JET FLOW PAST AN ELLIPSOID OF REVOLUTION BY MEANS OF A LASER DOPPLER ANEMOMETER

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We give the results of the experimental investigation of the flow of a blunt turbulent jet past an ellipsoid of revolution, without injection and with injection of a polymer solution into the boundary layer.

It is known that the kinematic characteristics of flow past a solid can be altered by using various methods that affect the boundary layer [1, 2]. One of the methods is the injection of a polymer solution into the boundary layer [2]. The measurement of the velocity field in this case by means of a hot-wire anemometer or a total-head tube entails sizable errors. This is because the filament of the hot-wire anemometer is contaminated by polymer particles or because the intake openings of the total-head tube are blocked with such particles [3].

The purpose of the present study was to use a laser Doppler anemometer (LDA) for investigating the kinematic structure of the flow of a blunt turbulent jet past an ellipsoid of revolution, without injection and with the injection of a solution of polyoxyethylene WSR-301 into the boundary layer. The use of an LDA for measurements in flows of polymer solutions has certain advantages over other known experimental methods of investigation [3-7].

The investigations were carried out on an experimental apparatus shown in Fig. 1. In a reservoir measuring $4.6 \times 1.5 \times 1.5$ m we set up a blunt turbulent jet flowing from a conical nozzle with an angle of conicity of 15° and an outlet opening diameter $d_0 = 12.4$ mm, at a constant velocity $U_0 = 3.33$ m/sec. In the main part of the jet we placed a model having the shape of an ellipsoid of revolution with semiaxes of $x_0 = 100$ mm and $y_0 = 10$ mm (the coordinate system is shown in Fig. 1). The major axis of the ellipsoid coincided with the axis of symmetry of the jet. The model was gripped at its tail end by a vertical holder of elliptical cross section, inside which there was a channel for the input of a polymer solution. This solution entered through a slit 0.8-mm-wide, cut at an angle of 45° to the semimajor axis. The slit was 20 mm from the nose of the model (see Fig. 1, lower right). The polymer solution was fed by means of a pump-free apparatus which made it possible to regulate the flow rate q through the slit from 1 to 15 cm^3/sec.

In our experiments we used solutions of polyoxyethylene WSR-301 at three concentrations: 0.005, 0.01, and 0.015 wt.%. The solution was first prepared in highly concentrated form and then stored for 2 days; it was diluted to the necessary concentrations immediately before the experiments. After the concentration of polyoxyethylene in the main reservoir reached 0.0001% in the experimental process, the water in the reservoir was completely renewed.

The LDA, set up according to a differential scheme (Fig. 1), consisted of an LG-38 laser, a beam-splitting unit, a focusing lens, an FÉU-79 photodetector unit with an intake objective, and electronic measuring apparatus.

At some distance along the y axis from the point of intersection of the laser beams (with the test volume) a mirror was placed in the water to reflect the direct scattered radiation in the direction of the photodetector. This arrangement made it possible, on the one hand, to place the photodetector and all the optical elements in one coordinated arrangement and, on the other hand, to obtain a good signal-to-noise ratio. The coordinated arrangement made it possible to locate a test volume measuring $60 \times 60 \times 500$ μ along the x and z axes without disturbing the adjustment of the optical scheme. Cross sections 1-8, at which the measurements were made,

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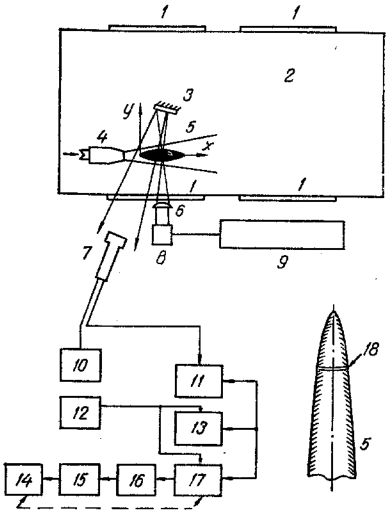

