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THREE-DIMENSIONAL STRUCTURE OF FLOW IN A SUPERSONIC UNDEREXPANDED JET

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Schlieren photographs of supersonic nonisobaric jets emanating from an axisymmetric nozzle into a flooded space clearly show longitudinal bands, whose origin has not been explained in the literature. Comparing the observed longitudinal bands in a jet with analogous bands arising in the case of subsonic flow past concave surfaces suggests that these phenomena are similar. The three-dimensional perturbations on concave surfaces consist of longitudinal Taylor–Goertler vortices, whose axes are parallel to the velocity vector of the undisturbed flow [1-6]. The vortices most likely form as a result of instability of the boundary layer owing to the curvature of the streamlines on the concave wall or in the region of attachment of the detached flow. The formation of vortices causes the distribution of the gas-dynamic quantities on the surfaces over which the flow moves to be nonuniform [7, 8]. It is proposed that the alternation of dark and light colored longitudinal bands in the photographs of both rarefied [9, 10] and dense [11-13] jets is caused by the development of coherent structures of the type Taylor–Goertler vortices in the flow. The presence of longitudinal vortex structures should result in nonuniformity of the distribution of gas-dynamic quantities in the jet.

The experimental investigations performed in this work are concerned with the study of this nonuniformity in a supersonic underexpanded jet.

The spatial nonuniformity was investigated by the method of photographing and measurement of the total and static pressures in the flow region lying between the suspended shock and the boundary of the jet in the so-called compressed layer [13]. For this we chose a supersonic axisymmetric jet whose Mach number in the outlet section of the nozzle is equal to $M_a = 1.5$ in the efflux regime with underexpansion ratio n = 10. The jet flowed out of a conical nozzle with exit diameter $d_a = 1.4 \cdot 10^{-2}$ m and aperture half-angle 8°. The Reynolds number of the jet, calculated with respect to the parameters in the outlet section of the nozzle, is $R_a \sim 10^6$. The jet setup is equipped with an IAB-451 optical system, with whose help schlieren photographs of supersonic nonisobaric jets were obtained with an exposure time $\tau = 2 \cdot 10^{-2}$ sec. The total and static pressures were measured with the help of the corresponding standard axisymmetric pressure pickups with openings $3 \cdot 10^{-4}$ m in diameter. The cylindrical static-pressure pickup had four openings, positioned at a distance of eight units from the vertex of the conical head. In order to reduce the error of measurement the angle of inclination of the pickups with respect to the axis of the jet was equal to the

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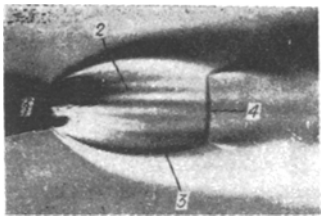

Fig. 1

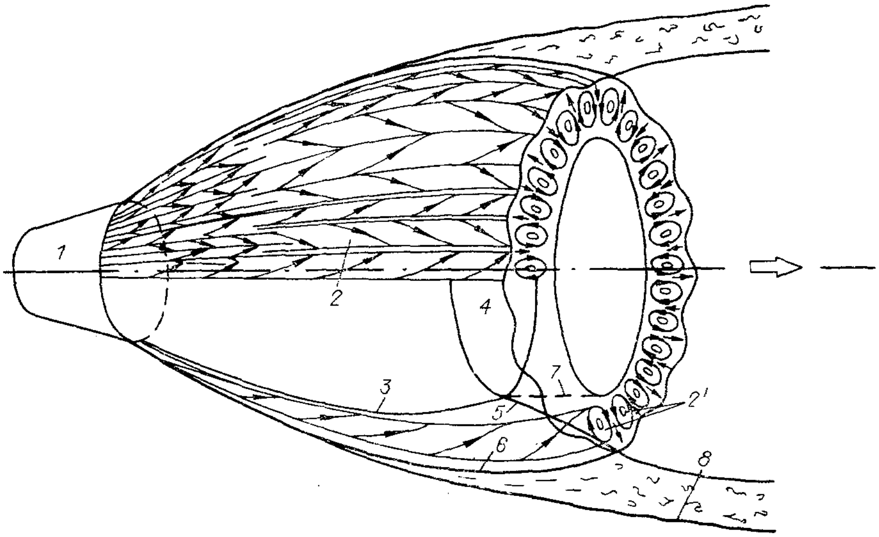

Fig. 2

angle of inclination of the tangent to the proposed streamline at the center of the compressed layer of the jet (the angle of inclination of the tangent is determined from the schlieren photographs). The displacement of the pressure pickups was measured in cylindrical coordinates, of which the coordinate x was directed along the axis of the jet, r was directed along the radius of the jet, and the peak of the polar angle φ was located on the axis of the jet. The pressure pickup was moved in discrete steps along x and r and continuously along the coordinate φ within the range of the polar angle from 0 to 53°. The measuring system consisted of an inductive pressure pickup of the type DMI and a secondary apparatus. The rms error of the system did not exceed ±3%. The measurements showed that the total pressure depends on all three coordinates and the static pressure depends on x and r.

