12. B. N. Antar and F. D. Collins, "Numerical calculation of finite amplitude effects in unstable laminar boundary layers," Phys. Fluids, 18, No. 3 (1975).
13. S. K. Godunov and V. S. Ryaben'kii, Difference Methods, Nauka, Moscow (1973).

INVESTIGATION OF JET FLOW PAST SLOTTED AND WEDGE-SHAPED NOZZLES IN A SHOCK TUBE

V. V. Golub, V. V. Grigor'ev,
Yu. I. Grin', S. N. Isakov,
I. M. Naboko, R. L. Petrov,
and V. G. Testov

UDC 533.601.1:534.202.2

Studies in shock tubes have been extensive in recent years. These studies are directed in search of techniques to increase the effectiveness of gasdynamic lasers in which, as a rule, plane sonic and supersonic nozzles are used for the production of a jet issuing into free space or channel. The published experimental studies are primarily devoted to the measurement of quantum characteristics of GDL (amplification factor, power developed). At the same time, gasdynamic studies are few and concern mainly the determination of the wave structure of the jet, though relaxation of vibrational energy is determined by the distribution of gasdynamic parameters in the flow: velocity, temperature, pressure, and density. In computing the properties of gasdynamic lasers it is usually assumed that the jet is one-dimensional and steady. However, experimental studies and computations [1-5] of jets brought out a number of significant features of the wave structure and the distribution of jet parameters. It was shown that the flow past a nozzle section can have a fairly complex spatial structure which affects the characteristics of the laser beam. In particular, flow nonuniformity leads to phase nonuniformities in the laser beam which has an important bearing on the operation of laser at increased power conditions. Besides, in experiments with nozzles in shock tube it is necessary to keep in view that a transient flow process precedes quasisteady jet efflux. In the present paper results are given for the experimental studies on three dimensional and plane jets in shock tubes under conditions similar to those in which studies on the laser characteristics [7, 8] of gas flows were conducted: transient time for the density field and the flow geometry, spatial characteristics of density distribution.

Measurements were made in shock tubes with low pressure channel of cross-section 40 × 40 and 35 × 70 mm. Plane sonic nozzles were set up at the low pressure end in the form of orifices with cross section $h \times a$ equal to 1.5 × 40 and 2.5 × 70 mm ($a/h = 27$ and 28.5) or plane wedge-shaped supersonic nozzle with an aperture angle of 30° and area ratio $A_a/A^* = 15$ at a height $h = 1.3$ mm.

During studies on spatial jet with sonic nozzle in the shock tube with square cross-section, the low pressure chamber and the reservoir were filled with nitrogen. The initial pressure p_1 was 36 GPa, Mach number M_1 of the incident shock wave varied in the interval $M_1 = 2.5$-3.5, and the degree of expansion $n = p_a/p_\infty = 16$-42. In the case of wedge-shaped nozzle the degree of expansion was varied in the range 15-70.

Measurements in rectangular shock tube for the sonic nozzle with $a/h = 28.5$ were made without the nozzle diaphragm with the initial pressure in the low pressure chamber and the decompression chamber $p_1 = 133$ GPa and degrees of expansion $n = 7.9$ ($M_1 = 2.0$) and $n = 12.8$ ($M_1 = 2.2$). When the Mach number of the incident shock wave $M_1 = 1.9$, $p_\infty = 1.33$; 13.3; 26.6; 53.2 GPa and $p_1 = 0.1$ MPa, the following parameters were obtained: ahead of the nozzle $p_5 = 1.9$ MPa, $\rho_5 = 6.43$ kg/M^3, and at the nozzle cross section $M_a = 4.35$, $p_a = 53.7$ GPa, $\rho_a = 0.1286$ kg/M^3. The measured time for the existence of constant deceleration parameters before the nozzle was $\sim$2.5 msec.

The flow in the 40 × 40 mm shock tube was visualized using the shadowgraph IAB-451. The investigation of the unsteady structure of three dimensional jet was conducted with the

---

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 76-80, November-December, 1982. Original article submitted October 28, 1981.

