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NUMERICAL AND PHYSICAL MODELING OF TURBULENT FLOW IN A DIVERGENT CHANNEL WITH A VORTEX CELL

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Turbulent flow in a channel with a vortex cell is analyzed numerically and experimentally. The influence of the rotation of a central body in a vortex cell, the viscosity, and the pressure gradient on the local and integral characteristics of the flow is evaluated.

1. Comprehensive investigations of low-velocity air flow in a plane channel with a circular vortex cell undertaken a few years ago using experimental and computational methods represent a component part of the program of basic work in the field of aerohydromechanics and thermal physics; this work involves an analysis of the means of controlling the flow about objects of various purposes with the use of vortex cells built into their contours. The concept of vortex cells appeared as an associative generalization of the idea of control of a turbulent boundary layer on an aircraft (having the shape of a plate with a midsection in the form of a thick profile) of the ÉKIP integrated aerodynamic circuit [1]. Its design was related to the cavities intentionally created on the surface of an object, to the central bodies located within them, and to the organization of distributed or concentrated injection–suction on the washed portions of the vortex cells. Thus, the control circuit of this apparatus provided for the expenditure of energy on implementing it.

The numerical analysis [2] of a simplified model of an elliptically shaped vortex cell with a central body of the same geometry confirmed the necessity of activating the cell, since in the passive version it virtually does not influence the pattern of flow about a thick profile. Conversely, as is shown in [3], introduction of a momentum along the contour of a vortex cell is capable of changing fundamentally the pattern of separating flow above the body in question and of imparting a smooth nonseparating character to it.

It became possible to significantly develop the investigations of flows with vortex cells by adopting the multiblock strategy of numerical modeling of different-scale separating flows based on intersecting structurized grids. One employed such algorithms primarily for analysis of circular vortex cells in the contour of a cylinder in flow in the laminar [4] and turbulent [5] regimes. For the first time the method of intensification of a flow circulating in a cell in the case of suction of a liquid through the surface of the central body was substantiated; this method enabled one to significantly change the pattern of flow about a circular cylinder [5] and a thick profile [6, 7]. One has detected the effect of explosive turbulization of the flow in a vortex cell [7] which, within the framework of the numerical model, implies an abrupt change in the flow pattern and the integral characteristics of a body, including a decrease in the drag and an increase in the lift-drag ratio (aerodynamic quality).

The thorough analysis [8, 9] of the method of control of flow about a thick profile using built-in vortex cells on the basis of employment of the zonal model of turbulence (proposed by Menter and describing wall flows correctly) has shown that a marked circulation occurs in the cells, which is responsible for the effect of increase in the circulation of the thick profile owing to the location of vortex cells within this profile; this effect is known as the effect of supercirculation.

Vortex cells can be activated by rotation of the central body, especially when circularly shaped cell and central body are selected [10]. However in [10] this is used as a means for setting into motion a part of the contour in flow and not for intensifying the vortex flow in a cavity. The influence of the rotation of a central body in a vortex

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cell on laminar and turbulent flow about a circular cylinder in the steady-state regime is analyzed in [11] in detail. In the latter case, a separating plate is used to stabilize the flow in a wake.

To verify the numerical results obtained use was made of the existing experimental data for smooth streamlined bodies since there were no physical experiments for bodies with vortex cells. The two-dimensional and three-dimensional multiblock algorithms have been tested for a plane-parallel channel with a circular cavity on one wall only in [12, 13]; the testing was carried out based on a detailed comparison of numerical and experimental predictions.

This work is a continuation primarily of the cycle of methodological investigations of vortex cells, including those in which the rotation of a central body, the pressure gradient, the Reynolds number, and the size and location of the central body have been taken into account.

2. Physical modeling has been carried out in a wind tunnel of the Institute of Mechanics at Moscow State University; this tunnel represented a modified version (considered in previous investigations [12, 13]) of a plane-parallel channel with a circular vortex cell without a central body.