Fig. 1

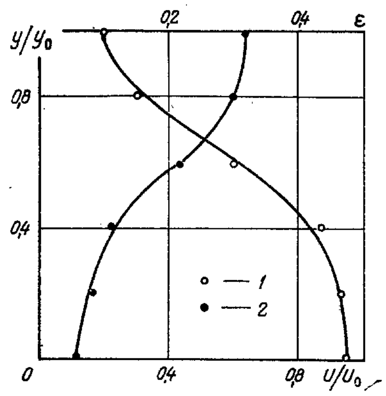

Fig. 2

Fig. 1. Block diagram of the experimental apparatus: 1) glass windows; 2) reservoir; 3) mirror; 4) conical nozzle; 5) ellipsoid of revolution; 6) focusing lens; 7) photodetector head; 8) beam-splitting unit; 9) laser; 10) photodetector power-supply unit; 11) amplifier; 12) marker generator; 13) frequency-spectrum analyzer; 14) recording potentiometer; 15) integrator; 16) quadratic voltmeter; 17) selective microvoltmeter; 18) polymer solution input slit.

Fig. 2. Velocity and turbulence-intensity profiles in the oncoming jet: 1) U/U_0; 2) ε.

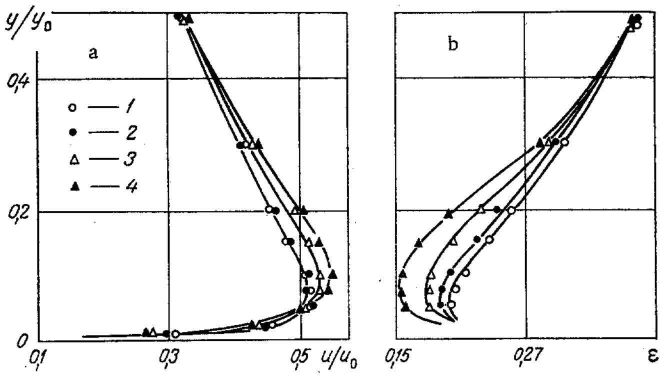

Fig. 3. Velocity (a) and turbulence-intensity (b) profiles at cross section No. 4: 1) without injection into the boundary layer; 2) with injection of water ($q = 15$ cm³/sec); 3) with injection of a 0.001% solution of WSR-301 ($q = 5$ cm³/sec); 4) the same with $q = 15$ cm³/sec.

were situated at distances of 10, 25, 35, 55, 75, 95, 115, and 140 mm, respectively, from the nose of the model in the downstream direction. The adjustment and monitoring of the operation of the LDA was carried out by means of a frequency-spectrum analyzer.

After appropriate processing of the signal of the electronic measurement part of the LDA, we recorded the spectrum of the Doppler signal by means of a recording potentiometer. For a sufficiently long averaging time, this spectrum can be identified with the probability density distribution of the velocity values. If the Doppler signal spectrum is close to a Gaussian spectrum, then the average velocity will be determined from the position of the maximum, and the turbulence intensity ε will be determined from its half-width [5, 8]:

$$\varepsilon = \frac{\sqrt{\overline{U'^2}}}{U} = \frac{1}{2.35} \cdot \frac{\sqrt{\sigma_t^2 - \sigma_l^2}}{f_D}. \qquad (1)$$

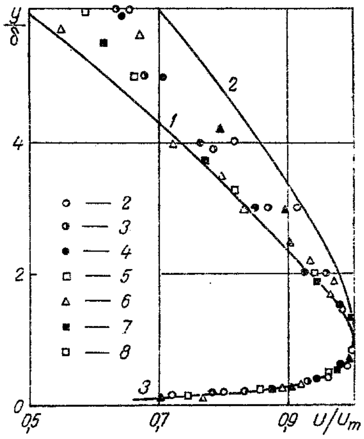

Fig. 4. Comparison of the experimental values of U/U_m at cross sections 2-8 with empirical relations: 1) curve calculated by formula (4) with C = 0.09; 2) by (4) with C = 0.06; 3) by (3) with C = 0.07. The form of the mark used for each point indicates the cross section at which the data were obtained.

