Journal of Engineering Physics and Thermophysics, Vol. 76, No. 6, 2003

NUMERICAL ANALYSIS OF THE INFLUENCE OF THE SHAPE OF THE VORTEX CELLS BUILT INTO A CIRCULAR CYLINDER ON A STEADY TURBULENT FLOW AROUND IT

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UDC 532:517.4

On the basis of numerical modeling of a steady two-dimensional turbulent flow around a circular cylinder with built-in vortex cells having smoothed edges, in the near wake behind which a separating plate is positioned, we have analyzed the efficiency of the active method of control of the flow by means of distributed suction from the surface of the central bodies located in the cells.

Introduction. Complex investigations of a subsonic flow around various objects with vortex cells built into their contour, carried out several years ago with the use of experimental and computational methods, are a part of the program of fundamental research in the field of aerohydromechanics and thermal physics devoted to analysis of a new method of control of the flow separation [1]. The conception of vortex cells has historically been developed on the basis of the generalization of the idea of control of the turbulent boundary layer on an ÉKIP-type aircraft of integral aerodynamic arrangement, shaped as a plate with a midsection in the form of a thick profile [2]. An embodiment of this idea is associated with cavities made deliberately on the surface of an object, central bodies located in them, and blow-suction organized on the parts of the contour of the vortex cells, around which flow flows. Thus, this method of control of the flow around such an apparatus requires an expenditure of energy for its realization.

A numerical analysis of a simplified model of a vortex cell shaped as an ellipse with a central body of a similar geometry, performed in [3], has shown that the flow circulating within the cell should be intensified, because the motion in a passive cell is very weak and practically has no effect on the pattern of a laminar flow around a thick profile. On the contrary, the introduction of a pulse along the contour of a vortex cell, as is shown in [4], can dramatically change the pattern of a separation flow around a profile and transform it into a streamline flow without separation.

The development of the multiblock strategy of numerical modeling of different-scale separation flows on the basis of intersecting structured grids has played an important part in the study of flow around bodies with vortex cells. Multiblock algorithms were developed and tested first of all for analysis of the operation of circular vortex cells built into the contour of a cylinder in the laminar [5] and turbulent [6] regimes of flow around it. It has been demonstrated that intensification of the flow circulating in a vortex cell built into the contour of a circular cylinder [6] or a thick profile [7, 8] by suction from the surface of central bodies located in it substantially changes the pattern of the flow around them and in doing so brings about, in the latter case, the formation of a flow without separation. The effect of explosive turbulization of the flow in a cell, leading to an abrupt change in the vortex structure and the integral characteristics of the body, including a decrease in the drag and an increase in the lift-to-drag ratio, has been revealed within the framework of the numerical model of flow around a circular cylinder [8].

A flow in circular vortex cells can be also intensified by rotation of the central cylindrical bodies positioned in them [9–11]. For example, in [11] the influence of rotation of the central body in a circular vortex cell built into a circular cylinder on steady laminar and turbulent flows around it has been analyzed in detail. In the latter case, a separating plate was positioned in the near wake behind the cylinder for stabilization of the flow. It should be noted

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Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 76, No. 6, pp. 38–44, November–December, 2003. Original article submitted February 27, 2003.

1062-0125/03/7606-1238$25.00

that with increase in the diameter of the central body, this method for control of flow reduces, in the limit, to the known method of action on the near-wall, low-head layers of fluid by means of movement of the part of a contour, around which flow flows, with a constant velocity [1].

The numerical results obtained within the framework of the multiblock algorithm were verified using the data of special physical experiments conducted in plane-parallel and widening channels with a circular cavity on one of the walls, including the case where a rotating cylinder was positioned in the cavity [12, 13]. Menter's low-Reynolds zonal model of shear-stress transfer has been much tested in a cycle of methodical investigations [14]. The influence of the rate of rotation of the cylindrical bodies within vortex cells, the velocity of suction from their surface, the pressure gradients, the Reynolds number, and the dimension and position of the central body on the flow around the body studied has been analyzed in detail.

