ON THE REVERSE FLOW ZONE IN STRONGLY ROTATING SUPERSONIC GAS STREAMS AND JETS

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UDC 533.501.1:533.607.11

Results of an experimental investigation of the reverse flow zone near the axis of a supersonic underexpanded jet and the helical gas jet in the diffusor portion of a nozzle are elucidated.

The gas flow in twisted supersonic jets and streams has a complex three-dimensional character. If the presence of an approximate similarity [1, 2] can hence be traced in weakly rotating jets and streams, then there is no self-similarity in strong rotation, and the flow configuration even changes qualitatively. Primarily this refers to the zone near the axis, where the translation gas motion under the effect of a large positive longitudinal pressure gradient is decelerated in the twisted jet and a domain of reverse axial flows can be formed near the axis.

Up to now, no investigation of the reverse flow zones in strongly rotating twisted supersonic jets and streams has been undertaken despite the practical importance of information on the configuration of such flows [3, 4]. This paper contains some results of such an investigation.

1. An experimental study of rotating supersonic gas jets escaping from a nozzle without a diffusor section has been carried out. It turns out that [1] for weak rotation and sufficiently high pressure of the decelerated stream, such a jet conserves an approximate self-similarity. The shock structure therein is hence analogous to a triple Mach configuration which holds for the flow of an untwisted underexpanded jet. The influence of rotation only results in displacement of the central disklike shock closer to the nozzle, where this displacement can be described, with satisfactory accuracy, by quantitative dependences. Further investigation shows, however, that the nature of the shock interaction is modified qualitatively as the degree of rotation in the jet increases at low stagnation pressure: self-similarity of the flow is absent and the disklike shock degenerates, being replaced by a system of curvilinear shocks.

As an illustration, a Toepler photograph of an underexpanded air jet escaping into the atmosphere from a nozzle without a diffusor section with a d = 5 mm critical section diameter at a p_∞ = 5 atm stagnation pressure and a degree of rotation $\alpha_* = v_\varphi^*/v_{max} = 0.205$ (v_φ^* is the rotational velocity of an ideal gas at the nozzle wall). Attention is turned to the analogy between the picture presented and the picture of shock

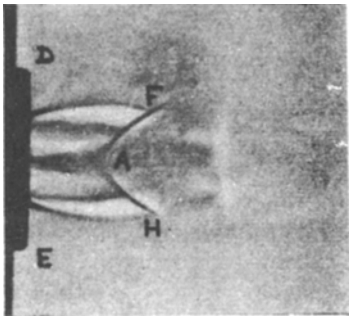

Fig. 1. Picture of shock interaction in an underexpanded strongly rotating jet.

Institute of Chemical Physics, Academy of Sciences of the USSR, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 20, No. 6, pp. 1036-1041, June, 1971. Original article submitted July 2, 1970.

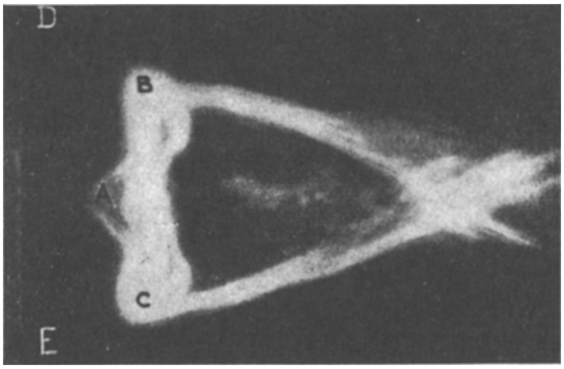

Fig. 2. Picture of the plasma filament scintillation in an underexpanded rotating jet.

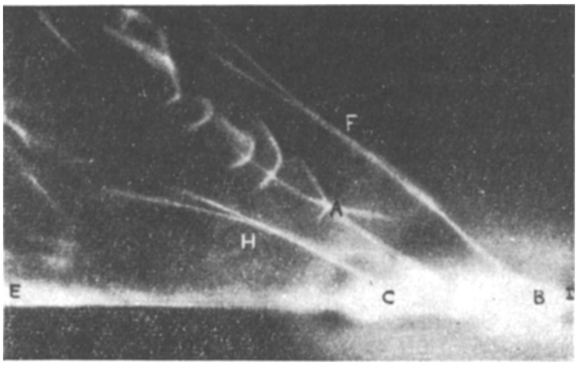

Fig. 3. Sweep photograph of the plasma front in a jet.

formation during the collision of a supersonic stream and an opposing axisymmetric jet relative to a small diameter. In both cases there is no normal shock, and it is replaced by a conical shock. The character of the flow observed in a strongly twisted supersonic expanding jet could probably be explained by the formation of reverse current zones near the flow axis at some distance from the nozzle. Then the deceleration of the main jet in the opposing stream of this zone indeed specifies the appearance of the conical pressure shock.

