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PULSATION SPECTRUM OF THE MIXING LAYER OF AN UNDEREXPANDED JET

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The very numerous investigations of the gas dynamics of underexpanded jets that have been made up to now have made it possible to find the determining parameters and the main laws of outflow [1-3]. The character of flow in the mixing layer of the initial section of a supersonic underexpanded jet is determined by the Reynolds number Re_L calculated from the distance to the central compression shock, the maximum outflow velocity, and the parameters of the flooded space [1]. A turbulent flow regime is observed for $Re_L > 10^4$. Because of the fact that the velocity drop over the thickness of the mixing layer has the order of magnitude of the speed of sound, turbulent gas mixing can lead to considerable pulsations of the gas-dynamic parameters. A study of the fluctuation quantities in such flows is associated with a number of difficulties. At the experimental level the problem consists in the necessity of using diagnostic methods with high temporal and spatial resolution.

In the present paper we investigate density pulsations in the initial section of a supersonic underexpanded jet escaping from a sonic nozzle. It proved possible to formulate this work in connection with the creation of a pulsed local method of density measurement, based on Rayleigh scattering of light [4].

Diagnostic Method and Experimental Setup

The use of the method of Rayleigh scattering to measure the concentrations of molecules in gas streams has a number of advantages over other methods [5]: the noncontact nature and the high localization of the measurements. But the drawbacks limit its wide application. First, the scattering cross section is rather small, and the traditional use of continuous lasers as the radiation source requires the use of storage systems to isolate the signal against the noise background. Therefore, investigations with a high time resolution are impossible. Second, the cross section for scattering on dust particles is proportional to the sixth power of their size, so that the use of the method in actual flows is hindered (in air under standard conditions, for example, the total number of dust particles is 10^4-10^5 cm^{-3} [6]).

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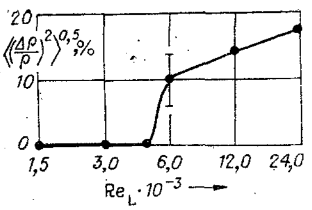

Fig. 1

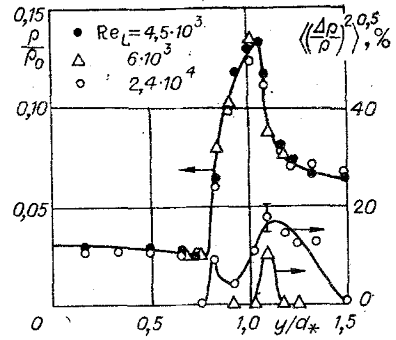

Fig. 2

The use of strong pulsed laser radiation (the second harmonic of a neodymium laser was used: pulse energy 10 mJ, length 20 nsec, wavelength 0.53 μm) allows us to reliably record the polarized component of the scattered radiation in one pulse. To eliminate the influence of dust on the measurements, the volume from which scattering was observed was reduced to $3 \cdot 10^{-6}$ cm^{-3}. The size of the volume was chosen from the condition that there was less than one dust grain in it, on the average. When a dust grain enters the investigated volume, the scattered signal increases and statistical treatment allows one to cut out the parasitic signals.

Abstracting ourselves from the details of the experimental setup, we note the limits of applicability and the possibilities of the method. Linear variation of the fraction of scattered light is observed with variation of the concentration of nitrogen molecules in the range of $3 \cdot 10^{16}$–$3 \cdot 10^{19}$ cm^{-3}. With a further decrease in concentration, the role of the noise of the recording apparatus increases, and the signal connected with stray illumination also becomes important. The useful signal is compared with the background at the concentration of $8 \cdot 10^{15}$ cm^{-3}. For a gas concentration above $3 \cdot 10^{17}$ cm^{-3}, the error of a single measurement does not exceed 10%. Making a series of several measurements (5–10) allows one to achieve errors at the 3–5% level in determining the average concentration. Moreover, the method makes it possible to measure the size of density pulsations in an investigation of turbulent flow. In this case, the dispersion of the readings when making a series of measurements is determined both by the errors of the recording apparatus and the presence of density pulsations in the stream. The relative rms size of density pulsations is calculated from the formula $\langle(\Delta\rho/\rho)^2\rangle^{0.5} = (\sigma^2 - \sigma_0^2)^{1/2}$, where σ^2 and σ_0^2 are the relative dispersions when series of measurements are made in a jet and in a quiescent gas, respectively ($\sigma_0 \approx 10\%$). The possibility of measuring pulsations in the density of a certain quantity depends on the error and the number of measurements [7]. For a series of 25 measurements, the method allows one to determine the relative rms pulsations in density at the 5% level with a confidence coefficient of 68%.

