EXPERIMENTAL STUDY OF TURBULENCE NEAR A DUCT WALL

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ABSTRACT: A specially developed stroboscopic instrument has been used to measure the instantaneous velocities in the wall region (including the viscous sublayer) in a turbulent liquid (water) duct flow. Values of the average velocity and the turbulent fluctuations are found as a function of the distance from the wall. The method employed is much simpler than hot-wire anemometry, although somewhat less accurate.

The hydrodynamics of the viscous sublayer and the transition layer in a turbulent flow is of great interest in connection with a whole series of theoretical and practical problems. However, the literature contains very few data even on such a classical problem as that of flow over a plane smooth surface without a pressure gradient [1, 2]. Moreover, all these data were obtained using a hot-wire anemometer, although the application of this instrument in the wall region not only involves considerable technical difficulties but also has certain fundamental limitations [3].

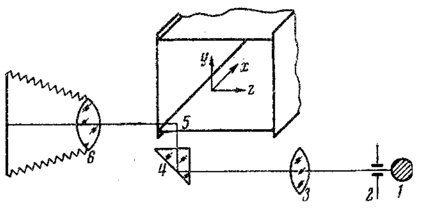

Fig. 1. Optical system of apparatus: 1) flash tube; 2) slit; 3) objective; 4) prism; 5) duct with transparent walls; 6) still or motion-picture camera.

Thus, for example, at high relative values of the turbulent fluctuations the hot-wire anemometer readings must be corrected by introducing a factor that depends not only on the value of the measured fluctuation component but also on the correlation between this component and the rest. The serious technical difficulties involved in making and operating hot-wire anemometers with particularly fine wires (to 1 micron in diameter) also impose a number of limitations: with respect to spatial resolution, flow velocity, gas purity, etc.

These disadvantages may be avoided by using the known method of flow visualization* consisting in introducing into the moving gas or liquid luminous tracers, which are then photographed. In particular, it is possible to obtain such tracers by introducing into a liquid or gas flow fine solid particles with good light-scattering or reflecting properties; photographing these particles in pulsed lateral illumination gives a continuous trace on a stationary film. By measuring this trace, two components of the instantaneous particle velocity can be computed; it is also possible to compute the instantaneous accelerations of a given volume element of liquid.

Of course, for this it is necessary that the solid particles introduced into the flow follow the liquid or gas sufficiently closely. Calculations show that this is the case if the condition

$$w_0 / g \ll 1 / f$$

is satisfied. Here w_0 is the sedimentation rate of a particle in the given medium under the acceleration of gravity g, and f is the characteristic frequency of the flow examined.

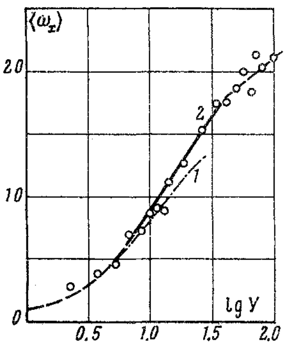

Fig. 2. Mean longitudinal velocity $\langle\omega_x\rangle$ as a function of $y = y_*$: 1) profile obtained in [5]; 2) author's results.

This condition is usually satisfied for a liquid medium; however, even in this case the particle size is of the order of 10 microns, so that photography must be carried out with a magnification of 3–10 times.

The experimental apparatus consisted of a circulation loop with an interchangeable working section and a special electronic circuit that ensured the pulsed (stroboscopic) illumination of the object; the optical system is shown in Fig. 1.

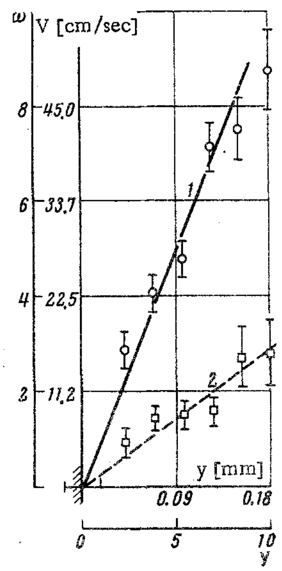

Fig. 3. 1) Mean longitudinal velocity $\langle\omega_x\rangle$; 2) mean square longitudinal fluctuation $\langle\omega_x'^2\rangle$.

Working section No. 2, on which most of the experiments were performed, was a transparent plastic rectangular duct measuring 17 × × 16 mm. The tracers were photographed in a section 475 mm from

*Apparently, the first author to apply the method of visualization to this problem was Fage [4]; in a comparatively recent article [5] the mean velocity profile was obtained with the help of a special stereoscopic microscope.

the inlet (i.e., about 30 times the duct dimension) near the bottom surface of the duct at a Reynolds number of the order of 20 000. The working medium was water at room temperature; fine particles of Al_2O_3 or Al (aluminum powder) were introduced. In the latter case it was also necessary to introduce small amounts of wetting agent. Before the experiments the particle suspension was clarified; in most of the experiments the Al particle fraction with $w_0 \leq 0.1$ cm/sec was used.