The working portion of the wind tunnel had the shape of a plane channel of length 0.5 m with a rectangular inlet cross section of height 0.05 m and width 0.08 m. The horizontal walls of the channel (upper and lower) could smoothly deviate by an angle of $\sim 5^{\circ}$, thus allowing flows with the required longitudinal pressure gradient. A base cylindrical cell 0.06 m in diameter whose axis is displaced by 0.015 m relative to the lower-wall surface was built into the lower wall of the channel at a distance of 0.25 m from the channel inlet. The length of the inlet cross section of the cell (distance between the sharp-pointed edges in the plane of the lower channel wall) was 0.052 m. The central rotating body represented a cylinder 0.04 m in diameter whose axis of rotation was located at a distance of 0.0225 m from the surface of the lower wall, which coincided with the position of the center of a vortex in an empty cell [12]. Rotation of the cylinder was ensured by an electric micromotor whose number of revolutions could smoothly vary up to 17,000 per minute. The velocity of the flow at the inlet to the channel varied in the range 15–35 m/sec, which corresponded to Reynolds numbers of $6 \cdot 10^4$ to $1.35 \cdot 10^5$ calculated from the distance between the edges of the cell.

The initial stage of investigations involved only obtaining the static-pressure distributions along the longitudinal axis of the channel and along the contour of the cell. The static pressure and the operating parameters of the tunnel (total and static pressures in the inlet cross section of the channel) were measured using Honeywell differential transducers of the corresponding ranges; the measurement error of the transducers was $\pm 0.25\%$. We selected atmospheric pressure or the static pressure at the inlet cross section of the channel as the bearing pressure in the experiments. Drainage holes located throughout the length of the lower wall (23 points) and uniformly along the contour of the cell (25 points) were connected to the transducer using a 48-channel automatic pneumatic commutator of the Central Aerohydrodynamics Institute.

For the convenience of presentation of the results of the numerical and physical experiments we introduce a coordinate system whose x axis is directed streamwise and whose origin of coordinates coincides with the leading edge of the cell.

We have obtained the distributions of the pressure coefficient $c_p = (p - p_{\mathrm{a}})/q_1$ along the length for a plane channel and a divergent channel with an angle of opening of 5° (angle of deviation of the upper wall). The longitudinal coordinate x beyond the cell is referred to the length of its inlet cross section (distance between the edges), while the coordinate x inside the cell is referred to the length of its contour (arc of the circle is 240°).

The vortex cell without a central body (one usually calls it a passive cell) virtually does not influence the flow in a channel in the case of both negative and positive longitudinal gradients of pressure. The additional resistance introduced by such a cell is demonstrated by a slight increase in the pressure in the channel in front of the cell.

In the experiments with an active vortex cell, the diameter of the rotating internal cylinder was selected in such a manner that the cylinder caught nearly 2/3 of the mixing layer located lower than the plane of the edges of the cell. By changing the flow velocity U at the inlet to the channel and the rotational velocity of the cylinder we could obtain different values of the swirl parameter that is equal to the ratio of the linear rotational velocity of the cylinder v to the velocity of the flow in the channel U; in the experiments, the values of this ratio were ~ 0.7 and ~ 1.7.

3. Turbulent flow of an incompressible viscous fluid in a plane channel in the presence of a circular vortex cell and in the absence of it has been modeled numerically for a plane-parallel channel and a divergent channel (with an angle of opening of 5°) with a rotating central body of basic (Fig, 1a) and modified (Fig. 1b) layouts. The latter case is distinguished by a much smaller diameter (0.64 against 0.77 in the basic version) and a smaller shift of its axis