As discussed above, the choice of the vortex-cell shape in the investigations carried out was in many respects accidental and determined by the simplicity of the geometry (ellipse) of the contour rather than for hydrodynamic reasons. Because of this, a cell adjoint to the surface around which flow flows had sharp edges. At the same time, an analysis of the geometric shapes of cavities for trapped vortices on the surface of a profile (see, e.g., [15]) points to the importance of smoothing of the cavity edges, especially in the case where they are positioned downstream of the flow. Therefore, the present work is oriented largely to the study of the influence of the shape of a vortex cell built into the contour of the test body — a circular cylinder — on a steady turbulent flow around it in the case of intensification of the flow circulating within the cell by means of suction from the surface of the central cylindrical body located in it with allowance for the additional drag of the cylinder arising due to the expenditure of energy for realization of control of flow by the method selected.

Formulation of the Problem. The problem on a steady two-dimensional turbulent flow of an incompressible viscous fluid around a circular cylinder with vortex cells is solved using a mathematical model based on a system of Reynolds equations. It is assumed that the flow is symmetric about the geometric plane of symmetry, which corresponds to the physical analog of flow around the cylinder in the case where a separating plate is positioned in the near wake behind it.

In the present work, the calculations were done using a model of shear-stress transfer [14] modified with allowance for the influence of the curvature of the lines of flow on the characteristics of turbulence within the framework of the approach of [16]. The additional semiempirical constant in the correcting linear dependence on the turbulent Richardson number (equal to 0.1) has been determined on the basis of a large number of numerical experiments.

The velocity of the incoming flow U_∞ and the diameter of the cylinder d are taken as the dimensionless scales.

Computational Method. The computational multiblock algorithm used is based on the procedure of global iterations, which has been developed for solving transfer equations by the finite-volume method on structurized intersecting ○-type grids. For each computational cell, the system of initial equations is written in the delta form in curvilinear coordinates, consistent with the boundaries of the computational region, relative to the increments of dependent variables, including the Cartesian velocity components. After linearization, the system of initial equations is solved using the SIMPLEC-type finite-difference procedure of pressure correction [16], which is based on the concept of splitting by physical processes and is written in the E-factor representation. To decrease the influence of numerical diffusion in calculations of flows with organized flow separation, which are very sensitive to errors in the approximation of the convective terms, the upwind scheme with quadratic interpolation is used in the explicit side of the transfer equations [16]. The discretization of the convective terms of the transfer equations of the turbulence characteristics was performed by the above-mentioned scheme [16] and by the scheme representing a variation of the TVD scheme [17]. At the same time, to avoid false oscillations in the reproduction of flows with thin shear layers, the mechanism of artificial diffusion was used in the implicit side of the equations in combination with upwind unilateral schemes for representation of convective terms. And to eliminate the nonmonotonicity of the pressure field in the discretization of the pressure gradient by the central-difference scheme on a centered template, a monotonizer [16] with an empirical cofactor, determined in the numerical experiments on flow of an incompressible viscous fluid around a cylinder and a sphere and equal to 0.1, was introduced into the block of pressure correction. High efficiency of the computational

