Досліджено новий спосіб керування енергоємними когерентними вихровими структурами (ЕКВС), які визначають процеси масо- і теплопереносу у вихрових камерах. Він полягає в раціональній організації напрямлених керувальних дій на ЕКВС системою неперервних упорядкованих вихрових шнурів від мініатюрного крила малого видовження, яке встановлене у проточному тракті впускного сопла камери. Запропоновано теоретико-експериментальне обгрунтування досліджуваного способу на основі принципу взаємної сприйнятливості вихрових структур

Ключові слова: когерентні вихрові структури, керування структурою течії, вихрова камера, криловий вихорогенератор, взаємна сприйнятливість вихорів

Исследован новый способ управления энергоёмкими когерентными вихревыми структурами (ЭКВС), которые определяют процессы массо- и теплопереноса в вихревых камерах. Он состоит в рациональной организации направленных управляющих воздействий на ЭКВС системой непрерывных упорядоченных вихревых шнуров от миниатюрного крыла малого удлинения, установленного в проточном тракте впускного сопла камеры. Предложено теоретико-экспериментальное обоснование исследуемого способа на основе принципа взаимной восприимчивости вихревых структур

Ключевые слова: когерентные вихревые структуры, управление структурой течения, вихревая камера, крыльевой вихрегенератор, взаимная восприимчивость вихрей

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EXAMINING THE TECHNIQUE TO CONTROL THE STRUCTURE OF CURRENT IN VORTEX CHAMBERS BY WING VORTEX GENERATORS

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1. Introduction

A rational organization of the processes of transfer of mass, pulse, and energy in the flows of liquids and gases in technological, energy, and transportation systems is one of the central tasks on improving efficiency. In order to intensify or, conversely, stabilize and block heat-mass-exchange, physical-chemical, electrophysical processes, the local or global swirling flows are applied. However, the effect of centrifugal forces and axial pressure gradients in the shear flows of vortex chambers (VC) causes the formation of coherent vortex structures (CVS) of different topology, with certain difficulties in determining the patterns of hydro-aero-dynamic and heat exchange processes. The mechanisms of formation, evolution, and interaction between such structures in the constrained swirling flows have been insufficiently studied up to now. Nevertheless, the emergence of CVS in swirling flows is typical of the working processes in many machines and assemblies. These include internal combustion engines, MGD-generators, gas-turbine and rocket engines, furnaces, plasmatrons, cyclones, nuclear energy plants, etc.

Traditional methods of flow control in the practice of designing devices of the vortex type are mainly oriented to changing the overall pattern of the current. This is typically achieved through the variation of geometrical parameters of machine design elements and by selecting operational characteristics at the macro level. When applying such integrated control methods, certain advantages in the efficiency of heat-mass-exchange are often attained at the expense of the elevated aero-hydro-dynamic resistance of the system. It is known at present that the most significant contribution to the turbulent diffusion and agitation of working media is produced by the energy-consuming components of current. Thus, in the constrained swirling flows, the defining role in the processes of transfer of mass, pulse, and heat belongs to the low-frequency components of the pulsating motion in the energy-intensive coherent vortex structures (ECVS). There are no for the time being any generally accepted techniques for the principles of control over ECVS, specifically at the micro level. Therefore, when addressing a general problem on enhancing the efficiency and reliability of machines and devices of the vortex type, it is an important task to devise advanced control methods for the specified ECVS in VC at minimal energy and material costs.

2. Literature review and problem statement

It is known that during motion of both laminar and turbulent flows along the curvature of bended surfaces, there is a viscous instability of the near-wall current in the fields of centrifugal forces. This leads to the formation of ordered vortices of the Taylor, Ludwig, Görtler, Dean type and their varieties. The heterogeneity of the flow structure in the averaged and pulsating motions, caused by them, leads to significant changes in the characteristics of transfer and in the hydro-aero-dynamic resistance of systems. These patterns of working processes were addressed in many theoretical and experimental studies into various areas of application of swirling flows [1–13].

Paper [1] investigated the complex structure of liquid flows with dispersed impurities in the field of centrifugal forces near permeable cylindrical surface in the rotating filter. The choice of the optimum ratio of Reynolds numbers in the radial and cyclic flow directions is supposed to improve the quality of purification. Ultimately, control over the process of purification is achieved by altering the design and operational parameters of the installation: variation in sizes and shapes of openings in the rotor element, frequency of its rotation, the magnitude of gap in the device's flow-through part. Study [2] examined swirling flows in furnace devices with the aim of improving the efficiency of vortex technologies for fuel burning and controlling their environmental performance. The internal aerodynamics of a vortex furnace depending on the location of burner jets was studied in order to prevent the precession of the vortex core and induction of powerful thermoacoustic oscillations. The authors argue, however, that the advantages and shortcomings of each design in the context of the examined processes can be identified only at the stage of full-scale testing or under experimental-industrial operation.

The swirling flows and their control is the focus of attention when designing turbines and compressors [3–5]. It is known that the detachment of flow on the working and the stator blades leads to the emergence of volumetric flow pulsations and a sharp decrease in the performance efficiency of a turbomachine. Work [3] is one of the typical ones for the direction of research into control methods for the nonstationary detachment on turbine blades that employ jet oscillators. It is still an open question to ensure high reliability of work of such control tools at actual installations. High efficiency of gas turbine units depends, first and foremost, on the temperature of gas. The development of new highly efficient cooling systems of turbine blades is tackled to paper [4]. To control the process of film cooling of the input blade edges, it is proposed to supply a coolant through the rows of cylindrical openings in semi-spherical indents and grooves. These geometrical irregularities act as vortex generators to intensify the process of heat exchange. The obtained integrated indicators confirm the improvement of temperature conditions of the blade though the technology for manufacturing a blade gets complicated. Study [5] covers a wider range of the application of vortex effects. In addition to the specified direction, the authors develop the idea of using a flow swirling for the curtain-based cooling of plasmatrons with a vortex stabilization of the arc, vortex burners, combustion chambers, etc. Experimental data at the integral level promise a certain improvement in the efficiency of the working processes of such devices.

