6. G. I. Barenblatt, V. N. Kalashnikov, and A. M. Kudin, Zh. Prikl. Mekh. Tekh. Fiz., No. 5 (1968).
7. S. A. Vlasov and V. N. Kalashnikov, Heat and Mass Transfer [in Russian], Vol. 3, Minsk (1972), p. 76.
8. V. N. Kalashnikov and A. M. Kudin, Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 2 (1972).
9. A. M. Kudin, G. I. Barenblatt, V. N. Kalashnikov, S. A. Vlasov, and V. S. Belokon', Inzh.-Fiz. Zh., 25, No. 6 (1973).
10. V. S. Belokon' and V. N. Kalashnikov, Nature, Phys. Sci., 229, 55-56, (1971).

USE OF LASER DOPPLER ANEMOMETER FOR THE INVESTIGATION OF TURBULENT FLOW OF POLYMER SOLUTIONS

N. A. Pokryvailo, D. A. Prokopchuk,
and Z. P. Shul'man

UDC 532.542.4

The results of measurements of the mean velocity, the intensity of the longitudinal and the transverse components of the fluctuation velocity, and Reynolds stresses in the wake of a disk with polyoxyethylene solution injected in the aft zone are presented. The measurements were made by a laser anemometer.

The drawbacks of the contact methods of measuring the averaged and fluctuation velocities of fluids, in particular, of polymer solutions, are due to the necessity of introducing the measuring devices into the flow that gets distorted thereby. These drawbacks led to the miniaturization of the measuring elements, on the one hand, and to the development of noncontact methods of measurement, on the other. One of the most promising measuring devices is the laser Doppler anemometer.

The method of measuring turbulent fluctuations with the use of laser technology utilizing the Doppler effect has been well substantiated by Goldstein and Hagen [1]. They demonstrated for the first time the possibility of computing the characteristics of a turbulent flow using the spectral analysis of the Doppler signal. The broadening of the Doppler signal is considered as a function of the probability density distribution of the values of the velocity in the flow. This method was further developed in [2-6].

At present, the most widely used laser Doppler systems are the "intersecting reference beam" system proposed by Goldstein [7] (one beam is used as the local oscillator), the "dual scattering" system developed by Brayton [8] (only the scattered light is detected from both beams), and the "Doppler meter" system introduced by Rudd [9] (all the forward propagating radiation, both scattered and nonscattered, is detected).

The "dual scattering" (differential) system is used in the present work. In principle, all these systems are equivalent and the use of each of these systems is dictated by the specific situation.

Let us consider the theoretical basis of the laser Doppler technique and the interpretation of the obtained output signals. The radiation scattered from the point of intersection of two coherent beams emitted by a single laser source is mixed in a photodetector to obtain beats of the Doppler frequency proportional to the initial flow velocity at this point, which is given by the following expression:

$$f_D = \left(\frac{n\bar{W}}{\lambda_0}\right)(\bar{e}_1 - \bar{e}_2). \tag{1}$$

Institute of Heat and Mass Transfer, Academy of Sciences of Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 29, No. 6, pp. 970-976, December, 1975. Original article submitted June 19, 1974.

Only one velocity component is measured – that which lies in the plane of the two intersecting beams and perpendicular to their bisector. In our scheme the Doppler signal is analyzed by an S4-8 spectrum analyzer. For a sufficiently large averaging time and small width of the passband of the spectrum analyzer the spectrum of the Doppler signal may be identical to the probability density distribution of the velocity values. The standard procedure of determining the velocity and the mean square value of the fluctuation can then be applied to the obtained signal representing the probability density distribution of the velocity values.