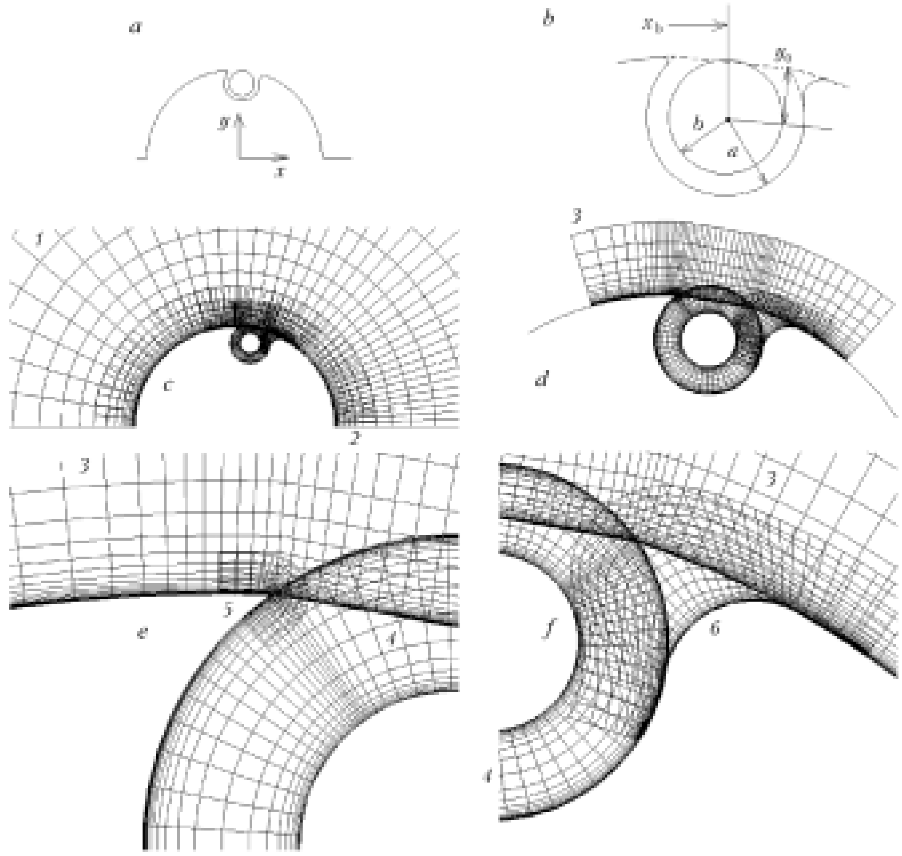

Fig. 1. Schematic of a cylinder with vortex cells (a), configuration of a vortex cell (b), and fragment of a multiblock, two-stage computational grid near the cylinder with a vortex cell (c) with embedded grids for the cell itself (d) and for the neighborhood of its left (e) and right (f) edges: 1) external grid, 2) grid adjacent to the cylinder, 3) grid covering the cell, 4) grid in the ring space between the contour of the vortex cell and the central body, and 5, 6) curvilinear grids adjacent to the rounded sharp edges.

procedure for solving discrete algebraic equations is insured by the use of the method of incomplete matrix factorization [16].

The computational procedure also includes an interpolation block for determining the dependent variables in the zones of overlapping of the subregions. It is based on the "method of linear nonconservative interpolation" [18].

Computational Grids. The problem was numerically solved assuming that the flow is symmetric about the geometric plane of symmetry (Fig. 1a), which makes it possible to reduce the computational region to the upper half-plane. A circular vortex cell of radius a with a center determined by coordinates x_b and y_0 is built into the contour of the cylinder (Fig. 1b). A central cylindrical body of radius b is positioned in the cell. The value of $x_b = 0.05$ was used in the calculations.

Figure 1 shows the computational grids constructed near the cylinder with a vortex cell having rounded edges, in the near wake behind which a separating plate is positioned. The radii of rounding of the leading and trailing edges are different. The trailing edge is smoothed to a greater extent. It is evident that the problem of generating computational grids is more complex in this case as compared to the problem of [11] because of the larger number of subregions considered.

