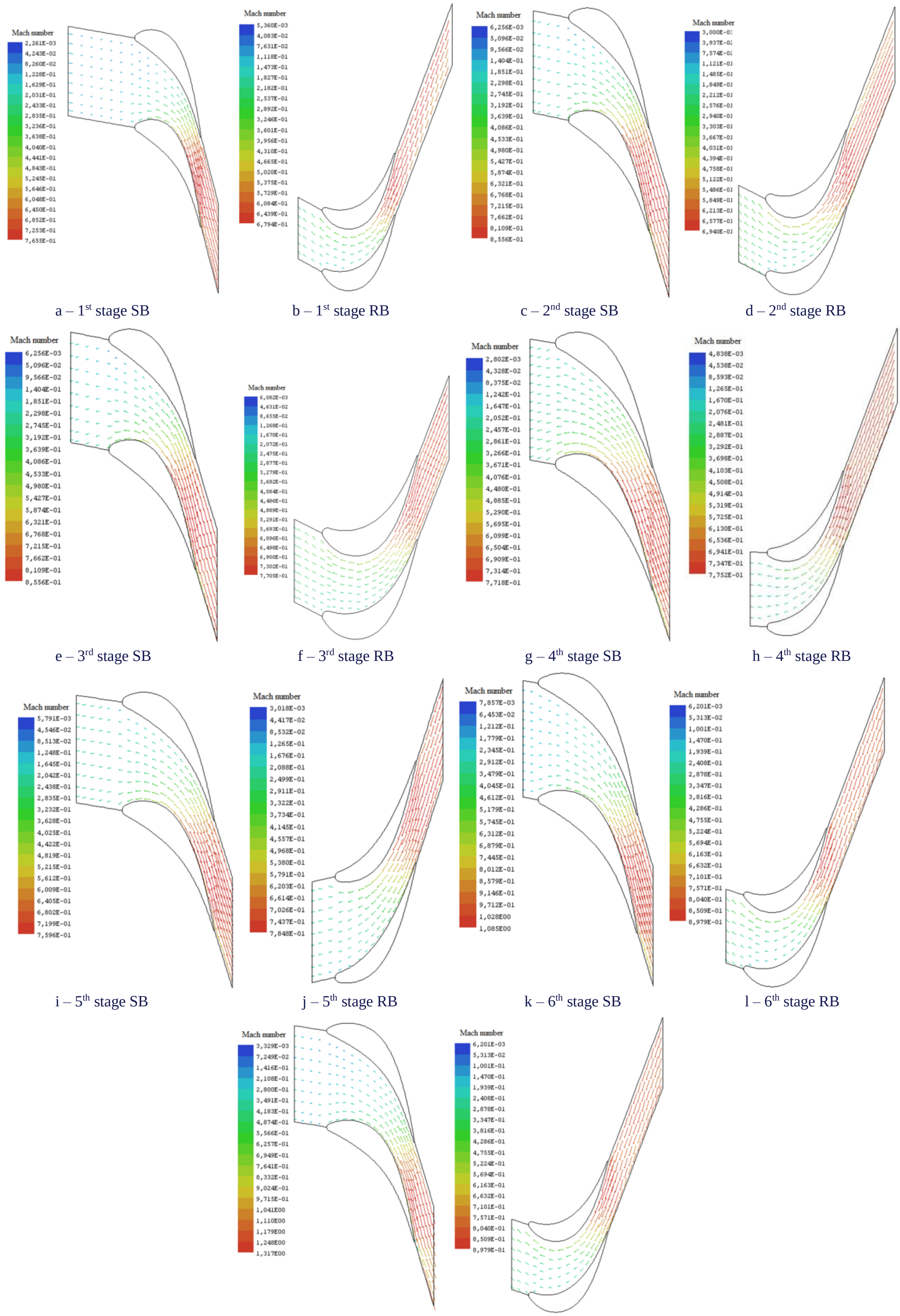


a – 1st stage SB; b – 1st stage RB; c – 2nd stage SB; d – 2nd stage RB; e – 3rd stage SB; f – 3rd stage RB; g – 4th stage SB; h – 4th stage RB; i – 5th stage SB; j – 5th stage RB; k – 6th stage SB; l – 6th stage RB; m – 7th stage SB; n – 7th stage RB

Fig. 9. New blades overview.

