*Представлено результати чисельного моделювання течії в ступені осьового компресора з кільцевим вдувом газу перед робочим колесом. Газодинамічна дія здійснювалася при роботі ступеня на границі зриву. Ефективність кільцевого вдуву досліджувалась при значеннях кута вдуву від 5° до 90°. Результати досліджень показали, що кільцевий вдув дозволяє покращити аеродинамічні характеристики ступеня компресора*

*Ключові слова: моделювання течії, газодинамічна дія, кільцевий вдув, ступінь компресора, гідравлічні втрати*

*Представлены результаты численного моделирования течения в ступени осевого компрессора с кольцевым вдувом газа перед рабочим колесом. Газодинамическое воздействие осуществлялось при работе ступени на границе срыва. Эффективность кольцевого вдува исследовалась при значениях угла вдува от 5° до 90°. Результаты исследований показали, что кольцевой вдув позволяет улучшить аэродинамические характеристики ступени компрессора*

*Ключевые слова: моделирование течения, газодинамическое воздействие, кольцевой вдув, ступень компрессора, гидравлические потери*

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# EXAMINING THE EFFECT OF ANNULAR INJECTION ON THE PARAMETERS OF THE AXIAL COMPRESSOR'S STAGE

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## 1. Introduction

Maintaining steady operation of compressor over a wide range of operating modes is one of the important tasks of engine building.

Applying different types of gas-dynamic action on the flow in a compressor makes it possible to improve parameters and characteristics of gas-turbine engines [1].

Of particular interest is to study methods of active gas-dynamic action on flow in the elements of gas-turbine engines. Gas-dynamic action makes it possible to reduce the level of losses and the flow non-uniformity caused by the aerodynamic traces. That is why examining the current in compressors' flow-through part is an important task in order to solve the problem on improving the efficiency of gas-turbine engines.

## 2. Literature review and problem statement

Paper [2] presents results of studies into control over traces by elements of an highly-loaded compressor using pulse injection. Article [3] reported that injection into the stator elements before the first stage reduces the level of circular non-uniformity of the flow. It was established experimentally and analytically that a gas-dynamic action on the traces makes it possible to reduce the level of vibrostrains in an impeller. Paper [4] analyzed efficiency of the pulse and continuous injection to enable stable operation of the compressor. Comparison of the results revealed that using a pulse injection was more efficient than the continuous injection. Articles [2–4] investigated effect of injection along the entire length of a blade through special openings. Implementing this method requires the use of blades of a complex design. In addition, the use of pulse injection complicates a system of automatic control.

Papers [5, 6] present results of research into effect of injection in the impeller on the parameters of stage of an axial compressor. The injection was performed through two slit openings before the impeller. Article [5] reported an increase in the degree of pressure and performance efficiency achieved at certain parameters of injection. An expression is given to determine performance efficiency coefficient considering the mass of air that is blown out. Paper [6] investigated the structure of flow during injection. It is shown that the level of flow non-uniformity after the impeller reduces. In article [7], authors presented results of research into combined use of discrete injection into peripheral part of the compressor and over-the-rotor unit. It is shown that optimal parameters can improve gas-dynamic stability of the compressor. However, in studies [5–7], the injection is carried out discretely through several slit openings. Under certain conditions, discreteness of injection may lead to an increase in the vortex-formation in a peripheral part of the impeller.

Paper [8] reports results of research into transonic impeller of the axial compressor. The injection was performed at different distances before the impeller from intruding channels. The height of an intrusion varied from 1 to 4 mm. It is shown that under certain injection parameters it is possible to enable alignment of velocity field in a peripheral part of the impeller.

Article [9] presents results of experimental and computational study of current in a low-pressure three-stage compressor. Additional air mass injection was carried out through several intruding nozzles, located at the input of the first stage. It is shown that using a gas-dynamic action on the flow led to the improvement of compressor characteristics. It was established in papers [8, 9] that intruding channels for injection is the source of vortex generation before the impeller. This can lead to deterioration of the aerodynamic characteristics of blade crowns.

Paper [10] reported results of research into impeller with a current recirculation in the peripheral part. Through special channels, part of the air was directed after exiting the impeller to the input. As noted, such a system can be effective even at a low flow rate of the recirculating air (0.2 % of the consumption per stage). However, there was a high level of losses observed in special channels of the rectangular cross-section.

Results of studies [1–10] demonstrated effectiveness of gas-dynamic action on the current in a compressor. At the same time, there are still unresolved problems related to the choice of optimal parameters of the gas-dynamic action. In particular, these are problems on the optimization of a current's parameters in the peripheral part of a compressor.

