Influence of pressure on the wake of a hydrophobic circular cylinder for a flow regime with Reynolds number of $2.2 \times 10^5$

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Abstract. Vortex flow structures in a turbulent wake behind a circular Teflon cylinder immersed in an incoming flow with a change in pressure for the Reynolds number $Re = 2.2 \times 10^5$ have been experimentally studied using a two-dimensional image (2D-PIV) of particles in a closed-circuit water tunnel. The obtained results are presented in the form of time-averaged velocity fields, Reynolds stresses, and distributions of turbulent kinetic energy. The flow data showed that the size of the wake flow region, Reynolds stresses and turbulent kinetic energy change depending on the pressure in the flow. As a result of a 20% reduction in pressure, the size of the vortex zone in the wake increases by about 20%.

1. Introduction
Cylindrical surfaces are widely used in heat exchange, energy and technical devices. The input edges of turbomachine blades and aircraft wings are usually part of a cylinder. Despite the geometry simplicity, the flow around a circular cylinder is extremely complex and depends on the streamlining mode. To date, many devices and strategies have been proposed for controlling the flow around a poorly streamlined body, including a separation plate, geometric modification of the surface, periodic purging and suction, distributed impact, and rotational oscillation.

Microstructured surfaces of hydrophobic material have been identified as a new tool that can be used to achieve a wide range of goals, such as flow and resistance control, anti-icing, anti-corrosion, and self-cleaning, mainly due to their ability to retain air pockets in surface textures when submerged in water [1–3]. The slippage property on superhydrophobic surfaces is essential for technical applications that use hydrodynamic flows with a high Reynolds number. Due to the low ratio of the dynamic viscosity of air to liquid at the gas-liquid interface, the flows "slide" over the surface, which leads to a decrease in the viscosity of the boundary layer as compared to conventional smooth walls. In [4] it is shown that high shear rates on a rough surface can cause "nanobubble" cavitation, which can increase the sliding effect and lead to the early appearance of nonlinear effects predicted in [5].

The measurements demonstrated a direct correlation between a decrease in pressure and an increase in sliding velocity along the air-water layer. In a number of experiments, this correlation was extended to a variety of superhydrophobic surfaces and flow geometries for static pressures of 100 kPa or more [6, 7]. In [8], the effect of ambient pressure and Reynolds number on the plastron volume on a superhydrophobic surface due to gas compression and diffusion was experimentally studied. Tests in the water tunnel were carried out both without flows and in transition and turbulent boundary layers at Reynolds numbers of up to 2100. The rate of diffusion increased with the level of under- or supersaturation and with an increase in the Reynolds number. Nanobubbles, which are likely to remain
in nanostructures, can help in initializing the nucleation process, facilitating the possible plastron recovery process.

In [9], the partial slip effect was experimentally studied using various superhydrophobic surfaces for Reynolds numbers of up to 10,000. It was found that for superhydrophobic surfaces with ridges aligned in the flow direction, the separation point moved upstream in the direction of the frontal cylinder braking point, and that the frequency of vortex formation increased in the normal direction. The dynamics of vortex formation was established to be very sensitive to changes in the distance between the structure elements, their size, and orientation along superhydrophobic surfaces. Effect of various superhydrophobic surface texture and gas content in the water at flow separation and subsequent vortex structures in a wake behind a circular cylinder for Reynolds numbers of 0.7–2.4 × 10⁴ was studied in [2]. To control the flow around cylinder using rough hydrophobic surfaces, it was recommended to have a smaller roughness width, which can stably hold air pockets. In addition, a higher gas fraction and a more uniform distribution of the roughness size help to improve characteristics such as delayed separation of vortices and reduced drag. In [10], in the range of Reynolds numbers from 45 to 15,500, the effect of surface modification and the Reynolds number on the wake behind the cylinder was studied under different flow regimes. Superhydrophobicity was shown to affect the flow significantly: an increased recirculation length was observed in the steady-state regime, and the beginning of vortex formation for a superhydrophobic cylinder was delayed for small Reynolds numbers.

There are almost no works of flow over the hydrophobic cylinder with high Reynolds numbers. This paper presents an experimental investigation of vortex structures in a wake behind a rough Teflon circular cylinder in a turbulent water flow with Reynolds number on diameter Re ≈ 2.2×10⁵ for non-cavitation regime, using the PIV method. Changes in the average main kinematic, geometric, and energy characteristics of the flow in the near wake of the cylinder are considered at pressure variation in the flow in front of the cylinder.

2. Technique and methodology of the experiment
A closed-circuit water tunnel [11] was used for experimental studies. A round cylinder with a diameter \( d = 0.026 \text{ m} \) was installed in the working section (figure 1) with a rectangular cross section of 0.08×0.15 \( \text{m}^2 \) (width × height). The walls of the working area were equipped with viewing windows for optical measurements. Flow rate control was performed using an ultrasonic flow meter with a relative volume error of no more than 2%. The free flow had a core with average velocity \( u_c \approx 7.95 \text{ m/s} \) (the boundary layer on the channel walls was about 10 mm) and a turbulence level of about 1.4%. The Reynolds number was determined by the velocity in the flow core and the cylinder diameter, and in our case it corresponded to about 2.2×10⁵.

