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.

LITERATURE CITED

1. W. Shiren and D. Dosange, "Study of a jet outflowing from a two-dimensional convergent nozzle," Raketn. Tekh. Kosmonavt., 6, No. 3 (1968).
2. M. Whirl, D. Schaffer, and R. Driftmayer, "Central shocks in free jets," Raketn. Tekh. Kosmonavt., 8, No. 12 (1970).
3. R. Driftmayer, "Correlation of parameters of free jets," Raketn. Tekh. Kosmonavt., 10, No. 8 (1972).
4. M. Ya. Ivanov, A. N. Kraiko, and V. P. Nazarov, "Certain results of a numerical study of off-design spatial jets of an ideal gas," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 4 (1972).
5. G. A. Simons, "The large time behavior of a steady spherical source expanding into an arbitrary ambient gas," AIAA Paper, No. 232 (1970).
6. V. A. Belavin, V. V. Golub, I. M. Naboko, and A. I. Opara, "Study of the nonstationary structure of flow for an outflowing shock-wave heated gas," Zh. Prikl. Mekh. Tekh. Fiz., No. 5 (1973).
7. I. M. Naboko, E. M. Kudryavsev, A. I. Opara, and V. V. Golub, "Structure of the flow of shock-wave heated gas under the conditions of a pulsing gas-driven laser," Teplofiz. Vys. Temp., No. 1 (1971).
8. A. V. Eremin, I. M. Naboko, and A. I. Opara, "Total working time in a shock tube when studying outflow from a hole in the end face," Teplofiz. Vys. Temp., No. 4 (1973).

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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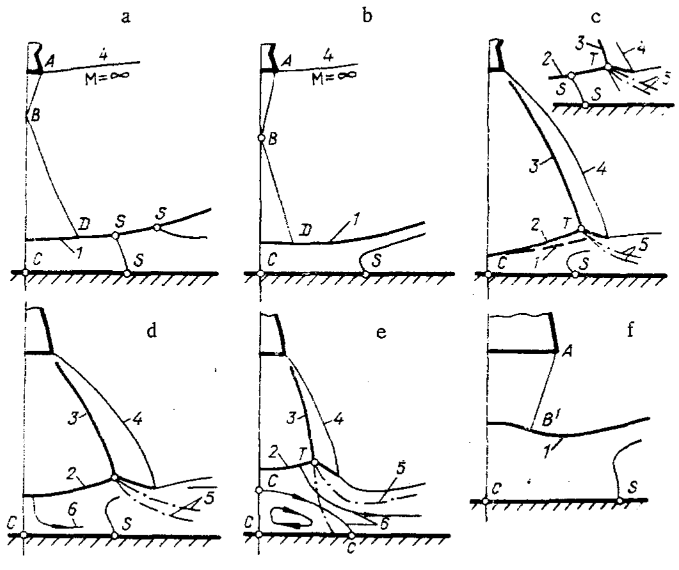

Fig. 1

1) S–S Mach line, closed in the central shock wave 1. Calculations using the range method [1] have demonstrated that in this case a second sonic point S appears in the shock at some distance from the point of emergence of the Mach line (Fig. 1a).

2) A narrow subsonic region (Fig. 1b) forms along the central shock wave and no sonic point forms in the shock. The type of sonic region is determined by the values of M and k [1].

§2. A compression layer between the jet boundary 4 and barrel shock wave 3 appears in the jet when $n < \infty$. This layer is a source of disturbances that are transmitted upstream of the subsonic region between the central shock 2 and the obstacle. The central and barrel pressure shocks interact with the formation of configurations made of three or four shock waves, as a function of the position of the point at which the pressure shocks intersect. A mixing zone (with boundary 5) is formed here along the tangential discontinuity. A triple configuration (Fig. 1c) is formed at the intersection point T in the case of subsonic flow behind the central shock.

The shape of the central shock near the point T will vary relative to $n = \infty$, such that pressures at the angles of rotation are equated on the spatial discontinuity beginning from this point. Such a structure is realized for high M. A similar process also occurs in the presence of two sonic points in the central pressure shock. A variation in the shape of the central shock leads to a variation in its intensity and brings about a reduction of the supersonic flow segment behind it in comparison with the case when the jet interacts with an obstacle in a vacuum.