Paper [6] reports results of the study into CVS and their contribution to the improvement of mixing the flows of fluids with the low and high level of pulses to enhance thermal convection. It is shown that the near-wall heat transfer depends mainly on the large-scale turbulent structures at high Reynolds numbers. The intensification of heat exchange is achieved by creating CVS in channels with the built-in longitudinal vortex generators. Despite the simplicity of this geometry, solving a problem on the calculation, prediction of reverse currents, and identification of CVS by vortex generators is a serious challenge at the stage of theoretical-numerical implementation. Study [7] addresses the influence of vortex generators on the improvement of thermal performance of a tubular heat exchanger. Vortex generators in the form of different wings were placed in the region of air flow over a sufficiently wide range of Reynolds numbers Re=5,300÷24,000. However, the result of comparison with smooth pipes shows that at an increase in the Nusselt number, the application of vortex generators leads to increased hydraulic pressure losses of the head.

Paper [8] summarizes authors' experience in the field of research into CVS related to the external problem of hydromechanics. 12 basic types of CVS were systemized that occur in the near-boundary layers when flowing around actual bodies, as well as the methods to control these CVS. It was found that in the near-boundary layer all energy exchanges are due to the peculiarities of, and interaction between, certain characteristic types of CVS. One of the most important conclusions of this work is in the following. In order to execute optimum control over patterns in flowing around a body, it is required to influence not the entire near-boundary layer, but a small area where the core of CVS forms, as well as the zone where the main exchange of energy takes place. In this case, the level of intensity of controlling action on CVS in the near-boundary layer can be an order of magnitude smaller in comparison with the characteristics of the entire near-boundary layer. Accordingly, to enable control, it would take an order of magnitude less energy than it is required when traditional control methods are employed. This is the principle of mutual susceptibility by vortex formations of the near-boundary layer to various control disturbances. The principle provides a tool to manage the process of laminar-turbulent transition in the near-boundary layers. The ideas of a given work were further developed in paper [9] that addressed control over the near-boundary layer on the wing RSG-36 using the vortex generators installed at its streamlined surface. The geometrical parameters of vortex generators were defined at which three-dimensional disturbances caused by them exert the greatest influence on the aerodynamic characteristics of the specified wing model. Paper [10] theoretically investigated complex effects in the formation of flow around the aircraft wings (AC) with the vortex generators mounted on them. The authors discovered the mutual influence between the longitudinal vortex structures, generated by vortex generators, and the transverse vortex structure, formed as a result of the non-stationary flow flowing around the wing. It is proven that the use of vortex generators improves take-off and landing characteristics of AC and makes it possible to use wings of greater thickness with a larger fuel volume. Increasing the critical angles of attack has a positive effect on the security of AC flights.

In [11], authors discovered and thoroughly analyzed characteristic types of regular CVS in different areas of vortex chambers with a developed dead part, which is proposed as an additional vortex generator. These include the following. In the nozzle region, these are the pairs of vortices in the corner areas of the inlet nozzle, the pairs of transverse vortices in the detachment area of the flow behind the nozzle, and the diverging vortices of the Görtler-Ludwig type on the concave wall of the cylindrical surface of the chamber. In the dead region, these are the quasi-Taylor vortices, spiral-like ECVS of the "whiskers" type, which diverge into a dead end and active parts of the chamber, and the near-axial tornado-like quasi-solid-body vortex. Detailed description of the vortex components of the overall flow in a chamber demonstrated the prospect of developing more efficient techniques to control CVS and, therefore, the processes of mass- and heat transfer in the devices of the vortex type. Experimental proof of this possibility, based on the generalized principle of mutual susceptibility of vortex structures, is given in papers [12, 13]. Energy-insignificant control disturbances of the input flow to VC from small indentations in the intake nozzle of the chamber increase spectral density of pulsation power speed, at the most energy-intensive frequencies, by approximately 2÷11 times. The studies discovered a phenomenon of the "reverse disintegration of vortices", that is, the "pumping" of energy density from small-scale in favor of the most large-scale vortex components of ECVS.

An overview of available studies reveals the following. Most of the research deals with rather approximate estimations of characteristics of swirling flows in terms of the external problem of aero-hydro-dynamics. Underlying the theoretical-numerical works are the existing models of turbulent currents while experimental research is based on examining flow patterns, mainly at the macro level. As a result, we are offered distribution diagrams of averaged flow parameters or a totality of conditional vectors, of the current trajectories, which very schematically indicate the motion direction of the particles of a liquid (gas). The application of such methods is limited by specific structures and not always adequate results of computer simulation of a turbulent shear flow. At the macro level, respectively, specialists tackle the issue of the organization of transfer processes in working environments in the internal currents in channels and chambers. Constructing more complex models of turbulence based on existing approaches does not solve a series of fundamental problems. In addition to known computational difficulties, among the essential ones is the following. In turbulent currents with a shear, a statistical totality of vortices that form the actual values of parameters is not a mutually independent set, which is required the central boundary theorem by Lyapunov. On the other hand, there exist the deterministic mechanisms of interaction between the components of turbulent currents. A turbulent current (and laminar, in certain cases), especially in the field of centrifugal forces, is accompanied by the motion of the ordered vortices, including those most energetically "charged".

Given a certain dualism of the nature of aero-hydro-dynamic processes in the flows of a vortex structure, different in scale, the traditionally proposed tools of integrated control over a turbulent transfer cannot be considered sufficient. The most promising direction in the search for effective means of control over the structure of a current appears to be the direction of development of the method of "subtle" influences on ECVS at the stage of their creation. The goal of the influences is to ensure the improvement of the flow mixing process in VC.

The development of such a method to control ECVS in vortex chambers based on the generalized principle of mutual susceptibility of vortex structures is the subject of present work.

3. The aim and objectives of the study

The aim of present study is to verify, theoretically and experimentally, the effectiveness of the method to control spiral-like ECVS in VC using the trailing vortex systems, generated by immobile wings, mounted in the inlet nozzle of the chamber. A problem is set to enable, in a targeted fashion and at minimal losses of energy, a "subtle" influence on ECVS and the characteristics of flow mixing in VC.

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

– to devise a reasoned procedure for the application of fixed wings in the nozzle of a vortex chamber, and to work out a criterion of their effectiveness for controlling actions;

– to perform a substantiated selection of geometrical and aerodynamic parameters for wings of this designation;

– to explore patterns in the formation of controlling vortex plaits under conditions of a constrained flow-through tract of the inlet nozzle of the chamber;

– to analyze a reaction of ECVS in the active zone of the chamber on controlling actions of a nozzle vortex generator.

4. Methods and technical means used in the study

The procedure for conducting the study implied the following stages:

– visualization of the flow in the inlet nozzle of VC when three types of wing elements of small elongation are mounted in it ($1 \leq \lambda \leq 3$);

– theoretical estimation of the efficiency of wing as a vortex generator in the inlet nozzle of VC;

– theoretical-experimental alignment of parameters for controlling vortices with controlled ECVS in the chamber;

– experimental validation of the effectiveness of influence of controlling actions of the nozzle vortex generator on the integrated characteristic of ECVS in the inlet cross-section of VC.

