INVESTIGATION OF BOUNDARY-LAYER TURBULENCE IN THE EDDY ZONE BEHIND A BLUFF BODY

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Recently the flow characteristics in various eddy zones have been the subject of thorough studies. The experimental investigation of turbulence in the eddy zone behind a bluff body, however, is associated with great difficulties due to the high level of pulsation. This applies also to hot-wire anemometer measurements. Consequently, even the simplest rotational flows (such as transverse flow past a cylinder, a shoulder, and so forth) have been insufficiently investigated; data on boundary-layer turbulence seem to be completely missing in the literature.

On the other hand, available data even on such integral characteristics as heat and mass transfer in the dimension relation $S \sim R^n$ (S is the Stanton number and R the Reynolds number) indicate a deviation from the conventionally accepted value of $n = -0.2$ [1]. In [2], it is shown that the velocity profile in the boundary-layer region of an eddy zone in a recess deviates from that calculated on the basis of convensional formulas for turbulent channel flow.

The experimental facility used to study flows behind cylinders consisted of a small water-filled recirculating system, the flow rate and the temperature of the liquid were kept constant with accuracy to 2% and 0.5°C, respectively. The blocking coefficient was $q = 0.5$. Instantaneous velocities in the flow were measured by a previously developed stroboscopic technique [3]; in the current series of experiments, small (~20 microns in diameter) gas bubbles, obtained electrolytically within the recirculating system, were used as markers.

The flow conditions in the recirculating system were chosen such as to produce a turbulent eddy zone at subcritical Reynolds numbers behind a cylinder; the corresponding range of Reynolds numbers lies, as we know, roughly between 500 (transition from a Kármán street to a turbulent eddy zone) and $2 \cdot 10^5$ (critical region of Reynolds numbers). The measurement results given below were obtained only for $R = 8 \cdot \cdot 10^3$.

The general pattern of the flow past a transverse cylinder as recorded in this paper agrees completely with that known from the literature. At the front side of the cylinder (Figure 1), a laminar boundary layer forms (in our experiments, the degree of turbulence of the oncoming flow was roughly 14%). Eddy zone 3, located behind the separation region, is divided from potential flow 1 by a relatively narrow mixing region 2 characterized by a large transverse velocity gradient.

It should be emphasized that the eddy zone (at least its boundary layer) is extremely turbulent, i.e., the pulsation rates here are on the order of, and even greater than, the mean velocity at a given point. This important peculiarity of the flow in the eddy zone was observed also for transverse flow past a plate. We can assert that the same effect occurs for other bluff bodies, such as a shoulder, recess, and so forth. It can be assumed with a high degree of confidence that the turbulence level in the oncoming flow has only a weak effect on turbulence in the eddy zone; furthermore, an appreciable lamination of the flow was observed in the narrow cross section of the recirculation system (for $\varphi = 90°$).

The instantaneous velocity fields in this cross section were measured by the already mentioned stroboscopic technique, followed by the computation of the averaged and pulsation components with respect to two coordinate axes (everywhere below, the x-coordinate is read along the tangent to the cylinder surface in the given section in the direction of positive φ angles, while the y-coordinate is ready from a and perpendicular to the cylinder surface). Measurements were performed in several cross sections with respect to the angle φ, namely, at the end point ($\varphi = 180°$), behind the separation point ($\varphi = 105°$), in the proximity of the separation point, and in the region of oncoming flow ($\varphi = 60°$).

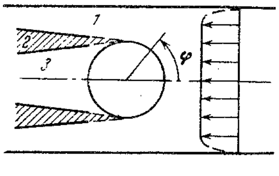

Fig. 1. Pattern of the flow past a cylinder.

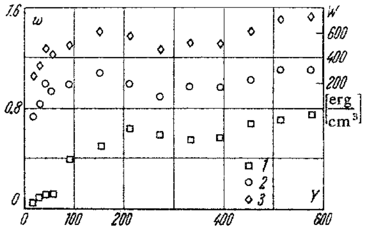

Fig. 2. Pulsation-rate and turbulent-energy profiles for the rear portion of the cylinder.