The spectrum of the Doppler signal usually has a Gaussian form and the mean velocity can be found from the maximum of the distribution curve. The vector of the instantaneous fluctuation of the velocity can be expressed in the form $\overline{W} = \overline{u}'e_x + \overline{v}'e_x$. For a turbulent flow it follows from Eq. (1) that

$$\Delta\overline{f_D^2} = \left(\frac{n}{\lambda_0}\right)^2 \overline{[W(\bar{e}_1 - \bar{e}_2)]^2}. \tag{2}$$

Then, if α is the angle between the plane of the intersecting beams and the x axis, Eq. (2) is written in the form

$$\Delta f_D^2 = 4\left(\frac{n}{\lambda_0}\right)^2 \sin^2\frac{\theta}{2}\,[\overline{u'^2}\cos^2\alpha + 2\overline{u'v'}\cos\alpha\cdot\sin\alpha + \overline{v'^2}\sin^2\alpha], \tag{3}$$

$$\frac{\Delta f_D^2}{f_D^2} = \frac{1}{u_0^2}\,[\overline{u'^2}\cos^2\alpha + 2\overline{u'v'}\cos\alpha\cdot\sin\alpha + \overline{v'^2}\cdot\sin^2\alpha]. \tag{4}$$

Thus it follows from Eq. (4) that in order to obtain the basic characteristics of the turbulent flow it is sufficient to carry out three measurements at each point, rotating the plane of the probing beams by three fixed values of angle α. Let $\Delta\overline{f_D^2}/f_D^2 = \sigma^2$ be the square of the variance of the Doppler signal. Then for the cases $\alpha = 0, +45°, -45°$ we have, respectively

$$\sigma_0^2 = \overline{u'^2}/u_0^2,\quad \sigma_{+45°}^2 = [\overline{u'^2} + \overline{v'^2} + 2\overline{u'v'}]/2u_0^2,\quad \sigma_{-45°}^2 = [\overline{u'^2} + \overline{v'^2} - 2\overline{u'v'}]/2u_0^2.$$

Thus, in order to find the basic characteristics of turbulence we have the following expressions:

$$\frac{\overline{u'^2}}{u_0^2} = \sigma_0^2,\qquad \frac{\overline{v'^2}}{u_0^2} = \sigma_{+45°}^2 + \sigma_{-45°}^2 - \sigma_0^2,\qquad \frac{\overline{u'v'}}{u_0^2} = (\sigma_{+45°}^2 - \sigma_{-45°}^2)/2. \tag{5), (6), (7}$$

A helium–neon laser LG-36 and the optical scheme shown in Fig. 1 were used for the measurement of the mean velocities and also the intensities of the longitudinal and transverse components of the velocity fluctuation and the turbulent tangential stresses.

The light beam from the monochromatic source of the helium–neon laser 1 is split into two beams by the divider 2 and lens system 3 and is focused at a given point of the flow. It should be noted that the divider, the mirror, and the lens system were made in the form of a single block which could be rotated about the axis of the laser beam. Thus the plane of the probing beams could be rotated by any angle relative to the flow in the channel. The position of the point could be changed in the longitudinal direction by moving the entire optical system along a rigid guide. The change of the position of the point of measurement in the transverse direction was accomplished by the displacement of the hydrochannel. The light beam reflected from the particles in the flow gets Doppler shifted in frequency and passes through objective 4, diaphragm 5, and falls on a PM-84 photomultiplier 6. The voltage taken from PM-84 is amplified by a wideband VZ-14 amplifier and fed to the S4-8 spectrum analyzer.

The spectrum of the Doppler signal averaged over 5 sec was recorded. The spectral half-width of the Doppler signal for a given position of the plane of the probing beams was determined from the spectrum and then the basic characteristics of the turbulence were computed from formulas (5)-(7).

The mean and the fluctuation characteristics of the turbulent flow were investigated on a continuous-action hydrodynamic tube (Fig. 2). A 4.5-kW electric motor sets an impeller pump into rotation through a clutch 2; the pump can ensure a discharge up to 2 liters/sec and a pressure up to 15 atm. The rotor of the pump 4 has rifling in the form of a multiple thread. A similar rifling but of opposite direction is made in the frame 3. The flow rate is regulated by the bypass segment with throttle 5. From the pump the liquid goes into a diffuser 6

