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ANALYSIS OF THE DRAG OF TWO DISCS IN A TURBULENT INCOMPRESSIBLE FLUID FLOW

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The effect of reducing the drag of two discs is investigated by using difference modeling of their flow by using the two-parameter $k - \varepsilon$ turbulence model.

Analysis of the aerodynamic drag of two blunt bodies located behind each other in a uniform flow is represented by one of the urgent problems of the aerodynamics of poorly streamlined bodies. Its practical value is to the necessity of predicting the aerodynamic characteristics of systems of poorly streamlined bodies, on the one hand, and to the tendency to organize the flow around bodies of revolution by using the premeditated formation of developed circulation zones near their surface in order to improve their characteristics substantially [1], on the other. It is established in [1-3] that a significant diminution in the profile drag is observed in the axisymmetric flow around groups of bodies comprised of two discs, or a disc and a cylinder, as compared to the case of their isolated flow. Thus, by setting a disc of appropriate size at the optimal distance ahead of a single disc, a configuration can be obtained whose total drag would be 81% less than for a single disc, while the profile drag coefficient for a disc—cylinder composition can reach the value 0.02, i.e., close to the pressure drag coefficient in the case of potential flow around a body.

As follows from the papers mentioned above, interaction between the wake behind a disc with the large-diameter disc located downstream can be stable in nature; the flow configuration is determined greatly by the presence of such elements of different scale as the viscous shear layer and the circulation zones. The sharp edges of the discs turbulizing the stream for comparatively moderate Reynolds numbers (on the order of 10^3) result in a mode of developed turbulent flow around the discs, for which a sufficiently weak dependence of the body drag on the Reynolds number, in particular, is characteristic. The complexity of the flow occurring around the discs and the interrelation between the components of its structural elements suggest turning to numerical modeling of the flow around the discs on the basis of solving the Reynolds equations by finite-difference methods in combination with a semiempirical two-parameter turbulence model $k - \varepsilon$ consisting of the introduction of two differential equations for the turbulent energy fluctuations k and its dissipation velocity ε, a number of semiempirical constants, and an algebraic expression for the turbulent viscosity coefficient. It is considered that such a turbulence model correctly describes the developed turbulent flow mode.

The purpose of this paper is to compute the drag of a configuration of two discs of different size in the stationary uniform flow of an incompressible fluid in the ranges of varia-

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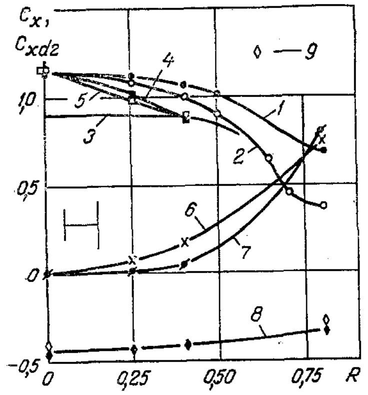

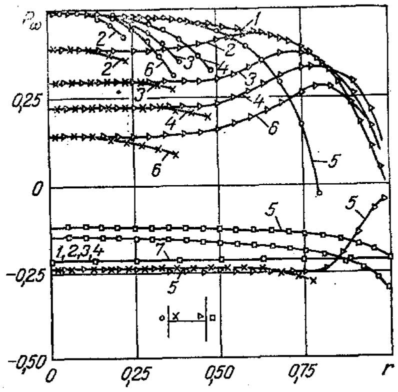

Fig. 1

Fig. 2

Fig. 1. Dependence of the drag coefficients of two discs (curves 1-5), the drag of the forward disc (curves 6, 7), base drag of two discs (curves 8, 9), on the radius of the forward disc R: 1, 2, 3, 7, 8, 9) L = 0.5; 4, 5) 1.0; 1, 4, 7, 8) computations by the method proposed; 3) computation by the method in [7]; 2, 5, 6, 9) experiment [2]; 6) corresponds to the case of flow around an isolated forward disc.