The expression under the radical sign is the difference in dispersion between the "turbulent" and "laminar" spectra of the Doppler signals for the same average velocity. For any velocity U the quantity σ_l^2 can be calculated from the known dispersion σ_{0l}^2 for laminar flow moving with velocity U_0 [9]:

$$\sigma_l^2 = \sigma_{0l}^2 \frac{U}{U_0}; \quad (2)$$

U_0 and σ_{0l}^2 were measured at the potential core of the jet at the outlet of the nozzle. The values of σ_l^2 were calculated by formula (2).

In our study we obtained a large quantity of experimental data, but the brevity of this paper makes it impossible to cite them all here. Therefore, as an example, we show in Fig. 2 in dimensionless form the curves of velocity and turbulence intensity in the oncoming jet at a distance of 5 mm upstream from the nose of the model; these curves are characteristic of the main segment of a blunt turbulent jet [10].

Figure 3a and b shows the curves of velocity and turbulence intensity for cross section No. 4 without injection and with the injection of a polymer solution into the boundary layer. An analysis of the data shows that the velocity curves are formed by two interacting boundary layers: the wall layer and the jet layer. The maximum velocity is reached at the interface between them.

It was established that the introduction of the polyoxyethylene solution leads to an increase in the thickness of the wall boundary layer and a considerable reduction in turbulence intensity, especially in the region where the two boundary layers join. As the flow rate q increases, the turbulence intensity decreases. It should be noted that the increase in turbulence intensity as we approach the surface of the model (see Fig. 3b) is due to the additional widening of the Doppler spectrum because of the high velocity gradient. A correction for this widening is difficult to make.

The injection of water leads to changes which are similar in nature but are smaller in magnitude than those for the polyoxyethylene solution. At the above-mentioned cross section this effect is practically undetectable, but it does appear at cross sections closer to the slit.

The experimental data were compared with known empirical relations for the wall and jet boundary layers. A function found suitable for calculating the wall boundary layer is a logarithmic relation in the form [11]

$$\frac{U}{U_m} = 1 - C\frac{\delta}{y}\lg\frac{\delta}{y}, \quad (3)$$

where C is a coefficient characterizing the ratio of the thicknesses of the wall and jet boundary layers, δ is the thickness of the wall boundary layer, and y is the running coordinate.

To calculate the velocity curves for the jet boundary layer, we can use the well-known Schlichting function

$$\frac{U}{U_m} = \left[1 - C^{3/2}\left(\frac{y}{\delta} - 1\right)^{3/2}\right]^2. \quad (4)$$

Figure 4 shows the experimental values for flow past an ellipsoid without the injection of a polymer solution into the boundary layer. The solid curves represent the curves calculated by formulas (3) and (4). It can be seen from the figure that in the wall boundary layer the velocity curves are similar. The experimentally determined value of C for this region is 0.07. In the jet boundary layer we do not observe complete self-similarity of the velocity curves, although all the experimental values lie between curves 1 and 2, calculated by formula (4) for values of C = 0.09 and C = 0.06, respectively.

NOTATION

x, y, z, coordinate axes; x_0, y_0, semiaxes of the ellipsoid; U_0, exit velocity of the jet from the nozzle; d_0, nozzle outlet diameter; q, flow rate of the polymer solution injected through the slit; ε, turbulence intensity; U, the x component of the average velocity; U', the pulsation x component of the velocity; σ_t, half-width of the spectrum of the Doppler signal from the turbulent flow; σ_l, half-width of the spectrum of the Doppler signal from laminar flow moving at the same velocity as the flow being measured; σ_{0l}, half-width of the spectrum of the Doppler signal from laminar flow moving at velocity U_0; U_m, velocity at the boundary between the jet and wall boundary layers.

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