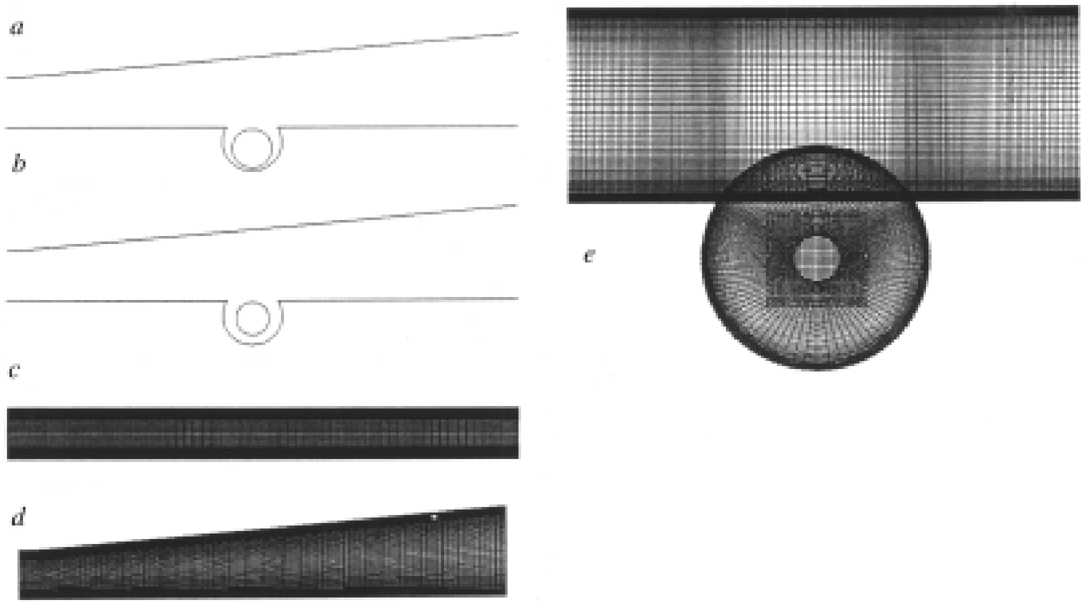

Fig. 1. Configurations of divergent channels with rotating central bodies (basic version (a) and modified version (b)) in a circular cell, narrow computational grids in a plane-parallel channel (c) and a divergent channel (d), and the fragment of a multiblock grid in a plane-parallel channel with a vortex cell (e).

relative to the center of the cavity (0.1 against 0.23). Nearly the same position of the cylinders relative to a mixing layer which develops in a circular cavity is selected. The main feature of the modified version is in selecting a position of the axis of rotation of the central body at which the cross section of the channel between the cell wall and the central body remains constant, in practice, whereas in the basic version it changes substantially.

The original application package is used as a computational tool to calculate turbulent flows in multiply connected regions within the framework of multiblock technology. The implicit factorized algorithm of solution of two-dimensional steady-state Reynolds equations which are closed using the two-parameter dissipative model of Menter is based on the concept of splitting by physical processes. The SIMPLEC procedure of pressure correction, representation of the equations in increments in dependent variables, approximation of convective terms on the explicit side of the equations of motion according to Leonard's quadratic upwind scheme and of the equations of transfer of turbulence characteristics according to the TVD scheme, introduction of additional diffusion with a transfer coefficient equal to a product of the reciprocal of the Reynolds number and the OTL coefficient (it is usually selected to be more than 1), and solution of algebraic difference equations by the method of incomplete matrix factorization are the characteristic features of the discrete model. Selection of a centered computational template which is the most acceptable for construction of an economical computational procedure of solution of the initial equations in generalized curvilinear coordinates leads to the necessity of using a pressure regularizer related to the matching of the pressure and velocity fields. As has been established by numerous test experiments, for the correction introduced the coefficient is selected to be 0.1 The Menter turbulence model is modified with account taken of the influence of the curvature of streamlines on the characteristics of turbulence within the framework of the approach described in [14]. In determining the pressure correction, the method of additive correction is used to accelerate the convergence of the iterative process. The parameters in the regions of intersection of subregions are determined by the method of nonconservative linear interpolation. The details of the algorithm are presented in [12, 14, 15].