Fig. 2. Distribution of pressure P_w over the disc surface: 1) R = 0, L = 0.5; 2) 0.25, 0.5; 3) 0.4, 0.5; 4) 0.5, 0.5; 5) 0.8, 0.5; 6) 0.4, 1.0 (computation); 7) for an isolated rear disc (experiment [2]).

tion of 0-0.8 for the radius R of the forward disc, and of relative spacing L between discs from 0 to 1.0, to investigate the mechanism of drag reduction of two discs as compared with the case of the flow around an isolated disc, and also to given an estimate of the applicability of the computational model utilized on the basis of comparing the computed results with experimental data [2]. Selected as characteristic quantities are the radius of the rear disc and the free stream velocity and density. The Reynolds number of the incident stream is taken to equal 10^5.

On the basis of a test computation of stationary turbulent flows [4], including the circulation zones contained [5], a computational model is selected for the flow around the discs for which the characteristic singularities are: 1) the recording of a system of Reynolds equations in canonical divergent form in cylindrical coordinates in natural variables, supplemented by equations for the turbulence characteristics k and ε; 2) utilization of a set of standard constants that are in the turbulence model [5] and are practically invariant for different problems; 3) application of an integrointerpolation hybrid pressure correction scheme to represent the equations in finite-difference form in combination with the computational mesh whose lines are parallel to the coordinate directions while the nodes to determine the velocity components u and v are shifted a half-spacing relative to the nodes at which the pressure and the turbulence characteristics are determined; 4) the solution of the system of difference equations by the linear scanning method [5]. Artificial diffusion that shades the physical transport processes exerts substantial influence on the solution of the problem in an approximation of the convective terms of the transport equations by a hybrid scheme in which central differences are used for a mesh Reynolds number $Re_c < 2$ and one-sided "against the flow" differences for values $Re_c > 2$. To diminish the artificial diffusion, condensation of the mesh nodes is performed in the neighborhood of the discs (the dimension of the minimal mesh spacing is 0.02). However, it should be noted that the computational mesh utilized does not permit a sufficiently accurate reproduction of the viscous shear layers, which to a considerable extent govern the flow around and drag of the discs.

The boundary conditions in the problem are posed mainly exactly as in [6]. The incoming stream parameters are given on the input boundary, "soft" boundary conditions on the output boundaries ($\partial/\partial n = 0$, where n is the normal to the boundary of the computation domain), and symmetry conditions on the axis of symmetry. In the case of the "soft" boundary conditions the parameters on the boundaries are determined by quadratic extrapolation of the parameters from the inner nodes of the computational domain. In contrast to [6], "soft" boundary conditions corresponding to reproduction of an equilibrium turbulent flow when generation of turbulence is equilibrated by its dissipation are posed on the input boundary for the turbulence characteristics. Then a practically zero turbulence level is realized in the station-

TABLE 1. Integral Characteristics of the Flow around Two Discs

R	L	c_{xp_1}	c_{xd_1}	c_{xp_2}	c_{xd_2}	l
—	—	—	—	0,68	—0,44	—
0,25	0,5	0,06	0,05	0,67	—0,42	0,57
0,40	0,5	0,14	0,09	0,58	—0,41	0,73
0,80	0,5	0,46	—0,33	—0,42	—0,33	0,98
0,25	1,0	0,05	0,03	0,56	—0,42	0,67
0,40	1,0	0,13	0,04	0,39	—0,40	0,78

ary flow mode in the free stream, and turbulence generation is realized as a result of stream interaction with the discs, as well as in the near wake behind them. The stream parameters in the neighborhood of the discs are determined from a computation of the cells adjoining the walls under the assumption of a negligibly small diffusion flow from the wall as compared with the remaining flows through the cell faces. As is shown in [6], such an approach permits computation of a flow with stream separation and pressure gradients.

Computations of the flow around two discs are executed on a mesh containing 60 × 30 nodes. From 8 to 9 nodes are on the forward disc and from 14 to 19 on the rear disc. The distances from the disc surfaces to the left, right, and upper boundaries are determined in the numerical experiments from the condition of negligible influence of the boundary conditions on the nature of the flow and the stream parameter distribution in the neighborhood of the discs as well as in the near wake behind them, and are selected equal to 12, 24, and 18, respectively. A solution of the problem for fixed values of R and L is obtained in 1500 iteration steps on the average, where the smallness of the increment in the turbulence characteristics in the iteration step is the convergence criterion. Let us note that convergence in the pressure distribution and, therefore, the disc drag is reached considerably more rapidly (after approximately 500 iteration steps) than in the turbulence characteristics. The relaxation coefficients utilized did not exceed 0.20-0.25.

