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# INFLUENCE OF THE OPERATING AND GEOMETRIC CHARACTERISTICS ON THE EFFICIENCY OF A POWERFUL STEAM TURBINE HPC FLOW PART

**Abstract.** *The results of a research of the various operating and geometric parameters influence on the efficiency of the high-power steam turbine high-pressure cylinder flow part for nuclear power plants is presented in the paper. The purpose of the research is to determine the rational characteristics of the high-pressure cylinder flow part to ensure its high gas-dynamic efficiency. Seven options of a high-pressure cylinder with different numbers of stages, designed for the characteristics of the promising AP1000 nuclear reactor, were considered. The research was caried out using modern methods of gas-dynamic calculation and designing of turbomachine flow parts, implemented in the IPMFlow software package. As a result of the analysis, rational values of the main characteristics of the stages, such as the dimensionless conditional rate of thermal drop, the ratio of the circular velocity of the rotor grid to the conditional thermal drop rate, and the effective angle of the stator in absolute motion, at which the greatest gas-dynamic efficiency is achieved, were established. The influence of the "diffusivity" of the meridional contours between the penultimate and last stages on the flow structure and gas-dynamic efficiency was analyzed. Among the considered options, the five-stage high-pressure cylinder has the lowest total kinetic energy losses and outlet velocity losses, which provides it with the highest total gas-dynamic efficiency. High-pressure cylinder with four stages has slightly worse gas-dynamic efficiency compared to the five-stage flow part, but, due to the smaller number of stages, it has lower metal consumption and cost. The results of the research can be used in the designing and modernization of domestically produced steam turbine equipment, which will contribute to increasing the competitiveness and energy security of Ukraine.*
**Keywords:** nuclear power plant, steam turbine, high-pressure cylinder, gas-dynamic efficiency, stage characteristics.

## 1. Introduction

Nowadays, all signs of the renaissance of nuclear power can be seen [1]. Even in Germany, which decided to “completely” abandon this type of generation in 2011 [2] and stopped the operation of its last three nuclear reactors on April 15, 2023 [3], discussions about at least restarting the recently stopped nuclear power units are developing with renewed vigor [4], even the head of the IAEA called this idea “logical.” [5]. The thoughts on the need to develop nuclear energy are supported not only by its cheapness, stability and large volumes of electricity generation, but also by its classification as a "green" energy source [6]. Another reason for the renewed interest in this issue is the great difficulties faced by “classic” green energy, such as wind and solar [7]. Very big problems have emerged in ensuring its profitability, stability and the ability to function effectively in the unified energy system [8]. There are great doubts about the prospects for overcoming these obstacles. Some countries, such as China, have instead opted to transition primarily to nuclear power generation. In the PRC, 8−10 new nuclear power units with a capacity of 1000+ MW are commissioned every year [9]. By 2050, it is planned to convert over 95 % of all generation to nuclear. In addition, development of power units based on small modular reactors [10] is a new direction in this field, which is developing very actively. This technology corresponds to the distributed generation paradigm and can be used as a shunting system for daily and seasonal dips and peaks in electricity consumption [11]. Additionally, developments aimed to modernize existing coal-fired power plants into nuclear power plants, including using IV generation nuclear reactors, are underway [12].

A significant problem associated with nuclear energy is the high cost of building and equipping the nuclear power plant (NPP) units [13]. One of the directions for solving this issue is to create less metal-intensive and, accordingly, less expensive and at the same time highly efficient and reliable steam turbine equipment [14, 15]. For this purpose, new steam turbine layouts are being developed. One of the options of such layout is shown in Fig. 1.

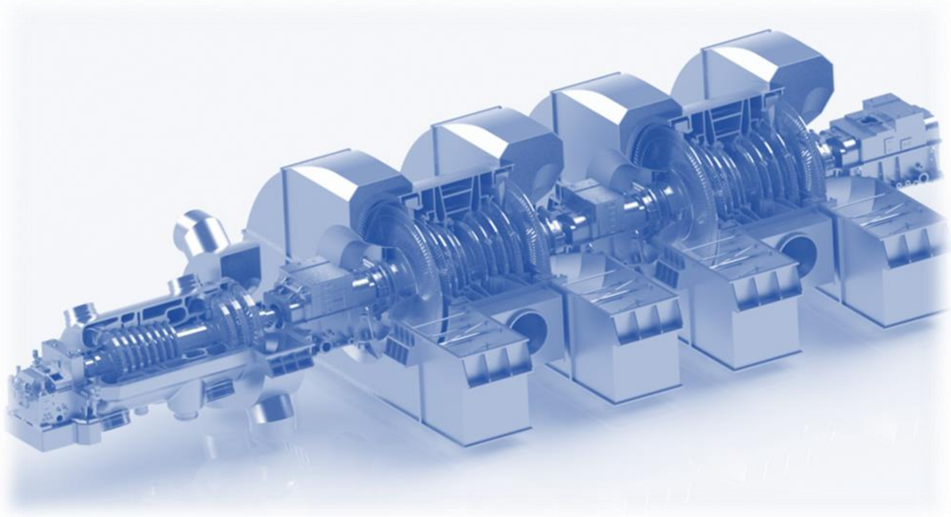

**Fig. 1.** View of a steam turbine for a nuclear power plant of the latest layout [15]

This layout, unlike most similar turbines, has three cylinders instead of four, and the low-pressure cylinder (LPC) is reduced by one (two instead of three). This is achieved by increasing the last stage rotor blade length. In addition, instead of a high-pressure cylinder (HPC) with two flows, one common high- and intermediate-pressure cylinder (HIPC) is implemented in this turbine. The HIPC has a lower metal content than the two-flow HPC and, in addition, allows for a more rational distribution of the thermal drop between the cylinders and a more efficient organization of the gas-dynamic process in the flow part.