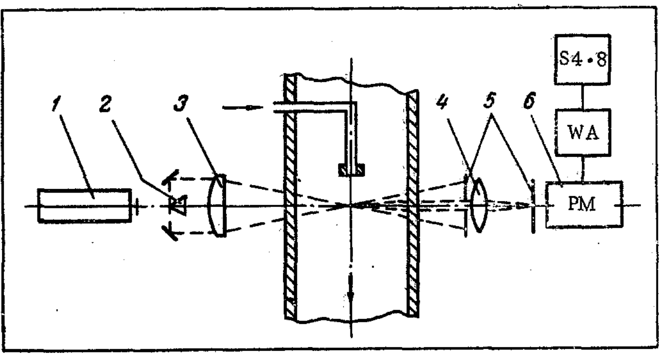

Fig. 1. Schematic diagram of the laser Doppler velocity meter.

with 4° aperture angle and from there it flows into tank 7 with a very small velocity. A honeycomb 8 and grid 9 are installed at the entrance to the operating channel, followed by a converger 10 with waisting degree 6. The cooling system 11 ensures a constant temperature of the liquid in the tube. The transverse cross section of the operating segment of the channel is 50 × 50 mm and its length is 3 m. The range of velocities is 0-1.5 m/sec and Re = 0-75,000. All the sections of the operating channel were made of transparent plastic.

The basic characteristics of the turbulent flow of water in the channel were measured at Reynolds number $Re = 7.5 \cdot 10^4$ for checking the equipment and the procedures. The length of the entrance segment was 52 gauge.

The results of the measurements as compared to those of Comte-Bellot are presented in Fig. 3. As evident from the figure, the results obtained with the laser Doppler anemometer are in good agreement with those of very careful measurements of Comte-Bellot [10]. The "differential system" of the laser Doppler velocity meter was used in the measurements. This geometry of the optical system does not permit a close approach to the wall of the channel in rotating the plane of the probing rays by + 45° and −45°; therefore, the results of measurements of the transverse component of the fluctuation velocity and Reynolds stresses for $y/D_k \leq 0.4$ are not presented in Fig. 3.

The flow behind a 12-mm-diameter disk was also investigated on the same equipment. It has been shown earlier [11] that on feeding a polymer solution in the wake behind a disk the velocity defect increases. In the present work, besides measuring the mean velocity, the intensities of the longitudinal and transverse components of the fluctuation velocity and also the Reynolds stresses were measured. The results of measurements in one of the transverse cross sections of the wake of the disk are shown in Fig. 4 for x/d = 6.

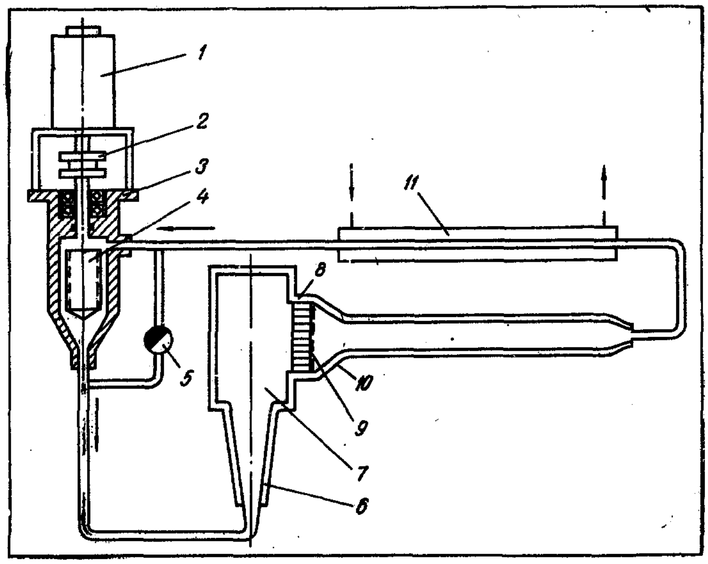

Fig. 2. Schematic diagram of the hydrodynamic channel.