The installation of a wing element in the inlet tract of the device may cause a certain growth in its aerodynamic resistance to VC. The formation behind a wing of the unstable vortex system in the accompanying trail cannot be considered as a factor in controlling the current. To compensate for the impact of this factor on the aerodynamic drag, we selected relatively thin wings of small elongation with a hydraulically smooth surface. The trailing vortex systems behind the wing cause induction resistance [14], which is traditionally weakened in aviation by variety of means. However, in this case, to control ECVS, it is implied that the vortex cords are used. In accordance with the general principle of mutual susceptibility of vortex structures, characteristics of vortex cords should be commensurate either with the characteristics of the Görtler-Ludwig vortices in the near-nozzle region of VC, or directly with the characteristics of ECVS [11].

The experiments were carried out at the aero-dynamic laboratory bench "Vortex chamber" designed to study internal vortex currents. The bench includes an experimental installation with a transparent working section in the form of VC with inner diameter d_0=0.102 m and total length L_0=0.635 m with a single nozzle. The nozzle has a flow-through tract, tangential relative to the chamber cavity, with a rectangular cross-section of 0.02×0.04 m^2, rounded at the corners. The measuring complex of the bench includes thermal anemometry equipment manufactured by company DISA Elektronik, Denmark, with a one-thread wire sensor, and standard devices to control flow rate and pressure with a set of pneumometric nozzles. The thermal anemometry equipment is connected to the analog-to-digital converter L-264 produced by firm L-Card, Russia, that is installed in the form of an extension board to an IBM-compatible computer. The set-up is also equipped with means of visualization, video and photo recorders for flow current, and coordinate devices. Measuring information processing was performed using the licensed software package PowerGraph Professional by Ltd DISoft, Russia. A given measuring complex enables direct study of the vortex structures, integrated and local characteristics of the turbulent current. Design of the bench and its elements are described in papers [11–13].

Constrained cross-section of the flow-through tract of the inlet nozzle of VC predetermines a change in the aerodynamic coefficients of the wing commensurate to it as a vortex generator relative to those values that correspond to its unlimited flow-over. In addition, at large angles of attack, it is possible to observe a shielding effect from the nozzle wall, which substantially affects the coefficient of lifting force of the wing. To minimize the impact of the constrained cross-section of the flow-through tract of the inlet nozzle, it is required to apply a procedure for the recalculation of aerodynamic coefficients, characteristic of research in the field of subsonic aviation, via the introduction of additional correcting coefficient of inductive resistance from the walls of the pipe. A small elongation of the wing-vortex generator also requires adjustment of aerodynamic characteristics, obtained during traditional blow of wings in aerodynamic tunnels.

It is impossible to account for all these factors by calculation, including numerical modelling. This necessitates conducting physical and, above all, visualization experiments aimed at proper selection of the geometrical and aerodynamical parameters of the wings-vortex generators. It is necessary to make sure that under the specified conditions of flowing around, there occurs a stable generation of vortex plaits that fly off the wings, which have to perform the function of controlling vortices. It is also important to estimate the topology in terms of capability to perform certain requirements of the concept of mutual susceptibility of vortex structures to control them in the cavity of VC. Only based on the acquired results of experiments will we be able to elucidate the prospect of their application in the context of the stated problem of control over coherent vortex structures in VC.

4. 1. Visualization of current in the inlet nozzle of a vortex chamber

Visualization of current is needed to determine the range of unseparated positive and negative angles of attack of the wings while maintaining the most favorable conditions for stable generation of controlling vortices under conditions of constrained flow-through tract of the inlet nozzle. We investigated the character of flow around two wings of rectangular shape in plan with a chord of 0.02 m, and around a wing of triangular shape with a height and base of 0.02 m each. Correct setting of the experiment requires ensuring a smooth current and the uniformity in the distribution of speed and pressure of air flow at the inlet to the nozzle. For this purpose, we mounted onto it a head with an inner profile in the form of the lemniscate of Bernoulli.

To study the peculiarities in the formation of controlling vortex plaits, we performed the visualization of current using a silk filament method. This is the traditional method, which is widely used in the experimental aero-dynamics. Given the size of the examined wings and nozzle, we applied silk filaments with a diameter of $0.2\cdot10^{-3}$ m. To determine the boundaries of continuous flow around the wing, light and light-reflecting silk filaments with a length approximately equal to two chords of the wing were glued at the front critical point in the middle of the wings chord. By observing the character of motion of a silk filament ("sticking" to the surface of the wing), we drew a conclusion about the trajectory of the current line and, accordingly, about a continuous or a separated flow around the wings. To determine the presence of trailing wing vortices, silk filaments with a length approximately equal to one wing chord were glued to the end surfaces of the wing in the region of the back critical point. When flowing around a body, silk filaments are oriented in the flow by the direction of velocity vector. Vertical and horizontal projections of the offset of each filament are the representations of angles of the flow lateral shift. In the presence of trailing vortices, each point of a silk filament executes a rotating movement and the entire silk filament describes in the rotation a conical surface.

During experiments, we made video and photo recording under specialized lighting; the data acquired were subsequently processed using a computer. Certain patterns in the flow around the wings with zero, pre-critical (continuous), and super-critical (separation) angles of attack in the nozzle of a vortex chamber are shown in Fig. 1. The angles of attack ranged within $-14^o \leq \alpha \leq 14^o$ at a speed of air flow incident to the wings of $\upsilon_\infty = 50{,}6$ m/s and a respective value of Reynolds number for the equivalent diameter of the nozzle of Re=93,760. The rationale for employing a wing that has a profile of bilateral convexity of the type MB253515 will be given below.

The experiments confirmed the presence of persistent trailing vortices on the wings-vortex generators of the examined types, which operate in the flow-through tract of the chamber's inlet nozzle. High-speed video-recording with a frequency of up to 1,200 frames per second revealed that silk filaments on each of the lateral surfaces of the wing demonstrate opposite directions of rotation. A change in the sign of wings' angles of attack results in that the rotation directions of the silk filaments change to the opposite. At zero angles of attack of the wings, the rotation of silk filaments is not observed. A silk filament, fixed in the middle of the wing, almost near its leading edge, demonstrated the presence or absence of the detachment of a near-boundary layer on the wings when the angles of attack varied. Research has shown that the characteristic angles of attack of the wings with small elongation in the VC nozzle (zero and maximum continuous) differ from similar characteristic angles of attack of the same wings in the free flow. This is due to the influence of the nozzle walls and a screen effect. Results of measurements are summarized in Table 1; they are used in the subsequent thermoanemometric studies.

