# FEATURES OF THE INTERACTION OF A SUPERSONIC OFF-DESIGN JET WITH A BARRIER OF FINITE DIMENSIONS

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This article examines the qualitative pattern of flow in the interaction of an off-design jet with a barrier. A criterion for unstable flow about the barrier is presumed to exist.

The interaction of an off-design jet with a barrier is a complex gasdynamic phenomenon. This complexity is due to the distribution of the parameters in the jet and the generation of shock waves and regions of intensive rarefaction. Also, a slightly off-design jet typically has a periodic structure in its initial section, this section gradually degenerating due to the effect of viscosity [1, 2].

In flow against a barrier, a significant role in forming the flow is played by the shape of the barrier and its transverse dimensions. To date, most studies have focused on the interaction of underexpanded jets with an infinite flat barrier [3-6]. More recently, attention has been increasingly given to the interaction of supersonic jets with a low degree of underexpansion and blunt barriers with transverse dimensions which are comparable to the diameter of the jet.

The IAB-451 unit was used to photograph jets in different flow regimes and with different barrier shapes. A typical case is shown in Fig. 1, where the air jet had the parameters $M_a = 2$, $n = 4$, $\Theta_a = 5°$, sphere radius $R = 2.4r_a$. Analysis of the change in the configuration of the shock waves with increasing distance between the barrier and nozzle revealed several characteristic zones.

Zone 1. The intensity of the "hanging" shock wave is low at the beginning of this zone. Thus, the central shock which appears before the barrier interacts directly with the boundary of the jet. The shock is nearly spherical in form (Fig. 1a), regardless of the form of the barrier (plane, cone with a high angle at its apex, a sphere of large radius, etc.). The deformation of the central shock seen as the barrier moves away from the nozzle is caused by nonuniformity of the flow in the region of the rarefaction wave on the one hand and, on the other hand, by the interaction of the central shock with the "hanging" shock of the free jet. This interaction leads for blunt barriers to the formation of shock waves with a triple configuration. Here, the curvature of the central shock in a certain neighborhood of the triple point may be opposite its curvature in the vicinity of the jet axis (Fig. 1b). It should be noted that the direction of the initial element of the central shock at the triple point is unambiguously determined by the angle of inclination of the "hanging" (incident) shock and the Mach number ahead of this point. The subsequent deformation — the development of a section of the opposite curvature — occurs in such a way that at a certain station it has curvature of one sign, i.e. convex toward the barrier (Fig. 1c). This station corresponds to the end of the first zone and the beginning of the second zone. For blunt barriers characterized by subsonic flow after the central shock, the position of the latter coincides with the station of the jet at which the first characteristic of the rarefaction wave, generated on the edge of the nozzle, reaches the axis of the jet.

Zone 2. The form of the central shock changes little in this zone, but there is a substantial increase in the distance between the shock and the barrier (Fig. 1d and e). This is because the rate of flow of the gas through the central shock wave decreases with increasing distance to the barrier, and there is accordingly an increase in the gas flow rate through the "hanging" and reflected shock waves. Also, the annular flow has a higher velocity and higher stagnation pressure than the flow which has passed through the central shock. Thus, greater distances than exist with the barrier positioned near the nozzle are needed to turn the flow. On the whole, the shock waves ahead of the barrier approach the configuration