Certain results computed on the basis of the viscous fluid model are represented in Figs. 1 and 2 and Table 1. Superposed for comparison in Fig. 1 are experimental measurement data of the total and base drags of an isolated disc and of two discs [2] for a free stream Reynolds number of 10^5, and the computational curve is also shown for $C_x(R)$ obtained following [7] within the framework of an ideal fluid model by using the discrete vortices method. It is considered that such an approach to modeling the flow around discs is justified for large Reynolds numbers when a developed turbulent flow mode is realized.

Comparing the drag coefficients determined experimentally in a wind tunnel [2], with the correction for stream overloading by the model taken into account, and those computed by using difference modeling for an isolated disc shows their quite good agreement in both the total and the base drags (Fig. 1). Nevertheless, as in analogous computations of the flow around a disc by using difference schemes of first-order approximation (see [6], say), the computed length of the circulation zone in the wake behind the disc is obtained approximately 20% smaller as compared with that observed in experiments, while the computed base pressure is not constant on the rear surface of the disc as is seen from Fig. 2, and differs by 20% on the average from the experimentally measured value, while this difference exceeds 30% near the sharp edge.

The organization of a separation zone ahead of the disc because of installation of a small-diameter disc results in a reduction in the pressure in the domain between the discs and in deformation of the pressure profile at the forward side of the disc with the formation of peripheral displaced pressure maximum with respect to the axis of symmetry (Fig. 2). An increase in the forward disc radius R from 0 to 0.4 is accompanied, for fixed L, by growth of the forward separation zone, displacement of the point of attachment of the streamline separating the circulation flow and the external stress (see Table 1), and the peripheral pressure maximum in the direction to the sharp edge of the disc, and also by a diminution in the magnitude of the pressure maximum and, therefore, of the integral load at the forward side of the disc C_{xp_2}. Therefore, a growing, screening influence of the forward over the rear disc occurs even for comparatively small values of R. At the same time, the base drag of the rear disc C_{xd_2} and length and intensity of the flow in the circulation zone behind it remain practically unchanged, which indicates the governing influence of stream separation from the sharp edge of the rear disc in wake formation behind the discs and the weak coupling between the circulation zones in the wake behind the discs and in the domain between the discs. It is interesting to note that the forward disc experiences strong interaction from the rear disc in the formation of the forward separation zone. In place of the reduced pressure domain ordinarily realized in the wake behind an isolated disc and characterized by negative values of the excess pressure (with respect to the pressure in the free stream), in the case of the flow around two discs an elevated pressure domain occurs behind the forward disc (Fig. 2), which, as is seen from Fig. 1, results in a significant diminution in the drag coefficient of the forward disc (curve 7) as compared with the case of its isolated streamline (curve 6).

Therefore, an increase in the radius R of the forward disc results in a reduction in the total drag of the discs because of a diminution of the contribution of the integrated load on the forward surface of the rear disc C_{xp_2} to the drag, on one hand, and because of the very small value of the forward disc drag, on the other. As the spacing L between the discs grows, a more rapid diminution occurs in C_x as R increases (see Fig. 1). Good agreement to 3-5% accuracy between the computed and experimental drag coefficients of two discs in the range of R variation between 0 and 0.4 shows the applicability of the computational model to estimate the drag of discs in a developed turbulent flow mode when the viscous effects in the stream are apparently quite substantial. At the same time, estimation of the drag of two discs within the framework of the ideal fluid model, obtained by the discrete vortices method, yields a significant (up to 20%) divergence from experimental results [2].