Interaction between the barrel and central shocks within the supersonic flow segment can occur with the formation of two resultant shock waves (cf. Fig. 1c, scheme in the upper right corner).

Pressure disturbances due to barrel shocks reach the jet axis as the over pressure parameter further decreases. The jet compression layer influences the position and shape of the entire central shock and, consequently, flow in front of the obstacle beginning with an over pressure parameter of n_*, which we will call the limiting factor. If departure of the central shock from the obstacle to the jet axis is equal to the shock departure in interaction in a vacuum when $n > n_*$, and if its shape is distorted only as the point T is approached, a decrease in the over pressure parameter when $n < n_*$ will continuously vary the position of the shock waves in front of the obstacle. A viscous migration layer that develops along the stationary discontinuity issuing from the triple point begins to substantially influence flow formation.

§3. The following flow regimes between the central shock and the obstacle may be realized as a function of the set of parameters M, n, k, and h, when $n < n_*$:

1) stable radial flow (Fig. 1d). In this case, the pressure maximum is situated at the center of the obstacle and gas spreads (streamline 6) from the flow axis.

2) highly unstable interaction begins with a further decrease in the overpressure parameter at which the compression layer exerts an ever-greater influence on near-axial flow. Since gas with lesser total pres-

TABLE 1

M	1	1,5	2			2,2		2,9	3
θ	—	5°	5°	15°	25°	0°	5°	6°43′	5°
n	5—15,5	2,5—13,5	1,2—7,5			1,8—4,5		1—2	1,25—2,5
h	0,25—4	0,25—3	0,25—3	0,5—3		0,25—2		0,25—2,25	0,25—3

sure flows near the obstacle than does gas that has passed through the barrel and reflected jet shocks, it becomes possible to close the viscous mixing region issuing from the triple point to the obstacle with the formation of a peripheral stopping point. Closure of the central point flow zone leads to a build-up of gas in it and a displacement of the central shock towards the nozzle, which leads to an increase in pressure in front of the obstacle followed by the opening of this zone [3, 4]. The central shock oscillates at a frequency depending on the nozzle diameter (for example, when d = 20 mm, the frequency is about 4 Hz). Such self-oscillatory instability can be considered as an intermediate regime.

3) Flow from the central circulation zone (Fig. 1e), which is characterized by a peripheral pressure maximum on the obstacle and by three stopping points, namely, in the viscous attachment zone to the obstacle of the mixing zone issuing from the triple point of the jet, at the center of the obstacle, and on the flow axis between the obstacle and the central shock [5]. Flow to the obstacle is directed towards the center near the axis. The experimentally observed stable flow pattern oscillates at a high frequency.

4) The regime of weak instability is a transitional regime to flow with an undisturbed first roll as the over pressure parameter further decreases. It is characterized by a high frequency and lesser amplitude of oscillation of the central shock than is the case for high instability; the pressure maximum is situated on the periphery.

5) Flow regime with an undisturbed first roll arises when the central pressure shock in front of the obstacle is situated in the second roll as the off-design factor further decreases [6].

§4. Interaction of a jet escaping into a vacuum from an infinite plane situated in front of the point of reflection B from the axis of the first rarefaction fan characteristic is in many ways analogous to that considered in Sec. 1 (Fig. 1f). It is different in that in the first case the central shock has a double curvature, that is, it is convex towards the nozzle within the region between the axis and the point B' and concave outside it (Fig. 1f). This fact has been experimentally and theoretically confirmed [2, 6]. The intensity of the central shock behind the characteristic AB' increases with distance from the central axis. The arguments given in Sec. 2 regarding the influence of external disturbances on flow in front of an obstacle also hold in this case, though some influence begins to be manifested at significantly lesser over pressure parameters. Its mechanism somewhat differs from that considered in Sec. 2, since the barrel shock wave formed when $n < \infty$ has an extremely low intensity near the nozzle and the central shock immediately escapes to the jet boundary, which also introduces disturbances into the interaction zone.