End-to-end calculations for the new LPC with 7 stages have been completed using h-type difference grids, akin to those utilized in the original LPC, with the total cells number about 7 million. The computational grid refinements near rigid surfaces correspond to $y^+ < 5$.

Figure 10 visualizes the flow in the designed flow part, and Fig. 11 demonstrates pressure distributions over the blade surfaces. The flow visualization results (Fig. 10) demonstrate the favourable flow picture. It should be noted that any flow separations or vortex flows are not observed here. The flow velocity in the interblade channel of the 7th stage is closer to subsonic (Fig. 10 m, n) compared to the original stage (Fig. 3 m, n). This approach leads to a lower value of kinetic energy losses.



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; i – 5th stage SB; j – 5th stage RB; k – 6th stage SB; l – 6th stage RB; m – 7th stage SB; n – 7th stage RB

Fig. 10. Velocity vectors in the mid-span blade-to-blade section.

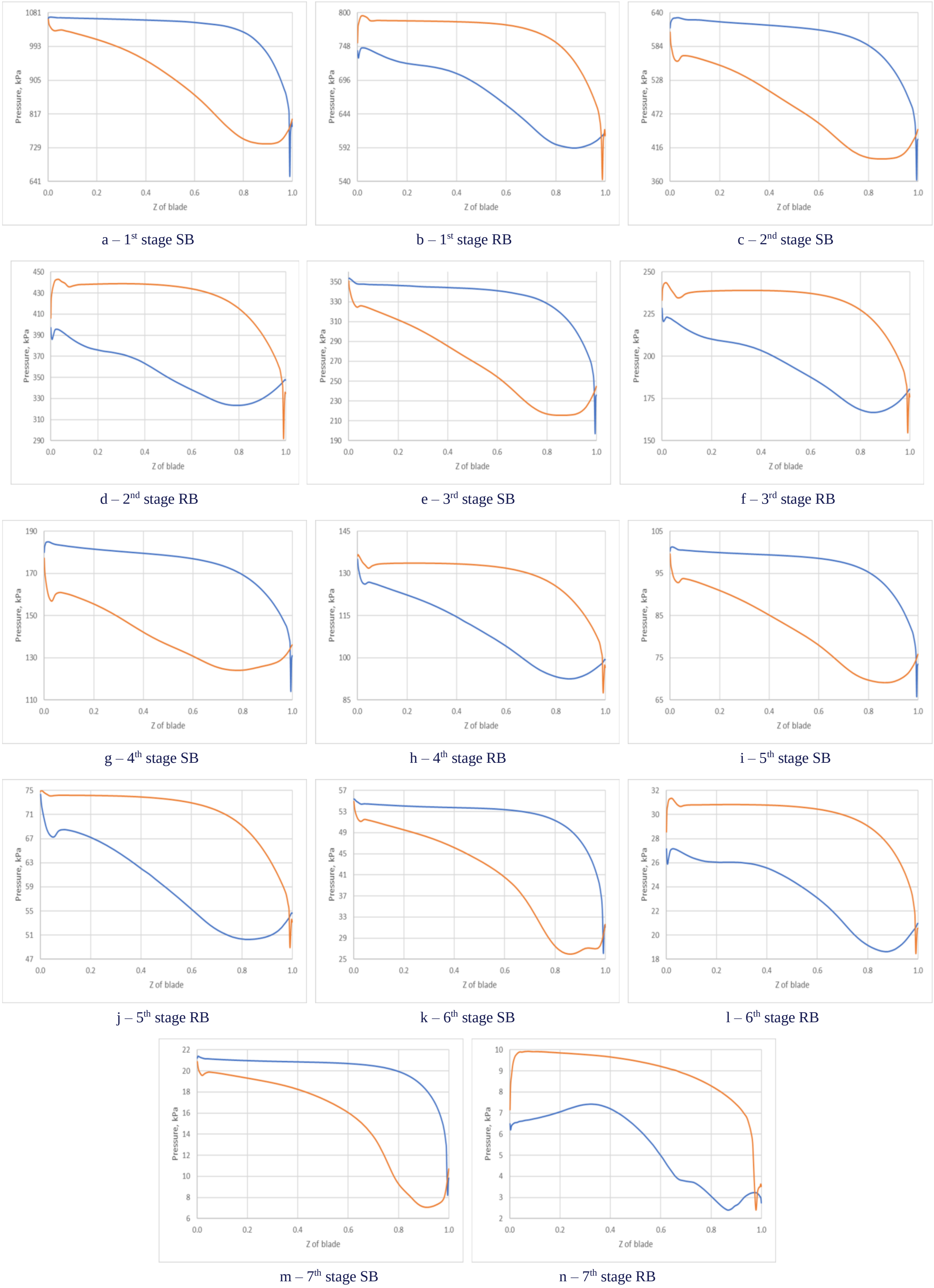


Fig. 11. Pressure distributions over the blade surfaces in the mid-span section.

Table 3. The primary integral and geometrical characteristics of the flow part.

Stage number	*D/L*	u/C_0	*ρ*	*η*, %
1	58.03	0.57	0.3979	94.77
2	27.69	0.60	0.3436	95.91
3	17.40	0.61	0.3910	93.71
4	10.73	0.66	0.4672	95.49
5	6.80	0.69	0.4861	95.78
6	4.54	0.69	0.3439	95.04
7	2.58	0.49	0.5042	90.13

From the results shown in Fig. 10, it can be concluded that a favourable flow pattern is obtained. The pressure distributions on the blade surfaces (Fig. 11) became essentially more monotonic compared to the original LPC (Fig. 4). These outcomes are obtained through the use of blades with smooth surfaces. The basic integral characteristics of the newly designed flow part are presented in Table 3.

By reprofiling the meridional contours, the increase in the average diameters for the first three stages has been successfully accomplished. It led to a number of advantages (see Table 3): decreased the relative blade height (increased value of *D*/*L*), the loading of stages became more optimal, the value of u/C_0 became closer to 0.7 [37], and the degree of reactivity increased. It is necessary to add