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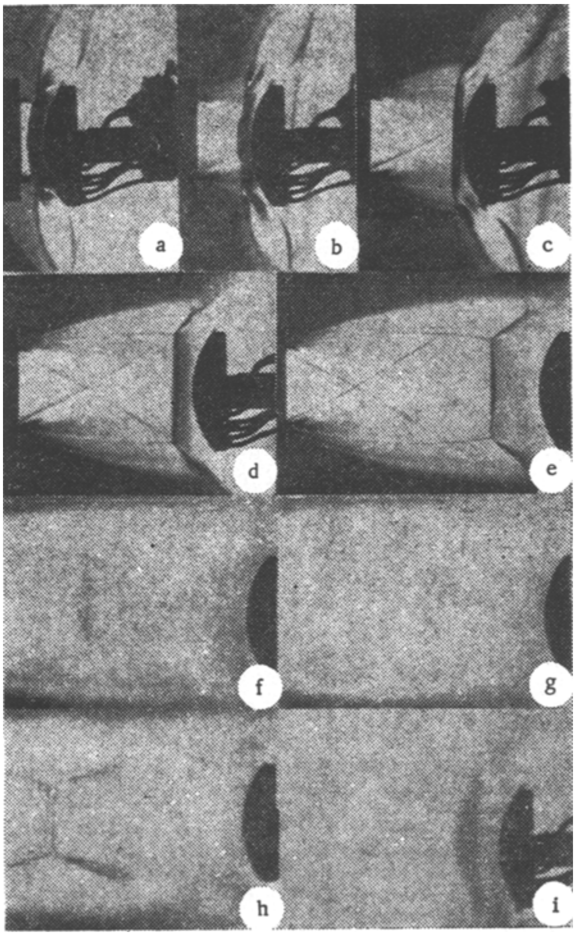

Fig. 1. Photographs of flow of an air jet about a spherical barrier with a radius R = 2.4: a) x = 0.5; b) 1; c) 2; d) 4; e) 6; f) 9; g) 10; h) 11; i) 16.

of the shock waves in the free jet. The end of zone 2 roughly corresponds to the station at which the "hanging" shock is reflected from the axis in the unperturbed jet. In the interaction with a flat barrier, this station is located somewhat closer to the nozzle (see below).

Zone 3. If the transverse dimensions of the barrier are greater than the Mach disk of the free jet, then the stable flow ahead of the barrier is disturbed, although its position and the parameters of the jet remain the same. It can be seen from Fig. 1f and g that the zone of instability is a certain region in front of the barrier. There are no clearly visible shocks. A high-speed camera was used to observe oscillations of shock waves ahead of the barrier, which periodically approached the barrier and moved away from it a certain limiting distance. The frequency of the oscillations was roughly 2000 Hz. This means that a certain volume of the gas ahead of the barrier also experiences oscillations, resulting in a loud noise and intensive vibration of the unit. It was established that the instability zone roughly corresponds to the zone of subsonic flow in the free jet (the features of this unstable flow are described below). The end of zone 3 is the position of the barrier at which a continuous shock wave appears ahead of the barrier (Fig. 1i). This is seen when the barrier is moved beyond the sonic section of the free jet.

With a further increase in the distance to the barrier, the character of the flow depends on the degree of underexpansion of the jet n. When n is small and the jet has a periodic structure, the above zones are repeated. In particular, the unstable flow regime may occur again.

A conclusion of practical importance which follows from analysis of the qualitative flow pattern for different types of barriers is that the form of the central and reflected shocks within zone 2 is nearly independent of the form of the barrier. In other words, the same

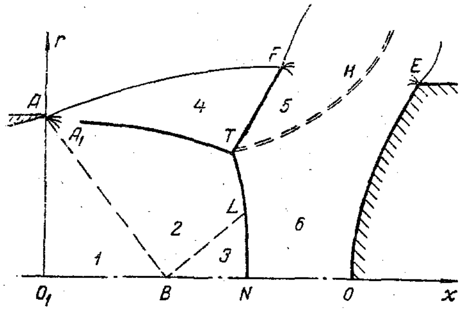

Fig. 2. Diagram of interaction of an off-design jet with a blunt barrier in zone 2: AF) boundary; $A_1T$, TN, TF) "hanging," central, and reflected shock waves; TH) contact surface; AB, BL) boundary characteristics; OE) barrier; 1, 2, 3, 4, 5, 6) characteristic regions of the jet.

given wave structure corresponds to different forms of fairly blunt barriers. In this case, shocks waves with a triple configuration are always generated, this configuration on the whole determining the form of the central and reflected shock waves (Fig. 2). This allows us to determine the mutual position of the shocks and the barrier by assigning the position of the point T and approximating the form of the generatrices of the shocks TN and TF with a parabola and a straight line, respectively. We can then approximately determine the pressure on the barrier and the total force exerted on it by the jet [7]. It should be noted that a similar conclusion on the stability of the shape of the shock waves was made in an analysis of photographs of counterflowing jets [8].

