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DEVELOPMENT OF THE FLOW PART OF REACTIVE TYPE HPC OF K-325-23.5 SERIES STEAM TURBINE BASED ON THE USE OF MODERN COMPUTER TECHNOLOGIES

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The results of gas-dynamic design of a new flow part of a reactive type high-pressure cylinder (HPC) of the K-300 series condensing steam turbine are presented. The turbine was developed 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 analytical construction of the spatial shape of the blade rows 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 stage, 3D end-to-end calculations of the HPC, which consists of 18 stages, were carried out. The technology of parallel computing was applied in the said calculations. It is shown that a significant increase in efficiency and power has been achieved in the developed HPC due to the use of reactive type stages with modern smooth blade profiles and monotonic meridional contours.

Keywords: *steam turbine, high pressure cylinder, flow part, reactive type blading, spatial flow, computational studies.*

Introduction

Despite the policy of the European Union to reduce greenhouse gas emissions [1] and high growth rates of "green" energy, steam turbines of TPPs and CHPPs make up a significant share in the total electricity generation balance. For example, the share of generated electricity at TPPs and CHPPs is about 30% in Ukraine, about 50% in Poland [2], and about 14% in the entire European Union [3]. In addition, due to the lack of a sufficient number of hydroelectric power plants and pumped storage power plants in Ukraine, the power units of thermal power plants perform functions of regulating capacities that are not characteristic for them. In the future, the load on thermal power plants of Ukraine in order to perform regulating functions will only increase. This is due to the plans to significantly increase the share of generation from renewable energy sources (sun, wind and others) [New Green Deal], which are known to be unstable and require a sufficient amount of not only maneuverable, but also compensating capacities [4].

Along with the development of green energy, another way to significantly reduce greenhouse gas emissions is to increase the efficiency of power generating equipment at TPPs and CHPPs. Equipment improvement ensures a decrease in the unit fuel consumption for generated electricity, which automatically leads to a reduction in harmful emissions [5].

One of the ways to improve the efficiency of the power generating equipment of TPPs and CHPPs is the gas-dynamic improvement of the steam turbines flow parts. This is especially important for Ukraine, where most of the existing power units of thermal power plants have worked out established and extended resources [6]. They require radical reconstruction or replacement with new power units [7, 8]. As a rule, the flow parts of powerful steam turbines are divided into three cylinders: high, medium and low pressure [9], the most problematic of which are HPCs. Among the powerful steam turbines of TPPs and CHPPs operated in Ukraine, almost all HPCs are made with impulse type stages [10]. This is due to the fact that such stages allow large (compared to reactive) thermal drops to be triggered, therefore, their number in the turbine is less, and, accordingly, the turbine production cost is lower. In addition, reactive type stages require better seals [11]. Studies of recent years related to the gas-dynamic improvement of the turbomachines flow parts, carried out using the methods of computational fluid dynamics 3D CFD [12, 13], indicate the advantage in efficiency of reactive type stages over impulse type [14].

One of the most widespread steam turbines with an impulse type HPC in Ukraine is the K-300 series turbine (more than 40 units have been installed and operated).

The article presents an option of a new reactive type HPC of the K-325-23.5 series turbine developed by JSC "Ukrainian Energy Machines" (formerly JSC "Turboatom"). The new flow part is designed in such a way that it can be accommodated within the dimensions of the existing turbine. The design was carried out using the methodology implemented in the *IPMFlow* software package. The methodology includes gas-dynamic calculations of various levels of complexity, as well as methods for constructing the spatial shape of the blade rows based on a limited number of parameterized values. It is shown that a significant increase in efficiency and power has been achieved in the developed HPC due to the use of reactive type stages with modern smooth blade profiles and monotonic meridional contours.

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* [15]. 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 ENO-scheme of increased accuracy and Menter’s k-ω SST two-equation turbulence model [16]. To take into account the thermodynamic properties of steam, method of interpolation-analytical approximation of the *IAPWS-95* equations was used [17]. 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 isolated turbine stages and flow parts of turbomachines as a whole [18].

To speed up the time of calculations in the *IPMFlow* software package, an original technology of parallel computing [19] has been introduced. The technology has the following main characteristics:

– it is used for computers with shared RAM;
– weakly depends on the operating system because each parallel process is an executable module;
– no less than one blade row (minimal 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 spatial shape of the blade row of the axial flow part, the method of analytical profiling [20], 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 spatial shape 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.

