the oscillation, i.e., $t \approx t_2 + \varepsilon$. Such a calculation requires two or three hours of computer time. The graph of the motion of standard cylinder can then be extended by the analytic solution. For cylinders with other mean density, the analytic solution for the quasistationary stage of the motion can be written down directly.

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LEADING ZONE OF SEPARATION OF THE FLOW OVER A BLUNT BODY (CALCULATED MODEL)

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For blunt bodies of any shape, the largest contribution to the drag is made by the profile component associated with the distribution of the pressure over the surface of the body. In the case of the flat end of a cylinder in a longitudinal stream at zero angle of attack the forces of friction do not give rise to any drag at all without allowance for the contribution of the side surface. In contrast to the traditional shapes in aerodynamics, a stable circulation flow is formed at the front part of a blunt body with a disk, this being due to flow separation on the disk [1-3]. As a result, the profile drag of such a body is to a large extent determined by the nature of the flow in the circulation region.

Figure 1 shows the schematic flow over a body of this kind (disk—cylinder combination) in a supersonic stream. Here, d is the diameter of the disk, l is its separation from the end of the cylinder, AB is the bow shock, and EH is a line separating the exterior flow from the region EFGH of the circulation flow. The figure indicates the coordinates and dimensions of the body used below (the cylinder diameter D is taken as the characteristic length in the calculations).

The analysis is restricted to the case of transonic and supersonic flow, when a single dominant large-scale vortex is formed in the region behind the disk. The results discussed below were obtained in the framework of the model of an ideal gas and a scheme similar to that described in [4, 5]. The quoted papers contain the results of analysis of properties of the scheme such as its accuracy and stability. Therefore, we shall consider only some features characterizing the formulation of the calculation.

The equations describing the flow in this model have the form

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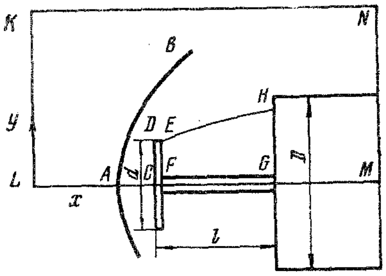

Fig. 1

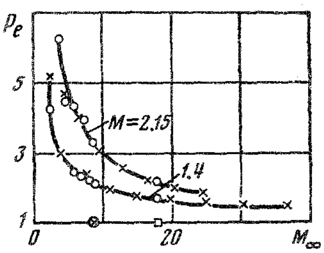

Fig. 2

$$\mathbf{q}\nabla\rho+\rho\nabla\mathbf{q}=0,\quad \rho(\mathbf{q}\nabla)\mathbf{q}+\operatorname{grad} p=0,\quad \rho(\mathbf{q}\nabla)I+p\nabla\mathbf{q}=0,\quad p-(\varkappa-1)\rho I=0$$

where $\mathbf{q}(u, v)$ is the flow velocity, ρ is the density, p is the pressure, I is the specific internal energy, and $\varkappa$ is the specific heat ratio (in the calculations $\varkappa=1.4$). A system adequate for the computational scheme is obtained from these equations by adding to the first three equations the terms ρ_t, $\rho\mathbf{q}_t$, ρI_t , respectively (the subscript denotes the time derivative).

The boundary conditions are the conditions of no flow on the surface of the body and the conditions characterizing the oncoming stream. The rectangular computational region KLMN (Fig. 1) covers the immediate vicinity of the body in the meridional section. On the side KL upstream of the body (the "entrance boundary") the parameters of the oncoming flow are specified. On the other sections of the boundary of the computational region the conditions of continuous continuation of zeroth order are imposed ("soft conditions"). The scheme is of the through-computation type, and this makes it possible to avoid the difficulties associated with separating the discontinuity surfaces and satisfying on them the jump conditions. In the majority of cases, the calculation is made from the time t = 0, when the investigated body is introduced into a uniform flow characterized by Mach number M_∞, until stabilization. As usual, the criterion of stabilization is a small value of the time derivatives of the characteristic variables.