The authors carried out a research «Analysis of the influence of operating and geometric characteristics on the efficiency of the axial turbine stages profile grids» [16] (hereinafter − "profile research"), which gives reasons to assume that modern flow parts of steam turbines have large reserves for their further improvement both in terms of increasing gas-dynamic efficiency and reducing metal consumption.

The results of a research of the influence of operating and geometric characteristics on the powerful steam turbine HPC flow part efficiency are presented in the paper. Several options of the HPC with different numbers of stages were considered for the characteristics of the promising AP1000 nuclear reactor.

The research was carried out based on the use of modern methods of gas-dynamic calculations and designing of turbomachine flow parts.

Ukraine has the industrial infrastructure, engineering, technical and scientific potential to organize the production of the newest steam turbines for nuclear power plants [15]. This makes the research results extremely important for increasing the competitiveness, economic and energy security of the country.

## 2. Methods of gas-dynamic calculation and profile grids designing

The design of the flow parts of an axial turbine is carried out according to the algorithm implemented in the IPMFlow software package using methods and models of various levels of complexity, from the one-dimensional method of selecting the main characteristics of the turbine stage [17], methods of analytical profiling of axial stages [18], to methods of three-dimensional viscous flows calculating in the turbine flow parts [19].

## 3. Problem statement

The object of the research was considered to be the powerful steam turbine HPC for a nuclear power plant of the newest layout (Fig. 2).

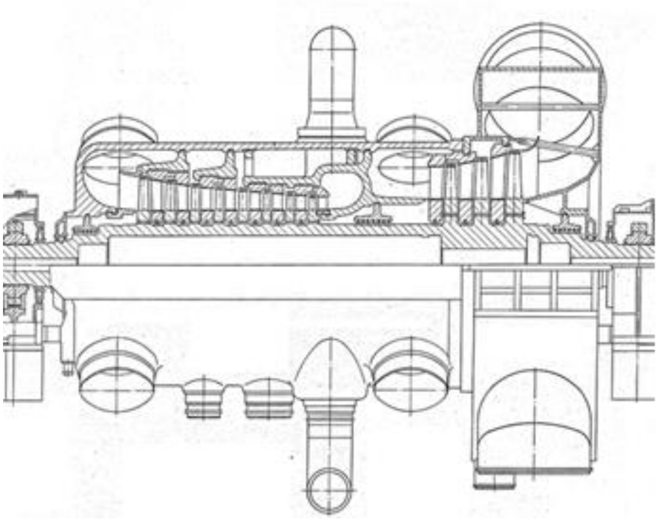

**Fig. 2.** View of steam turbine HIPC for NPP

The HPC flow part (Fig. 2, left) is located in the same housing as the intermediate-pressure cylinder (Fig. 2, right). Together they form the HIPC.

The HIPC flow part shown in Fig. 2 was designed with the participation of the authors for a promising low-speed (1500 rpm) steam turbine with a capacity of 1200 MW for NPP. This HPC (Fig. 2, left) is considered as the initial one. Its operating conditions are somewhat different from those under which the new HPC options are calculated in the research, but this does not affect the comparative analysis of the obtained results.

The operating conditions of the studied HPCs correspond to the characteristics of the newest AP1000 nuclear unit [20]:

- mass flow rate of steam at the inlet – 1765.27 kg/s;
- pressure at the inlet – 5.5831 MPa;
- temperature at the inlet – 270.9º C;
- enthalpy at the inlet – 2768.26 kJ/kg;
- pressure at the outlet – 1.1331 MPa;
- mass flow rate of steam in extraction 1 – 140.43 kg/s;
- mass flow rate of steam in extraction 2 – 77.558 kg/s.

The authors performed a "profile research", in which the influence of the main geometric and operating characteristics on the efficiency of profile grids (two-dimensional geometry) of axial turbine stages was analyzed and appropriate recommendations were provided. The results of the research showed that the value of the kinetic energy loss is significantly affected by $\lambda_{0t}$ (dimensionless conditional rate of thermal drop across the stage), and its optimal value is approximately equal to 1. This indicator actually determines the dimensionless thermal drop. Also, for the not last stage, better results are achieved at angles $\alpha_{1ef} = 69-71^{\circ}$ (effective stator angle in absolute motion). In modern HPCs, the parameter $\lambda_{0t}$ and $\alpha_{1ef}$ values, unlike a dimensionless quantity $u/c_{0t}$ (where u – circular speed of the rotor grid, $c_{0t}$ – conditional rate of thermal drop in the stage), are typically significantly different from the given ones.

Based on the results obtained for profile grids, research on the influence on the stages and the HPC as a whole (taking into account the spatial shape) was conducted for the following characteristics: $u/c_{0t}$, $\alpha_{1ef}$, $c_{0t}$ and $\lambda_{0t}$. The main difference of this research from the one conducted with the profile grids stages is that all losses are taken into account, such as profile, outlet, secondary, associated with the three-dimensionality of the flow and others, and not only profile and edge losses.

