STRUCTURE OF FLOW IN THREE-DIMENSIONAL TURBULENT WAKES

L. N. Ukhanova

The results are presented for an experimental study of the average flow parameters in three-dimensional turbulent wakes which form behind cylinders of finite elongation transverse to the flow and behind a cross-shaped obstacle.

Experimental data on three-dimensional turbulent wakes published earlier have covered the range of Reynolds numbers $Re = (6.3-70) \cdot 10^3$ [1, 2]. In the present work the results of measurements of the average parameters of the wake behind a cylinder of finite elongation transverse to the flow are presented for a wider range of Reynolds numbers. The range is broadened on the side of higher values up to those close to the critical value (up to $Re = 3.15 \cdot 10^5$). The effect of the elongation of the cylinder on the average parameters of the three-dimensional wake was studied. Round cylinders having flat ends and elongations $\lambda = 5, 6.1, 8.4, 10, 13.1, $ and $22$ were used. In addition, a study was made of the wake behind a cylinder of elongation $\lambda = 8.4$ having hemispherical ends. A case of more complex three-dimensional flow was also studied; the wake behind a cross consisting of two mutually perpendicularly crossing cylinders of the same elongation $\lambda = 15$, transverse to the flow.

The studies were conducted in wind tunnels of the closed type with an open working section. The cylinders (and the cross) were rigidly fixed with guy wires at the entrance to the working section of the tunnel perpendicular to the impinging stream. The blocking of the tunnel did not exceed 2% in any of the experiments. The level of turbulence of the impinging stream was less than 0.5%.

The measurements of average velocities were made either with a constant-temperature thermoanemometer having monofilament probes or with Pitot tubes. For measurements in the wakes behind single cylinders the thermoprobe was mounted in the stream so that its filament was parallel to the axis of the cylinder. For measurements in the wake behind the cross the probe was oriented parallel to the bisector of the angle between the cylinders, i.e., at a 45° angle to the axis of each cylinder. The average velocity profiles in the fixed cross sections were measured both along the axes of symmetry $y$ and $z$ and along lines parallel to them (the directions of the coordinate axes are indicated in Figs. 2 and 4). On the basis of these profiles lines of equal average velocities, isotachs, were constructed at the selected cross sections of the wake. In addition, the transverse dimensions of the wake were estimated from the distributions of average velocity $u(y)$ and $u(z)$ along the axis of symmetry.

As in the studies of flat and axially symmetrical jets and wakes [5], the width of the average velocity profile corresponding to half the velocity defect at the axis was taken as the effective transverse dimension of the three-dimensional wake. Since a three-dimensional wake which forms behind a cylinder of finite elongation transverse to the flow has two planes of symmetry ($xy$ and $xz$) each cross section of such a wake is characterized by two transverse dimensions, $\delta_y$ and $\delta_z$, determined by the profiles $u(y)$ and $u(z)$, respectively (see the flow diagram in Fig. 2).

The results of the experiments showed first of all that the nature of the three-dimensional turbulent wake is essentially unchanged in the entire range of Reynolds numbers studied. For the Reynolds numbers $7 \cdot 10^4 \leq Re \leq 3.15 \cdot 10^5$ the three-dimensional wakes behind cylinders of finite elongation develop in the same way as for $6.3 \cdot 10^3 \leq Re \leq 7 \cdot 10^4$. In all cases at a certain distance downstream from the cylinder the dimension perpendicular to the axis of the cylinder becomes the larger transverse dimension of the wake.

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Fig. 1. Average velocity distributions in cross sections of wake behind cylinder (\(\lambda = 5\), \(Re = 3.15 \cdot 10^5\)): a) average velocity profiles: 1) \(\bar{u}(y)\); 2) \(\bar{u}(z)\); b) isotachs. Solid lines: \(x = 15\); dashed lines: \(x = 5\).

Fig. 2. Variations in \(\delta_y(x)\) (a) and \(\delta_z(x)\) (b) for different \(\lambda\): 1) \(\lambda = 22\) (\(Re = 1.1 \cdot 10^4\)); 2) \(\lambda = 13.1\) (\(Re = 8.4 \cdot 10^5\)); 3) \(\lambda = 10\) (\(Re = 1.1 \cdot 10^6\)); 4) \(\lambda = 6.1\) (\(Re = 4.2 \cdot 10^6\)).

The isotachs in two cross sections of the wake behind a cylinder of elongation \(\lambda = 5\) and at \(Re = 3.15 \cdot 10^5\) are given as an example in Fig. 1. It is seen that the spreading of the wake in the plane of symmetry perpendicular to the axis of the cylinder occurs much faster than in the plane of symmetry passing through its axis. As a result, in cross sections of the wake distant from the axis of the cylinder by five or more diameters the isotachs have close to an elliptical shape with the major axis perpendicular to the axis of the cylinder. The characteristic average velocity profiles \(u(y)\) and \(u(z)\) in the corresponding cross sections of the wake are also shown in Fig. 1. It should be noted that while at small distances from the cylinder the velocity profiles have a dome-like shape characteristic for flat and axially symmetrical wakes, in more distant sections of the wake in both planes of symmetry the velocity profiles take on a saddle-shaped appearance. In this section of the wake the region of the maximum average velocity defect is shifted away from the longitudinal \(x\) axis. Because of the nonuniform variation in velocity across the wake the isotachs corresponding to this section of flow have a shape different from elliptical.

In the entire range of Reynolds numbers examined (from \(Re = 6.3 \cdot 10^3\) to \(Re = 3.15 \cdot 10^5\)) the wakes are characterized by a nonuniform distribution of the average velocity of transverse flow. The region of the three-dimensional wake characterized by a saddle-shaped distribution of average velocity in the cross sections is located closer to the cylinder the smaller the elongation \(\lambda\). For instance, in the wake behind a cylinder of elongation \(\lambda = 6.1\) (\(Re = 4.2 \cdot 10^4\)) this section is at a distance \(x \geq 11\), while in the wake behind a cylinder of elongation \(\lambda = 22\) (\(Re = 1.1 \cdot 10^6\)) it is at \(x \geq 70\). It should be mentioned that nonuniformity of the average velocity field of an analogous nature was observed in a study of three-dimensional submerged jets [4].

The clearest dependence of the extent of the sections of flow in which reorganization of the three-dimensional wakes occurs on the elongation of the cylinder can be observed from the variation along the longitudinal coordinate of the effective transverse dimensions of the wake (Fig. 2). For all values of the elongation \(\lambda\) examined the transverse dimension of the wake in the plane of symmetry perpendicular to the axis of the cylinder constantly increases along the entire flow. The transverse dimension of the wake in the plane of symmetry passing through the axis of the cylinder varies little at the start of the flow for small elongations (\(\lambda = 5\) and 6.1). For elongations \(\lambda \geq 10\) the effective transverse dimension \(\delta_z\) decreases markedly at the start of the flow, i.e., narrowing of the wake occurs in the \(xz\) plane of symmetry. As a result, the two transverse dimensions become equal at some distance from the axis of the cylinder determined by the elongation \(\lambda\). The size of \(\delta_z\) continues to decrease somewhat, but starting with a certain cross section of the wake further downstream both effective transverse dimensions increase but at different rates.