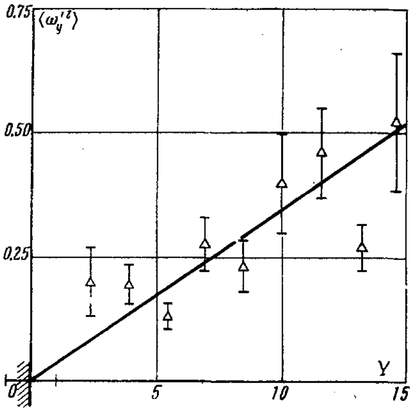

Fig. 4. Transverse fluctuation $\langle\omega_y'^2\rangle$ as a function of Y.

The flash lamp electronic control circuit was designed to ensure the brightest possible flashes and the most stable flash repetition rate. The impulsive discharge of the capacitors across the flash lamp was controlled with TGIL-400/16 thyratrons (discharge current to 400 A); strictly equal time intervals between flashes were ensured after suitable shaping with the sinusoidal voltage of a master oscillator, whose frequency could be varied within wide limits. At discharge parameters of 2 kV, 2 μF, the IFK-120 flash lamp gives a brightness of about 10^5 stilbs, and a flash time of the order of 20 μsec.

An image of a slit (Fig. 1) is projected by a lens through the transparent bottom surface of the working section, so that a narrow region of the liquid flow, several tenths of a millimeter deep along the z axis, is illuminated. Apart from the tracers, each frame registered a luminous mark on the bottom of the working section from which the y-coordinates of the tracers were reckoned.

Each frame, regarded as a certain set of tracers, characterizes the instantaneous velocity field; averaging the instantaneous values over different frames makes it possible to compute the average velocity and fluctuation fields.

Figures 2–4 show the results obtained in one series of experiments. In Fig. 2 the mean longitudinal velocity $\langle\omega_x\rangle$ (in dimensionless form) has been plotted in semilogarithmic coordinates.

The experimental points obtained lie mainly in the viscous sublayer ($Y = yV_*/\nu < 5$) and in the intermediate layer ($5 < Y < 30$). It is clear from the graph that in the intermediate layer the velocity profile can be approximated by the expression

$$\langle\omega_*\rangle = -5.7 + 14\ \lg Y.$$

The dynamic velocity $V_* = \sqrt{\tau/\rho}$ was computed from the pressure drop along the duct.

Within the limits of accuracy of the experiment (the principal error is associated with inaccuracy in determining the local value of the dynamic velocity) this coincides with the data obtained by Laufer [1] and Reichardt [2] by the hot-wire anemometer method. The data of these authors can be expressed by the equation

$$\langle\omega_x\rangle = -3.5 + 12.0\ \lg Y_*.$$

Figure 3 shows profiles of $\langle\omega_x\rangle$ and the longitudinal mean square fluctuation $\langle\omega_x'^2\rangle$ in the interval $Y < 10$, and Fig. 4 the transverse fluctuation $\langle\omega_y'^2\rangle$. The probable statistical errors plotted on these graphs were computed from the number of averaged values of the instantaneous velocity in each interval of Y. These data also agree with Laufer's data within the limits of accuracy of the experiment.

It is important to stress that in the viscous sublayer there is a very high level of longitudinal fluctuations $\alpha_x \equiv \omega_x^{-1}\langle\omega_x'^2\rangle$; our experiments gave $\alpha_x = (30 \pm 10)\%$. Thus, the viscous sublayer consists of randomly alternating regions with variable values of the local instantaneous shear stress τ_m. The extent of these regions in the longitudinal direction can be estimated from measurements of the instantaneous accelerations of a liquid mole. So far, only a rough estimate has been obtained, namely, that the extent of the smallest elements of these regions is not less than several tenths of a millimeter under the conditions studied.

A statistical analysis of the fluctuations in the viscous sublayer points to asymmetry in the distribution of the fluctuations with respect to magnitude and sign.

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REFERENCES

1. J. Laufer, "The structure of turbulence in fully developed pipe flow," NACA Tech. Rep. N1174, 1954.

2. H. Reichardt, "Die Wärmeübertragung in turbulenten Reibungsschichten," Z. angew. Math. and Mech., B. 20, 297, 1940.

3. J. O. Hinze, Turbulence [Russian translation], Fizmatgiz, 1963.

4. A. Fage and H. C. H Townend, "An examination of turbulent flow with an ultramicroscope," Proc. Roy. Soc. A. vol. 135, p. 656, 1932.

5. R. M. Nedderman, "The measurement of velocities in the wall region of turbulent liquid pipe flow," Chem. Eng. Sci., vol. 16, p. 20, 1961.

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