The acquired experience of the use of computational schemes like the one used in the present work suffices for reliable interpretation of the results obtained by means of it (see, for example, [5, 6]). It can be assumed that the result of the stabilization calculation reproduces the picture of the separation flow over the body and corresponds quantitatively to the case of large Reynolds numbers. Various circumstances mentioned below stimulate and justify the study of the flow near a body of this configuration in the framework of the adopted model.

It is known [7] that the drag of a flat end with sharp edges and transition on the side surface depends weakly on the Reynolds number if the latter is large. On the other hand, in a computational scheme of the employed type, which does not take into account the real dissipative effects, a mechanism of computational dissipation is still present, and its effect is qualitatively similar to that of physical viscosity. For flow in a cavity, which is a good model of the flow in the circulation zone, it was found in [8] that even at the Reynolds number calculated using the maximal flow velocity (Re $\geqslant$ 500) the vorticity in the central part of the cavity occupied by the developed vortex is virtually constant, and the vortex itself is separated from the walls by a comparatively thin viscous layer. In the considered case, when the circulation zone is open to the influence of the exterior flow, the flow velocity in it is comparable with the velocity of the undisturbed flow. As a consequence, the Reynolds number calculated using the maximal velocity in the circulation zone is fairly large. Finally, one must also bear in mind features of the problem such as the definiteness in the basic shape of the circulation region and the fixing of the flow separation point on the edge of the disk.

Variants of the problem were calculated with both constant and variable time step ht. The value of ht was varied depending on the calculated increment e of the specific internal energy I in the previous layer:

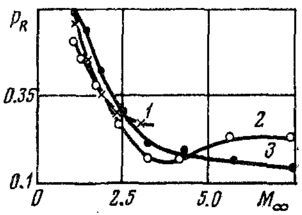

Fig. 3

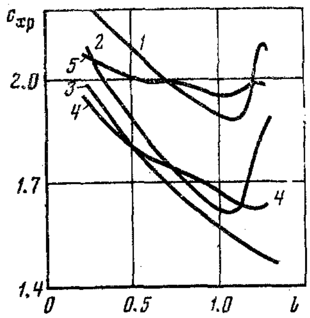

Fig. 4

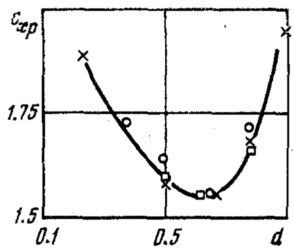

Fig. 5

$$ht = ht/(1+a),\quad e>\beta;\quad ht = ht(1+\alpha),\quad e<\gamma;$$

ht = const in other cases when $\alpha, \beta, \gamma = o(1)$, $a = O(1)$.

We now consider the results of the calculations for characteristic examples.

Figure 2, for a body in the case d = 0.375 and l = 1.333 for M_∞ = 1.4 and 2.15, shows the change in the pressure p_e at the base of the rod on the end of the cylinder (in fractions of the pressure p_∞ of the undisturbed flow) at the time $\tau = 16t\sqrt{p_\infty/\rho_\infty}/D$, where ρ_∞ is the density of the undisturbed flow. The calculation was made with constant (1) and variable (2) time step. On the abscissa, we have made marks corresponding to 270 and 540 steps of a calculation with ht = 0.033. The calculation with variable ht was continued until 270 steps. Note that the process develops along nearly coincidence trajectories in the two cases, which indicates stability of the calculation. It is evident that by using a variable time step one can advance further in the evolution of the process than with constant ht (for example, twice as far for M_∞ = 2.15). The increase in the step occurs mainly in the late, developed stage of the process, when a certain proximity to equilibrium has been achieved in the flow field. The largest automatically chosen step corresponds to numbers K in the Courant criterion somewhat less than unity.