Research object

One of the latest modifications of turbines of the K-300 series, namely K-325-23.5, was taken as the object of research. The turbine uses a nozzle steam distribution system [21]. HPC consists of a regulating stage and 11 impulse type pressure stages (Fig. 1).

The following values were set as the boundary conditions for the gas-dynamic calculation: total pressure and temperature at the HPC inlet (behind the control valves)are 22.6 MPa and 808 K, respectively, static outlet pressure – 3.92 MPa, and the mass flow rate – 277.7 kg/s [22–24]. End-to-end calculations of the original design of the HPC (12 stages) were performed on difference grids with a total number of cells of about 10 million.

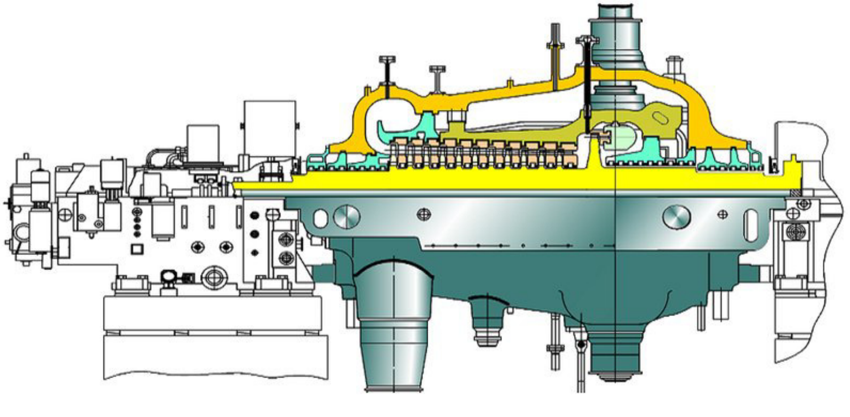


Fig. 1. Meridional section of the HPC of K-325-23.5 turbine [21]

Figures 2–5 show the isolines of the static pressure in the mid-tangential section.

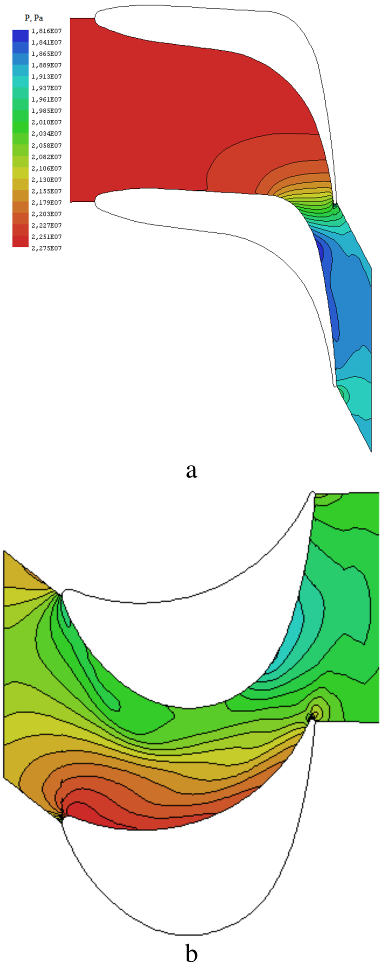


Fig. 2. Static pressure isolines in the mid-tangential section:
a – 1st stage stator blade (SB),
b – 1st stage rotor blade (RB)

