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SUPERSONIC FLOW OVER A SPHERE IN THE WAKE OF A BLUNT CYLINDER

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The authors use numerical solutions of the Navier–Stokes equations to investigate the influence of geometric factors on the flow structure ahead of a sphere and the surface distributions of pressure and heat transfer.

References [1-6] have conducted experimental and theoretical investigations of supersonic flow over bodies located in a wake region. It has been established that a nonuniform distribution of the incident flow parameters has an appreciable influence on the bow shock shape, the boundary layer structure, and the distribution of pressure, friction stress and heat transfer. It has been indicated that reverse circulation flows may form on the forward surface of blunt bodies. In the theoretical studies the wake flow was modeled by different shear flows. In the present paper the parameters of the flow incident on a sphere are adopted from the solution of the problem of the supersonic wake behind a blunt cylinder obtained in [7], using the Navier–Stokes equations under the flow symmetry hypothesis. We investigate how the shock layer structure and the distribution of drag and heat transfer on the surface of the sphere depend on the distance between the bodies and their radii.

1. We consider stationary axisymmetric flow over a sphere whose center is located on the axis of the supersonic wake behind a longitudinally washed blunted cylinder. The computation region is bounded by the body surface, the axis of symmetry, the bow shock, and a certain surface on which the normal velocity component of the gas is everywhere supersonic apart from a narrow wall region. The flow is described by the full Navier–Stokes equations. The specific heat of the gas is considered constant. The temperature dependence of the viscosity is approximated by the function $\mu \sim \sqrt{T}$, and the Prandtl number Pr = 0.7.

As boundary conditions on the bow shock we use the generalized Rankine–Hugoniot relations. On the body surface we assign conditions of no slip, impermeability, and either a constant temperature or a thermal insulation condition. The other two boundaries have, respectively, the symmetry conditions and approximate boundary conditions based on the hypothesis of a sufficiently smooth solution with respect to the angular coordinate. The stationary solutions are found by a time-dependent method. As initial data in most cases we assume the results of solving the problem for the close variant of the flow conditions.

2. The full unsteady Navier–Stokes equations for a compressible gas in spherical coordinates have been given in [7]. In solving the problem the distance from the sphere surface is normalized by the shock standoff distance. As a result the shock layer region examined is transformed into a rectangle. The original equations are written for the vector of the desired functions $X = \{u\ T\ v\ p\}^T$ in the form

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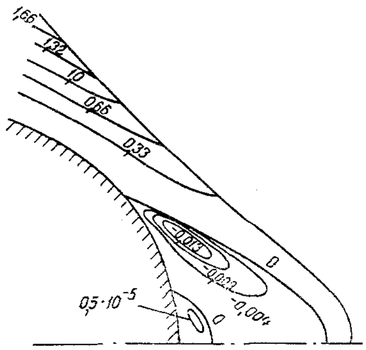

Fig. 1

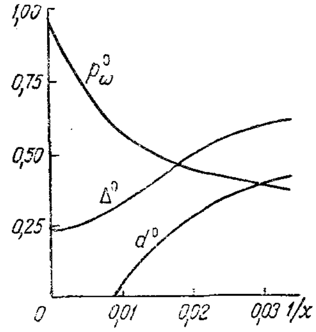

Fig. 2

Fig. 1. Picture of flow over the front surface of a sphere in a supersonic wake; x = 30, R = 10.

Fig. 2. The influence of distance between the bodies on the shock layer parameters; R = 5; all the quantities are dimensionless.

$$E\frac{\partial X}{\partial t}-\frac{1}{\rho}\frac{\partial}{\partial\xi}\left(A\frac{\partial X}{\partial\xi}\right)+B\frac{\partial X}{\partial\xi}+CX+D=0,$$

$$e\frac{\partial X}{\partial t}+b\frac{\partial X}{\partial\xi}+cX+d=0. \qquad (1)$$

