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INFLUENCE OF INJECTION ON STABILIZATION OF FLOW OVER AN AXISYMMETRIC BODY WITH A RECESS FACING INTO A SUPERSONIC ONCOMING STREAM

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Numerical modeling of supersonic flow over a body with an annular step formed by two coaxial cylinders is performed by the Godunov method within the framework of the model of an ideal gas. Regimes of nonsteady streamline flow and peculiarities of the flow associated with the presence of a cylindrical recess in the nose part of the body are analyzed. The influence of the intensity of injection of an annular wall jet from the bottom of the recess on flow stabilization and the body drag is investigated. The domain of the existence of steady streamline flow is established.

The presence of a recess in the nose section of a supersonic aircraft, as is well known [1], can provide for the efficient functioning of a coaxially directed sensor placed at the bottom of the recess. In earlier studies, however, flow of an oscillating nature was found in the vicinity of a coaxial cylindrical recess in a conical nose [2] and a cylinder [3]. When the geometry of the recess differs from cylindrical, flow of a nonsteady nature is also observed [4]. In [5] it was shown, using the example of flow over a hollow cylindrical body (a cup), that injection of an annular jet from the bottom of the recess against the oncoming stream can stabilize the flow.

In the present work, we performed a numerical investigation of supersonic flow over a cup mounted on the end of a round cylinder. An annular jet was injected opposite to the oncoming stream from the bottom of the cup. The influence of the injection intensity on flow stabilization and the drag of the configuration was studied.

1. We consider the flow over a cup–cylinder configuration by a stream of ideal gas with a Mach number $M_\infty = 3.7$. The length of the cup is $l/d = 1.6$, its wall thickness is $\delta/d = 0.04$, as in [3, 5], and the cylinder diameter is $D/d = 3.2$ (d is the diameter of the cup).

The system of gas-dynamic equations in Eulerian form, written in the cylindrical coordinate system, was given in [5]. The quantities were made dimensionless as follows:

$$r = \frac{\bar{r}d}{2},\quad x = \frac{\bar{x}d}{2},\quad t = \frac{\bar{t}d}{2a_\infty},\quad a = \bar{a}a_\infty,\quad u = \bar{u}a_\infty,\quad v = \bar{v}a_\infty,\quad \rho = \bar{\rho}\rho_\infty,\quad p = \bar{p}\rho a_\infty^2.$$

Here p is the pressure, ρ is the density, u and v are the components of the velocity vector along x and r (we assume that the component along the angle φ in this coordinate system equals zero), t is time, and a is the speed of sound.

For the initial data in calculations without injection we set the dimensionless parameters of the undisturbed oncoming stream:

$$p = p_\infty = 1/\gamma,\quad \rho = \rho_\infty = 1,\quad u = u_\infty = M_\infty,\quad v = 0$$

(γ is the adiabatic constant, equal to 1.4 in the calculations). Here and below, the bar above the dimensionless quantities r, x, t, a, u, v, ρ, and p is omitted.

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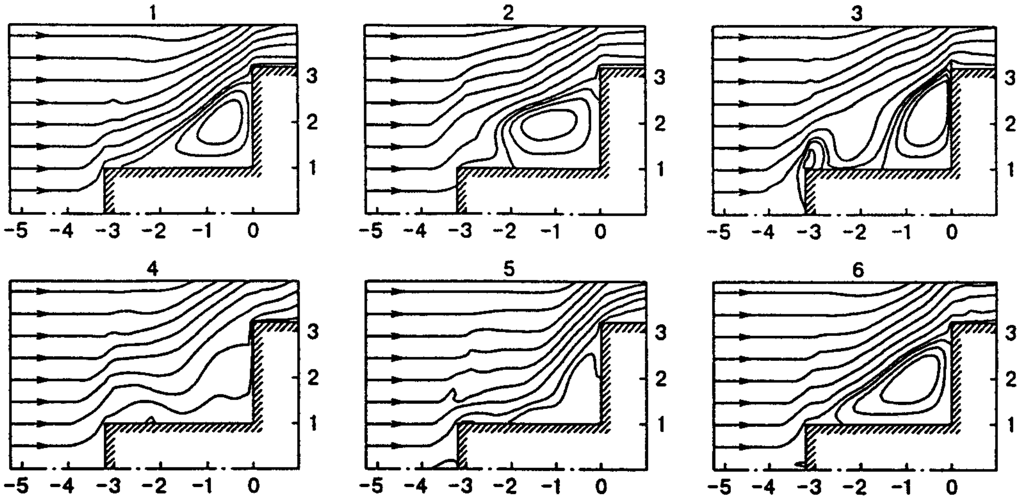