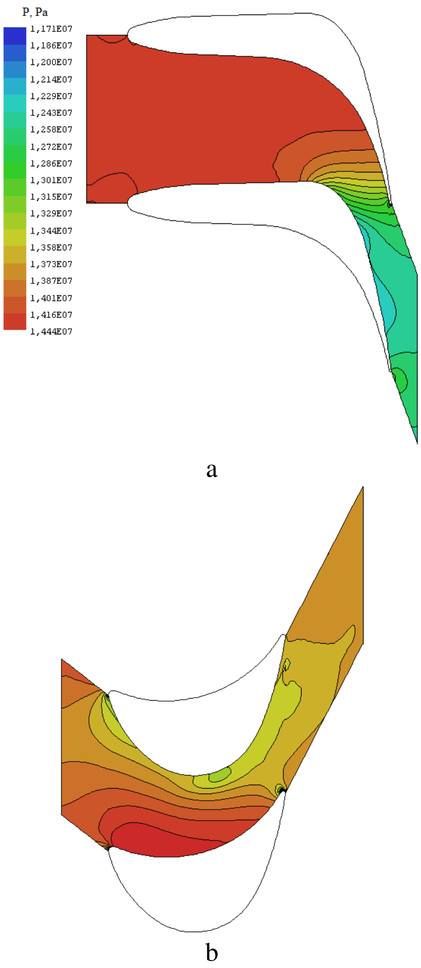


Fig. 3. Static pressure isolines in the mid-tangential section:
a – 4th stage SB, b – 4th stage RB

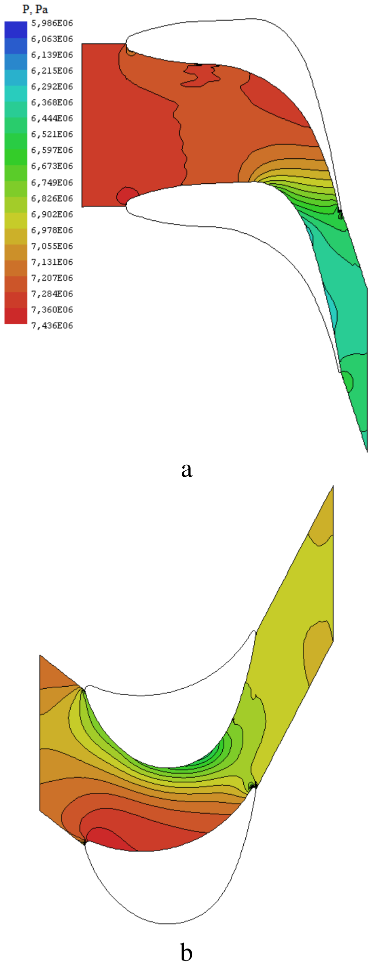


Fig. 4. Static pressure isolines in the mid-tangential section:
a – 9th stage SB, b – 9th stage RB

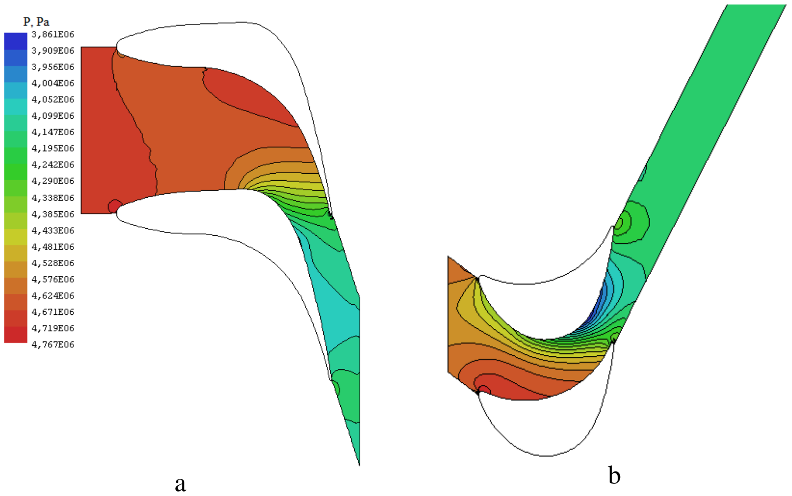


Fig. 5. Static pressure isolines in the mid-tangential section:
a – 12th stage SB, b – 12th stage RB

Table 1. Energy characteristics of the new HPC by stages

Stage no.	Efficiency, %	ro, %	Power, MW
1	61.37	0.10	13.71
2	70.08	0.05	9.23
3	82.02	0.04	8.73
4	80.92	0.05	8.51
5	81.75	0.05	8,32
6	82.78	0.09	8.27
7	83.31	0.08	8.09
8	83.65	0.08	8.26
9	83.46	0.08	8.23
10	84.84	0.13	8.43
11	85.82	0.15	8.10
12	86.35	0.28	9.31

From the given results, it can be seen that even at the nominal operation mode, the efficiency of the first (regulating) and second stages is very low and equals to 61.37 and 70.08%, respectively (Table 1). This is due to the very high loading of the first stage and the nonaxial flow angle into the second stage. The obtained level of gas-dynamic efficiency in the 1st stage, taking into account the peculiarities of its design (partiality), is standard, and the second one is very low. So, for the rest of the stages, the efficiency value is in the range of 80-86%, which is an acceptable value for the impulse type stages. The total efficiency of the initial flow part of the HPC is 85.9%, and the power is 107.2 MW at the nominal mode.

