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STUDIES OF THE THREE-DIMENSIONAL STRUCTURE OF A PULSED PERIODIC GAS JET

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An experimental study was carried out to investigate the flow pattern of a pulsed periodic gas jet at Re ~4000 and a modulation frequency of 200 Hz. Application of conventional and nonconventional optical methods of visualization of the flow field allowed a conclusion about the formation of several large-scale vortices by every pressure pulse.

Studies of large-scale coherent structures that arise in injection of pulsed periodic jets into a submerged space are of great interest, first, for finding physical characteristics of the interaction of the pulsed jets with the environment [1-3] and, second, because the pulsed periodic structures in turbulent jets and trails can be used in various fields of science and technology [4, 5].

The character of the arising coherent structures depends substantially on the Reynolds number for a particular flow and the method of modulation of the jet. In particular, in [6], where the flow was modulated by longitudinal pressure waves generated by a piston performing translational motions at Reynolds numbers varying in the range $0.5\cdot10^4-1.5\cdot10^4$, stable vortex rings appeared in the flow that were separated from the edge of the nozzle and propagated in the downstream direction over a distance of several tens of diameters of the jet without any substantial changes in their structure.

As the Reynolds number decreases, the flow structure of the pulsed jet changes substantially. As was shown in [2], at complete periodic modulation of the jet in the range $0.087\cdot10^4 < \mathrm{Re} < 0.31\cdot10^4$, the starting length of the jet was characterized by the presence of several unstable vortex rings and the vortex trail flow was distinctively turbulent.

Processes that lead to formation of periodic turbulent structures in outflowing pulsed jets are most frequently studied with such methods of flow visualization as dusting of the flow or the medium into which the jets flow out as well as with schlieren and interference methods. Moreover, quantitative information is obtained with Doppler laser measurement of the velocity, thermoanemometry, and other methods. In recent years the just enumerated methods are used in combinations.

However, it should be noted that the flow structure of the pulsed jets at low Reynolds numbers (of the order of magnitude of several thousands) is studied insufficiently. This can be explained both by the complexity of the object itself and by the difficulty of finding unversal methods for investigation of such pulsed periodic jets.

We tried to use unconventional methods to study the flow structure of a pulsed periodic jet at Reynolds numbers in the range $3000 < \mathrm{Re} < 5000$ and modulation frequencies in the range 100–200 Hz.

Methods and Experimental Equipment. A diagram of the experimental setup used to investigate the pulsed-jet parameters is shown in Fig. 1. The pulsed periodic gas jet was formed with the aid of a pulsed solenoid-operated valve. The gas flow was choked by a choking element (a metal ball) under the action of an electromagnetic field that was formed by an inductance coil. The choking element was returned to its initial position and the flow was released free by pressure forces of the gas at the moment of changing polarity of the alternating current that was

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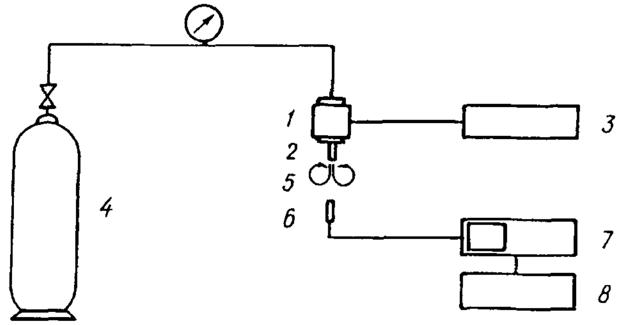

Fig. 1. Scheme of experimental setup: 1) solenoid-operated valve, 2) nozzle, 3) power unit, 4) gas vessel, 5) generated gaseous vortex, 6) pressure piezogauge, 7) oscillograph, 8) PC.