0021-8944/82/2306-0803$07.50

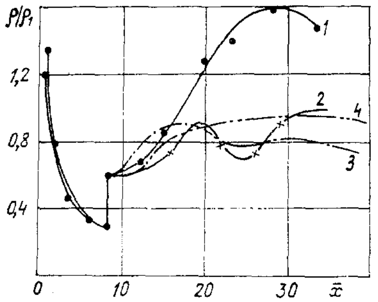

Fig. 1

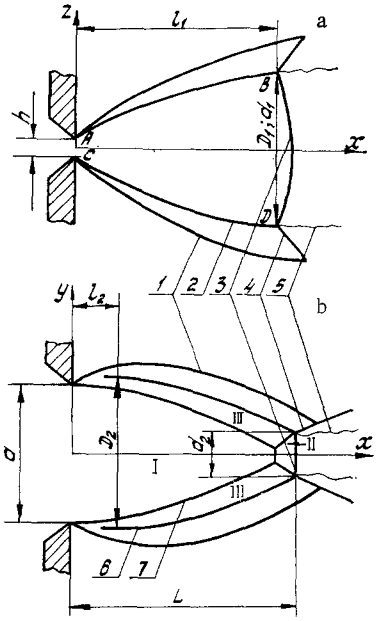

Fig. 2

major axis of the nozzle parallel and perpendicular to the optic axis of the shadowgraph. The synchronization technique made it possible to take pictures in mutually perpendicular directions at the same time τ from the start of the flow.

Measurements in the 35 × 70 mm shock tube were made with Mach—Zender interferometer, using the phase shift method as well as by setting up the interferometer with infinitely broad band. In order to correctly identify the band under the complex gasdynamic flow conditions simultaneous recording of interferograms in white and monochromatic light were made. The interferometer was calibrated in order to eliminate errors associated with the determination of wavelength of light at the outlet of the light filter and the distance between the mirrors in the set up which limit the nozzle in the zx-plane. It made it possible to express the magnitude of the shift in band width in units of density. A shift of one band width corresponds to a density variation of 0.025 kg/ m^3.

In shock tube studies it is necessary to know the transient time for the quasisteady flow of the off-design supersonic jet. Hence it is necessary to estimate the transient time for the density field as well as the transient time for the geometric flow structure.

Experimental investigation of the establishment of the density field in plane jets exiting from sonic and wedge-shaped nozzles was made using interferometry. The data obtained [Fig. 1, 1: 100 msec ($\bar{t}$ = 22.3), 2: 200 μsec ($\bar{t}$ = 44.6), 3: 400 μsec ($\bar{t}$ = 89), 4: 700 μsec ($\bar{t}$ = 156), sonic nozzle, a/h = 28.5] make it possible to state that the density field in the central segment of the region between the nozzle cross section and the Riemann wave changes very little (no more than 20%) after the stabilization of its position. While the data obtained for the relative density downstream behind the Riemann wave continues to vary during the entire observation period (up to 700 μsec). For the initial off-design flow past the orifice nozzle n = 7.9 a system of two "barrels" were observed in the field of

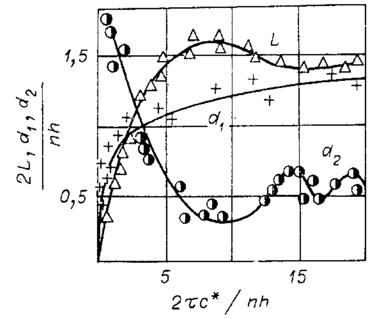

Fig. 3

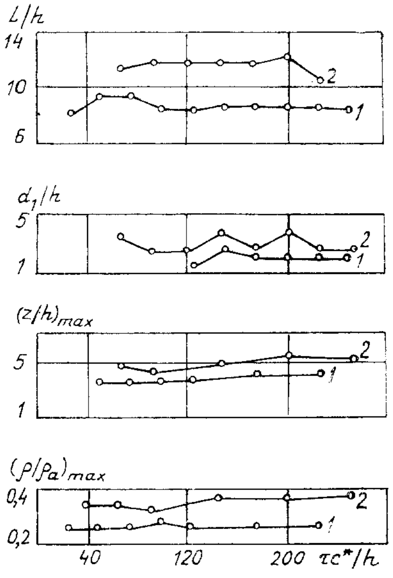

Fig. 4

vision of the interferometer whereas when the degree of expansion n = 12.8 the flow structure was single barreled. Investigation on transient times for geometric characteristics of the flow was conducted for plane as well as three dimensional jets.

