NOTATION

ν, kinematic viscosity of the fluid; a, thermal diffusivity of the fluid; d, nozzle diameter; u_0, fluid velocity at the nozzle throat; T^*, jet temperature; T_0^*, T_m^*, and T_∞^*, temperatures in the nozzle throat, at the jet axis, and of the ambient medium respectively; β, coefficient of thermal expansion of the jet; β_m, coefficient of thermal expansion at the temperature $T_m^* = {}^1/_2(T_0^* + T_\infty^*)$; $\alpha = \alpha^*(T_0^* - T_\infty^*)$; $\alpha^* = \frac{1}{\beta_m}\left(\frac{\partial\beta}{\partial T}\right)_P$, a dimensionless parameter characterizing the dependence of β on T^*; $Re = u_0 d/\nu$, Reynolds number; $Pr = \nu/a$, Prandtl number; $Gr = \beta_m g d^3(T_0^* - T_\infty^*)/\nu^2$, Grashof number; $x = x^*/Red$ and $y = y^*/d$, dimensionless coordinates, longitudinal and transverse, respectively; $u = u^*/u_0$, $V = (V^*/u_0)$ Re, dimensionless velocity, longitudinal and transverse, respectively; u_m, dimensionless velocity at the jet axis; $\Delta T^* = T_0^* - T_\infty^*$, excess temperature in the nozzle throat; $\Delta T = (T^* - T_\infty^*)/(T_0^* - T_\infty^*)$, dimensionless excess temperature of the jet; and δ, conventional jet width (distance from jet axis to point where $u = {}^1/_2 u_m$, $\delta = \delta^*/d$ being the dimensionless jet width).

LITERATURE CITED

1. K. E. Dzhaugashtin and A. V. Soldatkin, Propagation of axisymmetric jet under action of Archimedes forces," Izv. Sib. Otd. Akad. Nauk SSSR, No. 8, Issue 2 (June), 60-65 (1981).
2. A. Braun, "Effect of temperature dependence of volume coefficient of thermal expansion heat transfer during laminar natural convection," Heat Transfer, No. 1, 138-139 (1975).
3. H. Barrow and T. L. Sitharamao, "Effect of variation of volumetric expansion coefficient on free convective heat transfer," British Chem. Eng., 16, 704-705 (1971).
4. H. & K. Schlichting, Boundary Layer Theory, McGraw-Hill (1968).

CONDITIONS FOR MIXING TRANSVERSE CO_2 JETS WITH A SUPERSONIC NITROGEN STREAM IN A NOZZLE

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A flow visualization experiment has been performed in a planar supersonic nozzle with strong transverse jet blowing of CO_2. The authors have established the existence of two regimes for interaction of the jets with the main stream and with themselves. They have determined the dimensions of the zone where this interaction is strongest.

Jet blowing of gas into supersonic flows is widely used in contemporary facilities. The interaction of streams with a single jet has been investigated by a number of authors, e.g., [1-4]. In all these studies, apart from [4], they considered flows in channels of constant or slightly varying cross section with a small relative flow rate of blown gas. In [4], which studied flow in a nozzle, the flow rate of blown gas did not exceed 4% of the main stream rate. The flow structure in the conditions indicated varied appreciably only in the vicinity of the blowing location and was studied well. For the mixing nozzles with large relative flow rate of blown gas used in [5-8], it is of interest to study the interaction of a number of transverse jets among each other and with the main supersonic stream. The principal difference between this kind of flow and flows with transverse blowing of a single jet is that the perturbations brought in by the blown gas are not local, but change the structure of the entire flow. Apart from an investigation of the process of starting a nozzle with blowing, described in [6], the literature has no information on the structure of such flows.

In the present work flow visualization has been used to obtain pictures of the structure of flows and evaluate the dimensions of the zone of strong interaction of flows with transverse blowing of a number of CO_2 jets into a nozzle in an expanding flow of a mixture of a number of gases based on nitrogen, over a wide range of blown gas flow rate.