## 4. Results and discussion

Seven options of the HPC flow parts are considered. Their view is shown in Figs. 3–9, and some of their geometric and gas-dynamic characteristics are given in Table 1, where *Dmax* – maximum diameter, $\xi$ – kinetic energy losses, $\xi_{ov}$ – kinetic energy losses with outlet velocity, $\xi_{tot}$ – total losses.

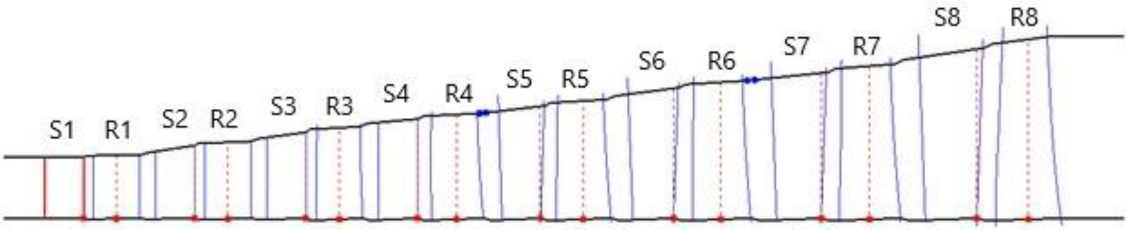


**Fig. 3.** HPC flow part, option 1

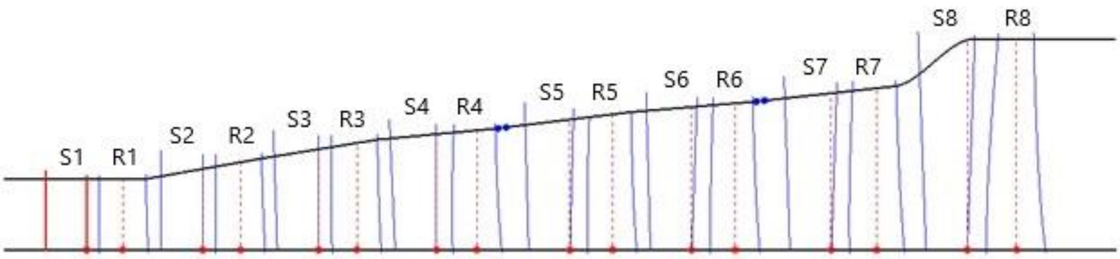


**Fig. 4.** HPC flow part, option 2

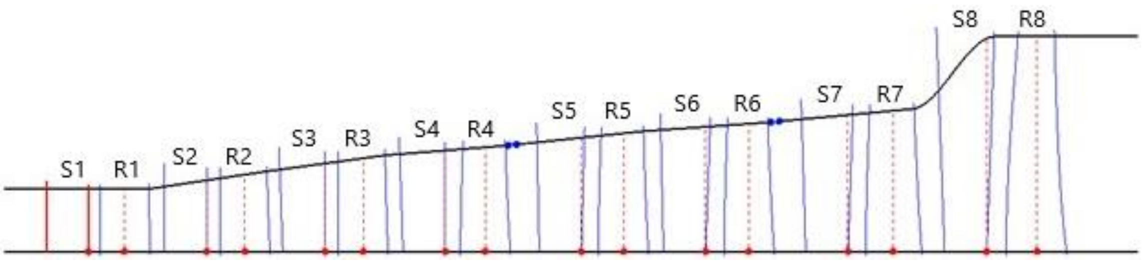


**Fig. 5.** HPC flow part, option 3

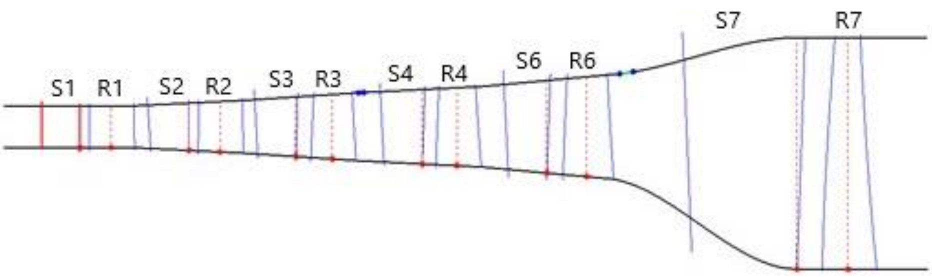


**Fig. 6.** HPC flow part, option 4

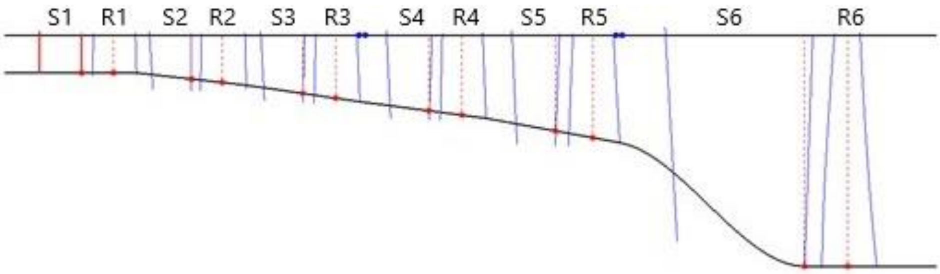


**Fig. 7.** HPC flow part, option 5

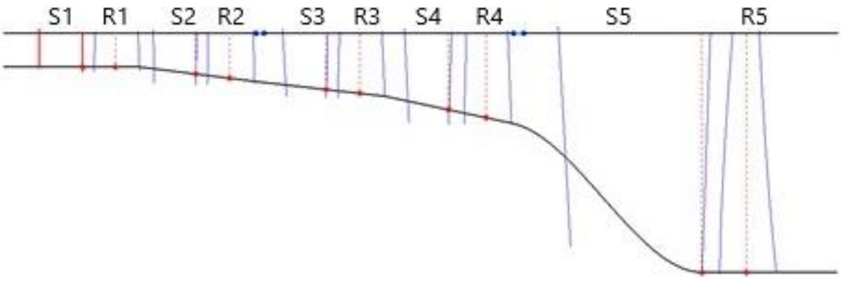


**Fig. 8.** HPC flow part, option 6

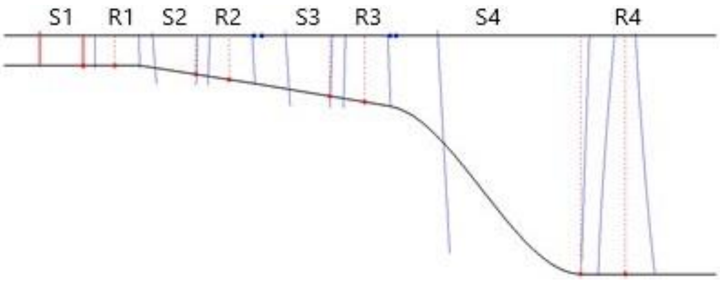


**Fig. 9.** HPC flow part, option 7

**Table 1.** Geometric and gas-dynamic characteristics of the HPC

| № | Number of stages | $\alpha_{1ef}$, °stage № 1 – n-1 | Dmax, m | $\xi$, % | $\xi_{ov}$, % | $\xi_{tot}$, % |
|---|---|---|---|---|---|---|
| 1 | 8 | 77 | 2.770 | 3.71 | 0.76 | 4.47 |
| 2 | 8 | 74 | 2.852 | 3.66 | 0.64 | 4.30 |
| 3 | 8 | 71 | 2.852 | 3.48 | 0.64 | 4.12 |
| 4 | 6 | 71 | 2.924 | 2.97 | 0.46 | 3.43 |
| 5 | 6 | 71 | 2.924 | 2.85 | 0.48 | 3.33 |
| 6 | 5 | 71 | 2.924 | 2.66 | 0.49 | 3.15 |
| 7 | 4 | 71 | 2.924 | 2.87 | 0.49 | 3.36 |

In Table 1, angle $\alpha_{1ef}$ applies to all stages except the last one. The value $\alpha_{1ef}$ presented in the table is given for an "equivalent" stage. An "equivalent" stage to the real one is a stage in which the height of the channel behind the rotor and constant meridional contours are the same as the real one. In addition, for an "equivalent" stage, other geometric characteristics are those that provide similar gas-dynamic characteristics (mass flow rate, power, etc.) under the same boundary conditions.