more about this solution's innovativeness. In the steam turbine world practice, the average diameter in LPCs usually increases essentially from the first stages to the last ones, but the hub diameter remains practically the same or slightly decreases. In the proposed flow part option, the difference in average diameters between the stages has decreased, and the hub diameter in the first stages has increased substantially compared both to the last ones and the original option. So, this made it possible to achieve the above mentioned advantages. The proposed approach has been used for the first time for the low-speed turbine. It is offered for implementation by JSC «Ukrainian Energy Machines». In global practice, during the steam turbine construction, a similar approach was first proposed by the authors for a high-speed turbine of the K-220-44 series [20]. Previously, the implementation of such structures was not carried out especially due to technological problems, since in this case, the rotor becomes significantly heavier. The JSC «Ukrainian Energy Machines» has solved this problem by using the technology of welded rotors manufacturing [39] which has ensured their reasonable characteristics both in terms of mass and strength.

To reduce the outlet velocity losses, the new rotor blade of the last stage has been used with a height of 1650 mm instead of 1450 mm in the original structure. However, increasing the blade length results in an even greater decrease in fanning value (decrease of *D*/*L*) that also leads to an additional reactivity degree decrease at the hub surface of the stages. To eliminate this negative effect, the saber-shaped last stage stator blade has been developed, Fig. 12.

Figures 13 and 14 illustrate the reactivity degree variation along the blade height and the velocity vectors in the 7th stage rotor at the mid-meridional section. From the obtained results, one can see that due to using the saber-shaped blade, the unevenness in the distribution of the parameters along the height in the 5th stage has significantly decreased compared to the original design (Fig. 7). Moreover, despite the extensive fanning, there has been an increase in the reactivity degree at the hub surface (Fig. 13).

