

UDC 621.165:532.6

THE GAS-DYNAMIC EFFICIENCY INCREASE OF THE K-300 SERIES STEAM TURBINE CONTROL COMPARTMENT

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The paper proposes ways to increase the efficiency of nozzle control for steam power turbines of the K-300 series, that, along with the K-200 series turbines, form the basis of thermal energy in Ukraine. The object of study is considered to be the control compartment (CC) of the high-pressure cylinder (HPC) of the K-325-23.5 steam turbine. In the paper, the calculation and design of the control compartment of the steam turbine was performed using the complex methodology developed in IPMach NAS of Ukraine, that includes methods of different levels of complexity, from one-dimensional to models for calculation of spatial viscous flows, as well as analytical methods for spatial geometries of flow parts description based on limited number of parameterized values. The complex design methodology is implemented in the IPMFlow software package, which is a development of the FlowER and FlowER-U software packages. A model of a viscous turbulent flow is based on the numerical integration of an averaged system of Navier-Stokes equations, for the closure of which the two-term Tamman equation of state is used. Turbulent phenomena were taken into account using a SST Menter two-parameter differential turbulence model. The research was conducted for six operation modes in the calculation area, which consisted of more than 3 million cells (elementary volumes), taking into account the interdiscand diaphragm leakage. According to the results of numerical studies of the original control compartment of the K-325-23.5 steam turbine, it is shown that the efficiency in the flow part is quite low in all operation modes, including the nominal one (100% power mode), due to large losses of kinetic energy in the equalization chamber, as well as inflated load on the first stage. On the basis of the performed analysis of gas-dynamic processes, the directions of a control compartment flow part modernization are formed and themodernization itself is executed. In the new flow part, compared to the original one, there is a favorable picture of the flow in all operation modes, which ensures its high gas-dynamic efficiency. Depending on the mode, the efficiency of the control compartment increased by 4.9-7.3%, and the capacity increased by 1-2 MW. In the nominal mode (100% mode) the efficiency of the new control compartment, taking into account the interdiscand overbandage leakage, is 91%.

Keywords: steam turbine, control stage, spatial flow, numerical modeling, gas-dynamic efficiency.

Introduction

Today a large share in the balance of power generation in Ukraine is held by thermal power plants (about 30%), most of which are power units with a capacity of 200 and 300 MW. A mandatory condition for the reliable operation of the integrated energy system is the availability of the necessary amounts of maneuvering and regulating capacities. Due to the insufficient number of HPPs and HAPPs, and the complete absence of power units based on gas turbines, power units of thermal power plants are mainly used in Ukraine to maintain the balance between generation and consumption of electricity. Due to the general global trend aimed to increase the share of renewable energy and the development of distributed generation, the need for

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the necessary amount of regulating capacity will increase. In addition to regulating capacities, there will be a need for reserve capacities. For the conditions of Ukraine, the main needs for regulating and reserve capacities, as of today, will be met by the power units of thermal power plants.

Most of the existing power units of thermal power plants in Ukraine have produced specified and extended resources; they need to be replaced by the new ones or are in need of radical reconstruction. Primarily those are power units with a capacity of 200 and 300 MW. Today, along with the traditional requirements for steam turbines of thermal power units, such as efficiency and reliability, there is an urgent need to increase their maneuverability and efficiency, including in operating modes with reduced power.

The world leaders in the development and production of steam turbines are the following companies: Siemens-energy [1], General-Electric [2], Mitsubishi Power [3], JSC "Turboatom" [4] and others. Most nozzle control systems for high-power steam turbines use a circuit in which the control (first) stage is on a medium diameter that is much larger compared to the next (second) stage of high-pressure cylinders (HPC). There is a radial pressure equalization chamber between the first and second stages. Previous studies of a similar scheme of the control compartment on the example of a steam turbine K-325-23.5 showed that the efficiency is quite low in all operation modes, including the nominal one (100% power mode) due to large losses of kinetic energy in the equalization chamber, as well as inflated load on the first stage [5, 6]. Today, leading manufacturers of steam turbines are gradually abandoning the use of radial pressure equalization chambers in nozzle-controlled control compartments, but it is difficult to understand how much this affects the gas-dynamic efficiency of the flow part from the existing open sources. There are also proposals to change the principles of nozzle control, in particular, a radial partial steam supply is proposed in papers [7, 8]. This approach has a number of advantages over the traditional circular partial steam supply, primarily in the fact that it ensures the absence of significant circular non-uniformity of gas-dynamic parameters [9]. Unfortunately, today the practical use of this approach is not yet performed due to the need to solve a number of design and technological problems.