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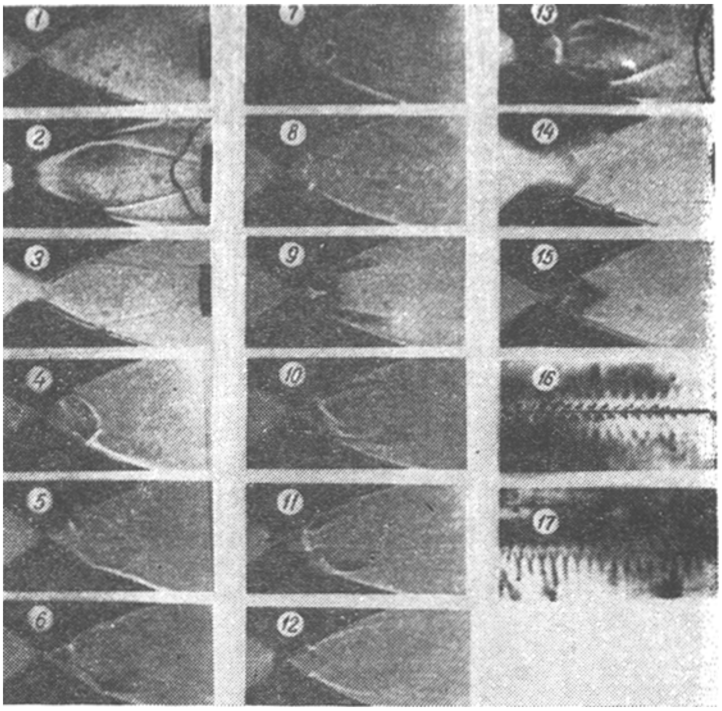

Figs. 1-17. Shadowgraph (1, 4-8, 10-12) and schlieren (2, 3, 9, 13-15) photographs of the nozzle and the flows in it: 1) nozzle with protuberances and model; 2) stationary flow without blowing; 3) quasistationary (hot) flow without blowing; 4-6) flow formed with one-sided blowing into the nozzle without the main stream; 4) n = 300; 5) 500; 6) 600; 7-9) flow formed with two-sided blowing into the nozzle without the main stream; 7) n = 60; 8) 100; 9) 200; 10, 11) flows with one-sided blowing into the stationary stream; 10) n = 200; 11) 500; 12, 13) flows with two-sided blowing into the stationary stream; 12) n = 30; 13) n = 200; 14, 15) flows with two-sided blowing into the quasistationary (hot) flow; 14) nozzle with protuberances and model; 15) nozzle used in [7, 8], n = 200; 16, 17) picture of deposition on the nozzle generators of solid particles contained in the main stream; 16) view from the nozzle exit section; 17) view in the axial plane of the nozzle.

Experimental Equipment. The experiments were conducted on the equipment described in [7, 8]. We used a planar contoured nozzle with a corner point of width 200 mm and a 1-mm throat height. The CO_2 was blown in through apertures of diameter 1 mm drilled perpendicularly to the nozzle generators in its supersonic part in a section of height 3.2 mm, distant 2.5 mm from the throat. The separation of adjoining apertures was S = 10 mm, and a number of apertures on opposite walls of the nozzle were displaced relative to one another by half a pitch. The flow visualization was accomplished with the help of a shadowgraph and a schlieren system. We used objectives with F = 200 mm and a type IFP-20 pulsed light source with a pulse duration of ~ 0.4 msec.

We investigated two flow regimes, differing in facility operating time and in the values of the mixture stagnation parameters. For the first regime the atmosphere was the reservoir, and in the second it was an electric discharge chamber in which nitrogen was heated to T_0 = 2.5 kK at P_0 = 8.4 atm [8]. The typical operating time of the facility with the discharge chamber (hot or quasisteady regime) was 1.5 msec. In the second variant (cold or steady regime) the operating time could reach several minutes and was limited only by the quality of pumping of the vacuum vessel (250-m^3 volume) into which the mixture discharged. The CO_2

was blown in from a bottle at room temperature. The typical time for discharge of CO_2 from the bottle to vacuum through the blowing aperture was ∿15 sec. The relative mass flow rate α of blown CO_2 was varied in the range 0.1-0.6. Clearly, in flows formed by a single blown gas that concern us here we have $\alpha = 1$.