The channel width in the inlet cross section and the velocity U are selected as dimensionless scales.

The channel turbulent flows are calculated in the range of variation of the Reynolds number from 10^4 to $1.35 \cdot 10^5$. The thickness of the boundary layer at the inlet to the channel is selected to be 0.01, the OTL parameter is selected to be 2, and the coefficients of relaxation are selected to be 0.5 in velocity, 0.25 in turbulence characteristics, and 0.25 in vortex viscosity. The characteristics of turbulence in the core of a uniform incoming flow at the inlet to the region are selected to correspond to the parameters of turbulence in the experimental setup (degree of turbulence

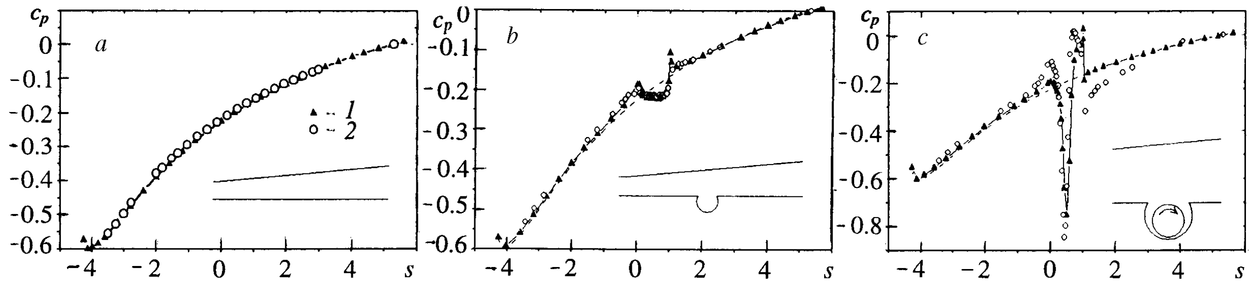

Fig. 2. Distribution of the pressure coefficient along the contour of the lower wall of a divergent channel: without a vortex cell (a) and with a passive vortex cell (b) at Re = $1.35 \cdot 10^5$ and with an active vortex cell in the basic version (c) at Re = $6 \cdot 10^4$: 1) calculated results; 2) experimental data; dashed curve, data for the divergent channel without a cell.

TABLE 1. Comparison of the Coefficients of Resistance of the Channel in the Presence of Vortex Cells and in the Absence of Them at Re = $6 \cdot 10^4$

Type of channel	$C_{x\ \mathrm{upp.w}}$	$C_{x\ \mathrm{lower\ w}}$	$C_{x\mathrm{v.c}}$
Smooth	–0.325	0.024	0
Basic version with a passive cell	–0.326	0.026	0.004
Basic version with an active cell	–0.322	0.032	0.009
Modified version with a passive cell	–0.322	0.026	0.004
Modified version with an active cell	–0.318	0.019	–0.005

is equal to 1.5%). "Soft" boundary conditions typical of solution of problems of this kind are specified at the outlet from the channel.

Figure 1c–e demonstrates some of the computational grids used in this work. The algebraic grid in a channel of constant or variable cross section which is adapted to channel walls contains 250 cells with a wall step of the grid of 0.001 along the longitudinal coordinate and from 60 to 100 cells along the transverse coordinate. The circular cavity is covered by an annular computational grid (mounted into the lower channel wall similarly to the vortex cell itself) (Fig. 1e). Along the window we select 41 nodes arranged with bunching in the region of a sharp-pointed edge; the step size near the edge is equal to 10^{-2}. It should be noted that in [12, 13] we selected a grid uniform along the circumferential coordinate, which degraded somewhat the quality of numerical solution in the vicinity of the sharp-pointed edges.