Fig. 1. Time variation of the location of streamlines in flow over the cylinder–cylinder configuration: $t = 80.8$, 83.8, 84.4, 85.0, 87.6, and 91.3 (fragments 1–6, respectively).

As the boundary conditions we adopt the conditions of nonpenetration at the surface of the body and the conditions characterizing the oncoming stream [5].

When injection was present at the body, we specified conditions of escape of the jet at sonic velocity, $M_j = 1$. The parameters of the jet were sent to the corresponding grid cells at the surface of the body. The injection intensity $k = \rho_j u_j^2 / \rho_\infty u_\infty^2$ was varied in the range 0.5–1.

We considered the injection of an annular wall jet with outside and inside diameters in outflow plane $d_1/d = 0.92$ and $d_2/d = 0.84$, and outflow parameters $u_j = -1$, $v_j = 0$, $\rho_\infty = kM_\infty^2$, and $\gamma_j = 1.4$ similar to those of [5]. As the initial data we used the fields of the gas-dynamic parameters obtained in a calculation without injection.

The numerical modeling was done by the Godunov method [6]. The basis for such a choice was given in [5, 7]. The calculations were made on a 60×70 grid. The distribution of grid nodes within the recess was made uniform. The ratio of sizes of the sides of a grid cell in the recess was $\Delta r/\Delta x = 0.4$ (24 nodes in the transverse and 33 nodes in the longitudinal direction). In [5], it was found that for such a ratio $\Delta r/\Delta x$, the results of a calculation of flow over a cup are close to the experimental data of [3] for $Re_\infty = 5 \cdot 10^5$.

2. It is well known [8] that the flow over a cylinder with a nose needle will be nonsteady if the ratio of the needle length to the cylinder diameter corresponds to the ratio of the cup length to the cylinder diameter adopted in the present work, $l/D = 0.5$. The flow over a needle–cylinder configuration is also largely determined by the ratio of the needle diameter to the cylinder diameter and the geometry of the needle. Conical or cylindrical bodies (sharpened, spherically blunted, or with a flat end, but with no recess) have been used as the needle. It can be expected that the character of flow over the cup–cylinder configuration under consideration will also be determined not only by nonsteady processes in the recess but also by the ratios of the length and diameter of the cup to the cylinder diameter (l/D and d/D). However, there are no literature data on flow over a cylinder with a needle having a "relative" diameter d/D corresponding to the "relative" cup diameter adopted in the present work. We note that "thin" needles ($d/D \sim 0.1$) have been considered in studies of nonsteady flow over bodies with a needle. In this connection, we made a preliminary calculation of a cylinder–cylinder configuration (we replaced the cup by a solid cylinder with the same length and diameter as those of the cup). We found that the flow over a cylinder–cylinder configuration has a nonsteady nature and is comparable to flow over a cylinder with a short needle. A review of papers which deal with flow over bodies with needles is given in [8].

Figure 1 gives a series of fragments of the calculation region, illustrating the time variation of the location of the streamlines. It is seen that the flow in the vicinity of the end of the cylinder of the larger

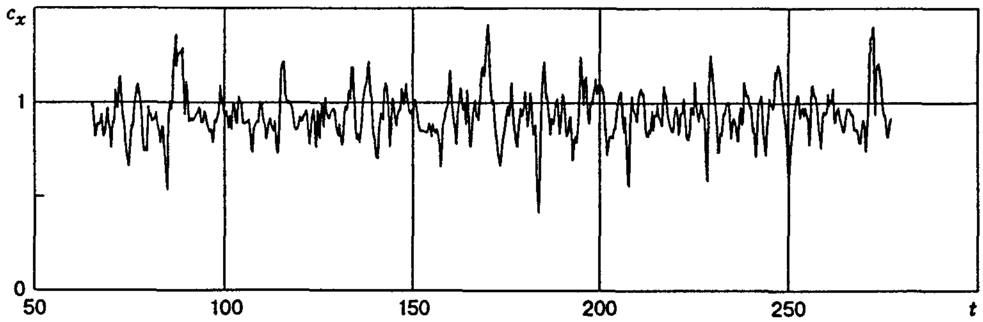

Fig. 2. Time variation of the drag coefficient of the cylinder–cylinder configuration.