A series of tests using the method of photographic tacking of a luminous plasma bunch moving in the jet was carried out to verify such a hypothesis. A plasma cloud was produced in the gas by a sparkover between discharger spikes and was entrained by the moving stream. Since the velocities of plasma removal in the supersonic jet are high, the recording of the displacement of the ionized gas front is accomplished by using the SFR high-speed photographic recorder ordinarily used to investigate detonation processes [5].

A picture of the scintillation of the ionized plasma filament in the rotating jet, obtained in the frame-by-frame survey mode under escape conditions analogous to those in Fig. 1, is presented in Fig. 2. The spiral motion streamlines are clearly seen, according to whose slope the magnitude of the relative rotational velocity v_φ/v_z of the gas near the nozzle can be determined. As has been assumed, there is a reverse flow domain with its narrow part turned upstream. (The point A is the forward stagnation point of the jet in the opposing stream of the reverse flow zone, and the points B and C are the discharger spikes extracted from the nozzle section DE.)

To obtain more complete information about the relatively fine structure of the backward flow zone, SFR photographs in the sweep mode were used. (Since the ionized gas moving with the stream scintillates slightly at a relatively high magnification, the photography was accomplished with a large aperture input objective 1:2.8 without using a slit.) In this case the moving mirror of the instrument, whose axis of rotation agreed with the jet axis, turned the image of the moving plasma front along a fixed photographic film. If the stream itself hence has the velocity component v_z perpendicular to the sweep direction (across the film), and the velocity component v_r along the film, then a record of the ionized gas front in the form of an oblique line is obtained as a result of adding the gas and sweep velocities. By knowing the linear sweep velocity, the magnification of the image K, and measuring the slope $\tan\beta$ of the track along the photograph, the magnitude of the axial and radial stream velocity components can be found

$$\frac{v_z}{v_s} = \frac{\operatorname{tg}\beta}{K}\left(1 \pm K\,\frac{v_r}{v_p}\right) \tag{1}$$

(the sign ± in the formula depends on which half of the axisymmetric jet is examined).

An illustration of the sweep photograph of plasma bunch motion in an underexpanded rotating jet with the parameters $d_* = 8$ mm, $p_\infty = 6$ atm, $\alpha_* = 0.175$ is given in Fig. 3. The letter notation here is the same

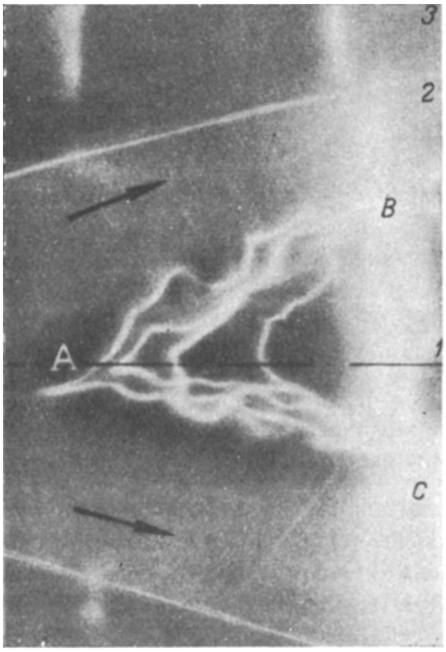

Fig. 4. Reverse currents zone in the diffusor part of a nozzle during rotating gas flow.

as in Figs. 1, 2. From the first, the presence of a reverse flow zone and the abrupt expansion of the jet (the points H, F) somewhat downstream from the forward stream stagnation point A are seen. By using (1), the components v_z, v_r on the jet boundary can be determined (the plus sign must be taken in the formula for the branch BF and the minus sign for CH). Thus, $v_s = 375$ m/sec, $K = 1.5$ corresponds to the picture shown in Fig. 3, from which we obtain $v_r = 50$ m/sec, $v_z = 200$ m/sec near the points H and F. Attention is turned to the inhomogeneous "vertebral" structure of the recording in the reverse currents zone. This permits making an important deduction about the nature of the configuration of the zone itself: it consists of a number of semicircular vortices imbedded in each other.

The magnitude of the velocity of the opposing motion of the gas near the axis of an underexpanded strongly rotating jet can be estimated by means of the sweep photograph. Thus, we obtain the quantity ~100 m/sec from the maximum slope of the reverse streamlines in Fig. 3. A somewhat lower value of the reverse currents velocity is obtained if another estimate is used. In our experiments, the recombination time, or more accurately, the time of ionized gas scintillation turned out to be ~100μsec. By measuring the magnitude of the reverse flow track and assuming that the scintillation of the track was cut off after the mentioned time had elapsed, we obtain the velocity ~80 m/sec.