On the nozzle generators over its entire width, at a distance of 8 mm from the throat, there were triangular protuberances of height 0.3 mm, and on the nozzle axis, at distance 15 mm from the throat, a cylindrical model of diameter 6 mm (Fig. 1) was mounted. From the angles of the density shocks arising in the flow over the protuberances, the flow Mach number values were estimated.

It can be seen (Fig. 2) from the photographs of the main stream without blown gas that for pressure drops greater than critical supersonic flow is established in the nozzle. In the flow over the protuberances there arise two pairs of inclined shocks forming the so-called N-wave configuration. In the stationary regime ahead of the model one can clearly see the detached shock wave which undergoes bending in both pairs of shocks, because the shocks do not degenerate into characteristics. The flow Mach number evaluated from the slope of the shocks at their point of intersection is $M = 4.1$. The design value of M for the same section is 4.8. The discrepancy can be explained by a decrease of the effective flow expansion power owing to the protuberances. No differences in principle were observed between the flow pictures in the cold and hot regimes (Fig. 3).

Structure of Flow Formed by Jets of Blown Gas. Photographs of the flows of blown gas in the nozzle without the carrier flow, when CO_2 came in from both nozzle walls, are shown in Figs. 4-9. The degree of underexpansion of the jet, n [2], calculated from the pressure in the vacuum vessel, varied in the range 50-600. For $n < n_1^* = 500$ in the one-sided blowing case and for $n < n_2^* = 100$ in the two-sided case one sees suspended barrel-shaped shocks with a Mach disk, i.e., a picture typical of immersed jets (Figs. 4, 5, and 7). The diameters of the barrel-shaped shocks d_m are proportional to $\sqrt{n}$, which agrees with the results of [2], obtained in an investigation of blowing of air jets into a supersonic air stream. For $n > n^*$ the flow picture changes sharply (Figs. 6, 9) and the individual jets are not seen. The change in the flow structure occurs for degrees of underexpansion which, according to [2], correspond to d_m being equal to the distance between adjoining jets. Thus, depending on the degree of underexpansion, one observes two different flow regimes, a regime where adjoining jets do not interact one with another (weak blowing) and a regime where they do interact (strong blowing). With strong blowing the flow formation occurs in a transition zone of length L_{tr} behind which the flow is comparatively uniform and supersonic. The length of the transition zone for the regimes examined does not exceed 2.5 nozzle heights at the blowing section.

Flow Structure with Blowing of CO_2 into the Stream. Two flow regimes are observed with blowing into the stream, as in the previous case, depending on the degree of underexpansion of the jets. For low values of n, when the individual jets are maintained, there is no Mach disk (Figs. 10, 12). This feature of the flow results from the fact that the jets are carried away by the main stream and expanded. It should be pointed out that a Mach disk was observed in [4] even with blowing at a distance totalling 0.8 heights of the nozzle throat. This difference between [4] and the present work is possibly associated with the fact that at low relative flow rates of blown gas typical of [4], the dimensions of the barrel-shaped shocks are small, and therefore the change in main stream pressure across them is also negligible. Because of the low nozzle height at the blowing section the main shock in the flow [2] is moved closer to the opposite wall of the nozzle. Thus, even for low values of n a perturbation from blowing is propagated to the entire height of the nozzle. Since the blowing is performed near the throat, the strength of the oblique shock ahead of the boundary-layer separation zone is so weak that it is practically unseen in the photographs. The main shock in the flow degenerates comparatively quickly into a characteristic. A weaker characteristic can be seen from the shock in the flow washing the jet nose. The point of intersection of these characteristics can be considered the end of the zone of strong interaction of the jets and the main flow.

It can be seen from Fig. 10 that at some distance from the blowing location the jet is unrolled in the flow direction. The ratio of the distance from the blowing aperture to the stream line on the jet axis after unrolling to the nozzle height at the blowing section was varied in the range 0.25-0.67 as a function of the degree of underexpansion of the jets (30-300).