Results and discussion

The new version of the HPC was developed in such a way that it would fit into the dimensions of the original flow part. The values corresponding to the initial HPC were set as the boundary conditions for the gas-dynamic design: total pressure and temperature at the HPC inlet (behind the control valves) are 22.6 MPa and 808 K, respectively, the static outlet pressure – 3.92 MPa, the mass flow rate – 277.7 kg/s.

The new HPC flow part consists of a regulating and 17 reactive type stages, a total of 18 stages. In contrast to the original design of the flow part, the regulating compartment of the new HPC is designed without a mixing chamber in order to reduce losses [25]. An increased axial distance between the first and second stages is applied to compensate for the absence of a traditional mixing chamber. When designing a new flow part, to ensure optimal loading of the stages, their number and distribution of thermal drops were chosen so that the value of u/C_0 was approximately equal to 0.7 (except for the regulating stage) [26]. The value of the outflow angle of the flow from the stages was designed close to the axial direction. The construction of the meridional contours, as well as the determination of the position of the stages in them (Fig. 6) was carried out using simplified (one-dimensional) methodologies. These methodologies are used to determine: the number of stages, average diameters, thermal drops and stage heights. At the next stages, using 3D CFD methods, the design of the stages was carried out separately, as well as the final end-to-end calculations and the entire HPC refinement. To obtain the final flow part of the HPC, it was necessary to consider, on average, 5–7 options of each stage separately and 3 HPC options as a whole. End-to-end HPC calculations (18 stages) were performed on difference grids with a total number of cells of about 15 million.

Figure 6 shows that the meridional contours are smooth, without overlapping, which helps to avoid the appearance of circulation zones (flow separations) in places of a sharp change in the shape of the meridional contours [27].

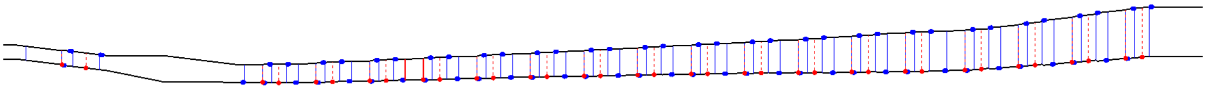


Fig. 6. Meridional section of the new HPC

Figures 7–11 show the isolines, and Figures 12–16 show the distribution diagrams of static pressure on the blades' surfaces in the mid-tangential sections.

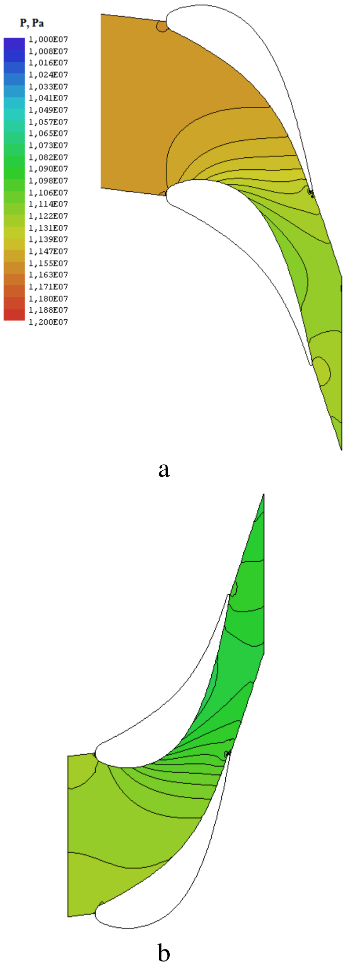


Fig. 7. Static pressure isolines in the mid-tangential section:
a – 2nd stage SB, b – 2nd stage RB