An experimental study was carried out in order to investigate the influence of the overpressure parameter on flow of a jet interacting with an obstacle near the nozzle section ($h < l$, where l is the distance between the nozzle section and the point B). In the course of this investigation, the position of the central shock in front of the obstacle was determined on Schlieren photographs for distinct M, n, and h. Table 1 illustrates the range of variation of these parameters in the course of the experiment. The nozzle with calculated M = 2.9 had a chopped profile, the other nozzles with $\theta > 0$ were conical (θ is half the apex angle of the nozzle); M was determined using a one-dimensional scheme.

Figure 2 illustrates the influence of these parameters on the distance x between the nozzle and central shock for M = 2.0 and k = 1.4.

Clearly, all the experimental results for low h (when n = 2.5, circles, and n = 6.2, triangles) are grouped about a single curve and are independent of n within this interval. The over pressure parameter has an effect with increasing h on the position of the central shock in front of the obstacle. Curve 1 depicts the dependence of distance x on efflux parameters obtained based on an approximate solution [7] describing interaction of flow from a spherical source with an obstacle in a vacuum, at which $h \gg r_*$ (here r_* is the critical radius of the source),

$$x = \frac{1 + \sqrt{\frac{k-1}{2k}(m+4)}}{\frac{2k}{k+1} + \sqrt{\frac{k-1}{2k}(m+4)}}(h - h_*), \qquad (1)$$

where $m = k(k-1)M^2$.

The magnitude h_* is the distance between the nozzle and the obstacle at which the central shock touches the nozzle edge [8].

Figure 2 implies that Eq. (1) can be used to determine the dependence of x on h and M when $h < l$, x being independent of n. Similar results of calculating x(h; M) when $h < l$ are given by the techniques set forth in [9] (curve 2). When the over pressure parameter influences the position of the shock in front of the obstacle, the empirical equation presented in [10] can be used to determine x,

$$\frac{x}{C} = 0.745 - 0.83 \exp\left(-1.73 \frac{h}{C}\right), \tag{2}$$

where

$$C = \mathrm{M}\sqrt{kn} \tag{3}$$

is the geometric similarity parameter. An analysis of the experimental data demonstrates that the value $h/C = 0.35$ is the lower limit at which Eq. (2) can be used. Points corresponding to $h/C = 0.35$ for jets with $n = 2.5$ and $n = 6.2$ are indicated in Fig. 2 by squares. Curves 3 and 4 correspond to a computation of the position of the central shock in front of the obstacle using Eq. (2).

Clearly, this equation describes well the experimental results when $h/C \geq 0.35$. The use of Eq. (2) when $h/C < 0.35$ contradicts the experimental results, since in this case x is independent of n and a calculation using Eq. (2) will lead to separation of the curves x(h) relative to the over pressure parameter.

On this basis, we will assume that the over pressure parameter begins to affect the position of the shock in front of the obstacle when $h < 0.35$ C, this position coinciding here with the position of the shock when the jet interacts with an obstacle in the vacuum.

According to Sec. 2, the over pressure parameter corresponding to $h = 0.35$ C is limiting. In view of Eq. (3), we may also obtain the form for determining it,

$$n_* = \frac{8.24}{k}\left(\frac{h}{\mathrm{M}}\right)^2. \tag{4}$$

Data are presented in Fig. 3 characterizing the influence of certain efflux parameters on the value of the limiting over pressure parameter (curves 1-3 for M=1, 2, and 3, respectively).

Equations presented in [7, 9] to determine the departure of a shock from an obstacle when $h > l$ and $n > n_*$ can be directly used. When $n < n_*$, the distance x is determined from Eq. (2).

Thus our analysis allows us to clarify the possible types of wave structure formed in front of an infinite two-dimensional obstacle when a supersonic convergent jet overflows it (cf. Fig. 1). The criterion (4), in conjunction with empirical dependences [10] to calculate the boundaries of interaction regimes when $n < n_*$, allow us to determine flow types when a jet overflows an obstacle. The region within which different interaction regimes exist as a function of n and h is shown as an example in Fig. 4 for a jet with M = 2.0 and k = 1.4.