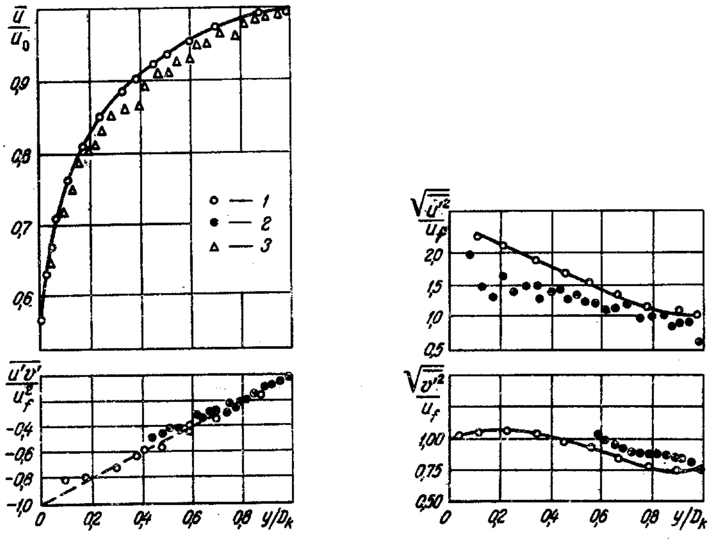

Fig. 3. The results of comparison of the mean velocity, the longitudinal and transverse components of the fluctuation velocity, and the turbulent tangential stresses (1 — Comte-Bellot data; 2, 3 — our data).

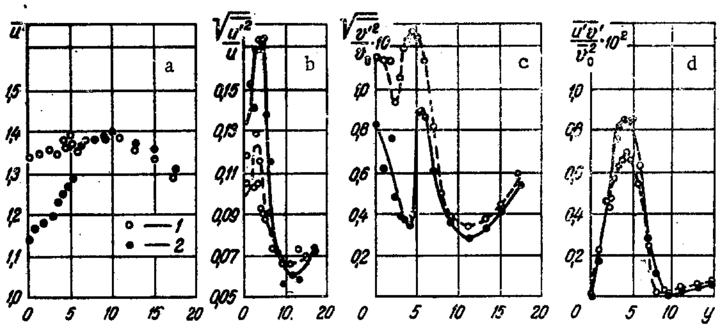

Fig. 4. Change of the mean velocity defect (a), longitudinal (b) and transverse (c) components of the fluctuation velocity and the turbulent tangential stresses (d) in the wake of a disk: 1) water; 2) polyox. ū, m/sec; y, mm.

The effect of the injection of polyethylene oxide on the basic characteristics of the flow in the wake of the disk was investigated for two concentrations of polyethylene oxide (PEO) — 0.1 and 0.5%. In order to eliminate the direct effect of the momentum of the injected polymer solution on the development of the flow a very small amount of polymer solution was fed into the aft zone of the disk ($q \leq 0.5$ cm^3/sec).

We discuss the main results obtained with the injection of 0.5% freshly prepared PEO solution. The measurements made in the transverse cross section of the wake at $x/D = 6$ show that the mean velocity defect increases sharply (Fig. 4a). As seen from Fig. 4a, the injection of the polymer does not produce any changes in the part of the velocity profile pertaining to the channel. The longitudinal component of the fluctuation velocity increases (Fig. 4b) and its largest value corresponds to the region of maximum shear velocity. In the region of the channel wall the values of $[(\bar{u}')]^{1/2}/\bar{u}$ become practically constant. The polymer additions have a significant effect on the decrease of the intensity of the transverse component of the fluctuation velocity (Fig. 4c). The decrease in the intensity of the transverse component of the fluctuation velocity agrees well with the increase of the velocity defect in the wake. During the injection of the polymer the turbulent tangential stresses increase in the region of the maximum by 20% (Fig. 4d). It should be noted that on injecting the polymer solution the radial gradient of the averaged velocity also increased due to the increased mean velocity defect. This could cause a certain increase in the turbulent tangential stresses. As regards the large decrease of the intensity of the transverse component of the fluctuation velocity, such manifestation of the action of PEO was observed in conditions of turbulence near the wall [12, 13]. Thus, a three- to fourfold decrease of the intensity of the transverse component of the fluctuation velocity was noticed in the experiments of E. M. Khabakhpasheva for a small decrease of the intensity of the longitudinal component.