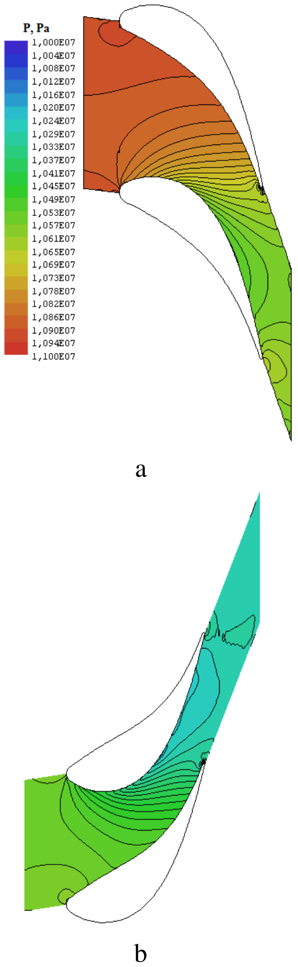


Fig. 8. Static pressure isolines in the mid-tangential section:
a – 3rd stage SB, b – 3rd stage RB

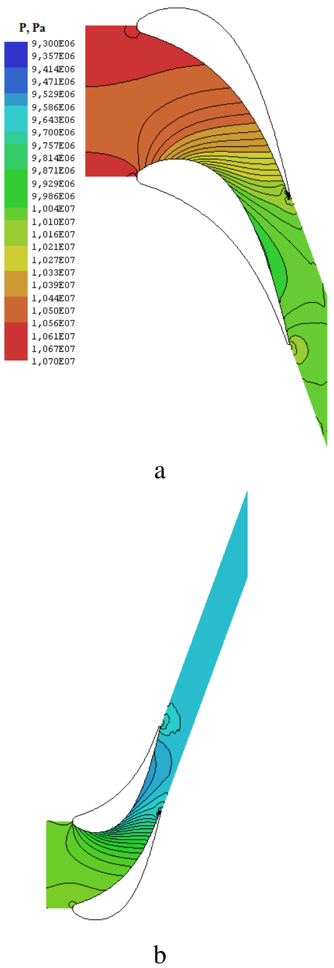


Fig. 9. Static pressure isolines in the mid-tangential section:
a – 10th stage SB, b – 10th stage RB

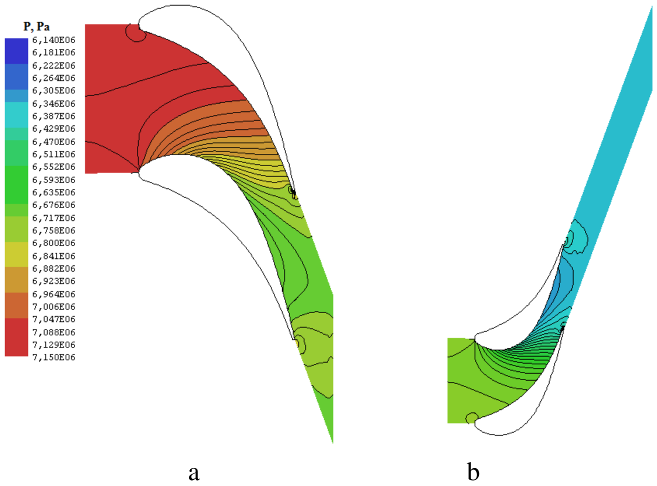
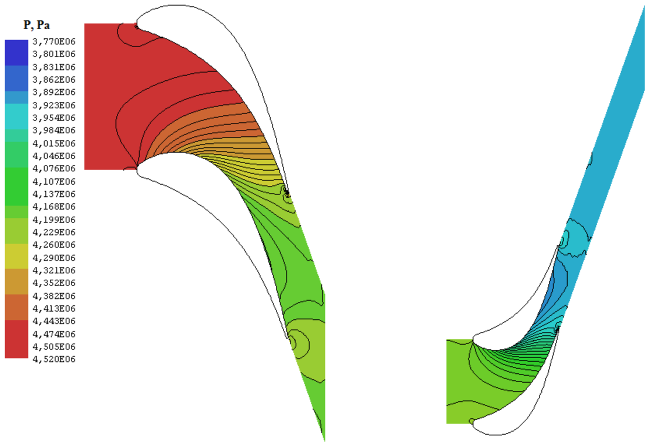
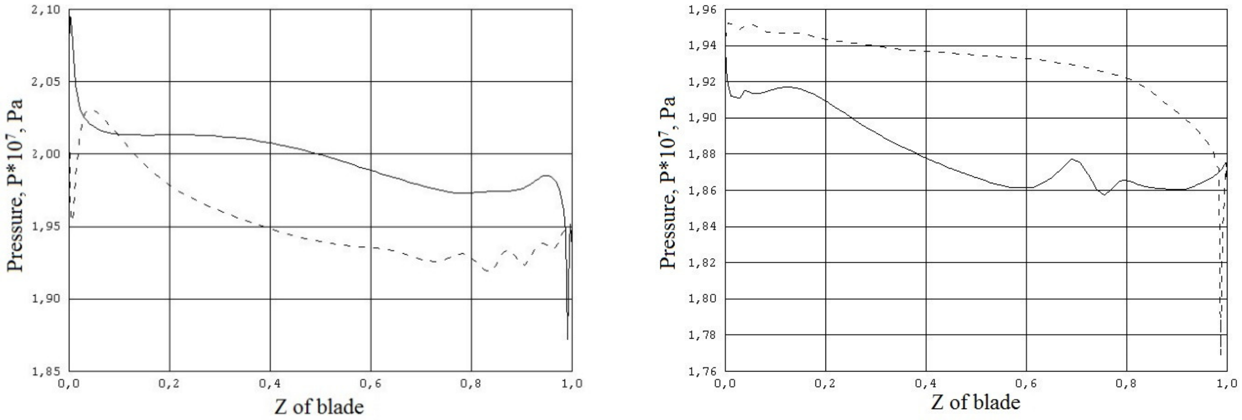