The first of the matrix equations (1) expresses the balance of the momentum in the plane tangent to the body surface and the energy balance. The second equation contains the momentum equations in the plane normal to the body and the continuity equation. System (1) is integrated in time with the aid of an implicit finite-difference scheme of second-order accuracy in the spatial coordinates [8]. The desired functions in the new time layer are found by the method of iterations. All the coefficients of system (1), including coefficients containing derivatives of the desired functions, are computed from the previous approximation. Here the full system of difference equations decays into independent linear subsystems for values of the desired functions on rays normal to the surface of the sphere. These subsystems are solved along each ray by vectorial marching. To accomplish direct marching we transfer the body surface impermeability condition to the shock wave at the same time as the marching coefficients are computed. Along with the generalized Rankine–Hugoniot relations this forms a closed system of five equations from which we find the values of the gasdynamic functions behind the shock and the speed of motion of the shock front. Then we determine a new value of the shock standoff distance from the body surface and perform backward marching. These calculations are done on all the rays θ = const, and then we go on to the next iteration or the new time step.

The results shown of computations of nonuniform flow over a sphere were obtained on a mesh of step sizes $\Delta\theta = 2.5°$, $\Delta\xi = 0.02$. The time-dependent solution was monitored with respect to values of the time derivatives of temperature and pressure. The calculations were continued until these quantities were less than 10^{-3} in absolute value at all nodes of the mesh. The monitor calculations showed that a reduction of the number of cells of the difference mesh and of the criterion for flow establishment did not lead to a noticeable change of the results. During the calculations we also verified that the integral law of mass conservation held. In the established solutions it was fulfilled to an accuracy of tenths of a percent.

3. Some results of the calculations are shown in the figures. These correspond to flow over a sphere in the wake behind a spherically blunted cylinder of length $L = 3.6\ R_0$ at $M_\infty = 3$, $Re_\infty = 200$, $\gamma = 1.4$, $k = 0.257$. The Reynolds number Re_∞ was calculated on the cylinder radius R_0. On the figures all the linear dimensions are referred to R_0, the pressure and the friction stress are referred to $\rho_\infty V_\infty{}^2$, heat flux is referred to $\rho_\infty V_\infty{}^3$, and the gass mass flow rate is referred to $\rho R^2 \rho_\infty V_\infty$.

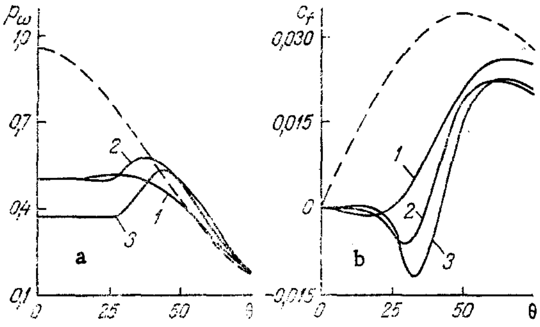

Fig. 3

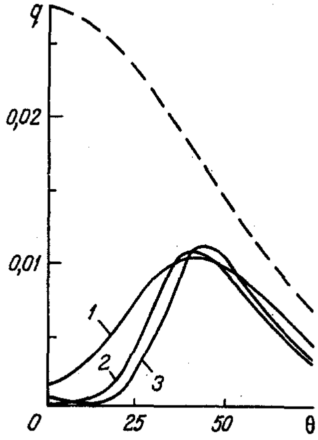

Fig. 4

Fig. 3. Variation of the dimensionless pressure (a) and friction coefficient (b) over the surface of a thermally insulated sphere. The quantity θ is in degrees.

Fig. 4. Variation of the dimensionless heat flux over the surface of a cooled sphere; k = 0.5.

The results of the calculations show that under the conditions examined there is a closed surface of reverse circulation flow ahead of the front surface of the sphere. Variation of the geometric parameters has a considerable influence on the shock layer structure. Increasing the sphere radius and reducing the distance of the sphere from the forward body lead to intensification of the circulation flow, to an even stronger variation of the shape of the bow shock, and to the appearance of a secondary reverse circulation flow in the vicinity of the sphere stagnation point. As an example Fig. 1 shows the location of the bow shock and the stream lines ahead of a thermally insulated sphere. The numbers on the stream lines indicate the dimensionless values of the gas flow rate.