The paper presents the results of a numerical study of the new control compartment flow part of the HPC of the K-300 series steam turbine of diagonal type in which there is no radial pressure equalization chamber. Instead of a radial equalization chamber, in order to unload the first stage, an additional stage is installed to the control compartment. The influence of the proposed measures on the flow structure and the efficiency of the flow part at different turbine operation modes is shown.

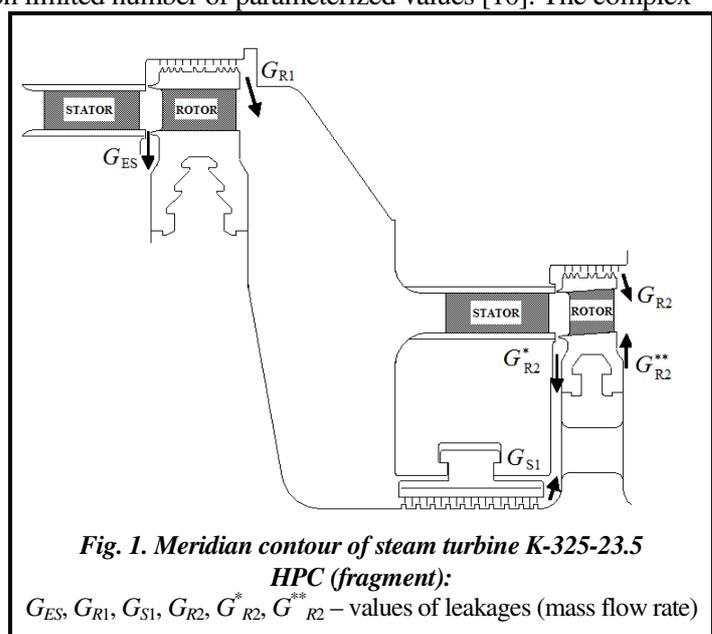
Methods of calculation and design of turbomachines flow parts

The calculation and design of the steam turbine control compartment was performed using the complex methodology developed in IPMach NAS of Ukraine. The methodology includes methods of different levels of complexity, from one-dimensional to models for calculation of spatial viscous flows, as well as analytical methods for flow parts spatial geometries description based on limited number of parameterized values [10]. The complex design methodology is implemented in the *IPMFlow* software package, which is a development of the *FlowER* and *FlowER-U* software packages.

A model of a viscous turbulent flow based on the numerical integration of an averaged system of Navier-Stokes equations [11–15], for the closure of which the two-term Tamman equation of state is used [16, 17]. Turbulent phenomena were taken into account using an SST Menter two-parameter differential turbulence model [18, 19].

Problem statement, object of study, the original design analysis

The control compartment of the steam turbine K-325-23.5 HPC (Fig. 1) that consists of the control stage (CS), the equalization chamber and the first stage of pressure (the second stage from inlet to the flow part) is considered as the object of study.



The calculated area consisted of approximately 3 million cells (elementary volumes).

The studies were conducted for six operation modes with the boundary conditions given in Table 1.

The calculations take into account the interdisc and diaphragm leakages, the scheme of which is shown in Fig. 1, and the values are presented in Table 2.