Fig. 10. Static pressure isolines in the mid-tangential section:
a – 14th stage SB, b – 14th stage RB



a b

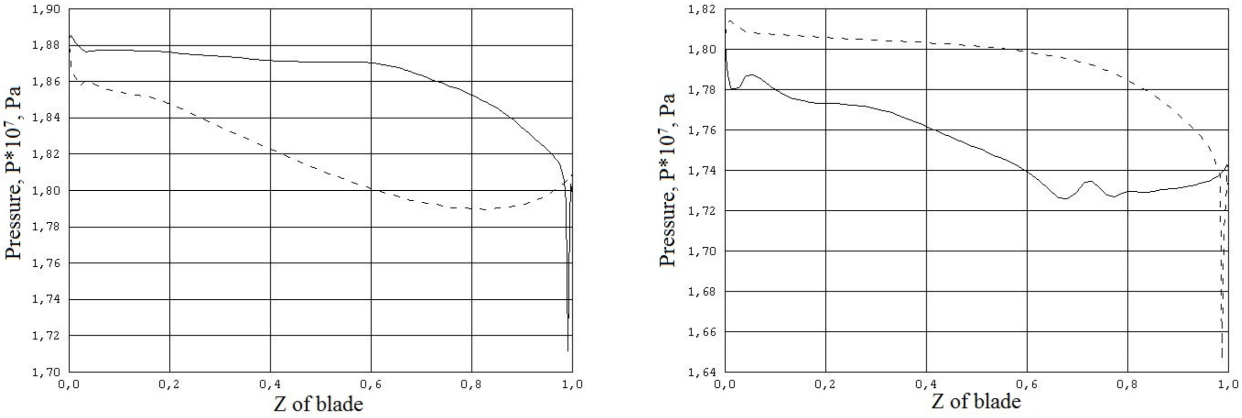
Fig. 11. Static pressure isolines in the mid-tangential section:
a – 18th stage SB, b – 18th stage RB



