Flow structure and turbulent kinetic energy of velocity fluctuations in a cylinder near wake at Re = 3900

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Abstract: SIV measurements of instantaneous vector fields of velocity have been performed in the near wake behind a circular cylinder in a cross flow at Re = 3900. Patterns of velocity profile evolution with the distance from the cylinder have been refined. Distributions of components of the turbulent production term of the turbulent kinetic energy transport equation have been estimated. Their main patterns and correlation with the formation and motion of large-scale vortices (Karman vortices) have been revealed.

1. Introduction

Rapid development and wide variety of numerical methods for simulation of turbulent flows entail the need for their thorough verification. In the context of separated flows, a cylinder in a cross flow is a classic benchmark problem. In practice, the most widespread simulation method based on Reynolds averaged Navier-Stokes equations is not accurate enough to even predict the parameters of an averaged flow in the cylinder wake. Large Eddy Simulation (LES) and relatively new Detached Eddy Simulation (DES) methods yield somewhat better results. Direct Numerical Simulation (DNS) is the most rigorous approach, and it is supposed to accurately predict the characteristics of turbulent flows regardless of their complexity. However, DNS is limited to relatively low Reynolds numbers. When non-uniform grids or restricted computational domains are employed to overcome these limitations, the results depend on these parameters. In all the above mentioned cases, thorough verification of numerical results against reliable experimental data is required.

In the literature, the numerical methods (LES, DES, DNS) for simulation of cylinder flows are verified at the Reynolds number of 3900. The majority of published papers deal with modification of LES technique [e.g. 1 – 5]. DNS of the flow under consideration has been performed in a limited number studies [6, 7]. Their main goal was to eliminate the controversy between the experimental and numerical (LES) results reported in the literature, namely the profiles of streamwise velocity component in the vicinity of $x/d = 1$ ($d$ is the cylinder diameter). U-shaped or V-shaped profiles are observed in this region depending on the simulation parameters. The experimental data for the profile shape in different stations along the wake are also inconsistent [4, 8 – 10]. LES and PIV in [4] yielded U-shaped profiles at $x/d = 1$, while PIV [9] documented V-shaped profiles. However, the reason for the controversy has not been clarified.
Thus, there is a clear shortage of reliable experimental data that would contain full information on experimental conditions as the basis for verification of numerical methods. Besides, almost all authors provide experimental and numerical estimations of only the profiles of velocity components, their RMS fluctuations and Reynolds stresses. Meanwhile, full information about all the components of the Reynolds stress tensor (turbulence production, dissipation, turbulent and viscous diffusion, pressure diffusion) is required in order to adequately simulate the flows. However, even the data on turbulent kinetic energy production in the cylinder near wake (which is far less challenging to measure) are extremely scarce.

The present paper develops our previous research [11], in which we experimentally studied the structure of the cylinder near wake at Re = 3900. The evolution of velocity profile with the distance from the cylinder is investigated in more detail here. New data on the patterns of turbulent production components of the turbulent kinetic energy transport equation are obtained in different wake zones.

2. Experimental setup and procedure
The rectangular test section (fig.1) had the height of 115 mm and the width of 150 mm. Its length was 300 mm. A 150-mm long cylinder with the diameter $d = 15$ mm was mounted at the distance of 60 mm from the channel inlet. SIV [12] measurements of instantaneous vector fields of velocity were performed in the wake at different distances from the cylinder ($x/d = 0.58, 1.06, 1.54, 2.02, 4.0, 7.0$ and $10.0$). The frame size was $43 \times 975$ pix, scaling factor $0.045$ mm/pix, framing rate $f = 12800$ Hz, video duration $2.0$ s. The Reynolds number in experiments was $Re = Ud/\nu = 3900$, where $U$ is the bulk velocity in the test section, $\nu = 1.45 \times 10^{-5}$ m$^2$/s is the kinematic viscosity of air.

3. Results and discussion
Fig.2 compares the velocity distributions behind the cylinder at the channel axis obtained by different authors. It demonstrates the sensitivity of these distributions to experimental conditions (channel width, blockage ratio, turbulence intensity, etc.) and parameters of numerical simulation (grid parameters, transverse size of the computational domain). Additionally, Fig.2 provides SIV measurements from the present research.