Schlieren pictures of free jet are given in [6] and the corresponding schematic diagram of the initial region of the jet along the minor and the major axes of the nozzle respectively are given in Fig. 2a, b, where 1 is the jet boundary, 2 is the cylindrical suspended shock, 3 is the Riemann wave, 4 is the reflected shock, 5 is the slip boundary, and 7 is the projection of the interaction region of suspended shock 2 (Fig. 2a) with spatial suspended shock 6 in the plane of the major axis (Fig. 2b).

The region I is the projection of the cylindrical free shock boundary on the yx surface whose trace in the zx plane are AB and DC, II is the projection of Riemann wave BC on the yx plane, III is the projection of free shocks that confine the jet to the side along the y axis while the surfaces of lateral free shocks are not cylindrical but are complex, three dimensional.

As a result of the analysis of Schlieren pictures, the dependence of the nondimensional height $2d_1/nh$, width $2d_2/nh$, and the location $2L/nh$ of the Riemann wave on the nondimensional flow time $\bar{t} = 2\tau c^*/nh$, where c^* is the velocity of sound in the critical section is plotted in Fig. 3. The Schlieren records with two orientations of the nozzle at the correspondingly same instants of time from the start of the flow made it possible to construct the spatial model of the jet. The unsteady wave structure obtained is transformed in space and time to a computationally obtained model of stationary flow from a rectangular nozzle [3].

On the basis of the above analysis and results of [6] it is possible to investigate the change in the location of the spatial jet boundary in the plane of the major axis with time for different sections.

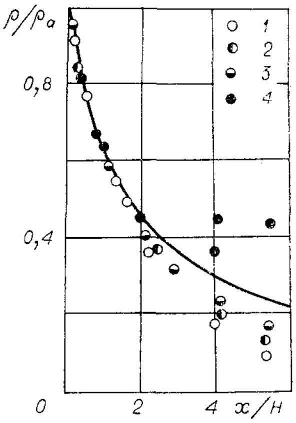

Fig. 5

Results of interferometric studies on the transient process of the plane jet flow structure in the rectangular shock tube are given by the parameters L/h, D_1/h $(z/h)_{max}$ in Fig. 4 for the degree of expansion 7.9 and 12.8 (lines 1, 2 respectively).

Thus the investigation of plane jet flow transient processes showed that under the experimental conditions described above it was possible to achieve quasisteady flow in the zone between the nozzle cross section and the Riemann wave.

Investigation of the steady flow of a free jet from an orifice nozzle shown in Fig. 2a, b showed that for n = 26 the amount of jet expansion in the direction of y-axis is small and the maximum value lies close to the nozzle cross section (D_2/a = 1, 2, l_2/a = 0.21). In the plane of the minor axis, however, the jet expansion is appreciable and the maximum value is attained near the Riemann wave (D_1/a = 29, l_1/a 27). As it flows from the rectangular nozzles with a fairly large value of a/h the increase in the degree of expansion n leads to an increase in the distance to the Riemann wave in the plane of the minor axis of the nozzle d_1 but the Riemann wave number d_2 in the plane of the major axis decreases.

The most prolonged in the interferograms of flow from supersonic nozzle was the stage of motion of unsteady gradient regions: the first wave in the surrounding fluid and the boundary of the jet. Quasisteady flow structure with n = 40 and M_a = 4.35 was established behind wedge-shaped nozzle after $\tau \sim 600$ μsec.

Similar studies using shadowgraph technique with wedge-shaped nozzle made it possible to determine the geometric dimension of the jet in quasisteady state in the xz plane and in the yx plane, in nitrogen and in a mixture of $0.1N_2O + 0.2N_2 + 0.7He$. These studies were made while varying n in the range 15-70. Depending on the gas, it takes 300-500 μsec to achieve the quasisteady values of the dimension in the section where the maximum value of population inversion ($\bar{x}$ = 12) of GDL [8] was realized. The maximum jet size in the direction of the major axis exceeded the nozzle width by 30%.

