Investigation of the influence of the surface material of a streamlined round cylinder on the parameters of the near wake using PIV and POD methods

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Abstract. In this paper, the influence of the surface material of a streamlined cylinder on the characteristics of large-scale velocity pulsations is experimentally investigated using the methods of studying the flow structure, namely PIV (Particle Image Velocimetry) and POD (Proper Orthogonal Decomposition). A comparison of the parameters of the near wake in the range of Reynolds numbers of 70 000 – 180 000 is presented for cylinders made of vacuum rubber (hydrophilic material) and fluoroplast (hydrophobic material) of the same diameter. Using the PIV method, instantaneous and averaged velocity fields are obtained. The size of the separation zone is determined based on the average velocity fields. The spatial shape and kinetic energy of the observed large-scale ripples in the wake region are analyzed using the POD statistical method. In the studied range, the transition to the critical flow mode for the fluoroplast cylinder is recorded. For the case of flow around a rubber cylinder, the character of pulsations in the wake zone remains unchanged throughout the studied range.

1. Introduction

Cylindrical transversely streamlined surfaces are widely used in various heat exchange, energy and heat engineering devices. Fuel elements of nuclear power plants, input edges of turbine blades, edges of wings and blades of aircraft, often represent a cylinder or part of a cylinder. Despite the apparent simplicity of the geometry, the flow around a cylindrical object is a complex phenomenon.

In the literature, there are such flow modes as subcritical (laminar boundary layer along the streamlined surface), critical (transition to turbulence in the boundary layer) and supercritical [1]. The critical flow mode is implemented in the range of Reynolds numbers from about 150,000 to 400,000 and is characterized by a significant reduction in the drag of the streamlined object. When implementing the critical flow regime, the flow characteristics depend on the turbulence level, surface roughness, surface material and general geometry of the experimental model, i.e., the ratio of the cross section of the channel to the frontal area of the cylinder, and length of cylinder to diameter [2].

The cylinder is a poorly streamlined body with a movable break point [3]. When the cylinder is streamlined, as a result of global instability, Karman vortices and longitudinal vortices are formed. In addition, small-scale Kelvin-Helmholtz vortices are formed in the shear layer as a result of increasing convective instability. Vortex shedding causes significant vibrations, acoustic noise and resonance, increased mixing, substantially increases drag and causes lift fluctuations. Therefore, controlling the flow separation from the cylinder surface plays a very important role in various engineering applications.
The literature analysis shows a lack of experimental studies of the influence of the cylinder surface material on the characteristics of the near wake. The hydrophobic properties of the material can have a significant effect on the boundary layer due to the formation of micro-bubbles.

2. Experimental setup
The experiment was conducted on the hydrodynamic tunnel of the closed type. The working part of the experimental setup circuit consists of a honeycomb, a heat exchanger, a confuser with a flow compression degree of 13.3, a horizontal transparent working section made of plexiglass, and a diffuser.

A PIV system consisting of a synchronization unit and a CCD camera (2048×2048 pixels, 8 bits) with a SIGMA 50mm 1:2.8 DG MACRO lens was used to study the characteristics of the near wake. The laser sheet was created using a dual solid-state pulse Nd: YAG laser (wavelength of 532 nm, pulse energy of 25 mJ, pulse duration of 10 ns, and pulse repetition rate of 1.3 Hz).

The working area of the setup is a transparent pipe with a rectangular cross-section of 150×80 mm$^2$ and a length of 1000 mm (figure 1). In the central part of the working area, a mount is provided for installing the cylinder. The cylinder is streamlined by a filtered tap water flow with a constant flow rate. Static pressure in the channel is 150 kPa. To implement the PIV method, polyamide particles — tracers with a diameter of 50 microns and a concentration of about 13 mg/kg are used. The boundary layer on the channel walls is about 10 mm, and the level of turbulent pulsations in the free flow is about 1%.

The measuring system is controlled using the ActualFlow software. The size of the measured area is approximately 140×140 mm. Instantaneous velocity fields are obtained using a cross-correlation algorithm with continuous displacement and deformation of elementary calculated cells and 50% overlap, the cell size being 32 × 32 pixels. The processing technique and details of the experiment are given in [4].