a

b

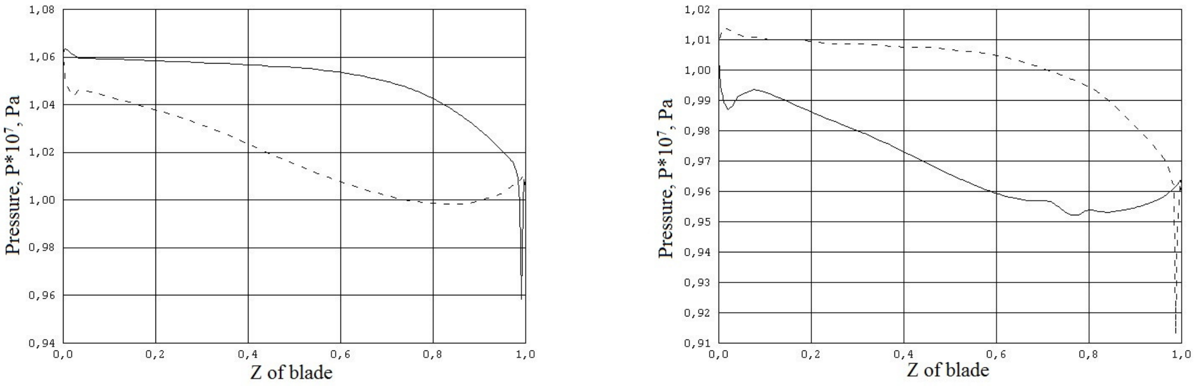
Fig. 12. Distribution of static pressure on the surfaces of the blades in the mid-tangential section:
a – 2nd stage SB, b – 2nd stage RB



a

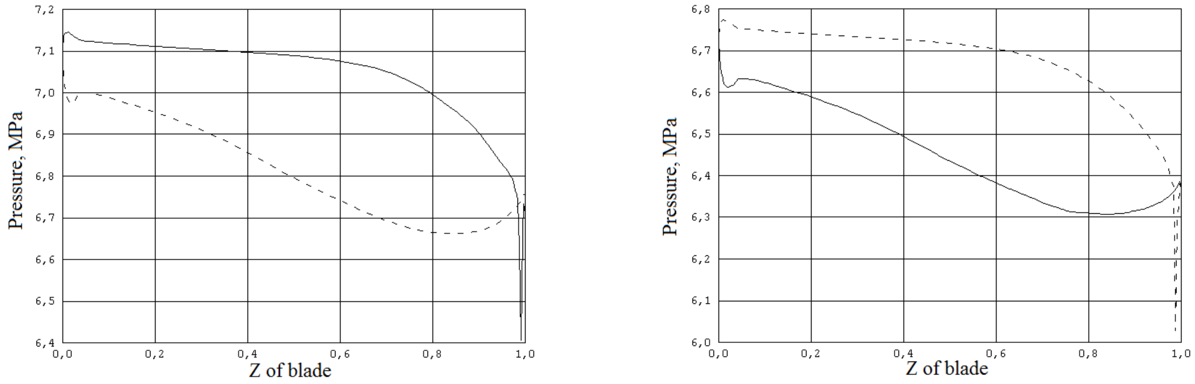
b

Fig. 13. Distribution of static pressure on the surfaces of the blades in the mid-tangential section:
a – 3rd stage SB, b – 3rd stage RB



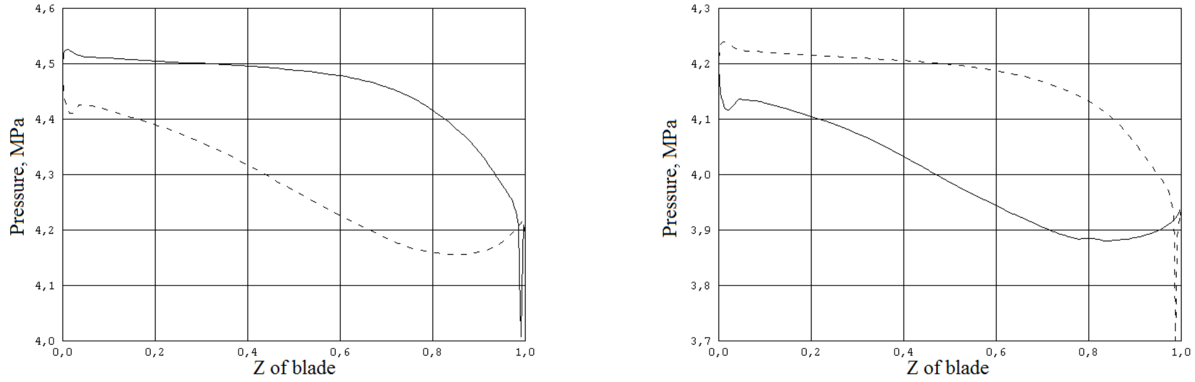
a b

Fig. 14. Distribution of static pressure on the surfaces of the blades in the mid-tangential section:
a – 10th stage SB, b – 10th stage RB



a b

Fig. 15. Distribution of static pressure on the surfaces of the blades in the mid-tangential section:
a – 14th stage SB, b – 14th stage RB



a b

Fig. 16. Distribution of static pressure on the surfaces of the blades in the mid-tangential section:
a – 18th stage SB, b – 18th stage RB