In the case of absence of a central body in a cavity we introduce a quasicentral body 0.2 in diameter with subdivision of the annular gap into 61 nodes arranged with bunching at the cavity wall (size of the wall step is 10^{-3} while the step at the quasicentral body is 8×10^{-3}). The zone of the quasicentral body is covered by a uniform rectangular grid (with a 0.5×0.5 region) containing 30×30 cells.

When a rotating central body is placed in the circular cavity the annular computational grid retains the same number of cells but the size of the wall step is selected to be 10^{-3} at the cavity wall and 8×10^{-4} at the central body.

4. Figures 2–4 and Table 1 present some of the results obtained.

The results given in Fig. 2 have a clear methodological character and are related primarily to the methodological aspects of numerical investigation, in particular, to verification of the multiblock computational algorithm and evaluation of the acceptability of the model of plane turbulent flow for description of three-dimensional, in essence, channel flow.

Good agreement between the calculated and experimental distributions of the pressure coefficient along the lower wall of the divergent (with an angle of opening of 5^o) channel demonstrates primarily the acceptability of the low-Reynolds zonal model of Menter for analysis of a turbulent low-velocity air flow with a pressure gradient (Fig. 2a).

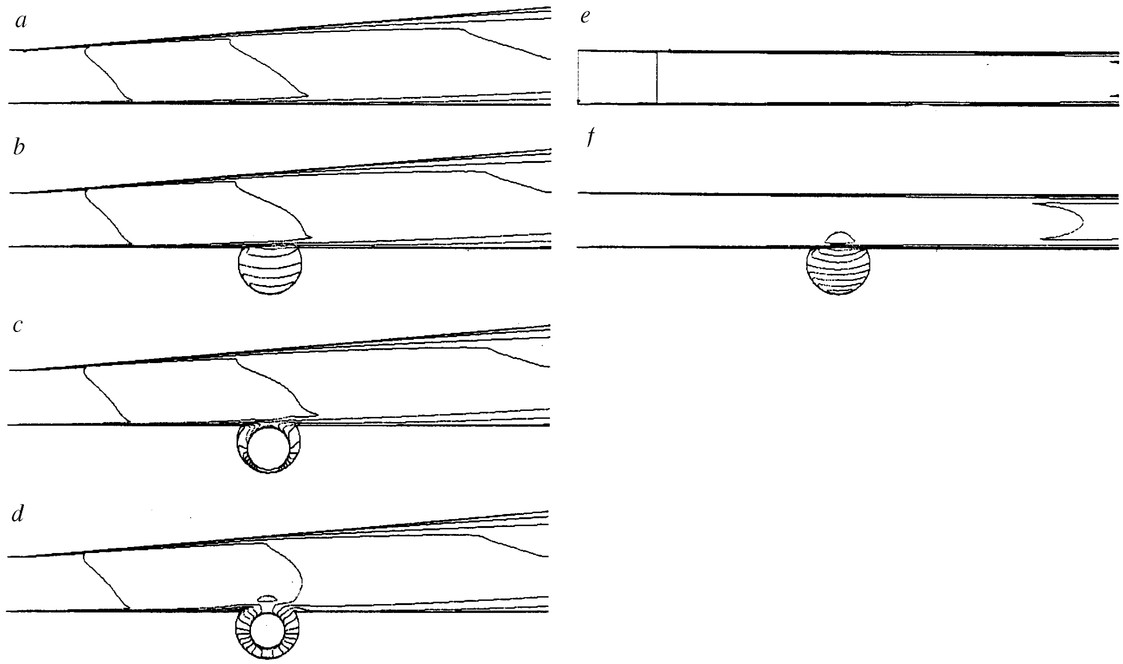

Fig. 3. Fields of isolines of the longitudinal velocity component, applied with a step of 0.15 in the positive region of variation of the quantities and with a step of 0.1 in the negative region, for turbulent flow in a divergent channel (a), in a divergent channel with a circular vortex cell without a central body (b), in a divergent channel with a vortex cell of basic (c) and modified (d) geometries, in a plane-parallel channel (e), and in a plane-parallel channel with a circular vortex cell (f). $Re = 1.35 \cdot 10^5$.

