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EFFECT OF THE PLENUM-CHAMBER DIAMETER ON THE TURBULENT CHARACTERISTICS OF A SUPERSONIC JET

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The effect of the flow character in the plenum chamber of a nozzle on the high-frequency boundary of the spectrum of fluctuations at the boundary of a supersonic, strongly underexpanded jet of nitrogen exhausted from a circular sonic nozzle into the ambient space was experimentally studied. The Reynolds number in the plenum chamber of the nozzle with a given throat area was varied by changing the diameter of the subsonic region. The high-frequency boundary of the spectrum of turbulent fluctuations was evaluated on the basis of two-point correlation functions of time. The technique for measurement of these functions was based on molecular scattering of light. Radiation of two pulse lasers with a controlled delay between the pulses was used as a source of light. It follows from experimental results that the high-frequency boundary of the spectrum of turbulent fluctuations and the spectrum itself vary significantly depending on the Reynolds number of the flow in the plenum chamber.

Introduction. The character of the flow at the initial section of a supersonic, strongly underexpanded jet is mainly determined by the Reynolds number Re based on the maximum exhaustion velocity, the viscosity of the ambient space, and the distance to the Mach disk [1–3]. The flow is turbulent at $\mathrm{Re} > 10^4$. The range $10^3 < \mathrm{Re} < 10^4$ corresponds to the laminar–turbulent transition; and as the Reynolds number increases, the distance at which the transition to the turbulent regime occurs shifts from the Mach disk to the nozzle exit. Depending on the size of the nozzle-edge roughness, the transition to turbulence can follow two different scenarios [4]. If the nozzle-edge roughness is $\delta/d > 5\cdot 10^{-3}$ (d is the nozzle diameter and δ is the characteristic height of the roughness), the transition to the turbulent flow regime occurs with violation of axial symmetry of the flow in the mixing layer. In this case, it is difficult to compare the turbulent flow characteristics for different nozzles because of the necessity of controlling the roughness height. The laminar–turbulent transition occurs without violation of axial symmetry if the mean free path of the molecules in the ambient space becomes comparable with the roughness height ($\delta/d < 10^{-3}$) [4]. Under these conditions, the turbulent characteristics are determined by the level of external disturbances and by the growth rates of these disturbances in the mixing layer. A part of the disturbances arise in the plenum chamber of the nozzle and is determined by the corresponding Reynolds number.

In the present work, we study the influence of disturbances arising in the plenum chamber of the nozzle on the high-frequency boundary of the spectrum of turbulent fluctuations at the initial section of a supersonic, strongly underexpanded jet.

Experimental Facility. A sketch of the experimental facility is shown in Fig. 1. The experiments were conducted in vacuum chamber 1 (1.2 m in diameter and 5 m long). The gas was evacuated by an NVZ-500 mechanical pump. The source of gas was a sonic nozzle 4.2 mm in diameter, which was located in the center of the chamber on a three-component micrometric traversing gear. The plenum-chamber diameter

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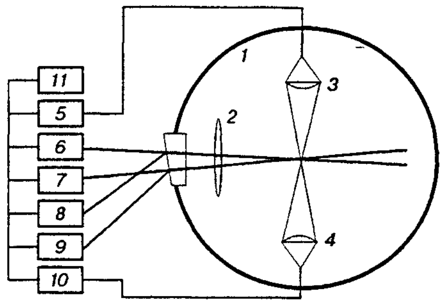

Fig. 1

could be varied by special inserts (40 and 80 mm). To obtain a uniform gas flow over the cross section of the plenum chamber, the gas was injected through an equalizing porous filter, which was a layer of foam rubber 10 mm thick reinforced by a metal disk whose diameter coincided with the diameter of the plenum chamber. The disk thickness was 1 mm. A set of orifices 2 mm in diameter covered the entire disk surface. The area occupied by the orifices was about 50%. The distance between the porous filter and the nozzle exit was 75 mm. The pressures in the plenum chamber of the nozzle and in the ambient space were measured by membrane gauges with an error of less than 0.5%. For changing the Reynolds number, the pressures in the plenum chamber and in the ambient space were varied proportionally. Under these conditions, the Mach disk position is almost unchanged.

In the experiments, we used a method for measuring the local concentration of the gas based on the Rayleigh scattering of light [5]. Two identical pulse laser systems 6 and 7 (Fig. 1) were used to measure the time correlations. Radiation of solid lasers operating in the regime of modulated Q-factor was transformed to the second harmonic by a nonlinear-optical crystal. The following parameters of radiation were used: wavelength 0.54 μm, duration 20 nsec, energy in a pulse 20 mJ, and repetition frequency 2 Hz. Laser radiation was focused by lens 2 (focal distance 400 mm) to a common spatial point located in the central region of the chamber. Measurement localization was determined by the geometry of focusing and collection of scattered photons. In the present experiments, the spatial resolution was 10^{-6} cm^3. The spatial region of measurements was a cylinder with a characteristic diameter of about 100 μm determined by the constriction diameter. The cylinder length was 100 μm. The location of the measurement point in the flow field was varied by moving the object of investigation. The time resolution was determined by the laser-pulse duration 20 nsec. The time between the pulses was varied within 0–1 msec with an accuracy of 1 μsec. Scattered radiation was collected by objectives 3 and 4 and transmitted by light guides to photomultiplier tubes 10 and 5 located outside the vacuum chamber. The energies of the reference light pulses were measured by photodiodes 8 and 9. All intensities were measured by charge-to-digit converters made in the CAMAC standard. Personal computer 11 was used to controlling the experiment and process the results.