diameter is detached. The point of flow separation lies at the lateral surface of the smaller cylinder somewhat downstream from its rim. A well-developed region of return-circulation flow is formed in the vicinity of the end of the larger cylinder and the lateral surface of the smaller cylinder. The attachment point of the flow lies on the end of the larger cylinder somewhat below its leading edge. As in the flow over a body with a needle, the pulsations have a diverging character. They arise from disruption of the balance between the gas thrown into the separation zone at the attachment point and the gas leaving it.

The experiments of [9] showed that one can distinguish two flow regimes that differ in the character of change in the shapes of the separation region during pulsations, the averaged pressures and heat fluxes to the surface of the body, and the spectral characteristics of the pressure oscillations. A flow regime without a noticeable change in the shape of the stagnant zone was called a regime of the first kind by Antonov and Gretsov [9]. The other regime, with strong changes in the shape of the separation zone, is called a regime of the second kind. In a transition from the first to the second regime, the pressure and the character of its distribution over the surface of the body change abruptly.

For the cylinder–cylinder configuration, we can also distinguish two characteristic flow regimes, which follow one another periodically. Figure 1 shows the positions of streamlines at times before and after the transition from the first regime to the second. It is seen that before the transition (fragment 1), the volume of the stagnant zone varies slightly and it remains approximately conical, although its boundary becomes now convex and now concave, and the positions of the separation points also oscillate with a low amplitude. The drag coefficient c_x of the cylinder–cylinder configuration in this flow regime varies in the range of 0.65–1.15.

After the transition (fragments 2–4), the flow separation point shifts toward the end of the cylinder of the larger diameter, the boundary of the stagnant zone becomes convex, and its volume decreases. By the time $t = 85.0$ (fragment 4) it has broken up, after which a new stagnant zone is formed (fragments 5 and 6). The drag coefficient in this flow regime varies in the range of 0.5–1.4.

The duration of the second flow regime (the process of breakup of the old stagnant zone and formation of the new one) is $\Delta t_2 \approx 9$, which is considerably less than the duration of the first flow regime. Figure 2 shows the time variation of the drag coefficient of the cylinder–cylinder configuration. One can see that the maximum amplitudes of c_x, corresponding to the breakup and formation of the stagnant zone, are observed at time intervals $\Delta t_1 \approx 80$–100. The calculation was carried out up to $t \approx 500$.

3. The flow over the cup–cylinder configuration (without jet injection) has an essentially nonsteady character. As in the flow over a cup [3, 5], stable pressure and density pulsations are observed in the recess. The main characteristics of the process (the average standoff distance of the shock wave, the amplitude of pressure pulsations, and the oscillation period) are close to the calculated [5] and experimental data [3] for $\mathrm{Re}_\infty = 5 \cdot 10^4$. Figure 3 gives the pressure variation at the center of the bottom of the cup. The crosses mark the calculated results for flow over a cup obtained in [5] on a 60×40 grid ($\Delta r/\Delta x = 0.4$). The oscillations are established at times $t \approx 750$. The Strouhal number in the steady regime is $\mathrm{Sh} = s/a_0\tilde{t} \approx 0.22$ ($\tilde{t}$ is the oscillation period, a_0 is the speed of sound at the stagnation temperature, $s = (l + \tilde{\Delta})$ is the characteristic length, and $\tilde{\Delta}$ is the average standoff distance of the bow shock from the rim of the cup). We note that