Quite a satisfactory agreement between the distributions of the pressure coefficient in the case of turbulent flow in a divergent channel with a circular cavity and in a plane-parallel channel with a cavity [12, 13] confirms the assumption of the two-dimensional character of flow in a channel with a circular cavity for a relative channel width of 1.6 (Fig. 2b).

In the basic version, the case of activation of a vortex cell by rotation of the central body (with a tangential component of the velocity on the surface equal to 1.7) located in the circular cavity, the calculated and experimental distributions of the pressure coefficient over the lower contour of the channel with a cell are quite similar in character, although one can observe appreciable differences in c_p in the vicinity of the cavity (Fig. 2c). It is possible that the rotation of the central body causes changes in the structure of the vortex flow near the lateral channel walls which in turn influence the character of motion of the fluid in the middle plane of the channel. Nonetheless, the agreement between the experimental and calculated results of this investigation seems quite satisfactory, which provides the basis for the conclusion on the adequacy of the developed numerical model to its physical analog.

As is seen from Fig. 2, the rotation of the central body leads to a significant redistribution of the pressure along the contour of the circular cavity with doubling of the maximum of the pressure coefficient in the vicinity of the trailing (far downstream) sharp-pointed edge and to an almost fourfold increase in the rarefaction in the bottom part of the cavity, namely, in the zone of the least flow area of the vortex cell. Activation of the vortex cell also contributes to a change in the distributions of the pressure over the channel wall in the vicinity of the circular cavity: to its substantial increase in front of the cavity and a very strong rarefaction behind it, which can demonstrate additional vortex formations in a wake behind the cavity that, as has already been indicated, can have a three-dimensional character.

Figure 3 combines calculated results for two types of channels in the presence of active and passive vortex cells of different types. The degree to which the presence of a circular cavity and of activation of a vortex cell exerts an influence on the pattern of vortex flow in the channel is of greatest interest.

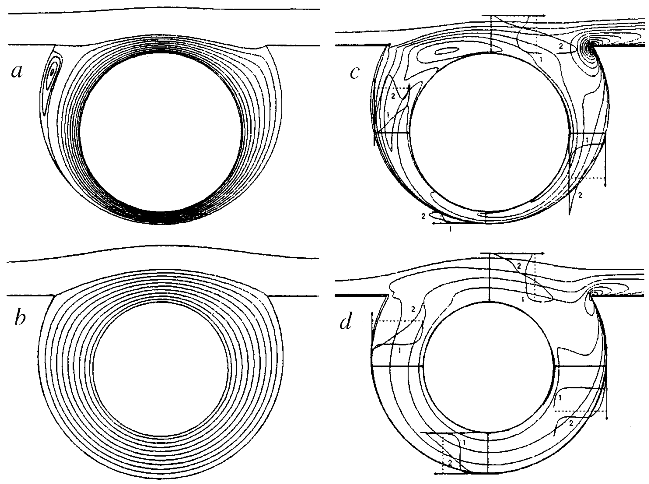

Fig. 4. Patterns of vortex flow in active vortex cells of basic (a) and modified (b) geometries in a divergent channel and the fields of isolines of turbulent-pulsation energies drawn with a step of 0.003 for the same layouts ((c) and (d) respectively); in c and d, the profiles of the modulus of velocity (1) and turbulence energy (2) in several cross sections of the vortex cells are applied; the dashed line shows the unit level of velocity and the level of 0.1 for turbulence energy. $Re = 1.35 \cdot 10^5$.

Comparative analysis of the pictures of isolines of the longitudinal velocity component demonstrates that the location on the lower wall in the divergent channel of the circular cavity (Fig. 3a and b) has no appreciable affect on the deformation of the velocity field even in the vicinity of the lower channel wall. In this respect, the situation is quite similar to that observed in the plane-parallel channel (Fig. 3e and f).