## 3. The aim and objectives of the study

The aim of present work is to devise recommendations for choosing rational parameters of annular injection in the stages of an axial compressor.

To accomplish the aim of research, the following tasks have been set:

– to conduct estimation-experimental study of current in the stage of axial compressor with an annular injection of gas before the impeller;

– to estimate the effect of change in the injection angle on the coefficient of full pressure losses in the impeller;

– to assess the impact of change in the injection angle on the degree of pressure increase in the impeller.

## 4. Method for studying a current in the stage of an axial compressor

The study was performed using a numerical simulation of the current that employed a 3D model of the stage of a compressor. We built a non-structured adaptive computational grid consisting of 2,013 million cells. In order to use a periodicity condition properly, estimated area of each blade crown consisted of one blade and an intrablade passage. The calculation of turbulent current was conducted by numerical computation of the Navier-Stokes equations. The equations were closed by the model of turbulent viscosity SST. We selected a second order calculation scheme with a local application of the first order calculation scheme.

Reliability of the obtained results was ensured by performing the test tasks [11].

## 5. Results of examining effect of annular injection on the parameters of stage in the axial compressor

The examined stage of an axial compressor consisted of three blade crowns: an input guide device, the impeller, the guide device. A 3D model of the stage is shown in Fig. 1. Basic parameters of the stage are given in paper [11].

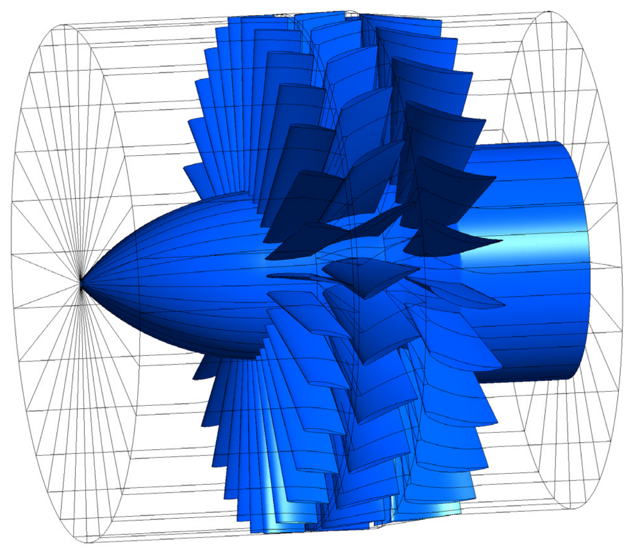

Fig. 1. Stage of axial compressor

The first stage of research implied the calculation of characteristic of the stage (rotor's rotation frequency $n$=8,154 rpm). A characteristic of the stage (Fig. 2) was calculated as the dependence of degree of pressure increase on speed coefficient.

The degree of pressure increase was derived from formula:

$$\pi = \frac{p_2^*}{p_1^*}, \tag{1}$$

where $p_1^*$ is the average total pressure value at the input to the stage, $p_2^*$ is the average total pressure value at the output of the stage. Averaging parameters of the flow was carried out by the principle of medium weight averaging for radius.

Speed coefficient was determined from ratio:

$$\lambda_c = \frac{c}{a}, \tag{2}$$

where $c$ is the axial flow speed at the input, $a$ is the speed of sound.

In Fig. 2, a line with dots denoted results obtained by numerical simulation of the current. Dots in Fig. 2 demote data of the physical experiment [12].

Comparison of the results of computational and physical experiments [12] revealed an error in the calculations of current during simulation of 0.09...0.83 %.

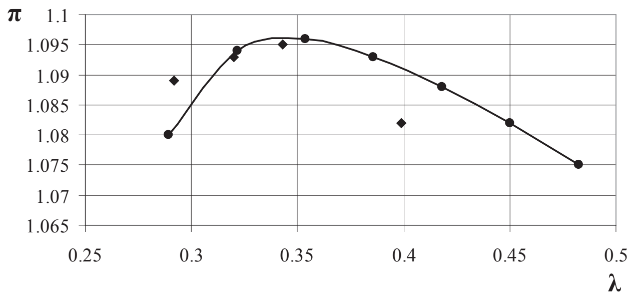


Fig. 2. Characteristic of the stage of an axial compressor

At the values of speed coefficient at the input of $\lambda_c < 0.32$ we observed detachments of the flow from blades during flow around. We also registered a decrease in the pressure increase degree and an increase in the level of hydraulic losses. That is why, in order to study effectiveness of the gas-dynamic action, we selected operating mode of the stage on the verge of detachment. Such a mode corresponds to axial speed at the input $c$=90 m/s and annular speed on the resulting radius $u$=170.7 m/s.