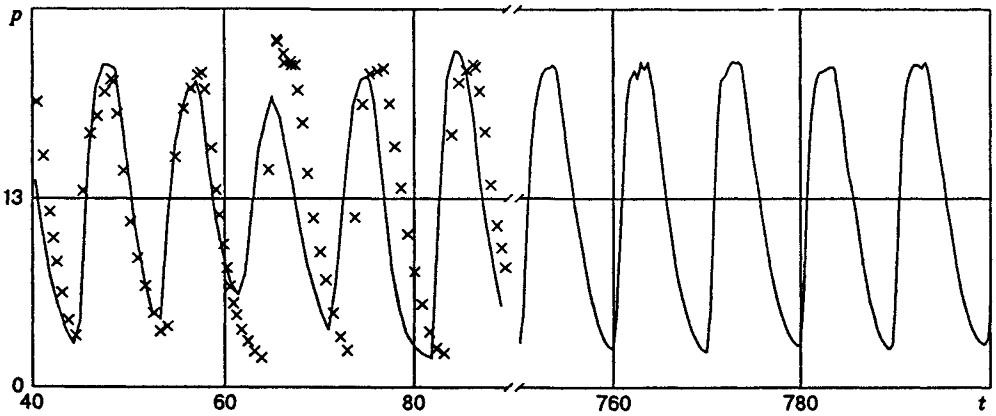

Fig. 3. Pressure variation at the center of the bottom of the cup: solid curves for flow over a cup-cylinder configuration; crosses for flow over a cup [5].

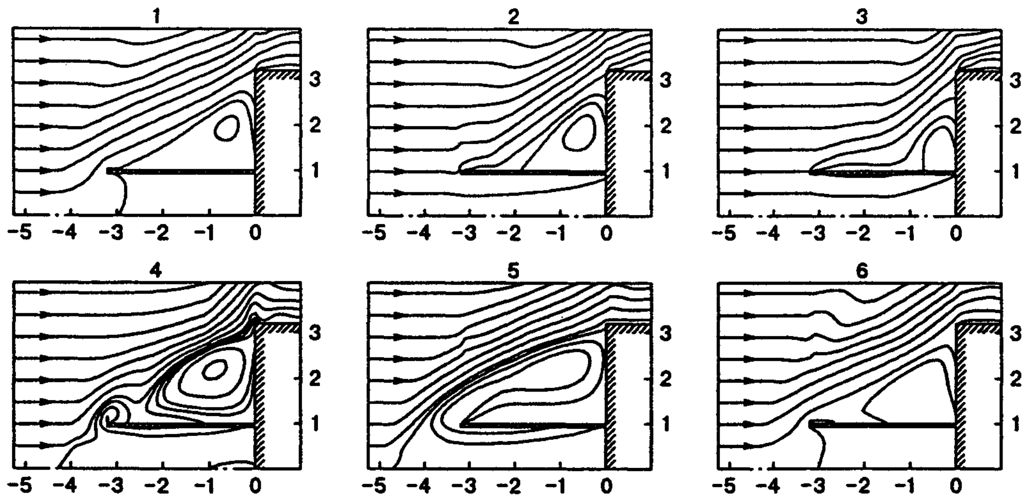

Fig. 4. Time variation of the location of streamlines in flow over a cup–cylinder configuration: t = 778.8, 780.2, 781.7, 784.2, 786.9, and 788.3 (fragments 1–6, respectively).

Sh = 0.237 was obtained in [5] for flow over a cup on the same grid.

The shape of the stagnant zone in the vicinity of the end of the cylinder undergoes significant changes in the process of pulsations. Figure 4 illustrates the variation of the positions of streamlines over one oscillation period. It is seen that before the onset of gas flow into the recess (fragment 1), the shape of the stagnant zone is approximately conical, its boundary is convex, the flow separation point lies on the lateral surface of the cup in the vicinity of its rim, and the attachment point lies on the end of the cylinder. In the process of gas inflow into the recess, the stream separation point shifts from the rim of the cup toward the end of the cylinder, while the volume of the stagnant zone is considerably reduced (fragments 2 and 3).