The experiments were made in a vacuum chamber with a diameter of 50 and a height of 60 cm, equipped with an evacuation system and optical windows for the entry and exit of laser radiation. The gas source, fastened to a three-component, micrometric coordinate mechanism (setting error 20 μm), was placed in the central part. The pressure in the nozzle forechamber was determined with standard manometers and vacuum gauges, while the pressure in the flooded space was determined with a liquid manometer. The error in establishing the pressures was no worse than 0.25%. In all the experiments the temperature in the nozzle forechamber was kept constant (295 ± 1°K), for which the gas was thermostatically controlled before entry into the forechamber.

Experimental Results

The escape of a supersonic nitrogen jet from a sonic nozzle with a critical cross section of diameter $d_* =$ 3.05 mm was investigated. All the experiments were made at an expansion ratio $N = p_0/p_\infty = 15.2$ (p_0 is the pressure in the nozzle forechamber and p_∞ is the pressure in the flooded space). The range of stagnation pressures was $1.25 \cdot 10^4$–$2 \cdot 10^5$ Pa, which corresponds to variation of Re_L in the range of $1.5 \cdot 10^3$–$2.4 \cdot 10^4$.

In Fig. 1 we give the rms size of density pulsations as a function of Re_L. The measurements were made at $x/d_* = 2.0$ in the middle of the mixing layer ($y/d_* = 1.1$). Here x is the distance from the nozzle cut and y is the distance from the axis of the jet. The sharp rise in the size of the pulsations in the region of $Re_L =$ $5 \cdot 10^3$ gives reason to state that in this case the zone of the laminar–turbulent transition lies near the cross section $x/d_* = 2.0$. The dynamics of the development of the region of existence of turbulent flow can be traced from Fig. 2, where we show transverse profiles of density and of density pulsations for different Re_L at the

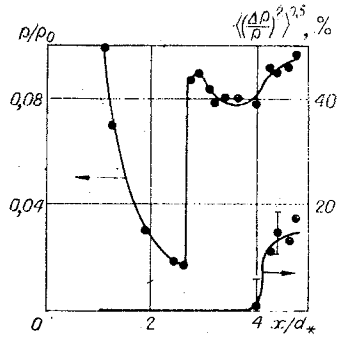

Fig. 3

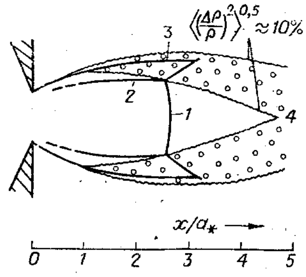

Fig. 4

distance $x/d_* = 2.0$. For $Re_L = 4.5 \cdot 10^3$ the flow is laminar, while for $Re_L = 6 \cdot 10^3$ pulsations develop in a narrow zone localized in the mixing layer. With a further increase in Re_L, the region of turbulent flow expands until the hanging compression shock is reached, which is seen from the profile of density pulsations for $Re_L = 2.4 \cdot 10^4$. The interaction of the turbulent flow in the compressed layer with the hanging compression shock leads to oscillations of the latter relative to the mean position. On the graph this appears in the form of a peak of the pulsations in the vicinity of the hanging compression shock.

As the measurements showed, in the entire investigated range of operating parameters, density pulsations are absent in the core of the jet, as well as immediately behind the Mach disk. The axial ($y = 0$) profiles of density and density pulsations for $Re_L = 1.2 \cdot 10^4$ are shown in Fig. 3. The density pulsations increase sharply at a certain distance behind the Mach disk, corresponding to the arrival of disturbances from the boundary of the jet at its axis.

An analysis of transverse profiles of pulsations at different distances from the nozzle cut allows us to establish the boundary of the zone of turbulent flow in the entire region of the initial section of the jet. In Fig. 4 we show the structure of the jet for $Re_L \approx 10^4$, where 1 is the Mach disk, 2 is the hanging compression shock, 3 is the boundary of the jet, and 4 is the zone of turbulent flow.

In conclusion, we note that the turbulent character of flow in the mixing layer leads to the propagation of acoustic waves into the surrounding space [8]. The localization of the measurements under our experimental conditions was $3 \cdot 10^{-6}$ cm³ (a linear scale of ~$1.5 \cdot 10^{-2}$ cm), which corresponds to the high-frequency branch of the acoustic spectrum of the jet (~2 MHz).

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