A gas-dynamic action on the flow was performed by injecting the air before the impeller through an annular slit. The effectiveness of gas-dynamic action on the flow was examined at several fixed values of injection angle γ in the range from 5° to 90°. Schematic of the gas-dynamic action by annular injection is shown in Fig. 3.

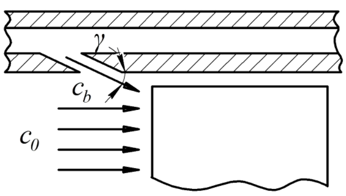


Fig. 3. Schematic of the gas-dynamic action by annular injection on the flow before the impeller

The intensity of gas-dynamic action on the flow was estimated by a coefficient of injection pulse $c_\mu$:

$$c_\mu = \frac{\rho_o c_o^2 F_b \sin\gamma}{\rho_o c_o^2 F_o}, \qquad (3)$$

where $\rho_o$ is the air density at the outlet from the slit, $\rho_o$ is the air density in the main flow, $F_b$ is the area of cross-section at the outlet from the slit, $F_o$ is the area of cross-section at the input to the impeller, $c_o$ is the air flow rate at the outlet from the slit, $c_o$ is the air flow rate in the main flow at the input to the impeller.

Total pressure loss coefficient was determined from formula:

$$\xi = \frac{p_1'^* - p_2'^*}{\frac{\rho_o w_m^2}{2}}, \qquad (4)$$

where $p_1'^*$ and $p_2'^*$ are the average values of total pressure in a relative motion at the inlet and outlet of the impeller, respectively; $w_m$ is the average relative flow rate in the impeller.

Fig. 4 shows dependence of the total pressure loss coefficient in the impeller on the injection pulse coefficient at different injection angles.

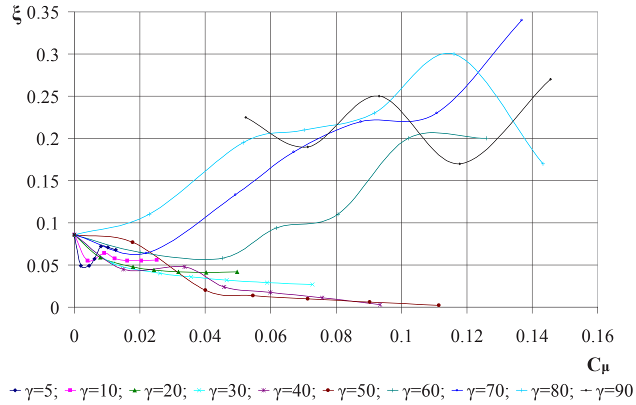


Fig. 4. Dependence of total pressure loss coefficient in the impeller on the injection pulse coefficient

Results of the calculation study demonstrated that at the values of injection angles γ>50° the gas-dynamic action corresponding to values of the injection pulse coefficient $c_\mu > 0.045$, leads to an increase in the level of losses in the impeller.

At injection angles γ≤50° and values of the injection pulse coefficient $c_\mu < 0.11$, a positive effect is observed. With a growth in the intensity of gas-dynamic action one observes the opposite effect – an increase in the vortex regions and, consequently, a growth of hydraulic losses.

For injection angles γ=5° and γ=10°, we observe a local minimum of losses that corresponds to value ξ=0.049. At injection angles γ=40° and γ=50°, the largest effectiveness of gas-dynamic action on the flow by annular injection is observed. For these variants, a total pressure loss coefficient in the impeller can be reduced to 0.005. At injection angle γ=20°, the loss coefficient can be reduced to 0.04. At injection angle γ=30°, there is a decrease in losses to 0.03.

The next step was to study the influence of annular injection on a change in the degree of pressure increase in the stage of an axial compressor.

Fig. 5 shows dependence of the pressure increase degree on the intensity of gas-dynamic action.

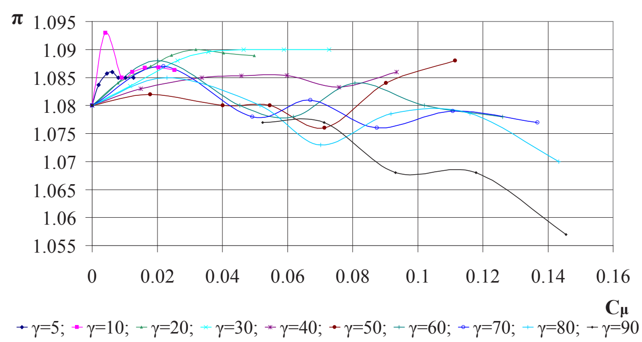


Fig. 5. Dependence of a pressure increase degree on the injection pulse coefficient

The results of computational experiment demonstrated that at rational values of the intensity of gas-dynamic action on the flow, a degree of pressure increase in the stage can be increased from 1.08 to 1.093. At injection angles γ=5° and γ=10°, local maxima occur π=1.093...1.086. At injection angles γ=20° and γ=30°, one observes a growth of the degree of pressure increase to 1.09. At injection angle γ=40°, a pressure increase degree grows to 1.086.