The dependence of p_R (the pressure at the base of the rod divided by the pressure determined by Rayleigh's formula) on M_∞ for some variants of the body geometry is shown in Fig. 3, in which curves 1-3 are determined, respectively, for the following sets of parameters d and l of the body: 0.375, 1.333; 0.5, 1.0; 0.375, 1.0.

Using the pressure found in the calculation, we can find the drag (the normal force) C_{xp} for these bodies with allowance for the contribution of only their leading part. The predicted error of the result is of order 10%. Figure 4 shows the data on the drag obtained in the calculation for bodies with different l and d in a stream with M_∞ = 1. Here, curves 1-5 are plotted for d = 0.25, 0.5, 0.625, 0.75, and 0.875, respectively. With regard to these data, we can make some comments.

Stabilization is achieved relatively late at large l. It is possible that the calculations in this part of the range are less accurate. With decreasing l, the curves converge on the value $C_{xp} \approx 2.5$ for a circular cylinder in a longitudinal stream in the case Re = $(0.2\text{-}1.88)\cdot 10^6$ [7]. At large l, one can expect the drag to cease to depend on l and be made up of the drag of the disk and the cylinder. In the calculation, this property was not obtained, since the largest considered value was l = 1.375. In the range l < 1, an increase in l, like an increase in the relative elongation, reduces the drag. It is therefore to be expected that for bodies of this shape there exists a $l(d, M_\infty)$ corresponding to a least C_{xp}. It should be noted that for each l one can find a $d(l, M_\infty)$ for which C_{xp} is minimal. A typical example illustrating this fact is shown in Fig. 5, in which l = 1, M_∞ = 1. In this diagram, the results obtained in calculations from essentially different initial conditions are indicated in various ways.

Obviously, it is meaningful to speak of the shape of a body of the considered type having the least drag. It is readily seen that in accordance with the data of the calculation for M_∞ = 1 in $l \in [0, 1.375]$, d $\in$ [0.25, 0.875] this corresponds to the point $l^* \simeq$ 1.375, $d^* \simeq$ 0.625, for which $C_{xp} \simeq 1.5$. If we bear in mind that the base pressure behind the end of the cylinder for M_∞ = 1 is $p_g \simeq 0.9$ [7], the drag (without allowance for friction) can be obtained by subtracting from C_{xp} the quantity $2p_g/(\varkappa M_\infty^2)$, which is approximately equal to 1.28, which gives $C_x^* \simeq 0.22$. The corresponding values of the drag (also after subtraction of the friction) for cylinders with conical, C_{xh}^*, and ogival, C_{xo}^*, nose parts with length l = 1.5 for M_∞ = 1 are C_{xh}^* = 0.445 and C_{xo}^* = 0.265 [7]. The drag advantage for M_∞ = 1 for ogival nose parts as compared with a body of the considered shape appear only for more extended nose parts. Thus, for l= 2.5, C_{xo}^* = 0.195 [7]. Note that for a conical nose part of the same length C_{xh}^* = 0.295 [7]. Thus, we conclude that bodies of this type belong to the class of bodies with small drag.

Summarizing, we can say that the results of the calculation of flow over a blunt body with disk placed in the front in accordance with a scheme similar to that in [4, 5] correspond to a simulation of the real flow in which the computational dissipation replaces the true dissipation, successfully fulfilling some of its functions. Under the conditions of a forward separation zone open to the influence of the oncoming stream, the presence of the computational dissipation ensures correct reproduction in the calculation of the flow field structure, the qualitative characteristics of the distributions of the main gas-dynamic parameters, and their interconnection. For example, one can assume with confidence that the conclusion of a comparatively small aerodynamic drag of bodies of these shapes, which has been drawn on the basis of the study of the model, corresponds to observation in reality, since the reduction in C_x in the calculated model occurs through the formation of a region of circulation flow between the disk and the leading end of the body, which is necessarily present under real conditions close to those considered here. The same also applies to the conclusion concerning the existence of the optimal values $l^*(d, M_\infty)$ and $d^*(l, M_\infty)$ corresponding to the minimal drag of the considered body.

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