Departure of the central pressure shock in region I is independent of the over pressure parameter. In region II, flow into the jet compression layer affects the position of the shock in front of the obstacle. Region III

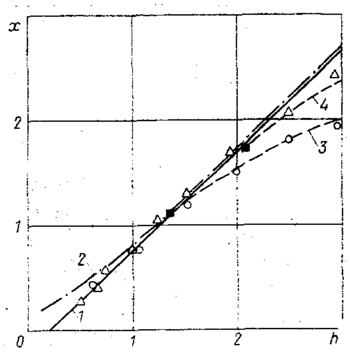

Fig. 2

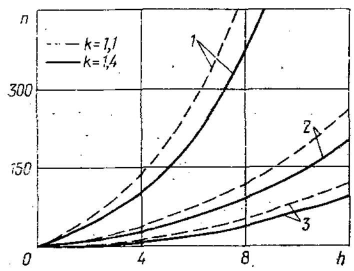

Fig. 3

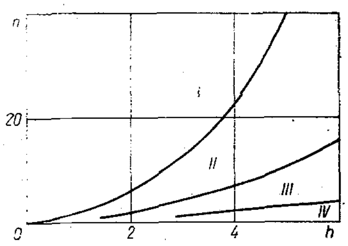

Fig. 4

is a transitional region for flow with undisturbed first roll (region IV). Here are realized unstable interaction regimes and flow from the central circulation zone.

The curves bounding regions I and III and III and IV were constructed using the empirical formulas (1) and (4), respectively, as presented in [10].

The qualitative analogy noted above between the interaction of a jet with an obstacle in a vacuum when $h > l$ and at great distances from the nozzle in the case of a bounded overpressure parameter allows us to extrapolate results presented in Fig. 4 to the case of large n.

LITERATURE CITED

1. M. G. Lebedev and K. G. Savinov, "Impact of an irregular supersonic gas flow on a two-dimensional obstacle," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 3 (1969).
2. N. E. Khramov, "Calculation of the interaction of an axisymmetrical supersonic convergent jet with an obstacle," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 5 (1966).
3. B. G. Semiletenko, B. N. Sobkolov, and V. N. Uskov, "Features of unstable interaction of supersonic jets with an infinite obstacle," Izv. Sibirsk. Otd. Akad. Nauk SSR, Ser. Tekh. Nauk, 3, No. 13 (1972).
4. A. G. Golubkov, B. K. Kuz'menko, V. A. Ostapenko, and A. V. Solotchin, "Interaction of a supersonic convergent jet with a two-dimensional bounded obstacle," Izv. Sibirsk. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk, 3, No. 13 (1972).
5. I. P. Ginzburg, B. G. Semiletenko, V. S. Terpigor'ev, and V. N. Uskov, "Certain features of the interaction of a supersonic convergent jet with a two-dimensional obstacle," Inzh.-Fiz. Zh., 19, No. 3 (1970).
6. I. P. Ginzburg, B. G. Semiletenko, and V. N. Uskov, "Experimental study of the interaction of a convergent jet with a two-dimensional obstacle perpendicular to the jet axis," Uch. Zap. Leningradsk. Univ., Ser. Gazodinam. i Teploobem (1973).
7. L. Roberts, "The action of hypersonic jets on a dust layer," IAS Paper 63-50 (1963).
8. A. L. Isakov and V. I. Pogorelov, "Approximate method of determining the minimally allowable distance between a nozzle and an obstacle," Izv. Vyssh. Uchebn. Zaved., Aviats. Tekh., No. 3 (1968).
9. V. I. Blagosklonov, "Approximate method of calculating axisymmetrical interaction of a freely expanding jet with an obstacle," Uch. Zap. Tsentr. Aéro-Gidrodinam. Inst. im. N. E. Zhukovoskii, No. 4 (1970).
10. B. G. Semiletenko and V. N. Uskov, "Experimental dependences determining the position of shock waves in a jet overflowing an obstacle perpendicular to its axis," Inzh.-Fiz. Zh., 23, No. 3 (1972).