Table 1. Boundary conditions for calculations of the HPC control compartment

Parameter	Mode, %					
	100	90	80	70	60	50
Full pressure before CS, MPa	22.73	22.53	21.40	22.00	19.40	16.10
Full temperature before CS, °K	808.5	808.5	808.5	808.5	808.5	808.5
Static pressure behind the compartment, MPa	16.58	14.95	13.14	11.63	9.97	8.31
Mass flow at the inlet, kg/s	277.8	250.0	222.2	194.4	166.7	138.9

Table 2. Leakages mass flow rate values

Parameter	Mode, %					
	100	90	80	70	60	50
\dot{G}_{ES} , kg/s	3.614	3.180	3.180	2.367	2.169	1.678
\dot{G}_{R1} , kg/s	4.64	2.90	2.60	–	–	–
\dot{G}_{S1} , kg/s	1.98	1.74	1.58	1.29	1.19	0.91
\dot{G}_{R2} , kg/s	2.36	2.09	1.74	1.58	1.45	1.12
\dot{G}_{R2}^* , kg/s	3.98	3.51	3.22	2.73	2.50	1.93
\dot{G}_{R2}^{**} , kg/s	3.76	3.40	3.13	2.64	2.42	1.87

The results of the research showed that in the equalization chamber, where the steam moves in both axial and radial directions, there are significant vortices and flow separations, not only in partial but also in nominal operation modes (Fig. 2). The presence of separation flows leads to significant losses of kinetic energy and reduced efficiency not only in the control stage, but also in the next stage (second stage) in all operation modes. The shape of the stator blades also contributes to the unfavorable picture of the flow in the second stage. The shape is not adapted to the under-designed flow angles (Fig. 2, 3).

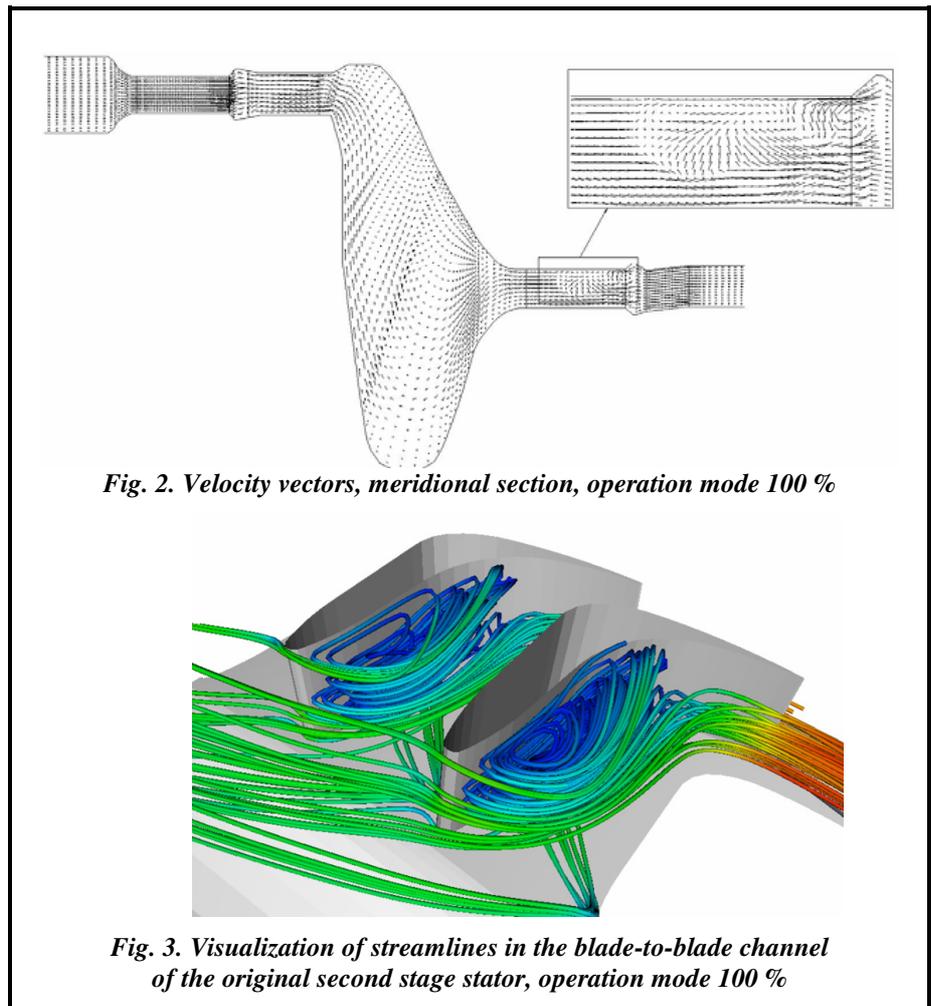


Fig. 2. Velocity vectors, meridional section, operation mode 100 %

Fig. 3. Visualization of streamlines in the blade-to-blade channel of the original second stage stator, operation mode 100 %