Visualization was accompanied by photo recording applying a method of serial photography by the digital cameras NIKON 1 V1 with the lens 1NIKKOR 18.5 mm F/1.8, and SONY DSC-RX100M5. Photo recording frequency was 5 frames per second for the camera NIKON 1 V1, and 24 frames per second for the camera SONY DSC-RX100M5. Resolution of frames was 3,840×2,160 pixels for the camera NIKON 1 V1, and 5,472×3,638 pixels for the camera SONY DSC-RX100M5.

Exposure of each frame was 1/100...1/200 seconds. To determine the direction and rotation frequency of the trailing vortices, we made high-speed video recording using the digital camera SONY DSC-RX100M5 at 1,000 frames per second with each frame exposure of 1/10,000 seconds. Resolution of each frame was 1,244×420 pixels. Next, we made the snapshots of each video fragment using the software VirtualDub ver.1.5.4. Frequency of rotation of the trailing vortices corresponds to the frequency of silk filament rotation. Its magnitude was determined by the number of snapshots in the video recording at one revolution of silk filaments. The data are given in Table 2 for the three types of vortex generators.

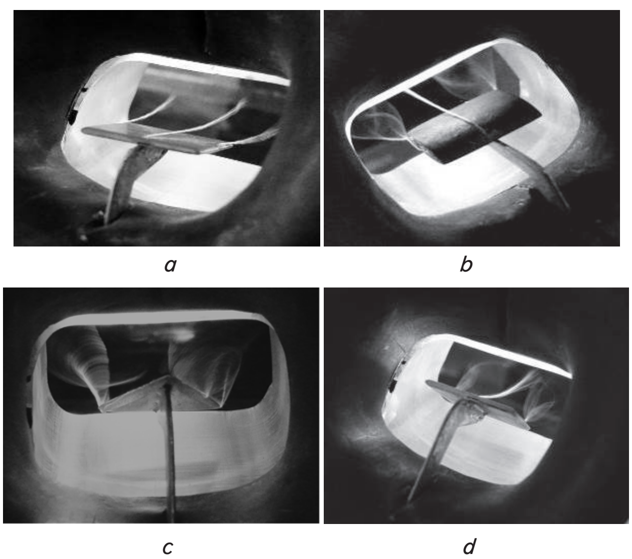


Fig. 1. Examples of current patterns visualization for the wings angles of attack: *a* – zero (a flat plate), *b* – maximum continuous (the profile MB253515), *c* – maximum continuous (a delta wing), *d* – separation (a plate)

Table 1

Dependence of character of the flow around wings in the nozzle on angles of attack

Type of wing	Character of flow around wing	Angle of attack, degree
Rectangular (profile – a flat plate)	Continuous	5
	Separation	>12
	Separation	<–6
Delta (profile – a flat plate)	Continuous	3
	Separation	>13
	Separation	<–8
Rectangular (profile – MB253515)	Continuous	8
	Separation	>14
	Separation	<–6

It follows from data given in Table 1 that the maximum modulo continuous angles of attack of wings in the VC nozzle are α_{max}=14° and α_{min}=–6°.

Table 2

Rotation frequency of trailing vortices at α_{max}>0

Profile of wing	Mean rotation frequency of trailing vortices *n*, 1/s	
	Re=55,000	Re=95,000
MB253515	189	259
Flat plate	176	236

The data in Table 2 specify visual realization of the physical process of the origin of trailing vortices in the confined space of a nozzle. The magnitudes of rotation frequency of trailing vortices in the formation regions are needed in order to calculate the transverse dimensions of vortex cords.

4. 2. Procedure of measuring the effectiveness of a wing-vortex generator

The characteristic of useful utilization of the inductive resistance of a wing- vortex generator, and an analysis of the basic factors that affect it, are proposed to obtain in two stages.

Infinite flow around the wing.

As it is known [14, 15], full aero-hydro-dynamic power of wing (the amount of energy that is taken by the wing from a flow of liquid per unit time) is equal to

$$N_R = R\cdot \upsilon_\infty,$$

where *R* is the full resistance of a wing in the flow; υ_∞ is the velocity of the flow that is incident to the wing.

Full resistance of a wing in the flow

$$R=\sqrt{c_x^2+c_y^2}\,\frac{\rho\upsilon_\infty^2}{2}S,$$

where ρ is the density of the medium; *S* is the area of the wing in plan; c_y is the coefficient of lifting force of the wing in the speed (current) system of coordinates; c_x is the coefficient of full resistance of a wing in the flow in the speed coordinate system, which, at subsonic flow around, without taking into consideration the impact of solid borders, is the sum of coefficients of the profile and inductive resistances, respectively: $c_x = c_x^{pr} + c_{xi}$, in this case, the profile resistance coefficient consists of a coefficient of pressure resistance c_x^p and friction resistance c_x^f.

In the context of our work, flow energy expenditures for the formation and support for the trailing vortex cords per unit time can be considered the useful power of a wing as the vortex generator. It can be expressed through the inductive resistance of wing R_i in the following form: $N_i = R_i\cdot\upsilon_\infty$, where

$$R_i = c_{xi}\frac{\rho\upsilon_\infty^2}{2}S.$$

The efficiency of applying the wing-vortex generator can be estimated via coefficient η, equal to the proportion of power spent on the creation and support of the vortex cords to the full aerodynamic power of the wing

$$\eta=\frac{N_i}{N_R}=\frac{c_{xi}}{\sqrt{c_x^2+c_y^2}}. \qquad (1)$$

For the wings with a finite elongation, coefficient of inductive resistance equals

$$c_{xi}=\frac{c_y^2}{\pi\lambda}, \qquad (2)$$

where λ is the elongation of the wing.