Instability of the Flow Regime. Study of the interaction of an underexpanded jet with a flat barrier [9] showed that unstable flow about the barrier is seen from the distance

$$h = x_c(1.26 - 0.17M_a), \tag{1}$$

which is somewhat closer to the nozzle than the position of the Mach disk of the free jet. It was also established that the zone of instability does not embrace the entire zone of subsonic flow of the free jet. When the subsonic zone is sufficiently extensive, stable flow about the barrier is disturbed only at the beginning ("strong instability") and end ("secondary instability") of the subsonic zone. A region of circular flow arises at the intermediate stations ahead of the barrier. The pressure diagram at these stations is characterized by a distinct peripheral maximum. This circumstance, seen in the present case, was noted in [4, 10, 11].

The reason for the first (strong) instability can be explained as follows (also see [10]). When the barrier is located a distance h from the nozzle edge, the contact surface (see Fig. 2) closes on the barrier. The possibility of such closure stems from the following factors. With increasing distance to the barrier, the distance from the nozzle to the shocks TN and TF also increases (the point T slides along the "hanging" shock, as it were). Here, the mass of the gas passing through the central shock TN decreases, and its stagnation pressure $(p_0)_{TN}$, characterizing the reserve of mechanical energy of the gas, becomes less than $(p_0)_{TF}$ in the annular flow passing through the shocks AT and TF. Also, the angle of inclination of the velocity vector at point T (after the central shock) also decreases with increasing distance to the barrier and the system of shock waves, approaching the angle of inclination in the free jet, i.e. the flow should turn through a greater angle $\Delta\Theta$ in the shock layer than at the barrier positions near the nozzle. Thus, the annular flow, having considerable mass and a greater pressure compared to the central flow, overlaps the central flow at a certain position, i.e. the contact surface closes on the barrier. These considerations allow us to suggest that there exists a criterion which takes these factors into account, i.e. the following functional relationship exists:

$$\mathrm{Ne} = f(\eta_T, (p_0)_{TF}/(p_0)_{TN}, \Delta\Theta), \tag{2}$$

where $\eta_T$ is the relative gas flow rate through the central shock wave.

When the value of Ne corresponds to its critical value, the flow becomes unstable. It should be noted that the quantities in the right side of Eq. (2) can be calculated if the structure of the shocks is known.

Another possible form of the criterion Ne is a function of the ratio of the projections of the impulses of the annular and central flows:

$$\mathrm{Ne} = \varphi(I_{TF}/I_{TN}). \tag{3}$$

In particular, the quantity Ne can be written directly in the form of the ratio of the projection of the impulse of the annular flow after the reflected shock TF in the direction normal to the barrier at the point E to the projection of the impulse of the central flow in the same direction:

$$\mathrm{Ne} = \frac{Q_{TF}(v \cos(\bar{v}, \bar{n}_E))_{TF} + p_{TF} \cos(\bar{n}_{TF}, \bar{n}_E) F_{TF}}{Q_{TN}(v \cos(\bar{v}, \bar{n}_E))_{TN} + p_{TN} \cos(\bar{n}_{TN}, \bar{n}_E) F_{TN}}. \tag{4}$$

We will reduce Eq. (4) to dimensionless form. For this, we introduce mean values of the parameters and refer the quantities to $Q_a v_a$. Then

$$\mathrm{Ne} = \{\gamma M_a^2 \pi_a (1 - \eta_T)[\xi_{T5} \cos(\bar{v}_{T5}, \bar{n}_E) + \xi_{F5} \cos(\bar{v}_{F5}, \bar{n}_E)] + [\pi_{T5} \sigma_{T54} \sigma_{T43} + \pi_F \sigma_F] \cos(\bar{n}_{TF}, \bar{n}_E) F_{TF} \xi_a\} \times$$
$$\times \{\gamma M_a^2 \pi_a \eta_T [\xi_{T6} \cos(\bar{v}_{T6}, \bar{n}_E) + \xi_{N6} \cos(\bar{v}_{N6}, \bar{n}_E)] + [\pi_{T6} \sigma_{T63} + \pi_{N6} \sigma_{N63}] \cos(\bar{n}_{TF}, \bar{n}_E) F_{TN} \xi_a\}^{-1}. \tag{5}$$

It should be emphasized that a necessary condition for the appearance of instability is sufficient bluntness of the barrier, the transverse dimensions of which should be greater than the diameter of the Mach disk of the free jet [12].