The first option of the flow part is the initial one (Figs. 2, 3), which is designed according to sustainable approaches in turbine designing. The meridional contours of this flow part are made with so-called "overlaps", which is also a classic approach.

The main geometric and gas-dynamic characteristics of the HPC option 1 stages, where Dm – diameter of the average cross-section of the blade, L – blade height, $\xi_{st}$ – losses in the stage, $C_2$ – flow velocity in absolute motion at the stage outlet, $Re_2$ – Reynolds number at the stage outlet, ro – reactivity degree, are shown in Table 2.

**Table 2.** Geometric and gas-dynamic characteristics of the HPC, option 1

| stage № | $\alpha_{1ef}$, ° | Dm/L | $\xi_{st}$, % | $C_2$, m/s | $u/c_{0t}$ | $\lambda_{0t}$ | $Re_2$ | ro |
|---|---|---|---|---|---|---|---|---|
| 1 | 76.9 | 11.37 | 3.07 | 57.01 | 0.525 | 0.635 | 6208181 | 0.159 |
| 2 | 76.2 | 9.54 | 3.20 | 56.29 | 0.541 | 0.635 | 5108035 | 0.206 |
| 3 | 75.8 | 8.16 | 3.71 | 55.67 | 0.560 | 0.633 | 4215213 | 0.223 |
| 4 | 75.1 | 7.27 | 3.89 | 57.85 | 0.572 | 0.637 | 3675643 | 0.252 |
| 5 | 75.7 | 6.53 | 4.13 | 57.60 | 0.577 | 0.650 | 3260577 | 0.245 |
| 6 | 75.2 | 5.78 | 4.20 | 59.50 | 0.578 | 0.673 | 2953007 | 0.269 |
| 7 | 74.3 | 5.27 | 3.96 | 62.89 | 0.5889 | 0.682 | 2771374 | 0.305 |
| 8 | 72 | 4.62 | 4.33 | 68.12 | 0.633 | 0.665 | 2850007 | 0.409 |

In general, the stages and HPC option 1 as whole have high gas-dynamic efficiency. Taking into account the fact that in paper [21] it was concluded that it is inappropriate to make “overlaps” of meridional contours, all subsequent options of flow parts were developed without “overlaps”.

The second option of HPC flow part (Table 1, Fig. 4) is designed with a smaller $\alpha_{1ef} = 74°$, and also with bigger Dmax. In this and subsequent HPC options, Dmax value was set so as not to exceed the design limitations. Despite the fact that this option does not have "overlaps", a generally sustainable approach to the designing of meridional section of the flow parts was followed. The value of the hub diameter is taken as constant.