Transformation of expression (1) with respect to (2) yields

$$\eta=\frac{c_y^2}{\pi\lambda\sqrt{c_x^2+c_y^2}}=\frac{1}{\pi\lambda}\sqrt{\frac{K_\infty^2}{1+K_\infty^2}}c_y,$$

where

$$K_\infty=\frac{c_y}{c_x}$$

is the aero-hydro-dynamic quality of the wing in the infinite flow. For the wings with a small elongation, coefficient of inductive resistance grows twofold [14, 15]

$$c_{xi}=\frac{2c_y^2}{\pi\lambda}.$$

Hence, the coefficient of efficiency of applying a wing as the vortex generator will be

$$\eta=\frac{2}{\pi\lambda}\sqrt{\frac{K_\infty^2}{1+K_\infty^2}}c_y. \qquad (3)$$

Examination of obtained function (3) allows us to draw the following conclusions:

1. A considerable impact on the magnitude of the coefficient of efficiency of applying a wing η is exerted by a wing elongation λ.
2. The most rational is the application of wings with a small elongation as a vortex generator.
3. The coefficient of lifting force c_y also significantly influences the criterion of efficiency η. But for most rectangular wings, it is limited by magnitude $c_y^{\max}\le 1{,}6$.
4. Aero-hydro-dynamic quality of wing K_∞ exerts an insignificant influence on the efficiency coefficient η. A growth of function (3) is limited by that the magnitude

$$\sqrt{\frac{K_\infty^2}{1+K_\infty^2}}\to 1$$

at $K_\infty\to\infty$. Thus, at $K_\infty=3$, magnitude

$$\sqrt{\frac{K_\infty^2}{1+K_\infty^2}}\approx 0{,}95,$$

that is, close to 1. This allows the application of wings that have an insignificant aero-dynamic quality as the vortex generators.

Constrained flow around the wing.

To account for the effect of boundaries proximity (a "tunnel effect"), we shall apply a procedure for the recalculation of coefficients, characteristic of research in the field of subsonic aviation: the effect of limiting walls of aerodynamic pipes (in our case, walls of the flow-through tract in an inlet nozzle) can be accounted for by the introduction of additional correcting coefficient of inductive resistance from the "tunnel effect" c_{xi}^T. Then the actual coefficient of resistance of the wing is $c_{xi}^T=c_x+c_{xi}^T$. The magnitude of c_{xi}^T is derived from formula

$$c_{xi}^T=-\varepsilon\frac{S}{F}c_y^2,$$

where F is the cross-sectional area of the flow-through tract of an inlet nozzle; ε is the coefficient that depends on the shape of the passing cross-section of the nozzle. The sign "–" denotes a reduced resistance compared to the real (a "tunnel" of the nozzle as an analogue of limiting plate disks at the front edges of the wing that prevent overflows and inductive resistance during blowing of profiles in aerodynamic wind tunnels). An analysis of the scientific literature reporting data on numerical experiments in the aerodynamic wind tunnels [15–18] confirms the correctness of taking into consideration the specified amendments, which allows us accurately enough to determine the impact of flow borders on the wing at different possible shapes of the VC inlet nozzle cross-section.

In the theory and practice of aerodynamic experiment, there is a well-known feature of studies in closed aerodynamic wind tunnels. Thus, for pipes with a circular cross section, based on theoretical calculations by Tietjens [15], verified experimentally, the shape coefficient ε=1/8. For pipes with a rectangular cross-section, according to Glauert [16], the shape coefficient is a function of the form $\varepsilon=f(H_T/D_T)$, where H_T, D_T are respectively, the height and width of the pipe cross-section. For closed and open pipes with an elliptic cross-section of the working part at wingspan not larger than 0.75 of the flow width, correction coefficient ε does not exceed 0.20...0.22.

In the examined case, the most rational way is, rather than taking into consideration the influence of the nozzle walls, to create such conditions for the flow around the wings in it, at which this influence can be minimized until one can disregard it. Estimates show that such a condition occurs at ratio $S/F\le 1/5$. Then, at any theoretically possible value of coefficient ε, the coefficient of inductive resistance from the walls of a flow-through tract c_{xi}^T will not exceed by modulo the magnitude of 0.04. When selecting the geometry of a wing with $c_y^{\max}\ge 1{,}0$ the effect of the constrained flow will not exceed 4 %, which may be neglected.

We shall determine an efficiency coefficient for the wing with a small elongation as a vortex generator for the case of flowing around by a finite flow. With respect to expression for coefficient c_{xi}^T, and to that the actual aerodynamic quality will be equal to

$$K=\frac{c_y}{c_x+c_{xi}^T},$$

we shall transform a formula for the efficiency coefficient at $K_\infty\to K$ to the form

$$\eta=\frac{2c_y}{\pi\lambda\sqrt{1+\frac{1}{K^2}}}=\frac{2c_y}{\pi\lambda\sqrt{1+\left(\frac{1}{K_\infty}-\varepsilon\frac{S}{F}c_y\right)^2}}, \qquad (4)$$

where $1/K_\infty$ is the inverse aerodynamic quality of the wing in an infinite flow (magnitudes for K_∞ are to be taken from known maps of wing profiles).

Based on the calculations by formula (4), we selected the optimum profile of the wing from known maps of wing profiles. However, the examined range of Reynolds numbers is different from those typical for aviation magnitudes $Re=10^6 \div 10^7$. We, therefore, employed the newest available data for wing blowing [19, 20] applied in aviation modeling when designing gliders, unmanned vehicles of small size, small air turbines, etc. The focus was on the desired maximum values for coefficient of lifting force c_y, which significantly affects coefficient of inductive resistance of the wing and efficiency criterion η. It was established that the series of aerodynamic profiles whose parameters in the range of Reynolds numbers Re=40,000÷100,000 are given in Table 3, fit best our purpose. Consequently, with respect to the manufacturability of the wing, we selected to be our basic object under consideration a wing with a profile of the type MB253515 of rectangular shape in plan the size of 0.02×0.02 m^2. However, in several cases, to comparison visualization patterns and flow-around parameters, we also performed blowing of wing elements of a vortex generator in the form of a rectangular flat plate of similar dimensions, as well as a delta wing with a span and height of 0.02 m.

