Studying the flow around a cylinder in the critical region by the PIV method

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Abstract. The paper presents the results of experimental investigation of transverse streamlining of a circular cylinder by turbulent water flow within a range of Reynolds numbers $1.75 \times 10^5$–$2.9 \times 10^5$. In the experiment, two circular smooth stainless steel and fluoropolymer (PTFE) cylinders, which have the same size and roughness, but differ in the degree of hydrophobicity, were used. Using the PIV method, the data on the averaged velocity field in the vicinity of the cylinders surface have been obtained. For these fields, the vortex structures in the near wake have been investigated, and their spatial and kinematic parameters have been compared. It is shown that starting from Reynolds number $2.1 \times 10^5$ the reverse flow length and the distance between the vortices behind the steel cylinders decreases by 2.2 and 2.3 times, respectively, in contrast to the fluoropolymer cylinder, where this distance decreases by 1.1 and 1.2 times.

1. Introduction

The cross-streamlined cylindrical surfaces are widespread in the heat exchangers as well as energy and technical devices. The input edges of the blades of turbo-machines, wings of aircrafts, as a rule, are part of the cylinder. Despite the simplicity of geometry, the flow around a circular cylinder is extremely complex and depends on the flow regime.

As it was first time proposed by Rochko [1], at least three regimes may be identified: subcritical (laminar boundary layer), supercritical, and transient or critical (transition to turbulence in a boundary layer). The critical range of Reynolds numbers is approximately $(1.5–4) \times 10^5$ and is characterized by a sharp decrease in the drag coefficient at cylinder streamlining. For different experimental setups, the flow characteristics in this range are sensitive to such factors as turbulence level and geometry of the model, including the blocking of the working channel, the ratio of length to diameter and possible surface roughness that can disrupt boundary layers before separation [2]. These parameters have a qualitatively different effect on the characteristics of the cylinder streamlining.

The conditions of streamlining and the dimensions of the vortex zones behind the solids are important for designing the arrangement of both single and groups of streamlined elements in the hydraulic and engineering designs. For construction and verification of modern mathematical models, it is extremely important to obtain experimental information for different modes of flow around model objects.

Distinguishing the properties of turbulence in the region of a middle wake is of primary interest for the physical analysis and modeling of turbulence of unsteady flows near the streamlined bodies. This understanding is a prerequisite for the development of adapted and effective methods of turbulence modeling for this category, characterized by a dual physical nature, organized or chaotic [3]. The PIV
method allows using noncontact measurement of instantaneous velocities to study the spatial distribution of turbulent quantities in the near wake of the cylinder [4].

This paper presents experimental studies of streamlining of smooth steel and fluoropolymer circular cylinders by turbulent water flow in the critical region at Reynolds numbers over the diameter \( Re \approx (1.75–2.9) \times 10^5 \) for the non-cavitation regime, made using the PIV method. In consequence of the research we present the comparative characteristics of the mean kinematic parameters of the vortex zone in the near wake of the cylinder.

2. Experiment

The hydrodynamic tube of closed type [5] was used for experimental studies. The unit was a hydrodynamic loop with the length – 6290 mm; height – 1770 mm; and width – 700 mm.

Velocity fields were measured by POLIS PIV (Particle Image Velocimetry) system, developed at the Institute of Thermophysics SB RAS and consisting of the programmed synchronizing processor; a CCD camera (2048 × 2048 pix\(^2\), 8 bits), equipped with a SIGMA lens 50mm f/2.8 DG MACRO; dual solid-state pulse Nd:YAG laser with a wavelength of laser radiation of 532 nm (pulse energy of 25 MJ, pulse duration of 10 ns, and pulse repetition rate of 1.3 Hz) with focusing and cylindrical lenses for creating a laser sheet; a mirror for cutting a particular section of the studied region in the work area; and additional mirrors on top to visualize a complete pattern of the flow.

The experimental diagram is shown in figure 1. A circular cylinder with a diameter \( d = 26 \) mm was mounted perpendicular to the side walls of a rectangular channel with a cross section of 0.08 m (width) × 0.15 m (height). A smooth steel and fluoropolymer cylinder with an average arithmetic deviation of profile \( R_a \approx 1 \) µm was used. The walls of the test area were equipped with viewing windows for optical measurements. The cylinder was streamlined by water flow at a constant volumetric flow rate. The superficial velocity \( u \) of the incoming flow was determined on the flow rate ratio to the cross-sectional area of the test section. The flow rate was measured using an ultrasonic flowmeter with a relative error over the volume of no more than 2%. Measurements of pressure and temperature before and after the cylinder were carried out by two pressure sensors and resistance thermometers, respectively, with an error of no more than 0.5%.

Experimental managements and data processing were carried out using the "ActualFlow" software package [6], designed to automate the process and to process and visualize the data. The thickness of the laser sheet was about 1 mm in the measuring area of the central longitudinal section of the test channel. The size of the measuring area was approximately 125×125 mm.