3D design development of the new HPC flow part

The main ideas used in the development of the new flow part were set out in [7, 8], they contain:

- rejection of the equalization chamber with a horizontal flow direction;
- moving the adjusting stage to the middle diameter that is located as close as possible to the average diameter of the second stage;
- ensuring the minimum possible value of partial admission degree of the control stage;
- installation of an additional stage on the site of the equalization chamber (in the axial direction), which ensures the effective operation of the thermal drop.

The new version of the control compartment was developed in the way for it to fit into the dimensions of the original compartment and to meet the conditions given in Table 1. In this case, the operation modes of the pressure stages located behind the control compartment do not change, which allows to keep their design unchanged.

The control compartment, instead of having two stages in the original flow part, is made with three stages (Fig. 4). Unfortunately, due to technological limitations, it was not possible to provide the same average diameter of the stages, which led to the diagonal shape of the control compartment in the meridional section. Fig. 5 shows the blade profiles of the new HPC flow part. The profiles of the stator blades of the 2nd and 3rd stages have thick leading edges; this is done in order to reduce the negative consequences associated with the uncalculated flow angles at partial operation modes.

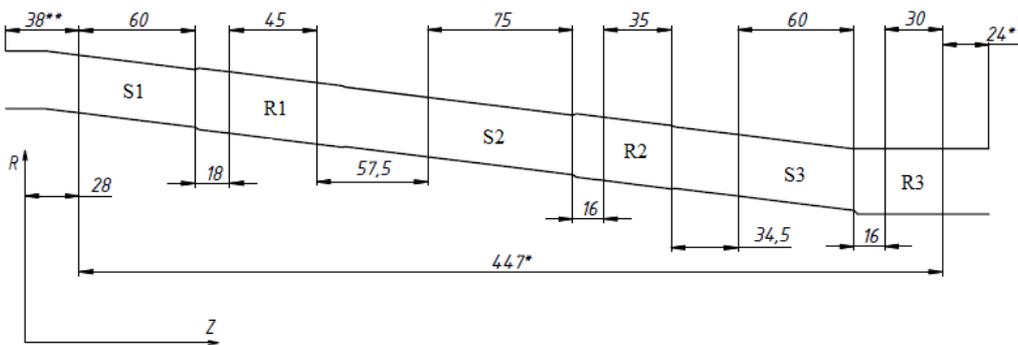


Fig. 4. The meridional section of the new HPC flow part

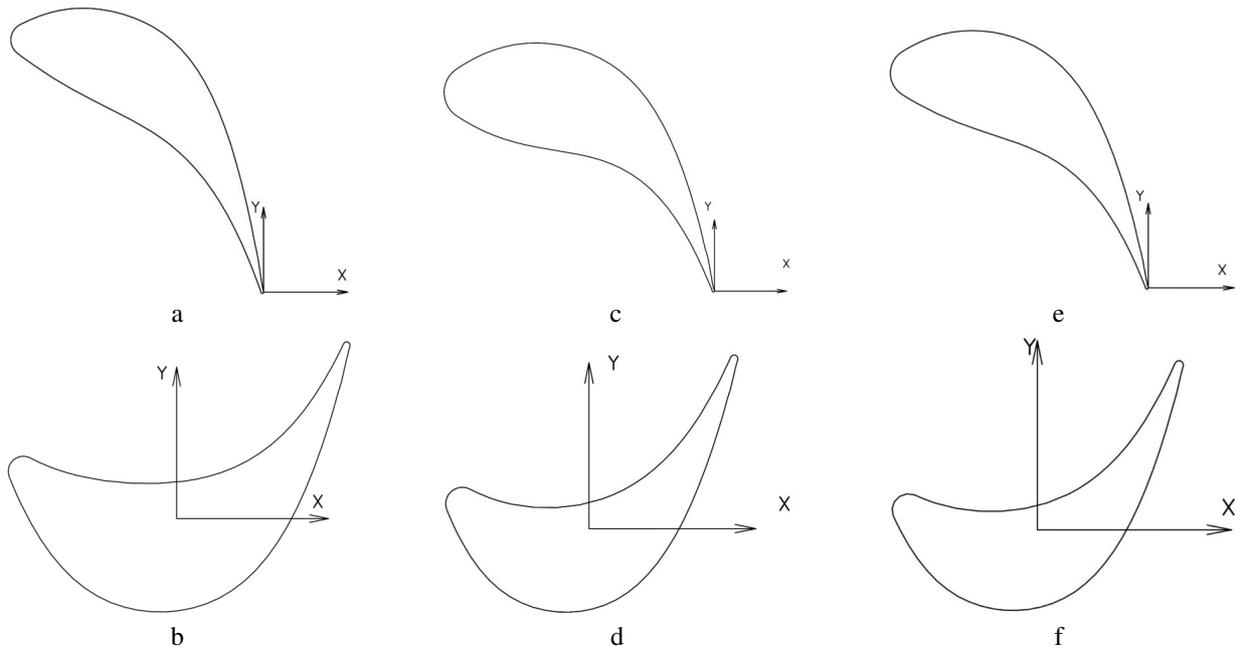


Fig. 5. View of the new flow part blades profiles:

a – first stage stator, b – first stage rotor, c – second stage stator, d – second stage rotor, e – third stage stator, f – third stage rotor

Calculations of the new control compartment were performed for the conditions given in Table 1. Steam supply through the control stage nozzle boxes was carried out with different degree of partial admission depending on a mode: 100% – 0.8 (48/60); 90, 80% – 0.58333 (35/60); 70, 60 and 50% – 0.36666 (22/60).

The simulation was performed on a computational grid with a total number of cells over 3.2 million. The calculations take into account the interdisc and diaphragm leakages, the scheme of which is shown in Fig. 6, and the values are presented in Table 3.

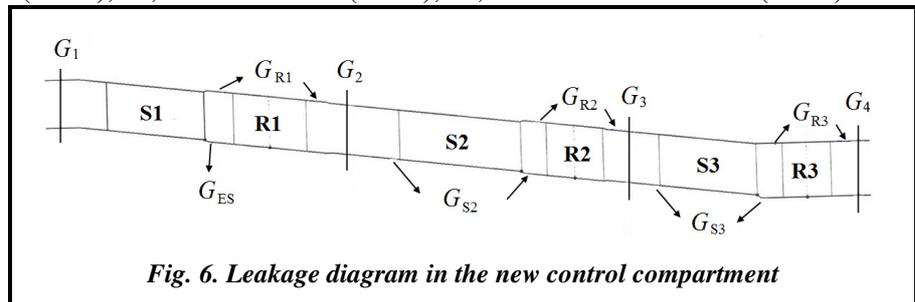


Fig. 6. Leakage diagram in the new control compartment

Table 3. Leakages mass flow rates in the new control compartment

Parameter	Mode, %					
	100	90	80	70	60	50
G_1 , kg/s	277.1	250.2	223.6	191.8	168.7	137.8
G_{ES} , kg/s	3.614	3.180	3.180	2.367	2.169	1.678
G_{R1} , kg/s	7.216	5.830	5.120	–	–	–
G_2, G_3, G_4 , kg/s	273.5	247.0	220.4	189.4	166.5	136.1
G_{S2} , kg/s	1.81	1.63	1.45	1.27	1.09	0.90
G_{R2} , kg/s	3.04	2.75	2.44	2.15	1.83	1.41
G_{S3} , kg/s	2.02	1.82	1.62	1.42	1.21	1.01
G_{R3} , kg/s	3.00	2.71	2.41	2.12	1.81	1.51