Figure 1 shows a schlieren photograph of a supersonic underexpanded jet flowing out of the nozzle 1. Figure 2 shows the approximate structure of the flow in the jet. In both figures the basic elements of the initial section of the underexpanded jet are designated identically. A characteristic feature of the flow structure shown is the vortex layer 2, consisting of a finite number of vortices 2' rotating in opposite directions. In the schlieren photograph a vortex layer appears in the form of dark- and light-colored longitudinal bands. In Figs. 1 and 2 the numbers 3-5 designate a suspended, central, and reflected shocks, respectively; the number 6 designates the boundary of the supersonic jet; 7 designates the contact discontinuity; and 8 designates the subsonic boundary of the jet. The proposed flow scheme in the jet is confirmed by experimental results, which are analyzed and discussed below.

Figure 3 shows plots of the azimuthal distribution of the total pressure behind the normed shock P_0' in the compressed layer of the jet. The results were obtained in the transverse section of the jet located at a distance $x_2 = 5.23r_a$ from the outlet section of the nozzle (r_a is the radius of the outlet section of the nozzle). Each curve in Fig. 3 corresponds to a definite radial distance from the axis of the jet to the total-pressure pickup. The relative values of the parameter $\bar{r} = r/r_a$ are as follows: 1) 3.70; 2) 3.50; 3) 3.34; 4) 3.24; 5) 3.07; 6) 2.92; 7) 2.90; 8) 2.80; 9) 2.73; 10) 2.50. The curve 1 was obtained by measuring the total pressure on the arc of a circle near the boundary of the

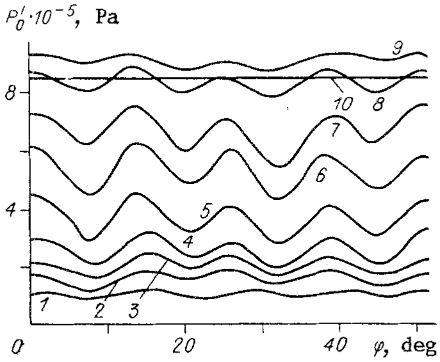

Fig. 3

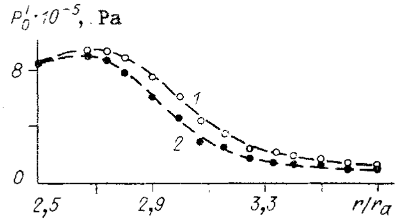

Fig. 4

jet and the curve 10 was obtained near the suspended shock. As follows from the graphs, the azimuthal distribution of the total pressure for r_1 and r_{10} does not depend or depends only weakly on φ. For the other radial distances, falling between these curves, the total pressure of the supersonic flow in the compressed layer of the jet is distributed nonuniformly over the azimuthal coordinate. The nonuniformity consists of a periodic alternation of the maximum and minimum values of the gas-dynamic quantity, and in addition the extrema on the wavy curves are recorded at approximately the same angles of rotation of the pressure pickup. The Mach number of the flow in the compressed layer of the jet, calculated from the measured total and static pressures, exhibits the same periodic nonuniformity of its distribution over the coordinate φ.

Graphs of the radial distributions of P_0' and M within the compressed layer of the jet are presented in Figs. 4 and 5. They were constructed based on the average maximum and minimum values of these quantities for φ ranging from 0 to 53°. The nonuniformity of the distribution of the gas-dynamic quantities is expressed in the separation of the curves into maximum 1 and minimum 2 values. Joining of the curves, which indicate equalization of P_0' and M in the flow, occurs in the subsonic boundary layer of the jet, on the one hand, and near the suspended shock on the other. The difference between the maximum and minimum values characterizes the degree of nonuniformity of the distribution of the gas-dynamic quantities in the compressed layer of the jet. The nonuniformity of the distribution of the gas-dynamic quantities is greater in the sections located closer to the nozzle than in more distant sections. Thus, the largest deviations of the total pressure in front of the direct shock P_0 and M at the extrema of the periodic curves in the sections x_1, x_2, and x_3 are equal to, respectively, $\Delta P_0 = P_{0max} - P_{0min} \approx 5.6 \cdot 10^5$; $4.3 \cdot 10^5$; $1.3 \cdot 10^5$ Pa, $\Delta M = M_{max} - M_{min} \approx 0.45$; 0.4; 0.2. The degree of nonuniformity of the distribution of the gas-dynamic quantities in the compressed layer of the first "barrel" of the unexpanded jet is equal to 10-22% of the average; this agrees with the data obtained on surfaces in the flow [7].