The main geometric and gas-dynamic characteristics of the stages of the second HPC option are shown in Table 3.

**Table 3.** Geometric and gas-dynamic characteristics of the HPC, option 2

| stage № | $\alpha_{1ef}$, ° | Dm/L | $\xi_{st}$, % | $C_2$, m/s | $u/c_{0t}$ | $\lambda_{0t}$ | $Re_2$ | ro |
|---|---|---|---|---|---|---|---|---|
| 1 | 74.1 | 10.89 | 3.05 | 68.35 | 0.538 | 0.616 | 7253412 | 0.251 |
| 2 | 72 | 8.671 | 3.22 | 60.81 | 0.606 | 0.568 | 5437531 | 0.33 |
| 3 | 72.5 | 7.36 | 3.26 | 57.47 | 0.632 | 0.562 | 4571824 | 0.388 |
| 4 | 73 | 6.78 | 3.57 | 56.67 | 0.617 | 0.589 | 3686808 | 0.384 |
| 5 | 73.5 | 6.09 | 3.70 | 57.70 | 0.629 | 0.595 | 3204831 | 0.417 |
| 6 | 73.3 | 5.73 | 3.93 | 61.23 | 0.608 | 0.630 | 2781944 | 0.394 |
| 7 | 73.3 | 5.28 | 3.88 | 67.16 | 0.589 | 0.669 | 2775514 | 0.385 |
| 8 | 73.7 | 4.32 | 4.70 | 60.15 | 0.652 | 0.645 | 1982027 | 0.448 |

The gas-dynamic efficiency of stages and HPC option 2 is slightly higher compared to option 1, and losses with the outlet velocity have decreased the most (Table 1). Due to the fact that the boundary conditions of first and second HPC options are somewhat different, it is not possible to reliably state which parameters had a significant impact.

The third option of HPC flow part (Table 1, Fig. 5) is designed with an even smaller $\alpha_{1ef} = 71°$, and Dmax is preserved as in HPC option 2. The value of the hub diameter is taken as constant.

The main geometric and gas-dynamic characteristics of the stages of the third HPC option are shown in Table 4.

**Table 4.** Geometric and gas-dynamic characteristics of the HPC, option 3

| stage № | $\alpha_{1ef}$, ° | Dm/L | $\xi_{st}$, % | $C_2$, m/s | $u/c_{0t}$ | $\lambda_{0t}$ | $Re_2$ | ro |
|---|---|---|---|---|---|---|---|---|
| 1 | 72 | 12.41 | 2.88 | 79.06 | 0.530 | 0.618 | 8449271 | 0.236 |
| 2 | 70 | 9.90 | 3.02 | 70.92 | 0.591 | 0.572 | 6462277 | 0.318 |
| 3 | 70 | 8.42 | 3.06 | 68.13 | 0.610 | 0.572 | 5406274 | 0.378 |
| 4 | 70.5 | 7.74 | 3.26 | 66.53 | 0.600 | 0.593 | 4320647 | 0.361 |
| 5 | 71 | 6.93 | 3.31 | 68.72 | 0.608 | 0.601 | 3810737 | 0.405 |
| 6 | 71 | 6.53 | 3.49 | 72.48 | 0.584 | 0.638 | 3281128 | 0.347 |
| 7 | 71 | 6 | 3.47 | 80.02 | 0.563 | 0.681 | 3281141 | 0.330 |
| 8 | 73.5 | 4.32 | 4.91 | 60.20 | 0.657 | 0.640 | 1984842 | 0.449 |

The gas-dynamic efficiency of stages and HPC option 3 have increased more significantly compared to options 1 and 2 (Table 1). Values $u/c_{0t}$ and $\lambda_{0t}$ have not changed much. Due to increased Dm/L and smaller angles $\alpha_{1ef}$, velocity $C_2$ and as a consequence $Re_2$ have increased. In turn, the $Re_2$ increase led to a reduction in kinetic energy losses $\xi_{st}$ except for the last stage. The last stage is almost the same for options 2 and 3. The task of the last stage is to ensure minimal losses with an outlet velocity $\xi_{ov}$, which make the greatest contribution. So, the principles of the last stage developing are different from those located before it.

The fourth option of HPC flow part (Table 1, Fig. 6) is designed with six stages. The purpose of this was to increase the thermal drop in the first stages and, accordingly, increase $\lambda_{0t}$. In order to ensure acceptable $u/c_{0t}$ values, the average diameters at the first stages were increased, respectively the hub diameter became variable. Angles $\alpha_{1ef} = 71^o$ were set as in the previous HPC, this value was maintained in subsequent HPC options. To enable an increase in the last stage outlet area and, accordingly, a reduction in losses with the outlet velocity, the value of Dmax was slightly increased (within the permissible limits).

The main geometric and gas-dynamic characteristics of the stages of the fourth HPC option are shown in Table 5.