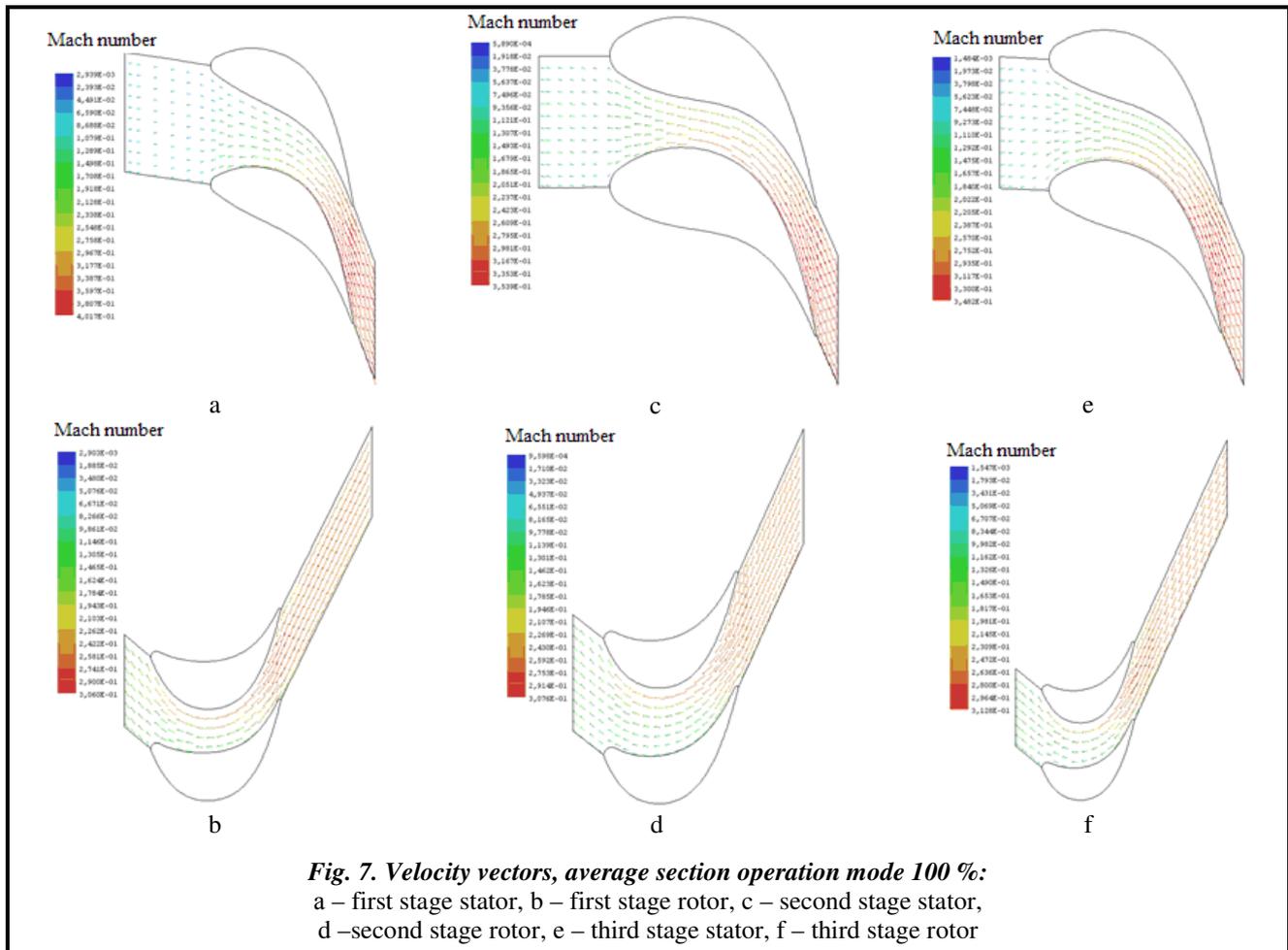
Fig. 7 shows the visualization of the flow in the flow part at operation mode 100%.

From the given visualization of the flow in blade-to-blade channel sit is seen that in the nominal mode there is a very favorable picture of the flow in which there are no flow separations. In other operation modes, the nature of the flow is somewhat different, in some cases there are slight flow separations, but in general the efficiency of the new flow part is much better compared to the original turbine (Table 4).