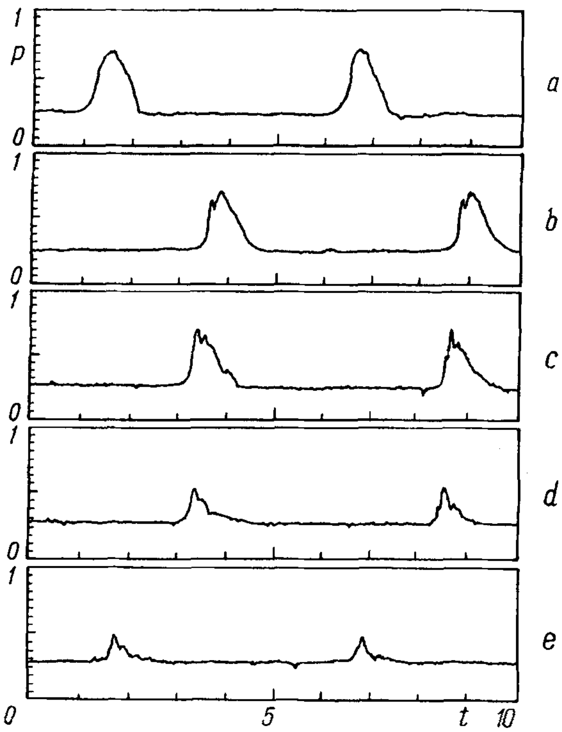

Fig. 2.Downstream axial evolution of shape of pressure P pulses, a) relative distance from nozzle exit section $L/d^* = 0.29$, b) 2.29, c) 4.57, d) 8.0, e) 9.71. Modulation frequency of jet is 200 Hz. P, rel. units, t, msec.

fed to the inductance coil. The design of the valve and an electronic power unit provided controllable and stable (with an error of $\pm 6\%$) frequency modulation of the jet in the frequency range 100–380 Hz. However, in the present work experiments were carried out only at a modulation frequency of 200 Hz. A circular channel with a diameter of 3.5 mm and a length of 35 mm was attached butt to the outlet of the valve. In this case the distance from the nozzle exit section to the flow choking section was 11 mm.

A technical-grade propane-butane mixture with 60.2% propane was used as a working fluid. The experiments were carried out at an inlet gas pressure of 2.7 atm. The gas flowed out into air at atmospheric pressure.

In the experiments, the evolution of the amplitude and shape of the total pressure pulse was studied both along and across the jet at different distances from the nozzle exit section of the valve. The total pressure pulses were recorded by a positionable calibrated piezielectric pressure gauge of the Piezotronix-113A21 type, whose signals were stored and processed with a Hewlett Packard 54501A oscillograph connected to an XT/286 IBM PC. It should be noted that while determining the value and shape of the pressure pulses, the sensor of the gauge was mounted perpendicularly to the flow. Thus, signals obtained corresponded to the dynamic pressure, since, as was

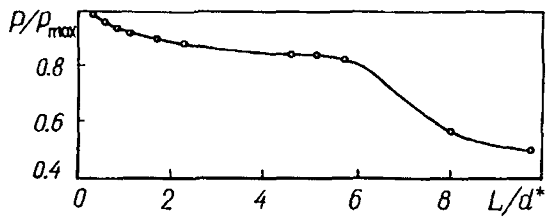

Fig. 3. Downstream variations of pressure pulses P/P_{max} behind nozzle exit section; modulation frequency of jet is 200 Hz.

shown by additional experiments, already at a distance of about one diameter from the nozzle exit section, the static pressure at the jet axis was equal to the atmospheric pressure. Moreover, because of the rather large sensing area of the gauge (2.5 mm), data obtained with it are integral and do not resolve the spatial gas dynamic microstructure of the flow.

Results and Discussion. Experimental data on the spatial downstream evolution of pressure pulses in the jet are shown in Fig. 2. As one can see from the oscillograms presented, at distances of about several diameters from the nozzle exit section of the valve, at the jet axis the pressure pulses have an almost triangular shape with approximately equal slopes of the front and rear edges. In this case the pulse duration is 1 msec. As the downstream distance increases, the macrostructure of the pressure pulse starts to manifest itself. In particular, at the peak of the pulse, several spikes appear that may probably be attributed to large vortices. It should be noted that the amplitudes of these spikes and their mutual locations change as the pressure pulse propagates downstream and the slope of the rear edge decreases substantially as the distance between the pulse and the nozzle exit section increases. The duration of the pulse itself varies insiginificantly.