Similar experiments were carried out with the injection of 0.1% PEO into the aft zone of the disk. The flow rate of the polymer solution was kept in the same ranges. The results of these measurements are in agreement with those discussed above, although all the enumerated effects are less pronounced.

Let us analyze the accuracy of the results obtained above. First of all, we note that the error of the measurements depends substantially on the signal-to-noise ratio of the given measuring system. In our equipment the maximum signal-to-noise ratio was attained experimentally by a choice of the optical parameters of the system and by the injection of the optimum concentration of scattering particles into the flow. Since the characteristics of the turbulent flow are computed from formulas (5)-(7), in which the quantity to be measured is the square of the variance of the Doppler signal $\sigma^2 = \overline{\Delta f_D^2}/f_D^2$, the main error is introduced by the inaccuracy in the determination of the frequencies from the spectrum of the Doppler signal. Thus, for example, for $\sqrt{\overline{u'^2}}/u_0 = 0.12$ the relative error in the measurement of σ^2 is 3% and for $\sqrt{\overline{u'^2}}/u_0 = 0.03$ it is 8%. In the measurements of the transverse component of the fluctuation velocity the maximum scatter of the points does not exceed 10-15%.

NOTATION

$\bar{e}_1$, $\bar{e}_2$, unit vectors of the incident light beams; $\bar{W}$, velocity vector; n, refractive index of the medium; λ_0, wavelength of the laser light; f_D, Doppler frequency; Δf_D, spectral half-width of the Doppler signal; α, angle between the mean velocity vector and the plane of the probing beams; Θ, angle of intersection of the beams; u_0, maximum velocity in the x direction; $\overline{\Delta f_D^2}/f_D^2 = \sigma^2$, square of the variance of the Doppler signal.

LITERATURE CITED

1. R. I. Goldstein and W. F. Hagen, Phys. Fluids, 10, No. 6 (1967).
2. C. Greated, J. Phys. E: Scientific Instruments, 3 (1970).
3. Yu. G. Vasilenko, Yu. N. Dubnishchev, V. P. Koronkevich, V. S. Sobolev, A. A. Stoppovskii, and E. N. Utkin, Laser Doppler Velocity Meters [in Russian], Nauka, Sibirsk. Otd. (1975).
4. Logan, Rocket Eng. Cosmonaut. 10, No. 7 (1972).
5. B. S. Rinkevichus, V. I. Smirnov, and V. F. Chernov, in: Transactions of Moscow Power Institute: Collection "Physics" [in Russian], No. 144, Moscow (1972), p. 65.
6. S. A. Vlasov, O. V. Isaeva, and V. N. Kalashnikov, Inzh.-Fiz. Zh., 25, No. 6 (1973).
7. R. I. Goldstein and D. K. Kreid, J. Appl. Mech. Ser. E, 34, No. 4 (1967).
8. D. B. Brayton, Paper Presented at the Electro-Optical Systems Design Conference, Sept. 16-18 (1969).
9. M. I. Rudd. J. Phys. E: Scientific Instruments, Ser. 2, 2, (1969).
10. J. Comte-Bellot, Turbulent Flow in a Channel with Parallel Walls, [Russian translation], Mir (1968).
11. N. A. Pokryvailo, Z. P. Shul'man, A. S. Sobolevskii, D. A. Prokopchuk, N. D. Kovalevskaya, G. M. Pashik, V. V. Tovchigrenko, and N. V. Zhdanovich, Inzh.-Fiz. Zh., 25, No. 6 (1973).
12. E. M. Greshilov, A. V. Evtushenko, L. M. Lyamshev, and N. L. Shirokova, Inzh.-Fiz. Zh., 25 (1973).
13. E. M. Khabakhpasheva and B. V. Perepelitsa, Inzh.-Fiz. Zh., 14, No. 4 (1968); 18, No. 6 (1970).