Table 4. Integral characteristics of the control compartment of the original and new turbines flow parts

Mode, %	G , t/year	Original control compartment				New control compartment					Δ Efficiency, %	ΔN , MW
		Efficiency, %	Capacity, MW			Efficiency, %	Capacity, MW					
			CS	2 stage	Compartment		CS	2 stage	3 stage	Compartment		
100	1001	83.7	13.2	8.48	21.71	91.0	9.1	7.37	7.24	23.7	7.3	2.00
90	894	83.4	17.7	7.49	25.24	88.8	12.7	7.96	6.37	27.0	5.4	1.79
80	798	74.0	17.0	6.56	23.53	81.8	12.6	8.35	5.38	26.3	6.5	1.98
70	701	74.7	21.1	6.00	27.07	80.0	16.7	7.31	4.55	28.6	5.3	1.52
60	614	73.7	19.6	5.36	24.93	79.8	15.3	6.76	4.34	26.3	6.1	1.42
50	501	73.7	16.5	4.43	20.97	78.6	12.8	5.67	3.57	22.0	4.9	1.06

From the given results it is seen that the proposed option of the flow part has a very high level of gas-dynamic efficiency in all considered operation modes: the efficiency increased by 4.9–7.3%, and the capacity increased by 1–2 MW. On the nominal mode (mode 1) the efficiency of the control compartment, taking into account interdisc and overbandage leakage, is 91%.



Conclusions

Based on the analysis of gas-dynamic processes in the flow part of the HPC control compartment of the steam turbine K-325-23.5, improvement directions are formed and its modernization is performed.

In the new flow part, in contrast to the original one, there is a favorable picture of the flow in all operation modes, which ensures its high gas-dynamic efficiency. Depending on the mode, the efficiency of the control compartment increased by 4.9–7.3%, and the capacity increased by 1–2 MW.

In the nominal mode (100% mode) the efficiency of the new control compartment, taking into account the interdisc and overbandage leakage, is 91%.

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Received 02 November 2020

Підвищення газодинамічної ефективності регулюючого відсіку парових турбін серії К-300

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В роботі запропоновано напрями підвищення ефективності соплового регулювання для парових енергетичних турбін серії К-300, які разом з турбінами серії К-200 складають основу теплової енергетики України. Як об'єкт дослідження розглянуто регулюючий відсік циліндра високого тиску парової турбіни К-325–23,5. Чисельні розрахунки та проектування регулюючого відсіку парової турбіни виконувалися за допомогою розробленої в ІПМаш НАН України комплексної методології, яка включає методи різних рівнів складності від одновимірних до моделей розрахунку просторових в'язких течій, а також аналітичних методів опису просторових геометрій проточних частин на основі обмеженої кількості параметризованих величин. Комплексна методологія проектування реалізована в програмному комплексі *IPMFlow*, який є розвитком програмних комплексів *FlowER* і *FlowER-U*. Модель в'язкої турбулентної течії ґрунтується на чисельному інтегруванні осередненої системи рівнянь Нав'є–Стокса, для замикавання яких використовується двочленне рівняння стану Таммана. Врахування турбулентних явищ здійснювалося за допомогою двопараметричної диференціальної моделі турбулентності SST Ментера. Дослідження проводилися для шести режимів роботи в розрахунковій області, що складалася з понад 3

млн. комірок (елементарних об'ємів) з урахуванням міждисккових і діафрагмових перетікань. За результатами чисельних досліджень вихідного регулюючого відсіку парової турбіни К-325-23,5 показано, що у проточній частині через великі втрати кінетичної енергії у камері вирівнювання, а також завищене навантаження на перший ступінь ККД є достатньо низьким на всіх режимах експлуатації, у тому числі на номінальному (режим 100 % потужності). На основі проведеного аналізу газодинамічних процесів сформовано напрями й виконано модернізацію проточної частини регулюючого відсіку. В новій проточній частині, на відміну від вихідної, спостерігається сприятлива картина течії на всіх режимах роботи, що забезпечує її високу газодинамічну ефективність. В залежності від режиму, коловий ККД регулюючого відсіку збільшився на 4,9–7,3%, а потужність – на 1–2 МВт. На номінальному режимі (режим 100%) коловий ККД нового регулюючого відсіку з урахуванням міждисккових і надбандажних перетікань становить 91%.

Ключові слова: парова турбіна, регулюючий ступінь, просторова течія, чисельне моделювання, газодинамічна ефективність.

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