At injection pulse coefficient $c_\mu = 0.11$, one observes an increase in the degree of pressure increase to π=1.088 for injection angle γ=50°. However, for injection angle γ=50° at the values of injection pulse coefficient of $c_\mu = 0.04\ldots0.08$, there is a decrease in the degree of pressure increase to π=1.076. For angle γ=60°, a pressure increase degree can be increased up to π=1.086 at the value of injection pulse coefficient of $c_\mu = 0.02$. At a gas-dynamic action with angles γ>60° at $c_\mu > 0.05$, the pressure increase degree is reduced.

## 6. Discussion of results of examining influence of annular injection on the parameters of stage of an axial compressor

We shall analyze results of numerical simulation of the influence of annular injection on the flow in blade crowns. Fig. 6 shows a velocity field after the impeller without a gas-dynamic action. The flow-around pattern shows that there are regions of detaching flow-around in the peripheral part. As a result of detaching mode of the flow-around, a level of non-uniformity of the flow increases, which leads to an increase in losses and to a decrease in the degree of pressure increase.

Fig. 7 shows a velocity field after the impeller with a gas-dynamic action. The use of annular injection made it possible to reduce the level of circular non-uniformity of the flow in the peripheral part of impeller, where we observed the largest regions of lowered speed (Fig. 6).

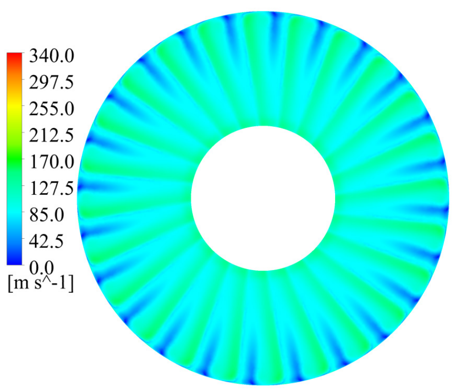


Fig. 6. Velocity field after the impeller without a gas-dynamic action

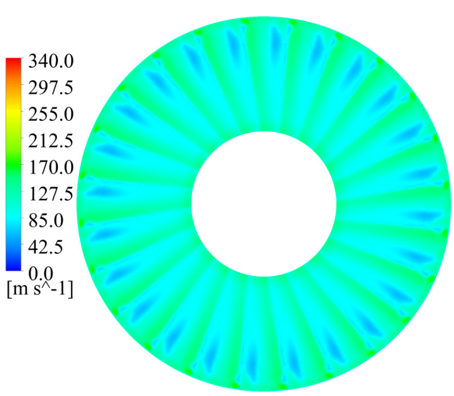


Fig. 7. Velocity field after the impeller with a gas-dynamic action

Fig. 8, 9 show a velocity field after the guide device. Gas-dynamic action on the flow made it possible to reduce the intensity of aerodynamic traces after the guide device (Fig. 9). There are no observed regions with reduced speed in the peripheral part, while in the middle and bushing part the width of aerodynamic traces significantly decreased.

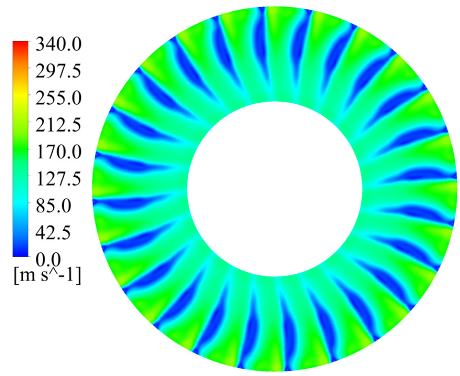


Fig. 8. Velocity field after the guide device without a gas-dynamic action

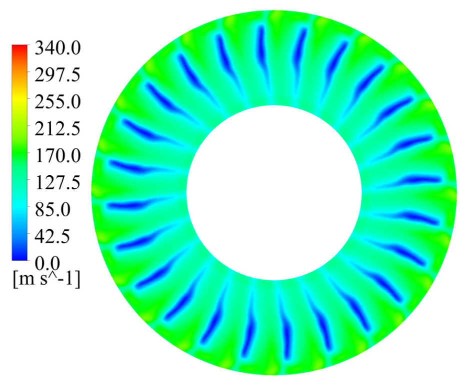


Fig. 9. Velocity field after the guide device with a gas-dynamic action

Fig. 10, 11 show velocity fields in the peripheral cross-section. Gas-dynamic action made it possible to change the character of a flow-around in the intrablade sections of stage of the axial compressor (Fig. 11). Application of annular injection changes the intensity of vortex character of the flow-around and improves stability of the current.