Analysis of the behavior of the total pressure in the jet (Fig. 3) shows that the downstream axial evolution of the pressure pulses has several stages. In the initial stage ($L \sim d^*$, where d^* is the diameter of the nozzle exit section of the valve), which is characterized by a rather rapid pressure drop as the perturbation propagates downstream, initial expansion of the jet occurs, the static pressure in the flow becomes equal to the ambient pressure, and a stable gas dynamic structure is formed. In the second stage ($L = 1 - 5.7d^*$) a slight monotonic decrease in the total pressure is observed, which can probably be attributed to gradual mixing of the flow with the medium and to an increase in the diameter of the jet. In the third stage ($L > 6d^*$) intense destruction of the stable gas dynamic structure that appeared in the initial stage starts, which is accompanied by a more intense drop in the total pressure and destruction of the jet.

As concerns the distribution of the total pressure over the jet radius, as was shown by measurements carried out at different sections ($L/d^* = 4.6$ and $L/d^* = 8.6$), within the error of the three-dimensional pressure record, the largest part of the gas in the jet expands inside a cone with a slope of the generatrix to the jet axis of $13-18^{\circ}$, which is somewhat higher than the corresponding slope (12°) for the case of a steady-state turbulent jet.

The average outflow velocity of the pulsed jet that was found from the time lag in signals from the pressure gauges located on a known base amounted to 12–16 m/sec (from $P_0 = 2.175$ atm and a modulation frequency of the jet of 100 Hz), which agrees with the velocity estimate equal to 17 m/sec that was obtained according to Bernoulli's law with the assumption that the velocity head of the jet was determined only by the initial pressure drop at the exit of the pulse valve.

Apart from measurement of the total pressure in the pulsed periodic jet, for investigation of the jet structure some methods were used that allowed visualization of the flow field. In particular, apart from the classic schlieren photography, methods based on outflow of the jet into a dusted space and on addition of fine-disperse particles to the pulsed periodic gas flow were used. Moreover, we tried to visualize the jet contour by ignition of its peripheral layers, which were a combustible mixture of atmospheric air and the outflowing gas (propane-butane).

Schlieren pictures of the pulsed periodic flow were obtained with an IAB-451 schlieren device (see Fig. 4a). An IFP-800 flash lamp with a light pulse duration of ~ 100 μsec was used as a light source. Experiments that were carried out with various orientations of the knife did not reveal any density gradients in the jet. Meanwhile, as can be seen from the schlieren photographs presented in Fig. 5A that recorded the various developmental stages of the

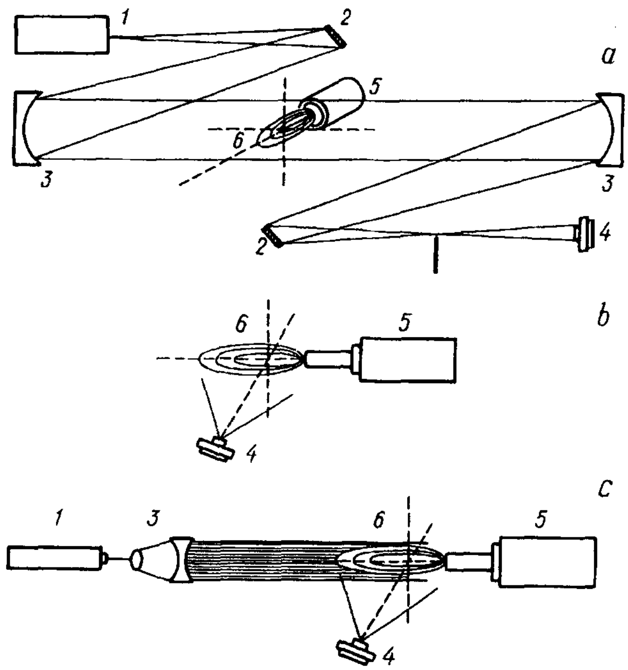

Fig. 4. Scheme of gas jet visualization with: a) schlieren method, b) direct photography, c) injection of jet illuminated by "laser knife" into dusted space; 1) laser, 2) flat mirror, 3) curved mirrors, 4) photocamera, 5) solenoid-operated valve, 6) pulsed jet.

pulsed periodic jet, three large-scale vortices can be distinguished in the longitudinal direction of the flow during a modulation period of the jet. Comparing the schlieren flow pictures with the pressure oscillograms (Fig. 2), it is possible to state that it is the three spikes on the background of one recorded total pressure pulse that correspond to the vortices spoken of above. From Fig. 5A-a it is possible to make a conclusion about spatial stability of the vortex structure of the pulse, since the distance between the vortices remained almost constant when they were displaced by distances of about $5 - 8d^*$.