To increase the resolution of different-scale structural elements, in the surface layer of thickness 0.1 we constructed an internal ring grid containing 30×120 meshes positioned with a near-wall pitch of 0.0001, a minimum pitch of 0.01 near the edges of the cell, and a pitch of 0.02 and 0.01 near the front and back critical points, respec-

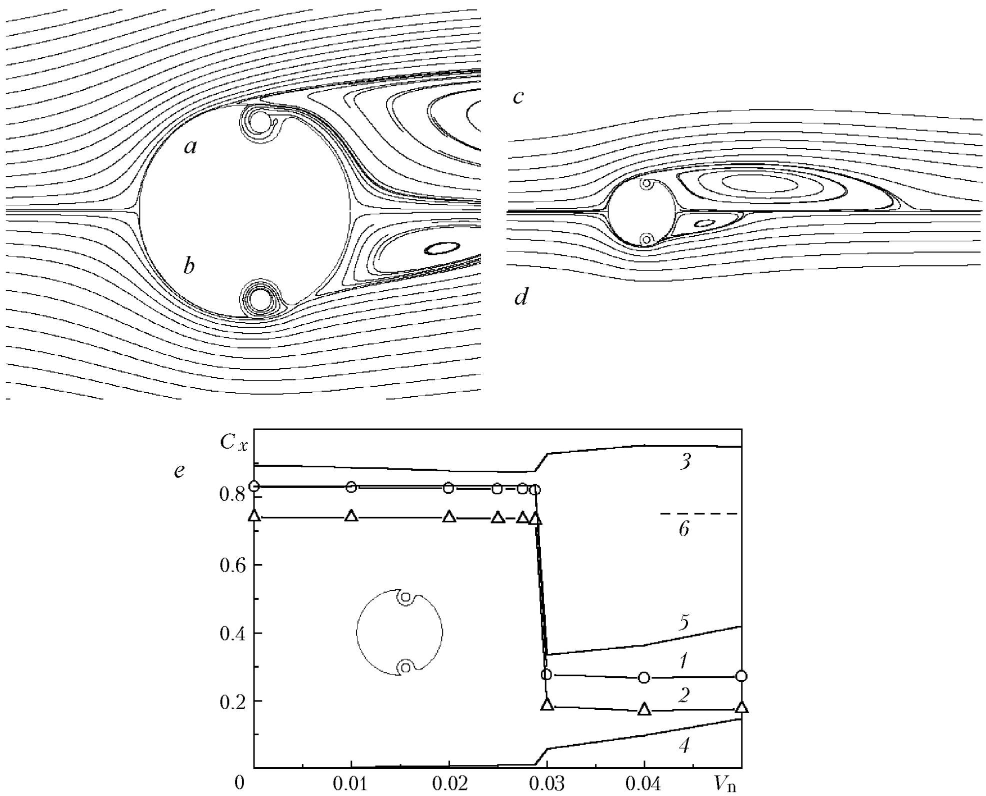

Fig. 2. Pattern of the flow around the cylinder with a vortex cell in the subcritical regime for different velocities of suction: a, c) V_n = 0.0289; b, d) V_n = 0.03; e) dependences of the drag of the cylinder and its components on the velocity of suction V_n [1, 2) coefficients of motion drag and profile drag; 3) friction coefficient (increased by a factor of 10), 4) additional drag coefficient estimated by the expenditure of energy for suction, 5) total drag (with account for the expenditure of energy), and 6) experimental data of Roshko for the smooth cylinder with a separating plate [19], dashed line].

tively. The outer ring is divided into two subregions extending to 3 and 35 along the radial coordinate and containing 30×80 and 20×80 meshes, respectively. In the first subregion, the minimum pitch is 0.2 in the radial direction and 0.02 in the peripheral direction (on the contour of the cylinder).

The computational grid covering the vortex cell is divided into three regions relative to the position of the sharp edges representing the points of intersection of the contours of the circular cell and the cylinder. The region positioned on the left of the leading edge has a length of 0.1, and the region positioned on the right of the trailing sharp edge has a length of 0.15. The thickness of the layer is 0.07 and the number of meshes is 30 along the vertical and 25 upstream and downstream of the edge. The grid pitch is 0.0001 near the wall and 0.001 near the edges.

The angular coordinate of the center of the window of the cell is 100°. The length of the window along the contour is 0.143 with 40 meshes.