The measurements at the end point, where the mean flow rate is close to zero, are of particular importance for understanding the mechanism of boundary-layer turbulence in the eddy zone. Figure 2 shows plots of the transverse 1 and longitudinal 2 dimensionless pulsation rates and of turbulent energy 3 for the rear portion of the cylinder. The turbulence at a distance from the solid wall is nearly isotropic (the third pulsation rate component u_z' was not measured, however, it will be assumed in the following that for the end point $u_z' \approx u_x'$). This isotropy no longer holds at the wall (the curvature of the wall can be safely neglected, since the cylinder diameter was $d = 2$ cm in the experiments). For $y > y_0$, the longitudinal pulsation decreases only slightly at the wall, and can be approximated by a power law with an exponent of 0.29, while for $y < y_0$, u_x' must be a linear function of y. The thickness of y_0 is defined as the point of intersection of the linear and power-law profiles. Transverse pulsation starts to drop at much larger values of y, its behavior as a function of y being close to linear.

Thus, there is a qualitative similarity between the longitudinal and transverse pulsations as a function of y and the analogous values in fully developed channel turbulence. It was found, however, that a quantitative similarity does exist. Indeed, one can introduce (purely phenomenologically, for the time being) a certain characteristic velocity V_+, and can write the velocities and distances from the wall in dimensionless form: $\omega \equiv u / V_+$, $Y \equiv yV_+/\nu$. Then, one might expect that for a properly selected V_+, the values of ω_x', ω_y', and Y_0 will become the same as in the case of fully developed channel turbulence. It was found, however, that this is not so; even when the value of V_+ is selected completely at random, it is possible to obtain a quantitative analogy only for any one of the mentioned characteristics of boundary-layer turbulence.

This important finding, which was observed also for another eddy zone, leads to the assumption that for $\tau \approx 0$ boundary-layer turbulence is of a somewhat different nature than for an averaged flow along the wall.

This difference is physically valid. We know that in the presence of an averaged flow along the wall the source of turbulent energy is precisely the interaction between the turbulent pulsations and the averaged flow; whereas in the absence of the latter, the principal sources of turbulent energy will be located beyond the boundary layer.

Such a concept is developed in [6], wherein it is proposed to use pulsation energy (far from the wall) averaged with respect to all three

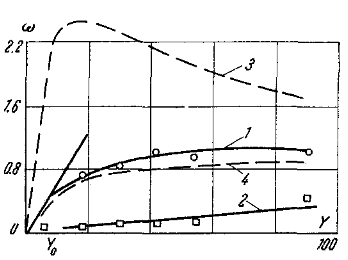

Fig. 3. Pulsation velocity profiles for small values of Y.

coordinates as the characteristic value. Then the characteristic velocity will be expressed as

$$V_+^2 \equiv \frac{1}{3}\langle u_x'^2 + u_y'^2 + u_z'^2\rangle\,|_{y \gg y_0}.$$

Figure 3 shows empirical dimensionless values of the pulsations (1 and 2 are ω_x' and ω_y' for the rear region of the cylinder, respectively, while 3 and 4 are the same values for fully developed turbulent channel flow [7]) for small values of Y. Here, $V_+ = 21.9$ cm/sec is calculated for $y = 2.6$ mm.

Comparison shows that the thickness of y_0 is appreciably less than the thickness of the viscous sublayer, determined from the equivalence between turbulent and viscous momentum transfer. This can probably be attributed to the action of local longitudinal pressure gradients which arise spontaneously when the molecules of the fluid are decelerated at the wall (such instantaneous flow patterns can be seen distinctly on photographs of tagged-particle tracks).

Another conclusion is that the total specific turbulent energy (curve 3 in Fig. 2)

$$W \equiv {}^1/_2\,\rho\,\langle u_x'^2 + u_y'^2 + u_z'^2\rangle$$

is hardly damped at the wall for $y > y_0$; for small y, the dependence W(y) approaches a power law with an exponent $m > 0.5$. Here, the turbulent energy of the transverse pulsations which lead to the onset of local pressure gradients along the wall is transferred into energy of longitudinal pulsations. Much stronger damping was predicted theoretically in [6], where the law obtained was in the form of $W \sim y^{1.33}$. An explanation for this can be seen in the fact that the laws for the damping and diffusion of turbulent energy used in [6] are of doubtful validity in the case of strongly anisotropic turbulence. A certain rise of the curves $u_x'(y)$ and W(y) in the region $Y \sim 100-250$ is possibly associated with the additional generation of turbulent energy under the action of pulsating shear stresses at the wall.

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