To evaluate the expanse of the zones of the jet, we can use the following relations. The boundary of zone 1

$$x_B = \cot(\alpha_a - \Theta_a), \tag{6}$$

where $\alpha_a$ is the Mach angle on the nozzle edge. The boundary of zone 2 is determined from Eq. (1) for a flat barrier and from the following empirical relation for other cases

$$x_C = 1.4 M_a \sqrt{kn}. \tag{7}$$

The boundary of zone 3

$$x_D \simeq 1.25 x_C. \tag{8}$$

For example, for a jet with the parameters $M_a = 2$, $\Theta_a = 5°$, $k = 1.4$, $n = 4$, we obtain the values $x_B = 2.1$, $x_C = 6.7$, $x_D = 8.4$.

In conclusion, let us present the critical values of Ne obtained for a flat barrier placed in an air jet with $k = 1.4$, $M_a = 2$, $\Theta_a = 5°$: a) $n = 8$ Ne = 35, b) $n = 20$ Ne = 75, c) $n = 50$ Ne = 90.

## NOTATION

r, radial coordinate; x, axial coordinate; R, radius of sphere; $\beta$, angle at apex of cone; Q, mass rate; v, velocity; $n = p_a/p_b$, degree of off-design of discharge; $\bar{n}$, vector of the unit normal; p, pressure; F, area; $\gamma$, ratio of specific heats; M, Mach number; $\eta$, relative flow rate of gas; $\Theta$, angle of inclination of velocity vector to jet axis; I, projection of impulse of the flow; Ne, criterion of beginning of unstable flow; $\sigma$, ratio of stagnation pressures on the shock wave; h, position of barrier at the beginning of strong instability; $\pi = p/p_0$, $\xi = v/v_{max}$, gasdynamic functions. Indices: 0, stagnation parameters; $a$, nozzle edge; b, jet boundary; C, Mach disk. The linear dimensions are referred to the nozzle radius. The other letter and number indices denote characteristic points and jet regions.

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# THEORY OF TRANSPORT OF ROCK PARTICLES DURING DRILLING WITH CONSIDERATION OF WATER ABSORPTION AND INFLOW

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An approximate one-dimensional theory of the process of transport of heavy solid rock particles by the flow of drilling mud in a vertical well is proposed.

The process of transport of solid rock particles by drilling mud plays an important role in the technological cycle of drilling. Imperfect bottom-hole flushing leads to collapse and shutdown of drilling. It is necessary to know the distribution of the concentration of solid particles in the annular space of the well to select the most efficient trouble-free drilling practices. The solid particles of fractured rock carried to the surface by the drilling mud have an order of $10^{-3}$-$10^{-7}$ m. Drilling mud is an aqueous suspension of clay with various additives; its viscosity is of the order of 20-200 cP. The free-fall velocity of the heavy rock particles in the mud does not exceed 1 m/sec in order of magnitude, and the characteristic drilling-mud velocity has an order of 10 m/sec. Therefore we will consider that the velocity of the solid particles is equal to the mud velocity. In addition, we will assume the well is vertical and the process is one-dimensional.

On the basis of the adopted assumptions we obtain the following equations of mass transport:

$$S\left(\frac{\partial c}{\partial t}+v\frac{\partial c}{\partial x}\right)=-cQ^-(x,\ t)+g(x,\ t), \tag{1}$$

$$vS=Q_0(t)+\int_0^x Q^+(x,\ t)\,dx-\int_0^x Q^-(x,\ t)\,dx. \tag{2}$$

Usually $Q^+$ and $Q^-$ are observed on the exposed, uncased section of the well and are associated with various complications occurring during drilling (for example, as a consequence of fractures, creep, or low strength of the rocks and lost circulation, water inflow, cave-in, etc., caused by these factors). Henceforth $Q^-$, $Q^+$, $Q_0$, and g are considered known.

Let us examine some solutions of Eq. (1).

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