Table 3

Parameters of aerodynamic profiles and the calculated efficiency coefficient

No.	Type of profile	$\bar{c}$, %	$\bar{f}$, %	c_y^{max}	$c_x(c_y^{max})$	$\alpha(c_y^{max})$	$k(c_y^{max})$	η_{max}
1	A-18	7.26	3.84	1.133	0.0632	11.03	17.9	0.257
2	GM15	6.70	4.76	1.239	0.0292	9.92	42.2	0.281
3	Davis 3R with a turbulator system	5.87	5.91	1.294	0.0700	11.75	18.5	0.294
4	AG16	7.11	1.18	1.143	0.1416	10.32	8.1	0.259
5	AG40d-02r Flap20deg wing with a flap, tilted at 20°	8.00	2.37	1.392	0.0774	5.04	18.0	0.316
6	MB253515	14.96	2.43	1.100	0.0260	14...18	42.3	0.250
7	Plate, rectangular in plan (λ=2.5)	3.10	0	0.750	0.1500	10.00	5.0	0.191

4. 3. Aerodynamic model of the wing vortex generator

According to the theorem by Zhukovsky, lifting force of the wing with an infinite span is proportional to the velocity of circulation Γ behind the contour that spans the wing. Therefore, based on the force action on the unperturbed flow, the wing, in the first approximation, can be replaced with an infinitely long vortex cord with the same velocity circulation as the wing has. Such a vortex cord, as it is known, is called the bound cord. This is the simplest aerodynamic model of the wing.

However, flow around the wing of a finite span is not of a flat-parallel character, but spatial, especially near its ends. If lifting force is implemented on the wing, then there is a flow of air through the end-edges to the region of low pressure above the wing. As a result, there forms a vortex shroud behind the wing, which consists of the so-called free vortices [14, 15]. Each pair of free vortices along the wingspan is closed on it by the corresponding bound vortex with its intensity. Due to the lack of stability, the vortex shroud at a certain distance from the wing is collapsed to two vortex cords. The approximate calculations consider an equivalent Π-shaped wing aerodynamic model with constant average circulation Γ along its span: two semi-infinite vortex cords that run down from the end edges of the wing are locked by one bound vortex (Fig. 2) Since the circulation velocity should be constant for the entire length of the vortex system, the circulation around free vortices is equal to the circulation around the bound vortex.

Lifting force of the main vortex at the distance between vortex cords of l_1, according to the Zhukovsky theorem, is $R_y = \rho_\infty \upsilon_\infty \Gamma l_1$. On the other hand,

$$R_y = c_y \frac{\rho_\infty \upsilon_\infty^2}{2} S.$$

The so-called connection equation for any cross-section of the wing follows from these relations

$$\Gamma = \frac{1}{2} c_y \frac{S}{l_1} \upsilon_\infty. \qquad (5)$$

The condition of equality between inductive resistances of the Π-shaped vortex system and the actual wing requires that the distance between free vortices l_1 should be somewhat larger than the wingspan l: $l_1=lk$, where $k>1$. The magnitude of k depends on the shape of wing in plan, on relative elongation of the wing, though it varies within $k=1.02\div1.04$ (Fig. 2).

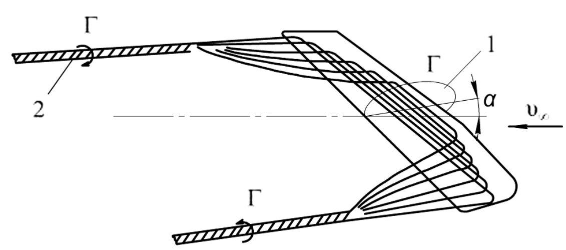


Fig. 2. Vortex schematic of the wing with a finite elongation: 1 — bound vortex; 2 — free vortices

For wings of rectangular shape, we have in plan (a thin rectangular wing; wing MB253515) $S=bl$, where $b=0.02$ m is the chord of the wing. Then, based on (5), we obtain:

$$\Gamma = \frac{1}{2{,}04} c_y \upsilon_\infty b. \qquad (6)$$

For a delta wing:

$$S = \frac{1}{2} l\,h,$$

where l is the base, h is the height. Then (5) takes the form:

$$\Gamma = \frac{1}{4{,}08} c_y \upsilon_\infty h.$$

We shall consider the accepted vortex system of the wing. According to the Stokes theorem, circulation Γ around the wing is equal to the flow of vortices

$$I = \iint_\sigma \vec{\Omega} \cdot d\vec{\sigma}$$

through surface σ, permeated with a set of vortex filaments with a local vorticity Ω_i by modulus along the width of the wing. If we introduce the averaged value of vorticity module

$$\bar{\Omega}=\frac{1}{\sigma}\iint_{\sigma}\Omega_i d\sigma,$$

then we obtain equality

$$\Gamma=\bar{\Omega}\sigma. \qquad (7)$$

But all the vortex filaments, directed along the wingspan, are included in the trailing free vortices with vorticity $\bar{\Omega}_v$ and cross-sectional area σ_v. Then, based on the second kinematic Helmholtz's theorem, we obtain

$$\bar{\Omega}\sigma=\bar{\Omega}_v\sigma_v.$$

Passing over to the averaged value of angular velocity $\bar{\omega}_v$ of the free vortices in accordance with a generally accepted model of locally undeformed gas volumes, expression (7) can be written in the form

$$\Gamma=2\bar{\omega}_v\sigma_v. \qquad (8)$$

5. Results of calculation and instrumental research

We shall calculate circulation velocity Γ from formula (6) for a wing of the type MB253515 and a rectangular plate at boundary values of the range of Reynolds numbers Re=55,000÷95,000. Coefficients of lifting force c_y^{max} are taken from Table 3 at the following, defined experimentally, maximum continuous magnitudes of angles of attack under condition that the nozzle: for the wing MB253515 $\alpha\left(c_y^{max}\right)=14^o$; for a plate $\alpha\left(c_y^{max}\right)=12^o$ (Table 1). In this case, we take into consideration that the coefficient of lifting force relative to thin profiles almost does not depend on the number of *Re* over a fairly wide range of its change. Based on data from Table 2, we shall also find corresponding values of the averaged angular velocity $\bar{\omega}_v$ of free vortices from formula $\bar{\omega}_v=2\pi n$, 1/s. Formula (8) allows us to calculate the values of cross-sectional areas of free vortices σ_v and, therefore, their diameters d_v. Main estimation parameters are given in Table 4.