As gas flows out of the recess, the volume of the stagnant zone increases and the separation and attachment points shift toward the rims of the cup and cylinder, respectively (fragment 4). The gas jet flowing out of the recess then merges with the stagnant zone (fragment 5). After the pressure drops in the recess (fragment 6), gas outflow ends and a new cycle begins. During the pulsations, the drag coefficient c_x of the cup–cylinder configuration varies in the range of 0.5–1.8

4. As noted in [5], injection of an annular jet orients the velocity vector in the boundary region near the wall of the recess opposite to the oncoming stream, which favors damping of pulsations in the supersonic gas

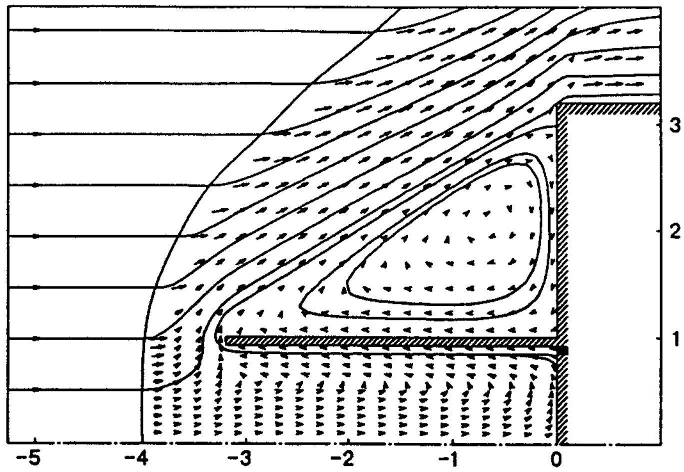

Fig. 5. Field of velocity vectors and positions of streamlines and the bow shock wave in the steady regime ($k = 0.7$) for the cup–cylinder configuration with the injection of an annular wall jet from the bottom of the recess.

flow over the cup. In the present work, we performed a series of calculations of the flow over the cup–cylinder configuration with injection of an annular wall jet of different intensities from the bottom of the recess. The injection intensity was increased with a step of $\Delta k = 0.1$ in the range $k = 0.5$–0.7.

It was established that the variations in the pressure at the center of the bottom of the cup and in the standoff distance Δ of the shock wave from the cup rim (normalized to the cup radius) as functions of the injection intensity are similar in character to the variations of these parameters obtained in [5]. At an injection intensity $k = 0.5$–0.6, for example, a considerable decrease in the amplitude of pressure pulsations is observed, while at $k = 0.7$ the pressure variation in the steady regime (at $t > 400$) was less than 0.001%. The standoff distance of the bow shock from the cup rim $\Delta \approx 0.8$ practically does not change with variation of the injection parameter k.

Figure 5 shows a fragment of the calculation region with the field of velocity vectors and the positions of the streamlines and the bow shock in the steady regime for an injection intensity $k = 0.7$. The well-developed region of return-circulation flow at the end of the cylinder and at the lateral surface of the cup is seen. The flow attachment point lies on the end of the cylinder, somewhat below its edge. A further increase in injection intensity leads to a shift in the attachment point toward the edge of the cylinder's end. For $k > 0.875$, we were unable to obtain a steady solution. Obviously, as the attachment point approaches the edge of the cylinder's end, the system's sensitivity to any kind of perturbation increases. This can disrupt the balance between the gas entering the region of return-circulation flow and the gas leaving it and induce pulsations. With variation of the injection intensity k in the range of 0.7–0.875, the drag coefficient c_x of the cup–cylinder configuration has the following values for the steady flow regime:

k	0.700	0.750	0.800	0.850	0.875
c_x	0.731	0.724	0.719	0.714	0.712

Thus, the results of our numerical investigation lead to the following conclusions:

• The nonsteadiness of the flow over the cup–cylinder configuration (without injection) is due to pulsations in the recess and pulsations of the return-circulation zone in the vicinity of the end of the cylinder;

• The main characteristics of the pulsations in the recess of the configuration considered are comparable to those obtained in [3, 5] for flow over a cup;

• The pulsations of the return-circulation zone are coordinated with the pulsations in the recess, in contrast to pulsations of the return-circulation zone in flow over a configuration without a recess, where two pulsation regimes are observed that follow one another periodically.

• The injection of an annular wall jet from the bottom of the recess leads to a considerable decrease in the pulsation amplitude for $0.5 \leqslant k < 0.7$.

A steady flow pattern is observed in the range of injection intensities $k = 0.7$–0.875. With a further increase in injection intensity (calculations were performed up to $k = 1$), the pulsations occur again, which is associated with the instability of the return-circulation zone as the flow attachment point approaches the edge of the cylinder's end.

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