Turbulent flow in the channel with a positive pressure gradient is retarded, losing velocity as the channel length increases. At the same time, in the plane-parallel channel of the length in question the velocity profile is not changed substantially. As a consequence, in the case of location on the lower wall of a circular cavity motions within the cavity differ in intensity. Clearly, in the case of a divergent channel circulation flow in the cavity turns out to be attenuated.

It is of interest to compare the largest values of the longitudinal velocity component in a circular cavity in the case of zero and nonzero pressure gradients in the channels, i.e., $u_m = -0.44$ and -0.3 respectively. In the physical experiment on a setup with overflow of the boundary layer, i.e., when nearly design conditions are realized in the incoming flow in a plane-parallel channel, $u_m = -0.43$ [7], which demonstrates quite an acceptable agreement between the numerical and experimental predictions and hence the high degree of adequacy of the computational model for description of separating turbulent flow.

Let us give some considerations on construction of vortex cells in the context of their testing in channel flows. The initial premise of the location of a rotating cylinder in the space of a circular cavity, tying it to the developing shearing layer, turns out to be not the only one and, as is seen from Fig. 3e and d, far short of the most substantial. Certainly, as demonstrated by the experience of control of flow about bodies using built-in vortex cells with the example of a circular cylinder and a thick profile, the global aspect of the problem is the most important: the action on the flow on a small scale is reproduced to the large-scale motion of the medium, leading to significant structural rearrangements, in particular, to a decrease in the dimensions (up to elimination) of the separation zone in a wake and as a consequence to a reduction in the drag. In the considered case of motion of the fluid in a plane channel one can hardly expect such global structural changes. Therefore, being engaged in comparative analysis of different versions of vortex cells on a channel wall, one must take into account primarily the positive tendencies in the character of turbulent flow in the channel, in particular, the high degree of filling of the velocity profile and the attainment of a smaller loss in motion of the fluid in the channel.

In this work, we test two versions of vortex cells which differ in the laws of change of the cross-sectional area of the internal channel. The basic version characterized by a sharp narrowing of the channel at the bottom of the cavity is set off against the modified version with approximately the same gap between the rotating cylinder and the cavity wall. As is seen from Fig. 3c and d, the first version of the cell even in the case of expenditure of energy on rotating the central body has no appreciable effect on the pattern of flow in a divergent channel. Conversely, the modified version looks somewhat more preferable, although if we take note of the flow along the upper deflected wall the action of the active vortex cell has no effect on it, in practice.

The difference in the motion of the fluid within the vortex cells in question is analyzed in Fig. 4 in greater detail. Certainly, for a specified tangential velocity of 1.7 on the rotating cylinder the intensity of circulation motion inside the cell is high. The model of the so-called "rolling" vortex is realized; this vortex introduces a momentum into the wall layers of channel flow, making them high-head. It is easily seen that despite the decrease in the diameter of the rotating cylinder, passage to the annular channel with a nearly constant cross section leads to a more intense circulation flow in the vortex cell. This is demonstrated by the nonseparating character of turbulent flow inside the modified cell (Fig. 4b) and by the more convex shape of the streamline separating the circulation zone from the channel flow.

It is well known [7, 11] that a vortex cell is a powerful generator of turbulence. It should be emphasized that in the cases in question the generation levels of turbulence within the active cell differ by more than two times; for the basic version the high energy level of turbulence corresponds to a significant drag of the cell.