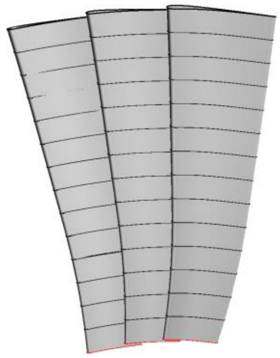


Fig. 12. 3D visual representation of the stator blades in the new design last stage.

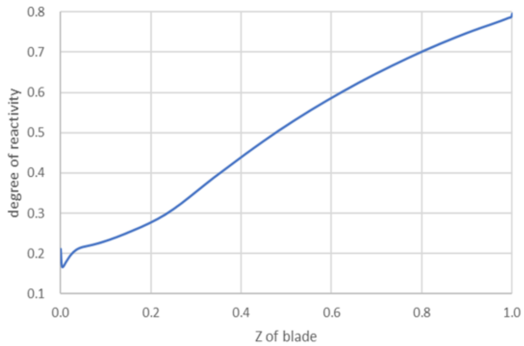


Fig. 13. Reactivity degree vs. the height of the rotor blade in 7th stage.

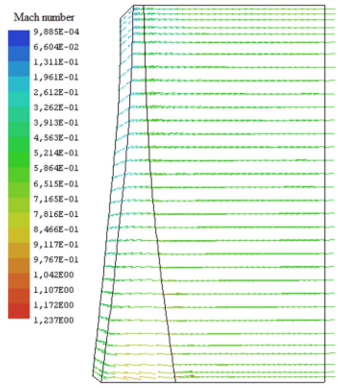


Fig. 14. Velocity vectors in 7th rotor stage at the mid-meridional section.

The redesigned flow part features smooth meridional contours without overlaps in the new configuration. This design guarantees the prevention of flow separation in these specific areas [40]. Indeed, for example, Fig. 15 visualizes the flow in the 5th stage. Compared to the original design shown in Fig. 7, the flow here is continuous.

Table 4 shows the basic flow part integral characteristics of the whole modernized turbine. One can see the significantly decreasing outlet velocity and, accordingly, the decreasing losses with outlet velocity. Due to the complex measures implemented to modernize the flow part, the efficiency increase was shown both in each individual stage (refer to Tables 1 and 3) and in the overall flow domain (refer to Tables 2 and 4).

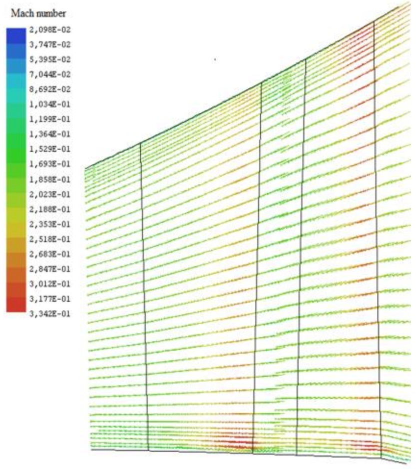


Fig. 15. Velocity vectors in 5th stage at mid-meridional section.

Table 4. The flow part main integral characteristics.

c_3, m/s	ξ_{ov}, %	η, %	Power (one flow), MW
230.8	3.1	91.42	139.387

6. Conclusions

- Analysis of 3D turbulent steam calculations in the initial design of the low-pressure cylinder flow part for the K-1000-60/1500 turbine has identified areas for improvement.
- The research has been carried using the techniques and software package for gas-dynamic calculations and the design of flow parts created at the IPMach NAS of Ukraine.
- A significant increase in the efficiency of LPC of the K-1000-60/1500 series steam turbine has been achieved.
- The total efficiency and power of the developed LPC flow part (single flow) are 91.42% and 139.387 MW, which is by 2.82% and 5.292 MW higher compared to the original one.
- LPC of this turbine consists of 6 flows, so the total increase in power is 31.752 MW.
- JSC "Ukrainian Energy Machines" (formerly PJSC "Turboatom") has approved the findings of the presented research.
- The methodology put forth, coupled with the acquired expertise, holds potential for utilization in the development and enhancement of LPC flow parts for other robust steam turbines at NPPs and TPPs within Ukraine and beyond.

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