The use of interferometer in the 35 × 70 mm shock tube made it possible to carry out the measurement of density fields in jets. Both the above-mentioned interferometer techniques (method of phase shift and infinite band width) were used for quantitative studies. Interferograms obtained through the displacement technique using monochromatic light, corresponding to the condition for the absence and presence of jet and identified with the help of interferograms obtained with white light, were analyzed by placing one on the other. The density fields were constructed on the basis of the intersection of the geometric centers of interference bands.

In the case of wedge-shaped nozzle the change in the density ratio was measured for n = 1; 2; 4; 40 and are shown in Fig. 5 (points 1-4 respectively). The computed curve (solid line) is obtained according to isentropic solutions assuming that the flow is established in the nozzle with greater length for the same values of the critical section and aperture angle. At distances of up to two diameters from the nozzle cross section (x/h = 2) the experimental results agree well with computations. The maximum variation in density along the axis was 35 and 45% at a distance of one or two diameters respectively. The results obtained make it possible to compute the initial segment of the jet of the gasdynamic lasers with one dimensional isentropic approximation. In interferograms obtained by adjusting the interferometer for infinite bandwidth, geometric centers of the bands correspond to the lines of equal densities. The profile of density variation in the xz plane was plotted on the basis of the axial distributions of density. It is seen from an analysis of the interferograms and density profiles that with an increase in the distance from the nozzle cross section, the jet core width is almost unaltered but the transverse dimensions of the jet increase rapidly with a gradual fall in the density from the core of the flow to the jet boundary.

It is also worth noting that in plane jets the zone of nonuniform parameters in the mixing layer is considerably larger in the direction of free expansion (along the z axis) than along the y axis due to the presence of the thin wall boundary layers. In three dimensional jets the transverse dimensions of the mixing layers are appreciable in both directions. Besides, schlieren pictures indicate that it is possible to make the jet turbulent which can significantly affect the quality of the laser beam.

Thus it has been shown that the transient time for quasisteady flow in jets past nozzles of different shapes (orifice, wedge-shaped supersonic nozzles) depends on concrete flow conditions. It was found during the study of the flow past orifice nozzles that there is a variation in density and the geometric structure of the jet for a period of 600 μsec in the operating jet volume. Quasisteady value of density is established immediately close to the nozzle cross section in ∿100 μsec. The jet characteristics past supersonic nozzle acquire quasisteady values within a period not exceeding 700 μsec for $n > 2$.

In carrying out studies on gasdynamic lasers in shock tubes it is necessary to consider not only the time to attain quasisteady flow conditions but also the characteristics of the realized flow parameters.

LITERATURE CITED

1. U. Shiren and D. Dosandzh, /Investigation of jet exiting from two dimensional underexpanded sonic nozzle," Raketn. Tekh. Kosmonavtika, 6, No. 3 (1968).
2. R. Driftmaier, "Correlation of free jet parameters," Raketn. Tekh. Kosmonavtika, 10, No. 8 (1972).
3. M. Ya. Ivanov, A. N. Kraiko, and V. P. Nazarov, "Some numerical results of off-design three dimensional jets of an ideal fluid," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 4 (1972).
4. I. M. Naboko, E. M. Kudryavtsev, et al., "The flow structure of shock-heated gas under the conditions of impulse gasdynamic laser," Teplofiz. Vys. Temp., No. 1 (1974).
5. V. G. Maslennikov and B. M. Dobrynin, "Transient process for the initial segment of plane supersonic jet of nitrogen at different degrees of flow expansion," Zh. Tekh. Fiz., 51, No. 6 (1981).
6. V. V. Golub, I. M. Naboko, and A. A. Kulikovskii, "Three-dimensional wave structure of unsteady gas efflux from plane sonic nozzle," Zh. Prikl. Mekh. Tekh. Fiz., No. 1 (1976).
7. A. S. Biryukov, A. Yu. Volkov, et al., "Study of gasdynamic N_2O-laser," Zh. Eksp. Teor. Fiz., 68, No. 5 (1975).
8. Yu. I. Grin' and V. G. Testov, "Measurement of the amplification factor of radiation in supersonic expanding flow of a gas mixture containing N_2O," Dokl. Akad. Nauk SSSR, 227, No. 5 (1976).