**Table 5.** Geometric and gas-dynamic characteristics of the HPC, option 4

| stage № | $\alpha_{1ef}$, ° | Dm/L | $\xi_{st}$, % | $C_2$, m/s | $u/c_{0t}$ | $\lambda_{0t}$ | $Re_2$ | ro |
|---|---|---|---|---|---|---|---|---|
| 1 | 71 | 21.24 | 2.30 | 90.79 | 0.585 | 0.705 | 9334614 | 0.415 |
| 2 | 69 | 16.90 | 2.52 | 93.72 | 0.571 | 0.732 | 7500807 | 0.385 |
| 3 | 68.5 | 13.16 | 2.88 | 86.06 | 0.580 | 0.730 | 5126993 | 0.381 |
| 4 | 69.5 | 11.09 | 2.82 | 90.82 | 0.584 | 0.736 | 4173665 | 0.374 |
| 5 | 69 | 8.53 | 3.18 | 78.35 | 0.578 | 0.754 | 3125087 | 0.340 |
| 6 | 74.3 | 3.61 | 4.37 | 50.90 | 0.741 | 0.563 | 1541235 | 0.494 |

In the fourth HPC option the increase in gas-dynamic efficiency is even more significant. In addition, due to the increase in the outlet area, losses with outlet velocity decreased. In the first stages, the thermal drop, Dm/L and $\lambda_{0t}$ have increased. The result was an increase in velocity and $Re_2$ values. These factors have become decisive in reducing kinetic energy losses $\xi_{st}$ in first stages and HPC as whole.

The fifth HPC option flow part (Table 1, Fig. 7) was developed on the basis of the fourth option with an orientation towards increasing of $u/c_{0t}$ and reactivity degree (ro) in first stages. For this purpose, the shroud diameter of the meridional contours was set to the maximum possible. At the same time, the last stage of the fifth option is practically identical to the fourth one.

The main geometric and gas-dynamic characteristics of the stages of the fifth HPC option are shown in Table 6.

**Table 6.** Geometric and gas-dynamic characteristics of the HPC, option 5

| stage № | $\alpha_{1ef}$, ° | Dm/L | $\xi_{st}$, % | $C_2$, m/s | $u/c_{0t}$ | $\lambda_{0t}$ | $Re_2$ | ro |
|---|---|---|---|---|---|---|---|---|
| 1 | 71.5 | 27.34 | 2.35 | 87.02 | 0.657 | 0.726 | 8320166 | 0.449 |
| 2 | 68.5 | 20.33 | 2.48 | 85.74 | 0.658 | 0.727 | 6767526 | 0.455 |
| 3 | 68.5 | 15.03 | 2.66 | 77.95 | 0.659 | 0.724 | 4725210 | 0.451 |
| 4 | 70 | 11.83 | 2.83 | 81.09 | 0.651 | 0.732 | 3847650 | 0.455 |
| 5 | 68.2 | 8.92 | 2.97 | 80.71 | 0.644 | 0.733 | 3207140 | 0.502 |
| 6 | 74.2 | 3.61 | 4.30 | 51.83 | 0.699 | 0.596 | 1570049 | 0.493 |

In the fifth HPC option gas-dynamic efficiency has increased. This was mainly due to the growth of $u/c_{0t}$ and ro values in the first stages, which is a consequence of the increase in average diameters. At the same time, the velocity $C_2$ and $Re_2$ values have decreased slightly, which negatively affects gas-dynamic efficiency.

To further increase the thermal drop in the first stages, the sixth HPC option flow part (Table 1, Fig. 8) is designed with six stages. The shroud diameter remained as large as possible, just like in the fifth option. The last stage is as close as possible to the previous option in terms of geometric and gas-dynamic characteristics.

The main geometric and gas-dynamic characteristics of the stages of the sixth HPC option are shown in Table 7.

**Table 7.** Geometric and gas-dynamic characteristics of the HPC, option 6

| stage № | $\alpha_{1ef}$, ° | Dm/L | $\xi_{st}$, % | $C_2$, m/s | $u/c_{0t}$ | $\lambda_{0t}$ | $Re_2$ | ro |
|---|---|---|---|---|---|---|---|---|
| 1 | 71 | 31.68 | 2.27 | 108.51 | 0.582 | 0.824 | 9599900 | 0.397 |
| 2 | 67.5 | 21.90 | 2.50 | 96.10 | 0.588 | 0.819 | 6621729 | 0.361 |
| 3 | 68.7 | 16.49 | 2.43 | 102.20 | 0.592 | 0.817 | 5086649 | 0.38 |
| 4 | 68 | 11.27 | 2.70 | 93.48 | 0.588 | 0.817 | 3452463 | 0.348 |
| 5 | 74.2 | 3.61 | 3.73 | 52.29 | 0.697 | 0.598 | 1571966 | 0.497 |

In the sixth HPC option a further increase in gas-dynamic efficiency is observed. In the first stages, the thermal drop, Dm/L and $\lambda_{0t}$ have increased. The result was an increase in velocity and $Re_2$ values. This affected the reduction in kinetic energy losses $\xi_{st}$ in the first stages. In addition, in the last stage, despite the very similar shape of the blades to the previous options, there is a significant reduction in kinetic energy losses. Due to the above factors, the gas-dynamic efficiency of the HPC as a whole has improved.

The next step was the development of the seventh HPC option (Table 1, Fig. 9) with four stages, which allowed to further increase the thermal drop in the first stages. The shroud diameter is the same as in HPC options 5 and 6, and the last stage is as close as possible to the previous three options.

The main geometric and gas-dynamic characteristics of the stages of the seventh HPC option are shown in Table 8.