Results and Conclusions. A flow of nitrogen was studied in the experiments. In a series of several hundred measurements, the time correlations were determined for a given delay between the laser pulses. We studied the exhaustion from a sonic nozzle 4.2 mm in diameter with the edge roughness less than 2 μm. Under these conditions, the transition to turbulence occurred without the appearance of a lobe structure at the jet boundary (the Knudsen number calculated on the basis of the mean free path in the ambient space and the roughness height was close to unity) [4]. The plenum-chamber diameter was 40 or 80 mm. The experiments were conducted for a jet expansion of 50. The Mach disk was located at a distance of 19.9 mm from the nozzle exit. The measurements were taken at a distance of 8 mm from the jet axis and 18 mm from the nozzle exit. In a nitrogen flow, this point is located in the mixing layer. The laser-beam axis was directed along the jet radius. The measurements were performed in the region of the first intersection of the laser beam with the jet. The Reynolds number varied within 4000–16,000, which corresponds to the turbulent

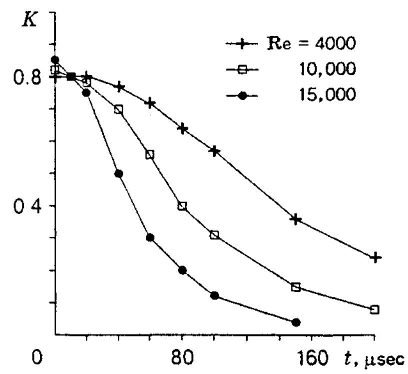

Fig. 2

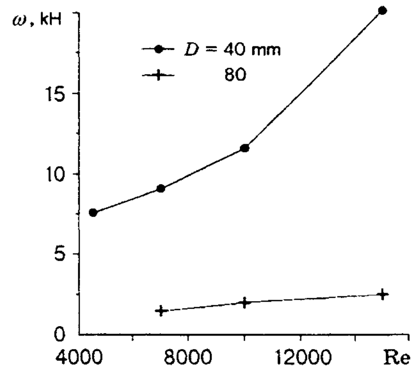

Fig. 3

flow regime at a distance of 19.9 mm from the nozzle exit. Figure 2 shows the normalized time correlation function $K(t)$ of the plenum chamber 40 mm in diameter. Though the measurements were conducted at one spatial point, the correlation function is other than unity at a zero shift in time. This is caused by the fact that two independent measurement channels are used in the experiments with a finite magnitude of the measurement error. The decrease in the correlations with time indicates their random character and turbulent flow regime. The spectrum of turbulent fluctuations can be reconstructed using the Fourier transform of the correlation function. In qualitative analysis, we characterize the spectrum of fluctuations by its high-frequency boundary. As a criterion for choosing this boundary, we use a reciprocal of time at which the correlations decrease twofold. The greatest gradient of decreasing correlation functions is observed in this region, which ensures the best accuracy.

High-frequency boundaries of fluctuations ω obtained for different plenum-chamber diameters D are shown in Fig. 3. It follows from Fig. 3 that the development of fluctuations at the boundary of a supersonic jet in the transition to the turbulent flow regime is related to the character of the flow in the plenum chamber of the nozzle. Estimating the Reynolds number of the gas flow in the plenum chamber of the nozzle for the Reynolds number of the jet flow $\mathrm{Re} = 10^4$, we obtain $1.5 \cdot 10^4$ and $7.5 \cdot 10^3$ for the plenum chambers 40 and 80 mm in diameter. Both cases correspond to the turbulent flow regime already in the plenum chamber of the nozzle. For the plenum chamber 40 mm in diameter, a more developed turbulent regime leads to an increase in the high-frequency boundary of the spectrum of turbulent fluctuations in the mixing layer of a supersonic jet. We note that the characteristic frequency determined from the plenum-chamber diameter (40 mm) and the velocity of sound is 10 kHz. This value is within the frequency range of fluctuations for this plenum chamber. For the plenum chamber 80 mm in diameter, the characteristic frequency is 5 kHz, which is significantly higher than the spectrum of fluctuations observed for this plenum chamber. The analysis conducted allows us to assume that the fluctuations at the boundary of a supersonic jet are related to amplification of disturbances arising in the plenum chamber. These disturbances, in turn, are determined by the Reynolds number of the plenum-chamber flow.

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