STUDY OF THREE-DIMENSIONAL WAVE STRUCTURE OF NONSTATIONARY GAS OUTFLOW FROM A PLANAR SONIC NOZZLE

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Results are reported of an experimental study of the three-dimensional structure of nonstationary gas outflow from a planar nozzle. Outflow of a heated shock wave in a nitrogen tube at different moments of time from the start of outflow (0-1 msec) in two mutually perpendicular directions is considered. A scheme for reconstructing the flow at different outflow stages is proposed. The dimensions of the Riemann wave are found to oscillate.

Jets flowing out of an axisymmetrical nozzle have been studied in many experimental and computational works. Papers dealing with planar jets are significantly fewer in number. Studies of planar flows undertaken by a number of authors [1-3] have revealed a number of features of outflow from a planar nozzle contrasting with that from an axisymmetrical nozzle. In particular, a generalized equation was obtained for determining the distance to the Mach disk in an axisymmetrical jet or Riemann wave (analog of the Mach disk) in a planar jet [3]. This equation reflects the experimentally established fact that the distance h in planar outlfow is independent of the adiabatic index γ, whereas $h \sim \sqrt{\gamma}$ for an axisymmetrical jet.

Data in published works on the numerical and experimental study of three-dimensional jets are few and far between. This is due not only to an increase in the dimensionality of the problem, but also to the occurrence of complex surfaces of discontinuity in the flow. However, interest in the characteristics of three-dimensional jets has grown in connection with their expanded use in aircraft flight control diagrams, fluidics, etc.

Jets flowing out of elliptical and nearly rectangular nozzles were calculated numerically in [4]. The calculated flow had a rather complex spatial structure.

One author [5] who considered the formation of flow from a stationary supersonic gas source within the framework of the theory of an ideal liquid noted that regimes are possible in which a secondary shock wave travels downstream from its stationary position and only subsequently returns to it.

Nonstationary flow structure has been experimentally studied [6, 7] for outflow from a planar nozzle. The jets were considered relative to the direction of the major axis of the nozzle, and consequently transformation of the jets in the plane of the major axis of the nozzle was not studied.

The current work was carried out using a shock tube measuring 40×40 mm^2 in cross section with a low-pressure chamber 4.0 m in length. The flow pattern was visualized by an IAB-451 shadow-indication instrument. A planar sonic nozzle with thickness $b = 1.5$ mm and length $a = 40$ mm, through which shock-wave heated gas flowed into an altitude chamber $400 \times 400 \times 600$ mm in volume, was mounted at the end of the shock tube. The pressure-equalization chamber was filled with nitrogen to 27 mm Hg, and nitrogen was also used as the drive gas. A tube regime was selected in which the Mach number of the incident wave $M_1 = 3$.

Under these conditions the resulting "core" of shock-wave heated gas will flow into the altitude chamber within about 5 msec. But it is impossible to consider the retardation parameters to be constant over the same

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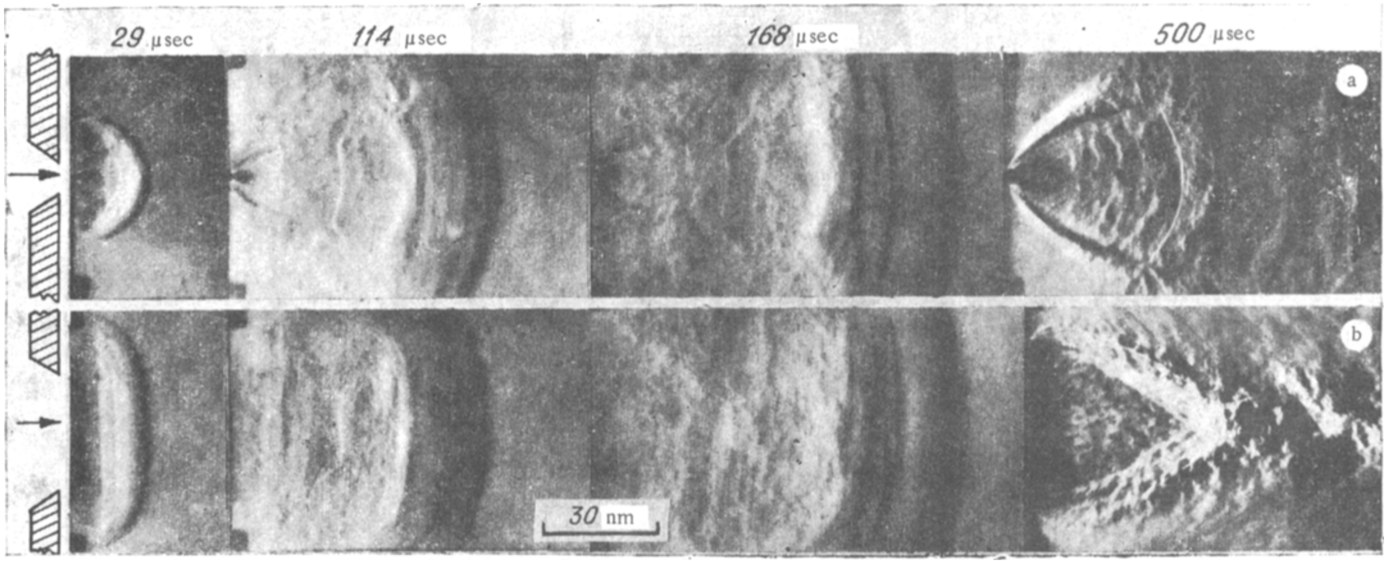