Table 4

Characteristics of the vortex system of wings with a rectangular shape in plan

Profile of wing	Re=55,000			Re=95,000		
	Γ, m²/s	$\bar{\omega}_v$, 1/s	d_v, mm	Γ, m²/s	$\bar{\omega}_v$, 1/s	d_v, mm
MB253515	0.32	1,186.92	13.14	0.56	1,626.52	14.76
Plate	0.22	1,105.28	11.25	0.38	1,482.00	12.76

In paper [21], authors calculated values of diameters d_1 and d_2 of the two main vortices that comprise spiral-like ECVS of the "whiskers" type in the near-wall region of the examined VC at the appropriate maximum value of the Reynolds number Re. At a distance of 2 mm from the chamber's inner wall d_1=29.18 mm, d_2=10.20 mm; at a distance of 4 mm – d_1=24.48 mm, d_2=21.42 mm. The average, for the near-wall region, values of diameters of the vortex ECVS components are equal to, respectively, $d_{1,a}$=26.83 mm and $d_{2,a}$=15.81 mm. A comparison of magnitudes of diameters of the free vortex cords, given in Table 1, with those specified above indicates the same orders of magnitudes up to the approximate equality. Thus, we have satisfied one of the main requirements for the mutual susceptibility of vortex structures. This fact is predetermined by the common geometrical and kinematical conditions for the formation in the confined space of a nozzle tract of both controlling vortex cords behind the wing and a spiral-like ECVS in the corner areas of the nozzle.

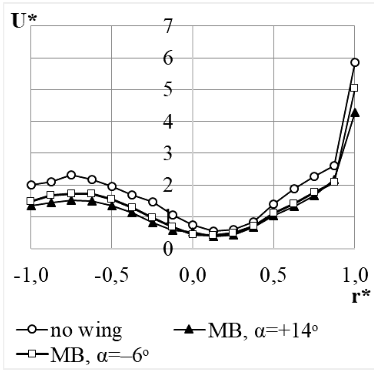
To estimate the effectiveness of controlling influences on ECVS, we used the chamber to measure the actual velocity in the vertical direction of the inlet cross-section of VC, and we separated components averaged by time, as well as pulsation components. This allowed us to calculate relative intensities of pulsations in the presence of a wing vortex generator of the type MB253515 (MB in short) at the boundary continuous angles of attacks and in the absence of a controlling influence. For example, we shall provide the most characteristic dependences at Re=95,000 (Fig. 3, 4). The following designations are used in the diagrams: $r^*=r/r_0$ is the dimensionless radius (r_0 is the inside radius of cylindrical part of VC); $U^*=U/W_a$, $W^*=W/W_a$ are, respectively, dimensionless circular and axial projections of the averaged local velocity (W_a is the average, for the inlet cross-section of VC, value of the flow rate);

$$\varepsilon_u=\sqrt{\overline{u'^2}}/U,\ \ \varepsilon_w=\sqrt{\overline{w'^2}}/W$$

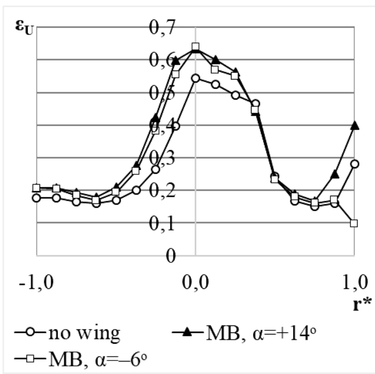
are the local relative intensities of velocity pulsation for separate components (a bar denotes instantaneous pulsation components of the velocity).

Analysis of diagrams reveals the following (Fig. 3, 4). Circular velocities correspond to one rotation direction of the vortex structures at the outlet from the chamber. The growth in the magnitudes of velocity in proportion to approaching the upper cylindrical surface of the chamber (Fig. 3, *a*) indicates the effect of a near-wall region of the spiral-like ECVS in active part of the chamber. Characteristic of the variants "control disabled" and "control enabled", a rising intensity of the pulsations of circular velocity closer to the axis of the chamber (Fig. 3, *b*) reflects a significant offset interaction between the rotating masses of gas and different circular components of velocity in the region of current between quasi-Taylor vortices and the near-axial tornado-like quasi-solid-body vortex [11].

Distribution of axial components of velocity (Fig. 4, *a*) shows the presence of a region of reverse current at the bottom of the chamber ($r^*<0$). This phenomenon is typical of vortex chambers and is explained by the influence of centrifugal force on the flow. For example, in the combustion chambers of gas turbine engines, reverse current regions are used to stabilize the front of flame. Regions of a significant growth in the intensity of pulsations of axial velocity are shifted to $r^*\leq0.5$ and to $r^*>0.75$ at controlling actions. Between the specified regions is a sharp decrease in intensity. This is explained by a complex three-dimensional interaction between flows at dominating circular velocity components over the axial components in the range of $0.5<r^*<0.75$. The region of $r^*>0.75$ demonstrates an obvious impact of the near-wall spiral-like ECVS.

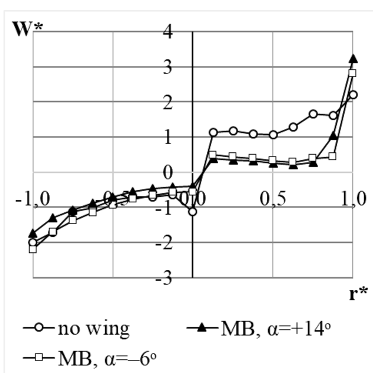


a



b

Fig. 3. Characteristics of flow in the inlet cross-section of VC: *a* – profiles of a circular projection of the averaged velocity; *b* – distribution of pulsation intensity of circular velocity



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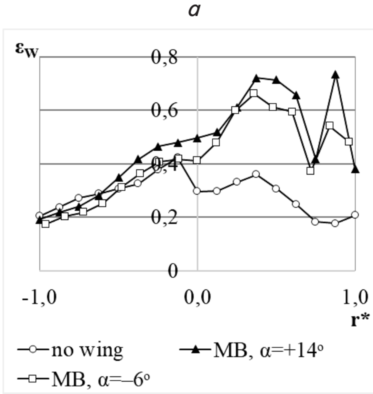
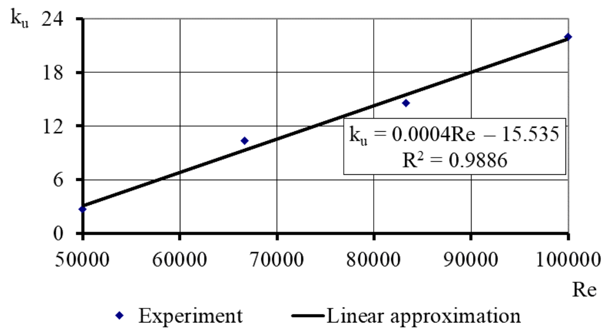


b

Fig. 4. Characteristics of flow in the inlet cross-section of VC: *a* – profiles of an axial projection of the averaged velocity; *b* – distribution of pulsation intensity of axial velocity

Calculations of change in the averaged, for the chamber's cross-section, intensity of pulsations in the presence of controlling actions $\Delta\varepsilon_{u,a}$, $\Delta\varepsilon_{w,a}$ (wing MB253515) relative to the values of $\varepsilon_{u,0}$ and $\varepsilon_{w,0}$ in the absence of control allow us to introduce respective indicators of the impact of a wing vortex generator: $k_u=(\Delta\varepsilon_{u,a}/\varepsilon_{u,0})\cdot 100$ % and $k_w=(\Delta\varepsilon_{w,a}/\varepsilon_{w,0})\cdot 100$ %. Dependences of the respective magnitudes on the Reynolds number of the flow at the inlet to VC nozzle are shown in Fig. 5. As can be seen, the examined points with a rather high accuracy are approximated by linear laws.