Evolution of the forward separation zone as the radius of the forward disc increases results in growth of the ejection capabilities of the viscous shear layer being developed behind the sharp edge of the forward disc, and therefore, in a progressing reduction in the pressure in the zone to quantities comparable and less than the pressure behind an isolated disc (Fig. 2). The shift of the stream attachment point in the neighborhood of the sharp edge here specifies passage to the mode of flow around discs with the formation of a single viscous shear layer enclosing the circulation zones in the domain between the discs and in the wake behind the discs. Such a flow mode is characterized by minimal drag of the discs [2]. As was established in a numerical experiment, the main contribution to the total drag of the discs in this case is from the forward disc, where its drag exceeds the drag of an isolated disc because of the strong diminution of the pressure in the domain between the discs. At the same time, the rear disc, which is entirely in the reduced pressure domain (Fig. 2), experiences the effect of a pulling force that occurs because of the pressure drop in the forward separation zone and in the wake behind the discs. Therefore, the total drag of two discs turns out to be less than the drag of the forward disc and can be considerably less than the drag of an isolated disc for a logical selection of the radius R.

As already noted, the introduction of significant artificial diffusion when utilizing the hybrid scheme results in errors in reproduction of the viscous shear layer, which specifies to a great extent the growing discrepancy between the computed and experimental values of C_x as R increases (see Fig. 1). It can be expected that an improvement in the quality of modeling the flow around discs on the basis of using schemes of higher order of approximation will permit obtaining more accurate results. Nevertheless, let us note the good agreement between the computed and experimental data for the base drag of the discs.

NOTATION

x, r, axial and radial coordinates; n, normal to the boundary of the computational domain; R, radius of the forward disc; L, spacing between the discs; l, a coordinate of the point of stream attachment during the flow around the rear disc; u, v, velocity components in the axial and radial directions; P, pressure that is excess relative to the free-stream pressure; k, turbulent fluctuation energy; ε, velocity of turbulent energy dissipation; Re, Reynolds number; C_x, C_{xd}, frontal and base drag coefficients; C_{xp}, integral load coefficient on the disc forward surface. Subscripts: 1 and 2, forward and rear discs; c, mesh; w, value at the wall.

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THERMODYNAMIC PROPERTIES OF 1-PENTANOL AT ATMOSPHERIC PRESSURE

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Data is generalized on the density, sonic velocity, and isobaric specific heat of liquid 1-pentanol and calculations are made of the isochoric specific heat, coefficients of adiabatic and isothermal compression, and enthalpy in the temperature range 194.95-411.13°K.

This study is a continuation of our work [1, 2] on analyzing, systematizing, and succintly representing experimental information on the thermodynamic properties of monohydric aliphatic alcohols.

The following equation was chosen as the approximating function to describe the temperature dependence of density, sonic velocity, and isobaric specific heat from the normal melting point up to the boiling point:

$$y = \sum_{i=0}^{n} a_i \tau^i, \tag{1}$$

where $\tau = T/1000$, while y respectively denotes ρ^{-1}, W, and C_p.

The coefficients a_i of Eq. (1) for ρ^{-1}, W, and C_p were determined by the least-squares method on the "Minsk-32" computer.

Density. Numerical data on the density of liquid 1-pentanol has been systematized in several handbooks [3-5]. The available empirical data on density at atmospheric pressure and on the saturation curve for the period before 1970 was generalized in the survey [4] in the form of a Francis equation. This equation describes initial values within the estimated error and is valid in the temperature range 253-393°K. Of the recommended values of ρ [4], the most accurate are those for 293.15 and 298.15°K, the averaging error for which was evaluated as ±0.0002 and ±0.0003 g/cm³. Comparison of the results of the generalization in [4] with later (1976) measured densities on the saturation curve [5] obtained at 293-490°K with an error less than 0.02% shows that they do not agree well with each other. Whereas the deviation at T = 293.15°K is 0.04%, it increases with temperature and reaches 0.5% at T = 393.15°K. Here, the values of density are too high in every case.

In the low-temperature range there is a limited amount of experimental data. The study [6] measured density on the saturation curve in the temperature range from 213 to 453°K with an error on the order of 0.1%. Comparison of the data in [5] and [6] shows that at 293-393°K the values agree to within 0.10-0.15% except for one point at T = 393.15°K, for which the de-

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