The time when the leading point of the reverse current zone of a supersonic jet enters the critical nozzle section is important for the practical use of twisted streams. This time can be determined by using the results in [6] about the distribution of the flow parameters along the radius of the critical nozzle section in a spiral isentropic stream

$$\frac{v_z}{v_{\max}} = \alpha_* \frac{J_0(m\xi)}{J_1(m)}, \quad \alpha = \alpha_* \frac{J_1(m\xi)}{J_1(m)}.$$

Here $J_0(x)$ and $J_1(x)$ are Bessel functions, $\xi = r/R_*$ and m is a known function of α_*. For small α_* (to $\alpha_* = 0.2$) the following relationship holds

$$m = 2\alpha_* \sqrt{(\gamma+1)/(\gamma-1)}. \tag{2}$$

If it is assumed that the reverse current penetrates the critical section of a nozzle without a diffusor part when the pressure at the nozzle section on the jet axis is commensurate with the pressure p_h of the ambient medium, then we will have

$$p_h = p_\infty \left(1 - \frac{\alpha_*^2}{J_1^2(m)}\right)^{\frac{\gamma}{\gamma-1}}. \tag{3}$$

The dependences (2) and (3) determine the connection between the pressure in the tank p_∞ and the degree of rotation α_* for the time of counterflow penetration into a nozzle without an expanding part.

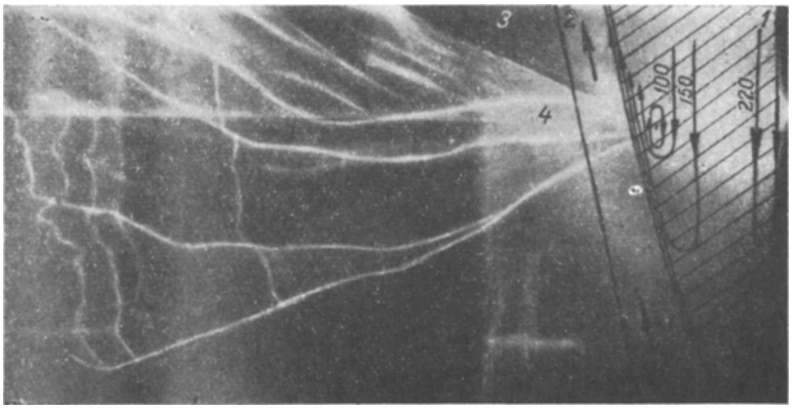

Fig. 5. Photographic scanning of plasma motion in diffusor and line of reverse current.

2. A reverse currents zone can be formed in the flow of a rotating gas stream in the supersonic diffusor part of a nozzle near the axis, just as in the case of a free twisted jet. The origin of such a zone causes the appearance of a complex picture of shock interaction in the nozzle, which exerts influence on stream separation from the walls and on the nozzle thrust characteristics.

A photograph of a series of plasma filaments excited by sequential spark discharges in the supersonic part of a transparent conical nozzle with $d_* = 6.7$ mm and $\delta = 12°$ half-angle is presented in Fig. 4 (degree of stream rotation $\alpha_* = 0.16$, tank pressure $p_\infty = 6$ atm, discharger spikes BC located between the critical and exit sections, 1) nozzle axis, 2) inner wall of the conical nozzle, and 3) outer wall). It is seen that the major portion of the nozzle cross-section is occupied by the reverse flow domain which penetrates deeply against the main stream but does not reach the critical section. The survey of such a scintillation picture of ionized gas intervals by using the rotating SFR mirror permits construction of the shape of the reverse currents zone to some approximation, and estimation of the magnitude of the velocities therein. The form of such a sweep photograph and the method of processing it in order to construct the reverse flow streamlines are illustrated in Fig. 5 (4 is one of the discharger spikes, the remaining notation is as in Fig. 4).

NOTATION

α_* is the degree of gas rotation;
p_∞ is the stagnation stream pressure;
d_* is the nozzle diameter.

LITERATURE CITED

1. Yu. A. Gostintsev, V. V. Zelentsov, V. S. Ilyukhin and P. F. Pokhil, Izv. Akad. Nauk SSSR, Mekh. Zhidk. i Gaza, No. 5 (1969).
2. A. Chervinsky, AIAA Jnl, 6, No. 5 (1968).
3. G. Swithenbank and N. Chigier, Vortex Mixing for Supersonic Combustion. XII Intern. Symp. on Combustion (1968).
4. T. B. Reed, J. Appl. Phys., 32, No. 5 (1961).
5. P. F. Pokhil, V. M. Mal'tsev, and V. M. Zaitsev, Methods of Investigating Combustion and Detonation Processes [in Russian], Nauka, Moscow (1969).
6. Yu. A. Gostintsev, Izv. Akad. Nauk SSSR, Mekhan. Zhidk. i Gaza, No. 4 (1969).