For the case of flow over a thermally insulated sphere Fig. 2 shows the stagnation point pressure, the bow shock standoff distance, and the thickness of the reverse flow circulation region on the axis of symmetry as a function of the distance between the bodies. In this case the flow circulation arises for x = 110, and the second vortex is not formed.

Figures 3 and 4 show the distribution of the drag and heat transfer parameters over the sphere surface. Curves 1-3 correspond to the following values of the distance between the bodies and sphere radius: 1) x = 70, R = 5; 2) x = 70, R = 10; 3) x = 30, R = 10. The broken lines show the results of calculating uniform flow over a sphere with $M_\infty = 3$, $Re_\infty = 10^3$. It can be seen that for reduced distance between the sphere and the cylinder and increased sphere radius the distributions of pressure, friction factor and heat flux show considerable variations, associated with a change of the nature of the flow in the shock layer. The pressure and the heat flux at the sphere stagnation point decrease, and peripheral maxima of these quantities occur at the points of attachment of the circulation flow. The friction factor becomes an appreciably nonmonotonic function of the angular coordinate, changing sign at the points of separation and attachment of the flow.

The results obtained for the bow shock shape and the pressure distribution agree qualitatively with the experimental data of [2], which investigated wind tunnel flow over a sphere in the wakes behind bodies of various shapes at Reynolds numbers $Re \approx 10^6$. The results cannot be compared numerically because of the difficulties in obtaining sufficiently accurate numerical solutions for the flow regimes examined in [2].

NOTATION

M, Mach number; Re, Reynolds number; Pr, Prandtl number; γ, ratio of the specific heats of the gas; k, temperature factor (ratio of the body surface temperature to the stagnation temperature); R_0, radius of blunting of the cylinder; R, sphere radius; L, cylinder length; μ, coefficient of viscosity; T, temperature; p_w, pressure on the body surface; c_f, friction factor; q, heat flux; ρ, density; V, velocity; θ, angle coordinate; ξ, distance from the body surface, referred to the bow shock standoff distance; x, distance between the cylinder and the sphere; Δ, bow shock standoff distance; d, thickness of the reverse circulation flow region; E, A, B, C, D, e, b, c, d, coefficient matrices of the Navier–Stokes equations; X, column vector of the desired functions; u, v, longitudinal and transverse components of the gas velocity in the shock layer. Subscripts: ∞, parameters of the unperturbed uniform incident stream; 0, parameters on the stagnation line.

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ANALYSIS OF INTERACTION OF SINGLE-LAYER MONOLITHIC DAMPING COATINGS WITH TURBULENT FLOW

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The article analyzes the effect of the spectral-energy and phase–frequency oscillation characteristics of damping coatings on the friction coefficient and on turbulent pressure pulsations.

The article [1] presented data on the change of turbulent friction and pressure pulsations on the wall for ten variants of single-layer monolithic coatings made of three different materials whose thickness varied. The viscoelastic properties of the materials were ascertained in a wide frequency range with deformations corresponding to the operating conditions of the coatings on line.

The present article analyzes the obtained results. For that we used the calculation of the oscillation characteristics of coatings whose algorithm was presented in [2, 3]. In the mentioned calculation the viscoelastic dynamic properties of the coating materials are taken to be constant in the entire range of the analyzed frequencies. Such an assumption is correct if this frequency range lies in the zone of the high-elasticity plateau; this is so in the case of the data of the polymer materials (Fig. 1 in [1]).

Trifonov [4] pointed out the substantial influence of the frequency characteristics of coatings on the magnitude of the effect of interaction of the deformed wall with a turbulent flow.

The main oscillation characteristics are the phase angle Θ_p between the pulsating pressure applied to the coating and the displacement of its surface, and the coefficient of dynamism K_d which is equal to the ratio between the amplitude of the forced vibrations of the surface of the coating and the displacement under the effect of an equal but static pressure. Semenov [3] pointed out the undulating nature of the change of Θ_p in dependence on the vibra-

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