**Table 8.** Geometric and gas-dynamic characteristics of the HPC, option 7

| stage № | $\alpha_{1ef}$, º | Dm/L | $\xi_{st}$, % | $C_2$, m/s | $u/c_{0t}$ | $\lambda_{0t}$ | $Re_2$ | ro |
|---|---|---|---|---|---|---|---|---|
| 1 | 71 | 35.79 | 2.23 | 135.38 | 0.509 | 0.947 | 10826144 | 0.227 |
| 2 | 66 | 24.59 | 2.65 | 118.93 | 0.515 | 0.946 | 6495938 | 0.187 |
| 3 | 67.5 | 14.56 | 2.80 | 116.23 | 0.517 | 0.941 | 4316833 | 0.198 |
| 4 | 74.2 | 3.61 | 4.45 | 52.42 | 0.695 | 0.600 | 1479518 | 0.490 |

In the seventh HPC option the gas-dynamic efficiency is very close to the fifth option, but it is less compared to the sixth option. In the first stages $\lambda_{0t}$ value is the largest among of all the considered options and is in the range of 0.94–0.95. From the experience of "profile research", it is known that such $\lambda_{0t}$ values are close to optimal. On the other hand, the $u/c_{0t}$ and ro values have decreased compared to previous options, which leads to increased kinetic energy losses. Compared to the sixth HPC option, kinetic energy losses in the last stage have increased. All this is the reason for the decrease in the HPC gas-dynamic efficiency compared to the previous option.

Taking this into account, it can be argued that for a given limitation of the shroud diameter, the sixth HPC option is the most rational for the first stages (except the last one). Because it optimally combines the effects of two oppositely acting factors of $u/c_{0t}$ and $\lambda_{0t}$ values.

Among the 5th, 6th and 7th HPC options, the smallest kinetic energy losses in the last stage are observed in the sixth one. As can be seen from Figs. 7–9, between the penultimate and last stages, the "opening" of the root meridian contour increases as the number of stages decreases. That is, the "diffusivity" of the flow part in the meridional cross section increases. This leads to increased kinetic energy losses. At the same time, the flow in such flow parts is significantly spatial and complex, and is influenced by many factors. In particular, the value and distribution of gas-dynamic parameters before the last stage. The velocity distributions along the channel height behind the rotor of the penultimate stage (before the last stage) are shown in Fig. 10.

It can be seen that the average velocity and its distribution over height for different HPC options differ significantly. As it is known, at higher velocity, flow is more resistant to possible separations, i.e. its increasing can be considered a positive factor. In addition, the largest changes in velocity along the channel height are observed in the fifth HPC option. In the seventh HPC option, the changes in height are smaller, but the presence of significant secondary flows (the presence of local extrema) is clearly observed, which negatively affects the gas-dynamic efficiency. The velocity is most evenly distributed over the height in the sixth HPC option. Based on this, it can be argued that the set of all factors that affect the gas-dynamic efficiency of the last stage is a non-monotonic dependence. Moreover, among the considered options, the last stage of the sixth HPC option is in the zone of the local minimum.

Thus, the sixth HPC option as a whole, based on the totality of the influence of all factors, has the highest gas-dynamic efficiency. Despite the fact that the seventh HPC option has a lower gas-dynamic efficiency, it has an advantage over the others, associated with a smaller number of stages, respectively, lower metal consumption and cost.

Based on the authors' experience in previous research, as well as the results presented in this paper, it can be stated that for stages other than the last one, the highest gas-dynamic efficiency can be achieved with the next characteristics: $\lambda_{0t} \approx 1$, $u/c_{0t} \approx 0.7$ (ro ≈ 0.5), $\alpha_{1ef} \approx 71°$. It should be noted that at smaller $\alpha_{1ef}$ values gas dynamic efficiency will most likely be higher, but this issue requires additional research.

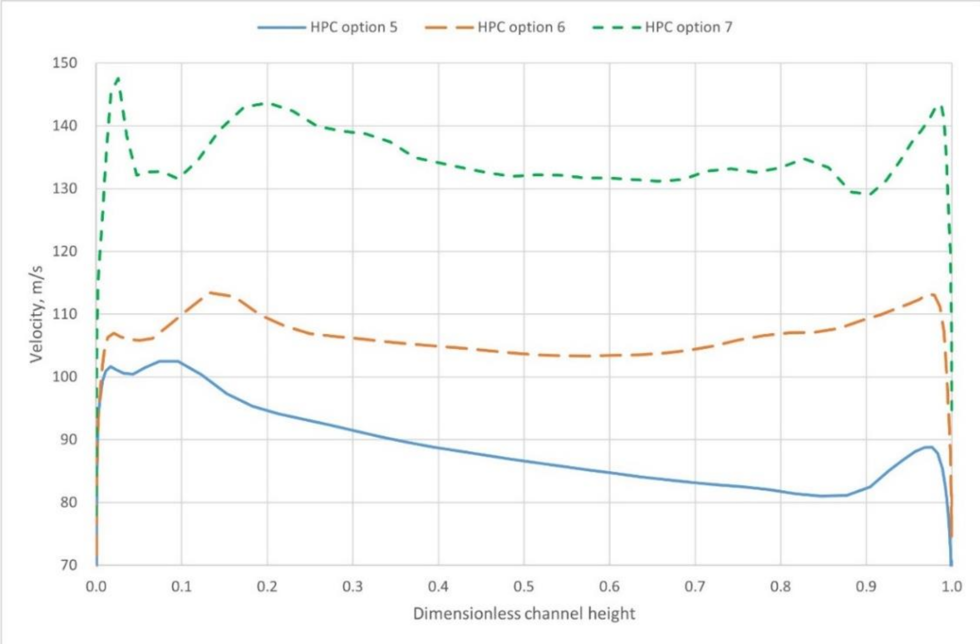


**Fig. 10**. Velocity distributions along the channel height for the penultimate rotor

For the last stages, due to the fact that their efficiency is significantly affected by losses with the outlet velocity, better performance is achieved with other characteristics. Among the considered options, they were equal to $\lambda_{0t} \approx 0.6$, $u/c_{0t} \approx 0.7$ (ro ≈ 0.5), $\alpha_{1ef} \approx 74^o$, but further research is needed to clarify them.