The profiles of streamwise velocity component, $U/U_0$, are plotted in Fig.3 at different distances from the cylinder, $x/d$. At $x/d = 0.58 - 1.54$, the profiles transform gradually from U-shaped to V-shaped. The main discrepancy in the published data (e.g. [2, 4, 7]), as far as the profile shape in the wake is concerned, was observed at $x/d = 1.06$. Combined analysis of Figures 2 and 3 along with the literature revealed that in all experiments and simulations U-shaped profile in the wake was documented at the normalized distance from the cylinder $x/X_{sep} = 0.5...0.55$ (where $X_{sep}$ is the distance from the cylinder to the point of the wake axis where the streamwise velocity is zero), while V-shaped profile was observed at $x/X_{sep} = 0.63...0.67$. $X_{sep}$ is the streamwise length of the separation region. Besides, in the former case, the station $x/d = 1.06$ is located at the distance of $\Delta x/d = -0.45...0.5$ from the point of maximum reverse flow velocity, while in the latter case it is at $\Delta x/d = -0.02...0.15$, which
Figure 2. Distributions of the streamwise velocity component along the central line of the cylinder wake: experimental data (a), DNS (b); 1 – PIV [4]; 2 – PIV [9]; 3 – PIV (taken from [6]); 4 – Hot-wire [10]; 5 – Hot-wire [8]; 6 – SIV; 7 – DNS (case I) [6]; 8 – DNS (case II) [6]; 9 – DNS (case E) [7]

is significantly closer. Thus, the shape of the velocity profile is determined by the position of the considered station relative to $X_{sep}$ and hence relative to the zone of the maximum reverse flow velocity in the wake.

The production term in the turbulent kinetic energy transport equation can be written as:

$$ P = -P_{uu} - P_{uv} - P_{vv}, \quad (1) $$

where $P_{uu} = <u'^2>\partial U/\partial x$; $P_{vv} = <v'^2>\partial V/\partial y$; $P_{uv} = <uv'>\partial U/\partial y + <uv'>\partial V/\partial x$.

SIV measurements yielded the distributions of the components of production term, $P_{uu}$, $P_{vv}$ and $P_{uv}$, of the turbulent kinetic energy transport equation at different stations along the cylinder near wake. These distributions normalized by $d/U_0^2$ are plotted in Figs.4 – 6. Production of turbulent fluctuations of velocity in the cylinder near wake occurs primarily at $x/d = 1 – 4$, which corresponds to the region where Karman vortices are formed. The order of the maximum values of $P_{uu}$, $P_{vv}$ and $P_{uv}$ components is approximately identical. The difference is that the maximum values of $P_{uu}$ and $P_{uv}$ are observed at the wake boundary, i.e. in the region of shear layers. Similar pattern in $P_{vv}$ distribution was revealed only at $x/d = 1.06$ and 1.54.

Figure 3. Profiles of streamwise velocity component at different distances from the cylinder
The maximum values of $P_{vv}$ at $x/d = 2.02$ were documented around the wake axis. This is the region where the maximum velocity of transverse motion of Karman vortices was observed near the wake axis [11].

Figure 4. Distributions of $P_{ uu}$ at different distances from the cylinder

Figure 5. Distributions of $P_{ uv}$ at different distances from the cylinder

Figure 6. Distributions of $P_{ uv}$ at different distances from the cylinder
Conclusions
Thorough analysis of SIV measurements in the near wake of the circular cylinder at $Re = 3900$ yielded more detailed (compared to [11]) information on the patterns of the transition from U-shaped to V-shaped velocity profile with the distance from the cylinder. The profile shape depends on its coordinate relative to the separation region and relative to the zone of minimal velocity at the wake axis.

Main patterns in the distribution of the components of the production term in turbulent kinetic energy transport equation have been revealed at different stations along the cylinder near wake. Turbulent energy production has been primarily observed within $x/d = 1–4$ zone of the wake. Correlation between the distributions of the components of turbulent production and formation and motion of Karman vortices has been described.

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