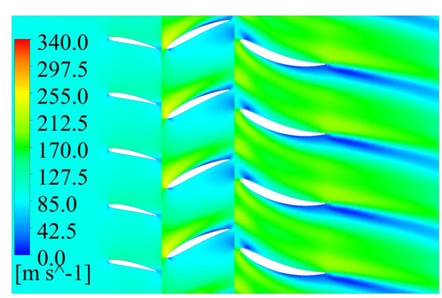


Fig. 10. Velocity field in the stage of axial compressor without a gas-dynamic action

The results of numerical simulation of the flow demonstrate that choosing a rational injection angle during gas-dynamic action on the flow before the impeller can enable improved aerodynamic characteristics of the blade crowns. In the range of injection angles from γ=5° to γ=90°, at angles γ=40°...50°, it is possible to ensure a reduction of the total pressure loss coefficient in the impeller from ξ=0.08

to $\xi$=0.005 at the values of injection pulse coefficient of $c_\mu = 0.09...0.11$. In this case, the pressure increase degree grows from $\pi$=1.08 to $\pi$=1.084...1.088.

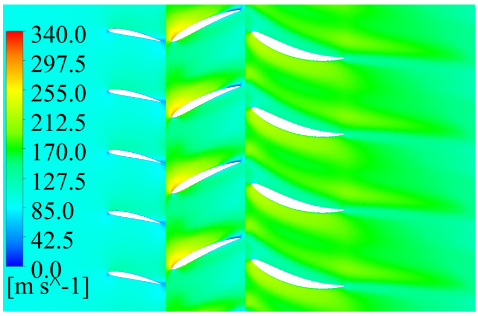


Fig. 11. Velocity field in the stage of axial compressor with a gas-dynamic action

At injection angles $\gamma$>50°, one observes deterioration of aerodynamic characteristics of blade crowns: a decrease in the degree of pressure increase and growth of the level of hydraulic losses.

Of particular interest is the gas-dynamic action at injection angle $\gamma$=30°. When the intensity of a gas-dynamic action in the range of injection pulse coefficient is $c_\mu = 0.04...0.072$, the degree of increase in pressure is $\pi$=1.09. In this case, a total pressure loss coefficient in the impeller is reduced to 0.032...0.028.

As shown by the results of research, the gas-dynamic control over the flow-around provides the possibility to improve internal aerodynamics of the stage of a compressor. Injection of gas through an annular channel destroys the vortex character of a current. Using the gas-dynamic action changes the angles of attack at the input of a blade crown.

Thus, the gas-dynamic action by annular injection on the flow in a stage of the axial compressor makes it possible to extend the range of detachment-free flow-around.

## 7. Conclusions

1. We performed numerical simulation of the current in a stage of the axial compressor with an annular gas injection before the impeller. The gas-dynamic action was carried out under the mode of operation of the stage on the verge of detachment. The annular injection was investigated at several fixed values of injection angle $\gamma$ in the range from 5° to 90°. The research results showed that the gas-dynamic effect on a current makes it possible to improve aerodynamic characteristics of the stage of an axial compressor. Visualization of the flow-around character demonstrated that the level of flow non-uniformity after the impeller and the guide device had decreased.

2. Results of the calculation study revealed that at injection angles $\gamma$>50° the gas-dynamic action, which corresponds to the values of injection pulse coefficient $c_\mu > 0.045$, leads to an increase in the level of losses in the impeller. At injection angles $\gamma \leq 50°$ and values of the injection pulse coefficient $c_\mu < 0.11$, one observes a positive effect. At injection angles $\gamma$=30°...50°, the total pressure loss coefficient in the impeller can be reduced from $\xi$=0.08 to $\xi$=0.03...0.005 at the values of injection pulse coefficient of $c_\mu = 0.06...0.11$.

3. Results of numerical experiment demonstrated that at rational values of the intensity of a gas-dynamic action on the flow, a degree of pressure increase in the stage can be enhanced from $\pi$=1.08 to $\pi$=1.093. At injection angle $\gamma$=30°, with the intensity of a gas-dynamic action in the range ofinjection pulse coefficient $c_\mu = 0.04...0.072$, the degree of pressure increase is $\pi$=1.09.

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