The center of the vortex cell of radius a = 0.1 is displaced relative to the line passing through the sharp edges by a distance y_0/a = 0.7. The contour is divided into two parts that bear against the lower and upper semicircles connecting the sharp edges. The lower semicircle contains 50 meshes positioned with a maximum pitch of 0.007, and the upper semicircle contains 20 meshes positioned with a maximum pitch of 0.0051. The edge pitch is equal to 0.002. Forty meshes are positioned with a minimum pitch of 0.0001 in the radial direction. The center of the cylindrical body of radius 0.5a coincides with the center of the circular cell.

The left edge is covered by a curvilinear grid that is divided into three regions: linear, from the edge of the cell outward (of length 0.015, 15 meshes); along the radius of rounding of the edge (of length 0.001, 8 meshes); and

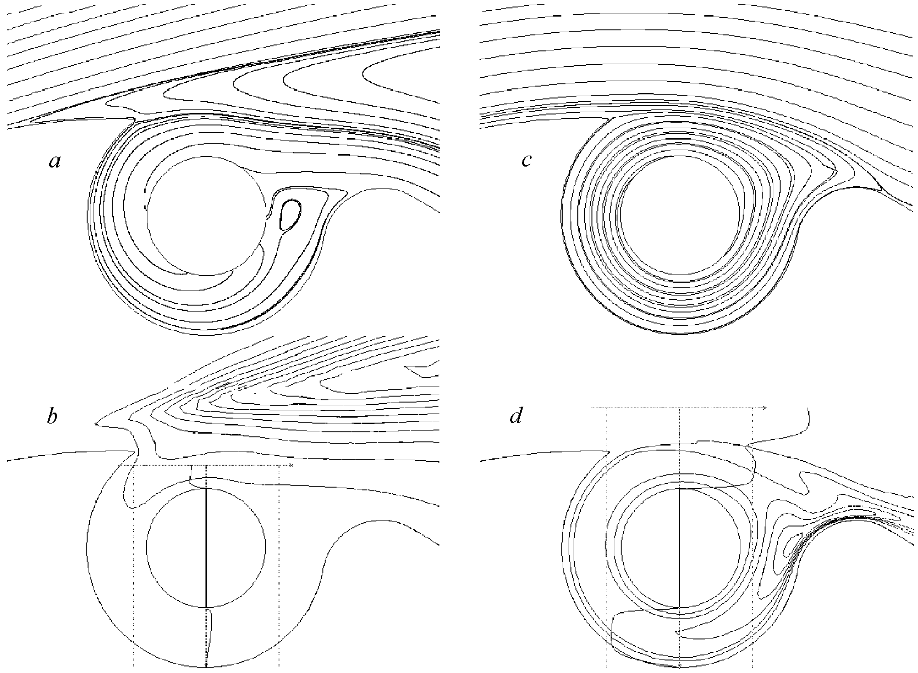

Fig. 3. Patterns of the flow in the vortex cell (a, c) and the isolines (b, d) of the kinetic energy of turbulent pulsations (drawn with a step of 0.05) with plotted profiles of the longitudinal velocity component (the dashed line shows single levels) for two velocities of suction: 0.0288 (a, b) and 0.03 (c, d).

linear, from the edge of the cell inward (of length 0.0101, 12 meshes). A grid of thickness 0.0075, containing 15 meshes positioned with a near-wall pitch of 0.0001, is constructed along the normal to the contour.

The curvilinear grid covering the right edge is also divided into three regions: linear, from the edge of the cell outward (of length 0.0502, 15 meshes); along the radius of rounding of the edge (of length 0.05, 20 meshes), and linear from the edge of the cell inward (of length 0.0401, 12 meshes). A grid having a thickness of 0.0401 at the edges and 0.0701 at the center and containing 35 meshes positioned with a near-wall pitch of 0.0001 is constructed along the normal to the contour.