It should be noted that the number of vortices can change with changes in the modulation frequency of the jet and in the Reynolds number typical of this frequency (for example, see [2] for comparison). These changes are accompanied by formation of coherent large-scale structures that affect turbulent transfer in the jet at a scale comparable with the size of the flow region.

For comparison, a schlieren photograph of an unmodulated turbulent jet is shown in Fig. 5A-a. This jet flows out of the nozzle at the same pressure in the photocamera as in the case of a pulsed periodic jet. It should be noted that the expansion semiangle of the free turbulent jet is somewhat smaller than it is for the pulsed periodic jet. It should be noted that in both cases the expansion semiangles correspond to the values obtained from measurements of the total pressure.

It seems interesting that the schlieren pictures of the flow agree qualitatively with results of peripheral flame visualization. Figure 5B shows photographs of a jet with a mixture of atmospheric air and outflowing propane-butane gas burning in its periphery. The flow patterns are obtained by direct photography of the jet (Fig. 4b) with an exposure of 1/500 sec. Both the photographs and the corresponding schlieren pictures show distinctly the structure of the flow core, which consists of two large vortices. However, in spite of the fact that this visualization procedure is rather simple, there are some complications in recording the flow structure in the immediate neighborhood of the nozzle because of weak intensity of the flame in this region.

In order to determine the characteristics of the flow core, we also tried to visualize the flow field by organizing outflow of the pulsed periodic jet into a dusted space and by the addition of fine solid particles to the jet studied (Fig. 4b). The jet was illuminated by a laser beam (a "laser knife"), and an ILGN-707 laser with a radiation power of 1 W at wavelength $\lambda = 0.7$ μm was used as a light source. In order to increase the intensity of