In the future, it is advisable to conduct research of the influence of Dm/L (spatial shape) and Reynolds numbers on the gas-dynamic efficiency of axial turbine stages.

**5. Conclusions**

Using modern methods of calculation and designing of turbomachine flow parts, the research of operating and geometric characteristics influences on the efficiency of the powerful steam turbine HPC flow part was conducted. Seven options of the HPC flow part were considered, six of which were for the characteristics of the promising AP1000 nuclear reactor. The considered flow parts have 8, 6, 5 and 4 stages. According to the results of the research, the following was established:

1. For stages other than the last one, the lowest kinetic energy losses can be achieved with the next characteristics: $\lambda_{0t} \approx 1$, $u/c_{0t} \approx 0.7$ (ro ≈ 0.5), $\alpha_{1ef} \approx 71^o$. Usually, in real stages of flow parts it is impossible to simultaneously provide these characteristics, therefore it is necessary to choose their rational ratio when $\lambda_{0t} \leq 1$ and $0.5 \leq u/c_{0t} \leq 0.7$.

2. Of the considered HPC options, the most rational ratio of $\lambda_{0t}$, $u/c_{0t}$ (ro) and $\alpha_{1ef}$ corresponds to the option with five stages.

3. For the last stage, losses with the outlet velocity have a significant impact on the gas-dynamic efficiency, to reduce which it is necessary to reduce $\lambda_{0t}$ value and increase $u/c_{0t}$ (ro) and $\alpha_{1ef}$ values. At the same time, their rational ratios must be chosen to ensure minimal total kinetic energy losses and losses with outlet velocity.

4. The gas-dynamic and geometric characteristics of the last stage differ significantly from the others, which leads to significant "diffusivity" of the flow part in the meridional section ("opening" of the contours) between the penultimate and last stages, which significantly affects the flow structure and gas-dynamic efficiency. Additional research is needed to establish the patterns of such influence.

5. Of the considered options for the last stage, the lowest total kinetic energy losses and losses with outlet velocity are observed in the HPC with five stages. This HPC option has the highest total gas-dynamic efficiency.

6. A four-stage HPC has slightly worse gas-dynamic efficiency compared to a five-stage flow part, but due to the smaller number of stages, it has a lower metal consumption and cost.

7. In the future, it is planned to conduct more detailed research of the influence of Dm/L (spatial shape) and Reynolds numbers on the gas-dynamic efficiency of axial turbine stages.

**Gratitude**

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# ВПЛИВ РЕЖИМНИХ І ГЕОМЕТРИЧНИХ ХАРАКТЕРИСТИК НА ЕФЕКТИВНІСТЬ ПРОТОЧНОЇ ЧАСТИНИ ЦВТ ПОТУЖНОЇ ПАРОВОЇ ТУРБІНИ

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**Анотація.** *У статті представлено результати дослідження впливу різних режимних і геометричних параметрів на ефективність проточної частини циліндра високого тиску (ЦВТ) парової турбіни великої потужності для атомних електростанцій. Метою дослідження є визначення раціональних характеристик проточної частини ЦВТ, які забезпечують високу газодинамічну ефективність. Розглянуто сім варіантів циліндра високого тиску з різною кількістю ступенів, розроблених для характеристик перспективного ядерного реактора AP1000. Дослідження проводилось з використанням сучасних методів газодинамічного розрахунку та проєктування проточних частин турбомашин, реалізованих у програмному комплексі IPMFlow. В результаті проведеного аналізу встановлені раціональні значення основних характеристик ступенів, таких як безрозмірна умовна швидкість теплового перепаду, відношення колової швидкості руху решітки ротора до умовної швидкості теплового перепаду та ефективний кут статора в абсолютному русі, за яких можливо досягти найбільшої газодинамічної ефективності. Проаналізовано вплив «дифузорності» меридіональних обводів між передостаннім та останнім ступенями на структуру потоку та газодинамічну ефективність. З розглянутих варіантів циліндр високого тиску з п'ятьма ступенями має найменші сумарні втрати кінетичної енергії та втрати з вихідною швидкістю, що забезпечує його найбільшу сумарну газодинамічну ефективність. ЦВТ з чотирма ступенями має дещо гіршу газодинамічну ефективність порівняно з п'ятиступеневою проточною частиною, але завдяки меншій кількості ступенів − меншу металоємність і собівартість. Результати дослідження можуть бути використані під час проєктування та модернізації паротурбінного обладнання вітчизняного виробництва, що сприятиме підвищенню конкурентоспроможності та енергетичної безпеки України.*

**Ключові слова**: атомна електростанція, парова турбіна, циліндр високого тиску, газодинамічна ефективність, характеристики ступенів.

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