Boundary Conditions. The velocity of uniform distributed suction from the surface of the central bodies V_n is expressed in fractions of the velocity of the incoming flow U_∞. The flow coefficient c_q is determined.

The parameters of an undisturbed flow are prescribed at the inlet of the outer boundary. The characteristics of turbulence are formulated just as in [6, 8, 11, 16] and correspond to the conditions of physical experiments. Thus, the turbulence energy at the inlet boundary k_∞ corresponds to the degree of turbulence of the incoming flow (Tu_∞ = 1.5%), and the scale of turbulence L_∞ is of the order of d.

The soft boundary conditions (the conditions of continuation of solution) are set at the outlet of the outer boundary. The symmetry conditions are set in the symmetry plane, and the adhesion conditions are set on the surface of the body, including the contour of the vortex cell.

Results and Discussion. A subcritical turbulent flow around the body is calculated within the framework of the stationary model at Re = $1.45 \cdot 10^4$ [11–13].

The additional drag arising as a result of suction from the surface of the central body is determined by the power necessary to maintain the fluid flow rate through the central body by analogy with the approach used in [11] for estimating the additional drag of a cylinder with rotating small-diameter cylinders built into its contour. For the case where two cells are positioned on the cylinder, we obtain

$$C_{x\mathrm{add}} = 2\, N_q \Big/ \left(\frac{1}{2} \rho U_\infty^3 d \right) = 4 p_{\mathrm{m}} c_q \,,$$

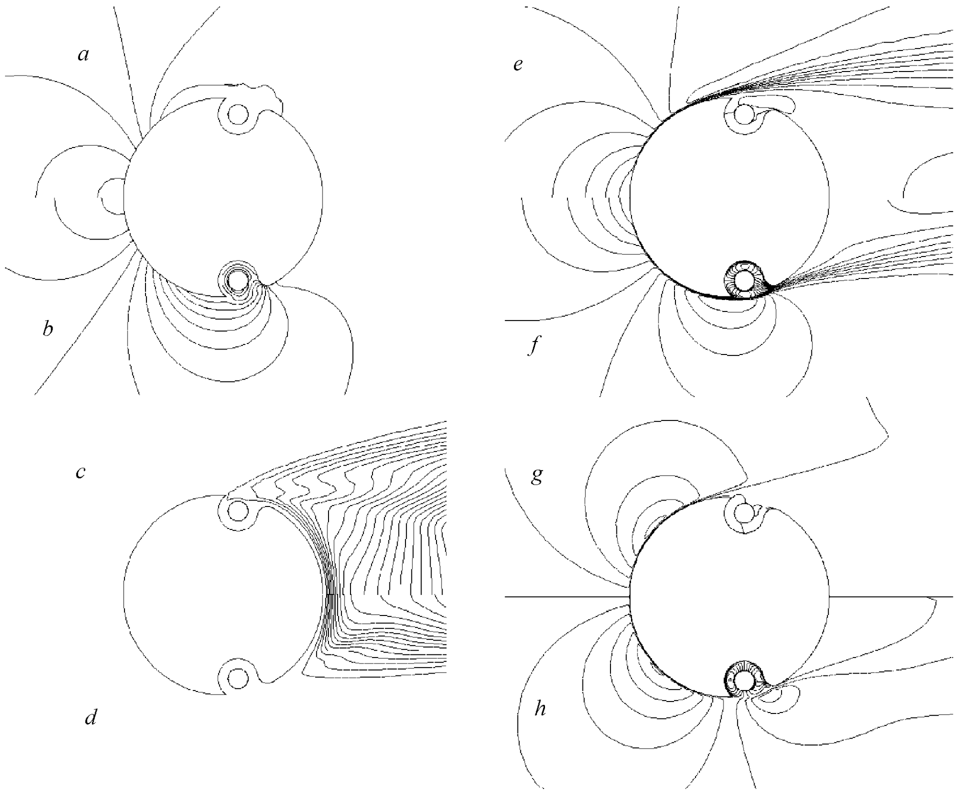

Fig. 4. Patterns of the isobars (a, b), the isolines of eddy viscosity (c, d), and the longitudinal (e, f) and transverse (g, h) velocity of the flow around the cylinder with vortex cells for two velocities of suction: 0.0288 (a, c, e, g) and 0.03 (b, d, f, h). The isobars and isotachs are drawn with a step of 0.15, and the isolines of eddy viscosity are drawn with a step of 0.0005.