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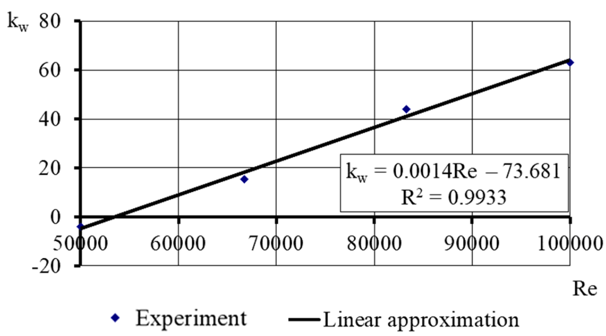

b

Fig. 5. Impact of controlling action of the wing MB253515 on pulsation intensity: *a* – for circular velocity; *b* – for axial velocity

A comparative analysis of change in the VC magnitudes, averaged for the inlet cross-section, $\Delta\varepsilon_{u,a}$ and $\Delta\varepsilon_{w,a}$, at the maximum value of Reynolds number $Re_{\max}$= =95,000, according to Figs 3, 4, shows the following. At a continuous value of the angle of attack of the wing MB253515 at α=14°, a growth of relative intensity of pulsations under control is: for circular velocity – 22 %, for axial velocity – 63 %. At a negative angle of attack of α=–6° the changes are: for circular velocity, +10 %, for axial, +47 %. At the minimum value of the Reynolds number ($Re_{\min}$=55,000) and angle of attack α=14° a change in the module of pulsation intensity for two components does not exceed 5 %.

Experimental determining of pressure loss at work of VC with vortex generators in the nozzle has shown that the maximum relative increase in losses does not exceed 1.7 % compared to the losses in VC without nozzle control over the structure of current. Thus, we have proven the efficiency of application of the proposed generalized principle of mutual susceptibility of vortex structures regarding control over the structure of current in VC.

6. Discussion of results of studying the influence of controlling vortex generators on the structure of current in a vortex chamber

This work is one of the stages in a series of experimental research into rational methods of "subtle" control over the processes of transfer of mass, pulse, and energy in the working environments of vortex chambers. Previous studies [12, 13] and the present work are brought together by the main principle – the concept of mutual susceptibility of vortex structures. Data from Table 4, along with analysis of Fig. 3, 4, prove the possibility of useful application, in order to accomplish the set goal, of traditionally "harmful" trailing vortex cords behind the wings with a small elongation ($1 \leq \lambda \leq 3$), which are installed in the flow-through tract of the inlet nozzle of VC. The "harmful" character is predetermined by a certain loss of the amount of motion for the creation of a pair of vortex cords that cause inductive resistance. At the same time, the use of wings with a small elongation significantly increases critical angles of attack, which, in combination with strict requirements to the state of streamlined wing surface, reduces their profile resistance. To ensure the permanence of the maximum value of lifting coefficient $c_y^{\max}$ over a rather wide range of the Reynolds numbers, the profiles of the examined wings were selected to be relatively thin. This is important because $c_y^{\max}$ significantly affects the criterion of efficiency η when using a wing as the vortex generator. In addition, mounting wing elements of thin profiles in the inlet nozzle of the chamber at continuous angles of attack does not lead to a significant growth in VC drag. It was noted above that the magnitude of additional losses of pressure on VC at the expense of controlling actions does not exceed the relative error of measurement.

It is important to emphasize that dimensions of the cross-section of trailing vortices make up to 30 % of the transverse dimensions of the controlled spiral-like ECVS. Obviously, the determining factors of the sensitivity of a powerful vortex formation in the chamber to the action of controlling vortex cords are the following:

– collinearity of axes of excitation of interacting systems;

– the effect of controlling vortex cords on the initial phase of ECVS formation since the wing's chord is commensurate to the length of a nozzle tract;

– commensurate energy characteristics of the interacting vortices, which are formed by the incoming flow.

As one can see, even the approximate П-shaped wing aerodynamic model, supplemented by experimental data on the rotation frequency of free vortex cords, yields a positive result. The prospects of the proposed method of control are predetermined by that the intensity and energy parameters of trailing wing vortices can be predicted and calculated.

We plan to continue research into variation of the relative span and shape of the wing in plan by conducting spectral and variance analysis of gas pulsating motion. This would make it possible to define the spatial-frequency regions of pulsation energy distribution more accurately both in ECVS and in controlling disturbances in order to improve the proposed method of ECVS control, and, therefore, the mass- and heat exchange processes in industrial installations.

In addition, it is planned to expand the examined range of Reynolds numbers for the parameters of incoming flow Re=55,000÷95,000 at variation of values for the ratio of cross-sectional areas of a flow-through tract of the nozzle and cylindrical part of VC (in this work, the ratio was fixed; it was 0.1).

7. Conclusions

1. We proposed a new method to control energy-intensive coherent vortex structures (ECVS) that define the processes of mass- and heat exchange in vortex chambers. It implies the execution of controlling actions on ECVS by the system of continuous ordered vortex cords that are generated by the fixed wings of a finite span, mounted in the inlet nozzle of the chamber.

2. We performed theoretical estimation of the effectiveness of using a wing as the vortex generator under conditions of a vortex chamber, and obtained an analytical expression for the criterion of efficiency η. It was determined that the greatest influence on its magnitude is produced by the relative wing elongation λ and the lifting strength coefficient c_y.

3. Based on the proposed criterion of efficiency, we selected the optimal wing profile in order to execute subtle control over ECVS, and determined that the most rational is to use wings with a small elongation.

4. The effectiveness of the proposed method to control the structure of flow in VC is proven by an increase in the averaged values of relative intensity of velocity pulsation at the outlet of the chamber from 10 % to 63 % while a growth of the chamber's aerodynamic resistance did not exceed the magnitude of a measurement error.

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