It follows from the analysis of the experimental data that the spatial distribution of P_0 and M in the flow in the compressed layer of the jet is nonuniform. Such a distribution of the gas-dynamic quantities in a boundary layer on surfaces in a flow is caused by Taylor–Goertler vortices [3, 6-8].

Therefore, the periodic change in the gas-dynamic quantities along the azimuth of the periphery of the jet and the nonuniformity of the distribution of the optical density in the schlieren photographs (longitudinal bands) could be caused by the presence of longitudinal vortices of the Taylor–Goertler type in the jet (see Figs. 1 and 2). The oppositely rotating vortices in the jet, as also on surfaces in a flow, form in the compressed layer a stable spatial vortex structure, which is superposed on the main flow of the compressed layer of the jet. Because the vortices rotate in opposite directions there form between the vortices longitudinal planes to which either high-head or low-head flows are drawn. In the transverse sections of the jet these planes correspond to radial lines, with the passage of which the pickup periodically records maximum or minimum values of the total pressure. The boundary (the isosurface with M = 1) becomes deformed as a result of the periodic immersions of high- and low-head flows on the boundary of the jet. From Fig. 5 it follows that the low-head flow (curve 2) reaches M = 1 on the boundary of the jet at shorter radial distances than the high-head flow (curve 1). For this reason, in the tranverse section the supersonic boundary (M = 1) acquires a relief-type form (as shown schematically in the upper

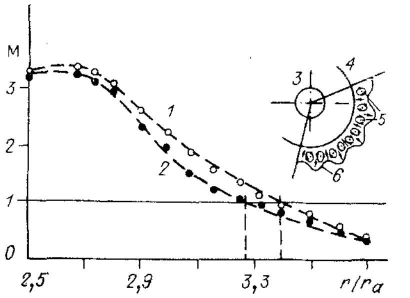

Fig. 5

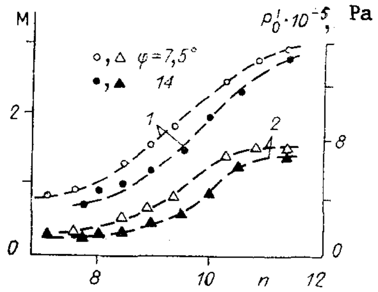

Fig. 6

right-hand corner of Fig. 5, where 3 is the nozzle, 4 is the suspended shock, 5 is the cross section of the vortices, and 6 is the boundary of the jet). An analogous distribution of P_0' and M in the compressed layer of the jet is obtained in the sections $x_1 = 2.29\ r_a$, $x_3 = 10.1\ r_a$, and $x_4 = 15.93\ r_a$ [14].

It was established that the vortex structure is stable with respect to a change in the state of efflux of the supersonic jet. The stability of the vortex layer accompanying a change of the underexpansion ratio of the jet made it possible to perform measurements along the radial lines, corresponding to the maximum and minimum values of the gas-dynamic quantities. The angle of rotation of the total-pressure pickup was set so that either P_{0max}' or P_{0min}' was measured. The fact that the measurements were repeated many times did not destroy the smoothness of the curves presented in Fig. 6 (the line 1 depicts the Mach number and the line 2 depicts the pressure).

The schlieren photographs of the jet show that the number of longitudinal bands is larger near the nozzle than at the end of the "barrel," i.e., the width of the bands tends to increase and the number of bands tends to decrease downstream along the jet. Each vortex in the jet is recorded in the schlieren photograph in the form of dark- and light-colored bands. If the azimuthal variation of the pressure is known, then it is not difficult to determine the number of vortices in the sections of the jet, since a vortex pair lies between two adjacent maxima or minima. The approximate number of vortices in the corresponding sections of the initial part of the underexpanded jet was determined from the plots of $P_0'(\varphi)$ (see Fig. 3). Thus, there are 84 vortices in the section x_1, 56 vortices in the section x_2, and 28 vortices in the sections x_3 and x_4. In order that the directions of the local velocity vectors of the adjacent vortices coincide, the number of vortices in any section of the jet must be even. As the distance from the nozzle increases the longitudinal vortices grow in size as a result of merging.

Thus, the results obtained in this investigation of the nonuniformity of the distribution of gas-dynamic quantities in an underexpanded jet are consistent with the hypothesis that in the compressed layer of nonisobaric jets there exist vortex formations of the type Taylor–Goertler vortices.

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