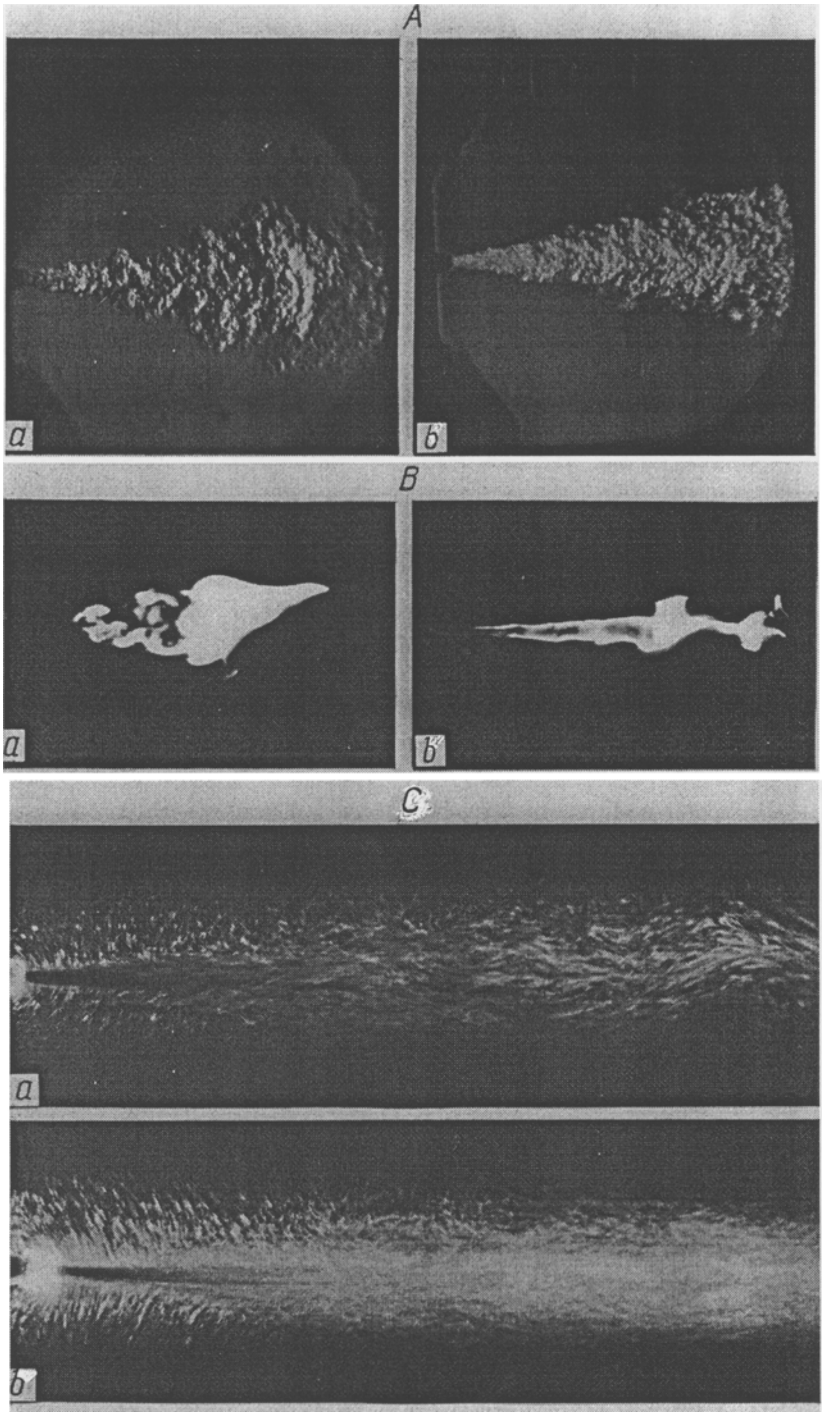

Fig. 5. Shapes of pulsed (a) and free (b) jets visualized by schlieren (A) and flame (B) methods and outflowing into dusted space with illumination by "laser knife" (C).

light scattered by the visualizing particles, the height of the "laser knife" was taken to be 4 cm, while its thickness was equal to ~0.2 mm. Therefore, the longitudinal axial section of the jet was fully seen only at distances of about first 20–30 diameters. Outside this region the "laser knife" illuminated only the central part of the jet.

In Fig. 5C one can see results of visualization of pulsed periodic (a) and unmodulated (b) turbulent jets in the case where they are injected into a dusted space. Comparison of the photographs presented shows that for the pulsed periodic jet, suction of gas from the surrounding medium to the central part of the flow is more intense in the region closest to the nozzle exit section. For the starting length of the pulsed jet, the velocity of gas inflow calculated in terms of the length of the tracks is about 2 m/sec. At a distance of about $30-40d^*$ from the nozzle exit section, the gas velocity increases (to 2.5 m/sec) in the flow periphery, while near the axis of the jet the gas velocity increases to 12 m/sec and higher. The direction of the tracks in this region shows that in their motion the vortices revolve about the jet axis. As regards the axial flow structure on the jet, there the flow has the form of a turbulent trail that resembles Karman's street. It should be emphasized that the version of the track visualization method used here does not reveal particular vortices, which is likely to indicate that the flow structure of the vortices deflects from the ideal toroidal shape. Moreover, the photograph shown in Fig. 5C-a demonstrates a rather complicated hydrodynamic flow structure near the axis of the pulsed periodic jet.

Unlike the previous method, the flow visualization with the aid of fine-disperse solids introduced into the flow illuminated by a "laser knife" at the valve inlet allowed us to determine the flow microstructure only approximately.

Conclusions. The schlieren method and the "contrast flame" technique appeared the most informative in studies of periodic structures in pulsed flows. Information obtained about the flow structure correlates qualitatively with measurements of the total pressure in the jet. As regards track methods, they give information about the flow velocities in various sections.

Studies that were carried out with the use of these methods show that in the case of a modulated gas jet that flows out at rather low Reynolds numbers (Re~4000) into a submerged space, a complicated hydrodynamic flow pattern appears that is characterized by formation of large-scale turbulent vortex structures that affect the flow organization in the jet as a whole. Each of the structures corresponding to a preset Reynolds number and modulation frequencies of the jet consists of three large-scale vortices, which, in turn, have a low-scale vortex structure.

NOTATION

d^*, diameter of nozzle exit section of valve, mm; L, downstream distance from nozzle exit section, mm; P, pressure in jet, atm; P_0, exit pressure at valve inlet, atm; P_{max}, maximum pressure in jet, atm; Re, Reynolds number; t, time, msec; λ, wavelength of laser radiation, μm.

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