With strong blowing into the stream (Figs. 11, 13) the flow picture is analogous, in the main, to that of blown gas with no main stream. The blown gas fills the whole nozzle cross section even at the blowing location, and the shock strength is only increased compared with the flow with no main stream. In this case the shocks in the main stream form a continuous configuration across the nozzle, information about which we gain from the picture of deposition of solid particles contained in the main stream in the hot regime (Figs. 16, 17). The precipitation occurs where the main stream touches the nozzle walls. Immediately behind the shocks we observe two flow zones, a central zone and a wall zone, separated by shocks. These can be traced to a distance of approximately 1.5 nozzle heights at the blowing section. No remarkable nonuniformities are observed downstream. One check of the flow uniformity is the smooth shape of the detached shock wave ahead of the model (Fig. 13). Therefore the point of disappearance of the boundary between the central and peripheral regions can be considered as the end of the zone of strong interaction of blown gas with the main stream.

The critical value of the degree of underexpansion n* at which there is transition from weak to strong blowing, both with the main stream absent, and with blowing into it, can be approximated satisfactorily by the relation $n < n^* \lesssim (S/r)^2$, where S is the distance between adjoining jets; and r is radius of the blowing aperture.

From the slope angle of the shocks with the same flow rates of the main stream and the blown gas we find the Mach number at the section ahead of the model to be M = 2.8, while it is 4.1 without blowing. Thus, transverse blowing leads to flow deceleration, but not as strongly as indicated by calculations on a one-dimensional model of instant mixing [7, 9]. In particular, for equal flow rates of blown gas and main stream the calculation based on this model predicts flow transition to subsonic.

There are no differences, in principle, between the flows with blowing in the cold and hot regimes (Figs. 14, 15), but the length of the transition zone L_{tr} is less in the second case. The reason for the decrease of L_{tr} may be the large values of the total and velocity heads of the main stream, which increase the mixing intensity. Also, one cannot exclude the possibility that due to the rapid change of the parameters of the main stream in the hot regime the images of some of the flow details are smeared. Therefore, one can consider that the length of the transition zone in the hot regime may reach a value of 2.5 nozzle lengths at the blowing section.

LITERATURE CITED

1. E. E. Zukoski and F. W. Spaid, "Secondary injection of gases into a supersonic flow," AIAA J., 2, No. 10, 1689 (1966).
2. V. S. Avduevskii, K. I. Medvedev, and M. N. Polyanskii, "Interaction of a supersonic stream with a transverse jet blown through a circular aperture in a plate," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 5, 193 (1970).
3. G. N. Abramovich, Applied Gasdynamics [in Russian], Nauka, Moscow (1976).
4. N. I. Kislyakov and V. B. Yavkin, "Penetration of jets blown into a transverse flow in a supersonic nozzle," in: Gasdynamics of Aircraft Engines [in Russian], Kazan Aviation Inst. (1981), p. 35.
5. V. N. Kroshko and R. I. Soloukhin, "Optimal regimes of inversion with thermal excitation of mixing in a supersonic flow," Dokl. Akad. Nauk SSSR, 211, No. 4, 829 (1973).
6. V. N. Karnyushin and R. I. Soloukhin, Macroscopic and Molecular Processes in Gas Lasers [in Russian], Atomizdat, Moscow (1981).
7. N. N. Ostroukhov and B. K. Tkachenko, "Efficiency of CO_2 excitation in a gasdynamic laser with mixing of gases," Kvantovaya Elektron., 5, No. 4, 924 (1978).
8. P. V. Belkov, V. V. Val'ko, A. S. D'yakov, et al., "A CO_2 gasdynamic laser based on mixtures containing carbon monoxide," Kvantovaya Elektron., 7, No. 11, 2385 (1980).
9. A. V. Lavrov and S. S. Kharchenko, "Application of an instant mixing model to analysis of the gasdynamic laser," Fiz. Goreniya Vzryva, No. 1, 147 (1980).