In the framework of this work, fluoroplast (hydrophobic) and rubber (hydrophilic) cylinders with a diameter $d = 0.028$ m are studied. The study is conducted at Reynolds numbers $Re = 70 000; 108 000; 143 000; and 179 000$. The Reynolds number is defined as the ratio of the product of the cylinder diameter and the incoming flow velocity to the kinematic viscosity of water at a temperature $t \approx 25^\circ C$. Four series of 1000 paired images have been obtained for each mode. The delay between images in a single pair is 150 microseconds, which provides sufficient resolution for the structure of the near wake behind the cylinders.
3. Results

Figure 2 shows the average longitudinal velocity fields for rubber and fluoroplast cylinders for Reynolds numbers \( \text{Re} = 108\,000 \) and \( 179\,000 \). There is an almost symmetrical distribution relative to the horizontal \( x \)-axis.

![Velocity fields for rubber and fluoroplast cylinders](image)

**Figure 2.** The average field of the longitudinal velocity component \( V_x \) relative to the velocity of the incoming flow \( U \) for the fluoroplast (from the top) and rubber (from the bottom) cylinders. Left column – \( \text{Re} = 108\,000 \), \( U = 3.8 \) m/s. Right column – \( \text{Re} = 179\,000 \), \( U = 6.4 \) m/s.

With the Reynolds number \( \text{Re} = 108\,000 \), the length of the recirculation zone for the rubber and fluoroplast cylinders is equal to 1.01 and 1.19 \( d \), respectively. However, with an increase in the Reynolds number, there is a sharp elongation of the separation zone for the rubber cylinder and a reduction in the length for the fluoroplast cylinder. The result for all the studied modes is shown in table 1.

| \( \text{Re} \) | Fluoroplast cylinder | Rubber cylinder |
|--------------|----------------------|----------------|
| 70 000       | 0.75                 | 1.27           |
| 108 000      | 1.19                 | 1.01           |
| 143 000      | 0.51                 | 1.56           |
| 179 000      | 0.35                 | 1.41           |

**Table 1.** The length of the recirculation zone for the studied cylinders in relative coordinates \( x/d \).

Using the POD method, the phase-averaged structure of velocity pulsations is analyzed. Ensembles of 1000 velocity pulsations fields were obtained for each value of the Reynolds number. The calculated eigenvalues \( \lambda_n \), represented as a spectrum and normalized on the total kinetic energy of pulsations, are shown in figure 3. This graph shows that for the case of a fluoroplast cylinder (figure 3, a), for Reynolds numbers \( \text{Re} = 70\,000 \) and \( 108\,000 \), the main contribution to pulsations is made by the first two POD
modes and their total share of the total energy is 65% and 45%, respectively. For Reynolds numbers Re = 143 000 and 179 000, the main contribution is made by the first four POD modes, and it is 47% and 35%, respectively. In turn, for the rubber cylinder (Figure 3, b), the main contribution to the intensity of turbulent pulsations is made by the first two POD modes over the entire studied range of Reynolds numbers: 56% at Re = 70 000 and 45% at Re = 179 000.

Figure 3. Spectrum of eigenvalues λ_n for fluoroplast (left) and rubber (right) cylinders.

Usually, the first POD modes are associated with large-scale vortex structures in the flow [5; 6]. It was previously shown that if the pulsations in a turbulent flow correspond to the quasi-periodic dynamics of vortex structures, then these structures will be reflected in the first two POD modes [7]. Figure 4 shows graphs of the total kinetic energy of pulsations $\bar{T} = \sum \frac{\bar{V}_x^2 + \bar{V}_y^2}{n}$ in the area of the return flow per the calculated cell on average for the studied cylinders.

Figure 4. Total kinetic energy per cell on average for rubber and fluoroplast cylinders with the contribution of all modes (a), and with the contribution of the first two modes (b).
The graph in Fig. 4a shows the total kinetic energy for these Reynolds numbers with the contribution of all POD modes, and the graph in Fig. 4b demonstrates the one taking into account the contribution of the first two POD modes. From these graphs, it can be seen that in the case of a rubber cylinder, the absolute value of the kinetic energy of the first two POD modes continuously increases over the entire range of Reynolds numbers.

Conclusion
Using the PIV method, an experimental study of the characteristics of large-scale velocity pulsations in the case of flow around a fluoroplast and rubber cylinder in the range of Reynolds numbers of 70 000 – 179 000 has been performed. A significant difference (up to 3 times) in the length of the region of reverse flows at Re = 143 000 has been found. The spatial shape and kinetic energy of the observed large-scale pulsations in the wake region has been analyzed using the POD statistical method. It is shown that for both cylinders, for Reynolds numbers of 70 000 and 108 000, the first two POD modes make the main contribution to the kinetic energy of pulsations in the wake. For large Reynolds numbers, the flow pattern around the rubber cylinder has not changed, but for the case of a fluoroplast cylinder, the main contribution has been made by the first 4 POD modes.

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