The results of the analysis of the resistance to the motion of the fluid in a divergent channel which are given in Table 1 make it possible to evaluate the efficiency of vortex cells built into the lower wall. Noteworthy is the above-mentioned circumstance that passive cells of different layout virtually exert no influence on the motion of the fluid in the channel and consequently on its resistance. However in activation of vortex cells one observes a significant difference in their efficiency based on the criterion of low drag. Whereas for the basic version the resistance of the lower channel wall substantially increases in relation to a smooth channel, in the modified version its resistance decreases by approximately 30%; the intrinsic resistance of the vortex cell turns out to be negative. The influence of the vortex cell on the resistance of the upper wall of the divergent channel seems insignificant, although it is present in the modified version.

The investigation performed stimulates a search for rational versions of activation of vortex cells, including those based on the criterion of minimum energy expenditure on implementing it.

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NOTATION

x, longitudinal coordinate; s, coordinate along the contour of the lower channel wall; p, pressure; p_a, atmospheric pressure; q_1, velocity head at the inlet to the channel; c_p, pressure coefficient; u, longitudinal component of the velocity; U, velocity in the uniform core of the incoming flow; C_x, drag coefficient; Re, Reynolds number. Subscripts: m, minimum value; lower w, lower wall; upp.w, upper wall; v.c, vortex cell; a, atmospheric.

REFERENCES

1. L. N. Shchukin, *Grazhd. Aviats.*, No. 6, 11–15 (1993).
2. S. A. Isaev, Yu. S. Prigorodov, and A. G. Sudakov, *Inzh.-Fiz. Zh.*, **71**, No. 6, 1116–1120 (1998).
3. P. A. Baranov, S. A. Isaev, Yu. S. Prigorodov, et al., *Izv. Vyssh. Uchebn. Zaved., Aviats. Tekh.*, No. 3, 30–35 (1999).
4. P. A. Baranov, S. A. Isaev, Yu. S. Prigorodov, et al., *Pis'ma Zh. Tekh. Fiz.*, **24**, Issue 8, 33–41 (1998).
5. P. A. Baranov, S. A. Isaev, and Yu. S. Prigorodov, *Pis'ma Zh. Tekh. Fiz.*, **24**, Issue 17, 16–23 (1998).
6. P. A. Baranov, S. A. Isaev, Yu. S. Prigorodov, et al., *Inzh.-Fiz. Zh.*, **72**, No. 3, 568–571 (1999).
7. P. A. Baranov, S. A. Isaev, Yu. S. Prigorodov, et al., *Inzh.-Fiz. Zh.*, **73**, No. 4, 719–727 (2000).
8. P. A. Baranov, S. A. Isaev, Yu. S. Prigorodov, et al., in: *Proc. IXth Int. Symp. "Methods of Discrete Singularities in Problems of Mathematical Physics (MDSPMPh-2000)"* [in Russian], Orel (2000), pp. 65–68.

9. S. A. Isaev, A. G. Sudakov, P. A. Baranov, et al., *Dokl. Ross. Akad. Nauk*, **377**, No. 2, 1–3 (2001).
10. V. J. Modi, M. S. U. K. Fernando, and T. Yokomizo, *AIAA J.*, **29**, No. 9, 1400–1406 (1991).
11. S. A. Isaev, Yu. S. Prigorodov, and A. G. Sudakov, *Izv. Ross. Akad. Nauk, Mekh. Zhidk. Gaza*, No. 4, 88–96 (2000).
12. S. A. Isaev, S. V. Guvernyuk, M. A. Zubin, et al., *Inzh.-Fiz. Zh.*, **73**, No. 2, 220–227 (2000).
13. P. A. Baranov, S. V. Guvernyuk, M. A. Zubin, et al., *Izv. Ross. Akad. Nauk, Mekh. Zhidk. Gaza*, No. 5, 44–56 (2000).
14. I. A. Belov, S. A. Isaev, and V. A. Korobkov, *Problems and Methods of Calculation of Separating Flows of Incompressible Fluids* [in Russian], Leningrad (1989).
15. S. A. Isaev, A. I. Leont'ev, P. A. Baranov, et al., *Inzh.-Fiz. Zh.*, **74**, No. 2, 62–67 (2001).