where p_{m} is the mean static pressure (related to the doubled kinetic head) on the surface of the central body in the cell. The dependences $C_{x\mathrm{add}}(V_{\mathrm{n}})$ and $C_{x\mathrm{int}}(V_{\mathrm{n}})$, where $C_{x\mathrm{int}} = C_x + C_{x\mathrm{add}}$, are plotted in Fig. 2.

The additional resistance of the cylinder increases approximately proportionally to the quadratic dependence on the velocity of suction of the fluid from the surface of the central body in the vortex cell. There is evidently an optimum value of V_{n}, at which the corrected drag is a minimum. In the case under consideration, $V_{\mathrm{n\,opt}} \approx 0.029$, at which $C_{x\mathrm{int}}$ has a value of 0.33 that is lower by 56% than the drag coefficient of a smooth circular cylinder.

The aerodynamic characteristics of the cylinder change stepwise when the velocity of suction from the surface of the central body increases (Fig. 2–4). It should be noted that there is a threshold value of V_{n} equal approximately to 0.03, at which the calculated drag of the cylinder decreases by a factor of 4. A similar pattern was observed earlier for a flow around a cylinder with elliptical vortex cells [8]. The reason for such behavior of C_x is the restructuring of the pattern of the flow: the jump-like movement of the separation point to the critical, back stagnation point of the flow is accompanied by a large decrease in the dimensions of the circulation zone in the near wake.

A further increase in V_{n} has practically no influence on the drag and its components, i.e., the threshold value of V_{n} can be considered as an optimum value by the criterion of minimum total drag. Clearly the additional drag caused by the expenditure of energy increases with increasing V_{n}, which leads to an increase in the total drag of the body.

We now consider the behavior of the flow in the vortex cell in the case where V_{n} passes through the threshold value (Fig. 3). Before V_{n} reaches this value, the separation flow in the cell is very weak and practically has no effect on the flow around the circular cylinder. At $V_{\mathrm{n}} \geq 0.03$ the intensity of the circulation flow in the cell sharply increases (the velocity is of the order of unity), which leads to its "explosive" turbulization. A powerful, large-scale, oppositely swirled vortex fits well into the cut of the cylinder contour, which can be considered, to a certain extent, as evidence of the rational choice of the vortex-cell shape.

TABLE 1. Comparative Analysis of the Drag Coefficients of the Cylinder with and without a Vortex Cell

Shape of body	C_x	C_{xp}	C_{xf}	$C_{x\mathrm{add}}$	V_n	c_q	$C_{x\mathrm{int}}$
A	0.748	0.729	0.019	–	–	–	0.748
B	0.779	0.681	0.0098	0	0	0	0.779
	0.743	0.658	0.0086	0.028	0.05	0.0628	0.771
	0.312	0.202	0.110	0.152			0.464
C	0.272	0.177	0.095	0.147			0.419

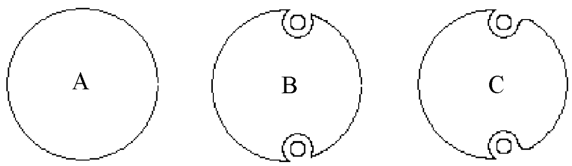

Fig. 5. Shapes of the bodies considered in Table 1.

To determine more exactly how the topology of the flow in the near wake of the cylinder changes when V_n passes through the threshold value, we analyzed the distribution of the eddy viscosity and the velocity components (Fig. 4). In this case, along with the above-mentioned strong deformation of the circulation flow in the wake, there takes place a change in the character of flow around the side surface of the cylinder. An increase in the velocity of the flow in the region of the cell stimulates the growth of rarefaction in it. As a result, the profile drag of the cylinder decreases sharply.

