FLOW STRUCTURE DURING VISCOUS INTERACTIONS OF A SHOCK WAVE WITH FLYING PARTICLES

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UDC 532.526

In the case of flight of bodies with high supersonic velocities, an important problem is that of decreasing the resistance of these bodies as well as lowering the thermal flux to the wall of the flying apparatus. One of the possible means of solving this problem can be the blowing of solid particles from the surface of the body toward the supersonic flow. A rearranged flow structure, leading to changes in the aerodynamic characteristics of the flying body, is possible during the interaction of flying particles with the leading shock wave (SW).

Consider the interaction process of a single flying particle with a standing SW. This statement is valid when the flow regime of "single" particles is realized, i.e., their interaction with each other can be neglected. This can occur under the condition $f/\ell > 5$, where d is the mean interparticle distance and ℓ is their characteristic size [1]. It is assumed that initially the SW front is planar, while the particle is an infinitely thin plate of finite sizes. The gas parameters on both sides of the SW are given by the equations of shock transition. At the moment of time $t = 0$ the particle starts moving from the zone of subsonic velocities (the high pressure zone) to the supersonic velocity zone. It is also assumed that the particle moves with constant velocity under vanishing angle of attack to the unperturbed flow.

The problem stated will be solved in the two-dimensional approximation by using the full system of Navier–Stokes equations for a viscous, heat conducting gas, written down in the following form:

$$\frac{\partial f}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} = 0,$$

$$f = \begin{vmatrix} \rho \\ \rho u \\ \rho v \\ E \end{vmatrix}, \quad F = \begin{vmatrix} \rho u \\ \rho u^2 - \sigma_x \\ \rho uv - \tau_{xy} \\ (E - \sigma_x) u - \tau_{xy} v - \lambda \dfrac{\partial T}{\partial x} \end{vmatrix}, \quad G = \begin{vmatrix} \rho v \\ \rho uv - \tau_{xy} \\ \rho u^2 - \sigma_y \\ (E - \sigma_y) v - \tau_{xy} u - \lambda \dfrac{\partial T}{\partial y} \end{vmatrix},$$

$$E = c_V \rho T + \rho u^2/2 + \rho v^2/2, \quad \sigma_x = -p - \frac{2}{3}\mu\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) + 2\mu\frac{\partial u}{\partial x},$$

$$\sigma_y = -p - \frac{2}{3}\mu\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) + 2\mu\frac{\partial v}{\partial y}, \quad \tau_{xy} = \mu\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right).$$

Without loss of generality it can be assumed that the particle moves along the line $y = 0$. In this case the boundary conditions are assigned in general form $\partial u/\partial y = \partial \rho/\partial y = \partial p/\partial y = v = 0$ — the symmetry condition of the flow at $y = 0$, $u = v = 0$ — the sticking condition of gas particles to the surface of the plate, and $\partial T/\partial y$ — the thermal isolation condition of the plate. The gas flow parameters obey the known relations at the external boundaries of the calculated region: The supersonic flow parameters at the left boundary, and unperturbed subsonic flow parameters at the right boundary (the calculation is concluded when the perturbation of the plate track reaches the right boundary). The position of the upper boundary of the calculated region is chosen in such a manner that the condition $\partial f/\partial y$.

A crucial aspect of solving the Navier–Stokes equations with the use of difference schemes is the choice of the corresponding numerical algorithm. The main requirement is that of good approximation properties, i.e., the algorithm must be sensitive to small changes in the Reynolds number at high values of this number. For this purpose we constructed an explicit difference scheme of third order of accuracy, described in great detail in [2]. The pattern of the difference scheme was chosen in such a manner that the viscous terms in the Navier–

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 115-118, March-April, 1987. Original article submitted January 14, 1986.

 0021-8944/87/2802-0270$12.50

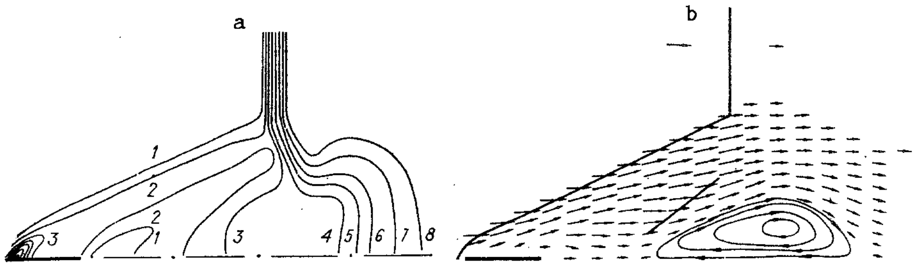

Fig. 1

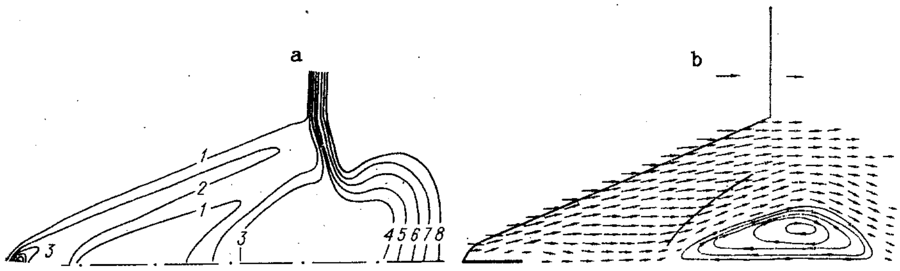

Fig. 2

Stokes equations could only decrease the extent of nonmonotonicity of this scheme, which makes it possible to avoid unphysical oscillations in the numerical solution.