Fig. 1

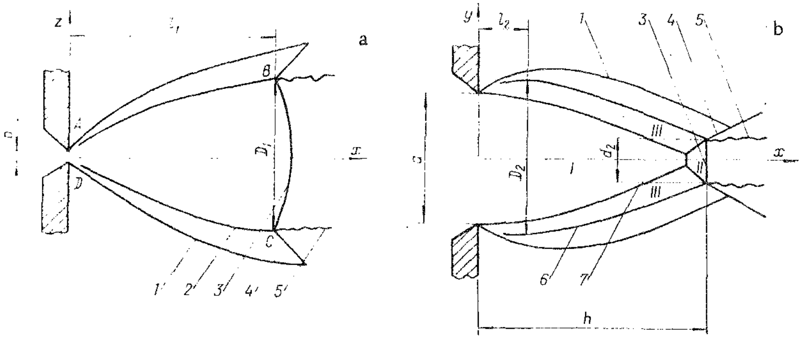

Fig. 2

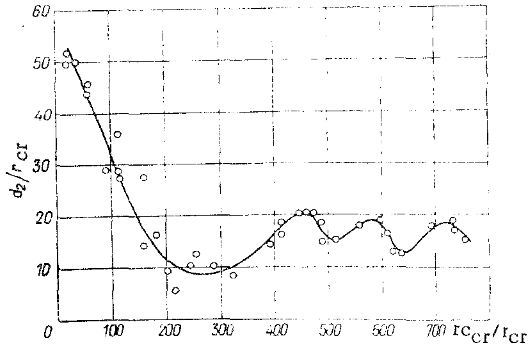

Fig. 3

period of time. The earliest disturbance of the state of the gas at the end of the shock tube is induced by a wave resulting from the interaction of the contact surface and the reflected shock wave.

The arrival time of this disturbance at the end of the shock tube can be calculated using H. Mirels' theorem.

The total working time at the end of the tube amounts to 500 μsec, as calculated for our conditions using previous [8] results. The critical cross-sectional area of the nozzle is 4% of the tube end face, allowing us to consider the gas parameters at the end face constant during the working time. Total pressure and temperature at the end face are $p_0 = 1400$ mm Hg and $T_0 = 1300$°K, respectively, for these operating conditions of the shock tube.

Two series of experiments were carried out to study the nonstationary structure of a three-dimensional jet. In the first series, the major axis of the nozzle was mounted parallel to the optical axis of the shadow-indication instrument (Fig. 1a), while in the second series it was perpendicular to it (Fig. 1b).

The synchronization system allowed the process to be photographed at different but pairwise equal moments of time from the start of outflow. This made it possible to construct a spatial model of jet outflow from a planar nozzle for different moments of time.

It should be noted that definite difficulties may arise in analyzing the Toepler patterns of three-dimensional flow, since a single photograph may depict both the barrel shocks and the projection of the regions within which the barrel shocks interact on a given plane.