From the given results, it can be seen that due to the use of smooth blade profiles described by curves of the 4th and 5th orders the distribution of static pressure on the blades is rather monotonic. This indicates a high level of gas-dynamic perfection of the flow part, which is confirmed by the values of the integral characteristics given in Table 2. Table 3 shows the total gas-dynamic characteristics of the original and new

HPC. The efficiency of the first (regulating) stage is about 77%, while for the rest of the stages it is in the range of 92-95%. The total efficiency of the developed flow part of the HPC is 93.5%, and the power is 116.7 MW at the nominal mode. The increase in the efficiency of the new flow part in comparison with the original one will amount to 7.6% and 9.5 MW in terms of efficiency and power, respectively.

Conclusions

On the basis of variational calculations of three-dimensional turbulent steam flows, a three-dimensional model of the spatial shape of the new HPC flow part of the K-325-23.5 steam turbine has been developed. The research was carried out using the developed at IPMach NAS of Ukraine methods and software systems for gas-dynamic calculation and design of flow parts.

The results and analysis of calculations of the final version of the initial and new flow parts of the steam turbine K-325-23.5 HPC are presented. The new flow part consists of one regulating and 17 reactive type stages, in contrast to the original design with 12 stages.

The total efficiency of the developed HPC flow part is 93.5%, and the power is 116.7 MW at the nominal mode, which is by 7.6% and 9.5 MW higher than the original turbine.

The proposed approach and the gained experience can be used in the development and modernization of the HPC flow parts of other powerful steam turbines that are in operation or can be installed at TPPs and CHPPs both in Ukraine and in other countries.s (Fig. 2, 3).

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Table 2. Energy characteristics of the new HPC by stages

Stage no.	Efficiency, %	ro, %	Power, MW
1	76.91	0.22	9.21
2	91.98	0.46	5.48
3	92.94	0.46	5,61
4	93.84	0.47	5.76
5	93.55	0.46	5.84
6	93.76	0.49	5.67
7	94.02	0.49	6.18
8	93.94	0.46	6,22
9	94.16	0.46	6.39
10	94.19	0.46	6.52
11	94.34	0.46	6.61
12	94.47	0.47	6.73
13	94.63	0.47	6,80
14	94.76	0.47	6.91
15	94.62	0.48	6.16
16	94.82	0.47	6.63
17	94.92	0.46	6.78
18	95.03	0.47	7.17

Table 3. Integral characteristics of HPC

HPC type	Mass flow rate, kg/s	Efficiency, %	Power, MW
initial	277.7	85.9	107.2
new	277.7	93.5	116.7
difference	+0,0	+7,6	+9.5

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Розробка проточної частини ЦВТ реактивного типу парової турбіни серії К-325-23,5 на основі використання сучасних комп'ютерних технологій

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Представлено результати газодинамічного проєктування нової проточної частини циліндра високого тиску (ЦВТ) реактивного типу конденсаційної парової турбіни серії К-300. Проєктування виконано з використанням комплексної методології, яку реалізовано в програмному комплексі IPMFlow. Методологія містить газодинамічні розрахунки різних рівнів складності, а також методи аналітичного побудування просторової форми лопаткових трактів на основі обмеженої кількості параметризованих величин. В 3D розрахунках турбулентних течій враховано реальні термодинамічні властивості води й водяної пари. На заключному етапі проведено скрізні 3D розрахунки ЦВТ, що складається з 18 ступенів, в яких застосовано технологію паралельних обчислень. Показано, що в розробленому ЦВТ за рахунок застосування реактивних ступенів із сучасними гладкими профілями та монотонними меридіональними обводами досягнуто суттєвого приросту коефіцієнту корисної дії та потужності.

Ключові слова: *парова турбіна, циліндр високого тиску, проточна частина, реактивне облопачення, просторова течія, розрахункові дослідження.*

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