Instantaneous velocity fields were calculated using an iterative cross-correlation algorithm with continuous displacement and deformation of elementary computational cells and 75% overlap of computational domains. The initial size of the elementary calculation area was 64×64 pix, and the final size was 8×8 pix. The obtained vector fields of instantaneous velocity were subjected to two consecutive validation procedures: signal-to-noise ratio with a coefficient of 2 and an additive median filter with an area of 7×7 pix [7, 8]. The error in velocity measurement in our case was on average 2% and 5% at displacement by 8 and 2 pixels, respectively [9].

![Figure 1. Experimental arrangement: 1 – flow; 2 – laser; 3 – mirror; 4 – camera; 5 – test section; 6 – mirror; the white points are tracer particles.](image-url)
Previously, in the test area without a cylinder, the velocity field was measured by PIV in the vertical central section (1000 double images for 12 minutes). The average velocity field was used to obtain the longitudinal $v_x$ and transverse $v_y$ velocity components, pulse velocity values, etc. It was found that the velocity profile has a core of constant velocity (the boundary layer on the channel walls was about 10-12 mm) with the level of turbulence of the longitudinal velocity component $T_u \approx 1\%$.

### 3. Result and Discussion

Figure 2 shows the average (2000 dual images for 25.5 min.) velocity fields $v_x/u$ at steel cylinder streamlining by a non-cavitation turbulent flow in the central part of the channel. Here $u$ is the superficial velocity; $x$ and $y$ are the longitudinal and transverse dimensionless coordinates in fractions of $d$. The flow is from left to right.

The average characteristics of the flow show the anti-symmetric pattern of alternating vortices, whose averaged image gives a configuration of two symmetrical vortices. It was revealed that immediately behind the cylinder, a stable turbulent region is formed; at that, formed vortices rotate in opposite directions: one – clockwise (from the upper part), and another one – counter clockwise (from the lower part). Between vortices, the fluid moves in the opposite direction to the main flow. The outer boundary of the reverse flow area is limited by the line on which the longitudinal velocity component is equal to zero. Therefore, along the symmetry axis of the near wake, the average velocity of the reverse flow varies nonmonotonically: it is zero on the surface of the cylinder and at the end of the reverse flow region, and becomes maximal approximately in the middle part [10]. Below, figure 3 presents comparative graphs of dimensionless mean velocities $v_x/u$ at different distances relative to the center of the steel cylinder for the above flow regimes (figure 2).

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**Figure 2.** Velocity field $v_x/u$: (a) – $Re = 2.07 \times 10^5$, (b) – $Re = 2.84 \times 10^5$. 

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On the averaged velocity fields for $v_x$ and $v_y$, equal to zero, the coordinates of the centers of vortices were determined with a relative error below 1%. Tables 1 and 2 show the main dimensionless dynamic and kinematic parameters of the vortex zone behind the steel and fluoropolymer cylinders.

Table 1. Parameters of vortex structures behind a steel cylinder

| Re ($10^5$) | 2.07 | 2.37 | 2.54 | 2.84 |
|-------------|------|------|------|------|
| Reverse flow length $l_r$ ($d$) | 1.00 | 0.72 | 0.60 | 0.45 |
| Maximum velocity of reverse flow $v_{max}$ ($u$) | 0.32 | 0.21 | 0.18 | 0.17 |
| Distance between centers of vortices $\Delta y_v$ ($d$) | 0.51 | 0.45 | 0.29 | 0.22 |

Table 2. Parameters of vortex structures behind fluoropolymer cylinder

| Re ($10^5$) | 1.75 | 1.96 | 2.12 | 2.20 | 2.48 | 2.9 |
|-------------|------|------|------|------|------|-----|
| Reverse flow length $l_r$ ($d$) | 0.96 | 0.72 | 0.67 | 0.61 | 0.61 | 0.61 |
| Maximum velocity of reverse flow $v_{max}$ ($u$) | 0.27 | 0.28 | 0.29 | 0.23 | 0.21 | 0.20 |
| Distance between centers of vortices $\Delta y_v$ ($d$) | 0.55 | 0.36 | 0.32 | 0.28 | 0.27 | 0.27 |

The work [10] provides $v_{max} = (0.15–0.25)u$ and the lengths of reverse flows $l_r = 0.5d \approx$ const for Reynolds numbers over $1.5 \times 10^4$. In [3, 4], $l_r \approx (0.7–1.05)d$ for Reynolds numbers $(1–2) \times 10^5$.

4. Conclusions

It was revealed that for a steel cylinder with an increase in the Reynolds number from $2.07 \times 10^5$ to $2.84 \times 10^5$, the reverse flow length decreases by 55%, the maximum reverse flow velocity – by 47%, and the distance between the vortex centers – by 57%.

For the fluoropolymer cylinder, the maximum reverse flow length and the distance between the vortex centers were noted at Re = $1.75 \times 10^5$. The decrease was 36% and 51%, respectively, at Re =
2.9×10^5. The maximum velocity of the reverse flow varied from 0.27u to 0.2u, and the maximum was observed at Re = 2.12×10^5 and amounted to 0.29u. The overall decrease was 31%.

The parameters of the near wake for the fluoropolymer cylinder are shown to weaker depend on the Reynolds number, especially when Re > 2×10^5.

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