A decrease in the dimensions of the separation zone in the near wake leads to a decrease in the intensity of the flow in it and a decrease in the level of eddy viscosity.

Table 1 gives the values of the drag and its components for the cylindrical bodies shown in Fig. 5 in the case where a separating plate is positioned in the wake behind them. In this case, the velocity of suction $V_\mathrm{n} = 0.05$ exceeds the optimum value. For configuration B, the radii of rounding of the sharp edges are the same and equal to 0.001.

It should be noted first of all that there takes place bifurcation of the flow around cylinder B with vortex cells at the same level of suction in them. In the first case, suction was switched on when a separation flow around the cylinder was already formed, i.e., the problem was solved at the initial condition $V_\mathrm{n} = 0$. In the second case, modeling of flow around the cylinder was begun at the instant the fluid struck the body with switched-on suction in the cells. This duality is easily explained by the fact that in the case where the structure of a separation flow of the type of flow shown in Fig. 3a is formed, any increase in the level of suction has no effect on the topology of the flow but the character of the separation flow becomes somewhat more pronounced. At the impact initial conditions, the flow around the cylinder is close to a potential flow; as a consequence, powerful large-scale vortices are instantaneously formed in the vortex cells.

The data for cylinder B (see the table) correlate well with the results of the calculations done in [8] for the case of vortex cells with sharp edges.

Smoothing of the trailing edge of the cell enhances its action on the flow. The drag of the cylinder decreases more significantly in this case. At a radius of rounding of the edge of 0.05 the total drag of the cylinder decreases by approximately 10% as compared to that of the cylinder with a cell with sharp edges and by almost a factor of 2 in comparison with the drag of a smooth circular cylinder.

CONCLUSIONS

The method of control of the flow around a circular cylinder with vortex cells built into its contour in the case of intensification of the flow in the cells by suction from the surface of central bodies located in them has been numerically substantiated. It has been shown that an action on the flow in a small-size cell can cause a transformation of a large-scale vortex structure in the wake behind the cylinder and substantially decrease its drag. An estimation of the additional drag caused by the expenditure of energy has made it possible to determine the optimum values of the velocity of suction at which the drag of the cylinder is minimum. The efficiency of the method of control is estimated at about 56% at the geometric dimensions of the vortex cells and the Reynolds number under consideration. Smoothing of the sharp edge of a ring vortex cell positioned downstream of the flow leads to an approximately 10% decrease in the drag with allowance for the expenditure of energy.

This work was carried out with financial support from the Russian Foundation for Basic Research (projects 02-01-00670, 02-02-81035, and 02-01-01160).

NOTATION

x, y, Cartesian coordinates; ρ, density of fluid; U_∞, velocity of an undisturbed flow; d, diameter of the cylinder; μ, coefficient of dynamic viscosity; p, static pressure related to the doubled kinetic head; k, energy of turbulent pulsations; Re, Reynolds number ($\mathrm{Re} = \rho U d/\mu$); a, radius of the vortex cell; x_b and y_0, coordinates of the center of the vortex cell; b, radius of the central body; V_n, velocity of suction from the surface of the central body; C_x, C_{xp}, and C_{xf}, coefficients of motion drag, pressure drag, and friction drag; $C_{x\mathrm{add}}$, coefficient of additional drag caused by the expenditure of energy for the maintenance of suction from the surface of the central bodies; $C_{x\mathrm{int}}$, drag coefficient of the cylinder with vortex cells corrected for the expenditure of energy; N_q, power necessary to maintain suction from the surface of the central body in the vortex cell; c_q, flow rate through the surface of the central body in the cell. Subscripts: opt, optimum value; m, mean; n, normal; b, body; add, additional; int, integral.

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