Preliminary calculations by this flow scheme of a viscous gas near an infinite planar plate in the boundary-layer approximation, and comparison of the results obtained up to Reynolds numbers Re = 10^7 with the accurate solution [3], gave good agreement. Similar studies with the use of explicit difference schemes of first and second order accuracies showed that these schemes can provide satisfactory results, respectively, only up to Re = $5 \cdot 10^2$ and $5 \cdot 10^4$, while in the opposite case the calculated thickness of the boundary layer exceeds its exact value due to the substantial effect of the viscosity scheme.

Taking into account what was said, the problem stated was solved by a third order accuracy scheme. The calculations were carried out for a Prandtl number Pr = 0.7, a heat capacity ratio γ = 1.4, and under the assumption that the coefficients of dynamic viscosity μ and heat conductivity λ are constant. It must be noted, however, that the numerical algorithm is well realized for arbitrary dependences of μ and λ on the physical properties of the medium. The calculation results for Re = 1000 at two moments of time, when the rear end of the plate proceeds from the SW by 2.5 and 4.3 calibers, are shown in Figs. 1 and 2 in the form of pressure and velocity fields. The correspondence between the pressure value p and isoline number N in Figs. 1a, 2a is given by the equation $p = 5.5 \cdot 10^4(1 + N)$ Pa. The Re value was determined by the particle size and the parameters of the unperturbed supersonic flow. The parameters of the flow bending are the following: M = 2.1, p = 10^5 Pa, T = 300 K. At the initial moment of time the particle is located at a distance equal to half its longitudinal size from the SW, and starts moving toward it with velocity M = 1.5. Due to the fact that in the given problem the flow near the particle track is of most interest, we will not dwell in any detail on the complicated flow nature at the tip of the plate and near its leading edge.

As follows from Figs. 1 and 2, the presence of a flying particle leads to the formation of a condensation close to a conical abrupt change, moving along the flow and adjacent in its lower base to the direct SW. This generates a substantial variation in the flow structure in the region considered. Due to the fact that the gas pressure behind the conical discontinuity, and particularly near the particle track, is substantially lower than the pressure behind a planar discontinuity, the gas starts moving from the high pressure region behind the particle, and a dilution wave propagates on the opposite flow. The gas flow acquires a velocity in the dilution wave, and is then slowed under the action of the velocity thrust, and at a certain distance from the standing SW it turns into a vortex (Figs. 1b, 2b). Thus, two symmetric vortices, whose sizes increase with the particle motion, are formed behind the flying particles. A secondary SW is formed in the supersonic velocity region at the vortex system.

If the particles flying with the surface of the body flow interact with the SW head, we have behind it a simultaneous drop in pressure and temperature, leading, respectively, to a decrease in resistance of the flight apparatus, as well as to lowering of the thermal flux toward the walls. This interaction mechanism also occurs (Fig. 2) when the interparticle distance exceeds their characteristic size by 5 times and more. This fact, on one hand, justifies the assumption made above concerning flow in the "single" particle regime, and, on the other hand, implies that for variations in the flow structure in the SW zone the deviation between particles discarded from the body flow might be small.

The transmission problem of an SW front by particles moving toward the supersonic flow was first generated in experimental studies of flow around bodies filled by a hypersonic flow [4, 5]. It has been established that as a result of the interaction of the shock layer with particles rebounding from the flow surface an SW perturbation is generated.

The perturbations were manifested in the form of conical abrupt changes, traveling above the flow. The experimental technique used, however, did not allow for a complete explanation of the internal flow structure generated in the case, which, in turn, made it difficult to explain the effects observed. Thus, it was noted in [5] that a particle is not found in all perturbed sudden changes, and that in several cases, when there are no particles in the apex of the conical discontinuity, the apex is not closed. It was also established in [5] that the half-angles of conical perturbations with particles in the apex are smaller than the half-angles of the discontinuity opening, but there are no particles in the apex. This is also verified by the calculations described above: the SW front formed at the vortices are steeper than the conical discontinuity generated at the particle (see Figs. 1 and 2).

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MAGNETOIMPULSIVE GENERATION OF A CUMULATIVE COMPRESSION WAVE

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UDC 539.893+62—987/—988

The importance of obtaining high pressures is well known. Scientific investigators have achieved particularly significant results in this direction through dynamic methods based on the use of powerful shock waves generated by one means or another [1-4]. However, even if we ignore the specific difficulties inherent in these methods, they may not be usable because in many cases they require a smooth (non-shock) increase in pressure. The problem of obtaining such pressures is solved relatively easily by the use of magnetic fields. For example, [5] described experiments involving the isentropic compression of organic glass to 400 GPa by a magnetic field directed along the axis of a copper tube containing the test specimen. The magnetic field was intensified to a magnitude corresponding to a pressure of 400 GPa (~10 MG) by compressing it with a steel tube accelerated by products from the detonation of an explosive and positioned coaxially with the copper tube. A similar geometry was used in [6], which reported on the phase transformation of quartz to the super-dense state at a pressure of 125 MPa. This state had not been observed in tests with shock waves. The use of explosives in experiments of the type just described, however, may limit the range of application of this method of developing high pressures. Attention is thus being given to another possible use of impulsive magnetic fields: to compress the test substance with a shell

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 118-123, March-April, 1987. Original article submitted January 20, 1986.

0021-8944/87/2802-0272$12.50