Figure 2a depicts the scheme of the initial jet section considered along the major axis of the nozzle, while Fig. 2b depicts the scheme along the minor axis of the nozzle. The digits in both projections denote the boundaries of the jet (1), a cylindrical barrel shock (2), Riemann wave (3), reflected shocks (4), sliding surface (5), and projection of the region of interaction (7) of barrel shocks visible in Fig. 2a with spatial barrel shock (6) on the plane of the major axis.

Let us consider a schematic representation of the initial jet segment along the minor axis of the nozzle (Fig. 2b). Three regions are depicted in the scheme:

Region I, the projection on the yx-plane of the surface of the cylindrical barrel shock, whose trail on the zx-plane is AB and DC.

Region II, the projection of the Riemann wave BC on the yx-plane.

Region III, the projection of the barrel shocks bounding the jet from the side, i.e., in the ±y direction.

It should be noted that unlike the barrel shocks AB or DC, whose surface is cylindrical, the surface of the lateral barrel shocks is a complicated three-dimensional surface. Cylindrical segments also form on it as the ratio a/b decreases, both projections of the jet subsequently becoming qualitatively similar.

The influence of rarefaction waves disrupting the jet is manifested more rapidly along the y axis than along the z axis as the overpressure parameter $n = pa/p\infty$ increases. This leads to the width d_2 of the Riemann wave decreasing with increasing n, given the same outflow phase, and the distance from it to the nozzle section (h) increasing.

Let us estimate the degree of expansion of the jet in the direction of the y and z axes under our outflow conditions, based on a measurement of the maximal dimensions of the barrel shocks in the corresponding planes. It is evident that a jet in the direction of the y axis expands insignificantly and that the maximal dimension of the major axis in the plane is near the nozzle section.

If we consider the corresponding critical nozzle dimensions as the characteristic dimension in the zx- and yx-planes, we find that $D_2/a = 1.2$ when $l_2/a = 0.21$, whereas $D_1/b = 29$ and $l_1/b = 27$. Such behavior of the jet can be explained by analyzing the interaction of rarefaction waves arising as the nozzle edges are streamlined. When $a/b = 27$, rarefaction waves formed as the long nozzle edges are streamlined reduce the pressure more rapidly in a neighborhood of the intersection of the jet boundary with the plane of the major axis than in a corresponding intersection with the plane of the minor axis.

A dependence was constructed as a result of processing a large series of Toepler diagrams for the width d_2 of the Riemann wave on outflow time (Fig. 3). The curve was constructed with dimensionless coordinates $t = \tau c_{cr}/r_{cr}$, $d_2 = r_{cr}$, where c_{cr} is the speed of sound in the critical section and $r_{cr} = b/2$.

Thus the spatial wave structure of flow at different outflow stages was reproduced, based on an experimental study of a nonstationary jet outflowing from a planar nozzle. Our scheme for reconstructing the flow also allows us to construct the wave structure of the gas-driven jet segment for stationary outflow based on published experimental data. The resulting nonstationary wave structure is transformed in space and time to a model of stationary outflow from a computationally obtained rectangular nozzle. The dimensions of the Riemann wave are established as a result of an oscillatory process.

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TYPES OF WAVE STRUCTURE IN THE INTERACTION OF A CONVERGENT JET WITH AN INFINITE TWO-DIMENSIONAL OBSTRUCTION

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Possible types of wave structure formed in the first roll of a convergent supersonic jet as it interacts with an infinite two-dimensional object are indicated in this work based on a generalization of results from theoretical and experimental studies. The influence of the Mach number, overpressure parameter n, isentropic exponent k, and the location h of the obstacle on the wave structure is considered.

§1. The interaction of jet efflux into a vacuum ($n = \infty$) from an infinite two-dimensional obstacle [1, 2] beyond the point of reflection from the first characteristic axis AB (BD is the reflection characteristic) of a rarefaction fan (Fig. 1) has been studied chiefly theoretically.

It has been indicated [1] that the influence of flow irregularity at a nozzle exit is substantial only in direct proximity to it and does not alter the qualitative flow pattern. A shock wave concave with respect to the nozzle is formed in front of the obstacle (central shock wave). Two types of flow distinguished by the configuration of the Mach line are possible behind the shock [1].

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