The pressure (overpressure) \( \Delta p \) of the flow was monitored by pressure-rarefaction sensor (an error of no more than 0.5%) connected to a tap located at the center of the sidewall of test section at a distance of 0.3 m upstream of the cylinder. The absolute pressure \( p = p_a + \Delta p \) (\( p_a \) is atmospheric pressure) in the experiments was approximately 150, 130, and 120 kPa. The temperature in experimental studies was maintained at approximately 23°C using a refrigeration unit and a heat exchanger, and was measured and controlled by thermal resistance sensors with an error of about 0.5%. The working fluid was the filtered tap water. The relative volume content of air (\( \text{O}_2, \text{N}_2, \text{CO}_2 \)) in cold water was approximately 0.02 at atmospheric pressure. The gas content did not change inside the tunnel during all experiments.

The PIV POLIS measuring complex created at the Institute of Thermophysics SB RAS was used to study velocity fields. It consisted of several main elements: a double solid-state pulsed Nd: YAG laser with a 532 nm radiation wavelength (pulse energy of 25 mJ, pulse duration of 10 ns, pulse repetition rate of up to 1.3 Hz) with focusing and cylindrical lenses to create a laser sheet; a CCD camera that registered images with a resolution of 2048×2048 pixels and then transmitted them to a personal computer for processing. The system was synchronized using a programmable processor. The thickness of the laser "sheet" formed by a cylindrical lens was about 1 mm in the measuring area of the
central longitudinal section of the working channel. Figure 1 shows the main POLIS elements and the location of the cylinder in the work area.

![Figure 1. Experimental setup for the velocity measurement. The white points are tracer particles.](image)

Experiment control and data processing were performed using the "ActualFlow" software package, designed to automate the experimental process, as well as to process and visualize data. 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. Subpixel interpolation of the cross-correlation peak was performed at three points using one-dimensional approximation by the Gaussian function. The initial size of the elementary computational domain was 64×64 pix, and the final size was 8×8 pix. The obtained vector fields of instantaneous velocity were subjected to two validation procedures: by the signal-to-noise ratio with a factor of 2 and an additive median filter over the 7×7 pix region. The error in velocity measurement depended on the displacement of tracers and the number of frames. In our case, it was on average 2% and 5% with a displacement by 8 and 2 pixels, respectively.

Velocity fields were measured near the cylinder in the vertical plane (x, y) along and across of the flow in fractions of the diameter d, being \(x/d\) and \(y/d\), respectively. The size of the computational domain was 1120×720 pixels, which corresponded to approximately \(-0.7 \leq x/d \leq 2.4\) and \(-1.0 \leq y/d \leq 1.0\) with the center of the circular cylinder located at the origin.

In this paper, we consider and investigate the flow around a Teflon cylinder with a surface structure obtained using standard turning, which gives an almost regular structure of longitudinal micro-grooves and ridges of roughness located along the flow. The roughness of the hydrophobic surface of the Teflon cylinder is evaluated using an Ntegra Prima HD atomic-force microscope. The arithmetic mean surface roughness \(R_a \approx 1.2 \, \mu m\), the distance between the middle of the adjacent grooves and ridges on the cylinder surface is about 20–25 \(\mu m\). The contact angle for a water drop placed on the cylinder surface is approximately 100° (measured by the side-view of a water drop).

The velocity was measured at the mid-span of the cylinder, and 1500 pairs of instantaneous velocity fields were obtained to analyze the time-averaged flow statistics. The studies were carried out with a decrease in the pressure \(p\) in the flow in front of the cylinder from 150 kPa to 120 kPa for a cavitation-free flow regime.

3. Results and discussion

The average characteristics of the flow behind the cylinder show the anti-symmetric pattern of alternating vortices, whose averaged image gives a configuration of two almost symmetrical vortices. Formed vortices rotate in opposite directions: one rotates clockwise (from the upper part of the cylinder), and another one rotates counter clockwise (from the lower part). Between vortices, the fluid moves in the opposite direction to the main flow. Along the axis of symmetry \((y/d = 0)\) of the wake, the value of the mean reverse flow velocity changes nonmonotonically: it equals zero on the surface of the cylinder and at the end of the reverse flow region \(l_r\) is reverse flow length), and becomes maximal.
The velocity is negative in the recirculation region and it reaches a positive value as the liquid is carried away from the medium further downstream.

Table 1 shows experimental results for the main average kinematic parameters of the near wake depending on the pressure. Within the considered pressure range, the rough hydrophobic surface affects the turbulent wake behind the circular Teflon cylinder. It can be seen that all the presented parameters increase with a decrease in pressure by 18-20%.

![Table 1](image)

| Pressure before cylinder, kPa | 150 | 130 | 120 |
|------------------------------|-----|-----|-----|
| Reverse flow length, \(l_r(d)\) | 0.49 | 0.56 | 0.59 |
| Maximum velocity of reverse flow, \(\bar{u}_{r_{\text{max}}}(u_c)\) | 0.20 | 0.22 | 0.24 |
| Distance between centers of vortices, \(\Delta y_v(d)\) | 0.28 | 0.30 | 0.33 |

Figure 2 demonstrates the fields of the components of the Reynolds normal stress \(\bar{u}_x'^2\) and \(\bar{u}_y'^2\) in the cylinder wake, normalized by \(u_c^2\) (\(u'_x, u'_y\) are the pulsating components of the streamwise and transversal velocity, respectively).

![Figure 2](image)

**Figure 2.** Fields of the normalized streamwise \((\bar{u}_x'^2/u_c^2)\) – (a, c, e) and transversal \((\bar{u}_y'^2/u_c^2)\) – (b, d, f) components of Reynolds normal stress (PIV data) in the wake behind a cylinder: (a) and (b) – \(p = 150\) kPa, (c) and (d) – \(p = 130\) kPa, (e) and (f) – \(p = 120\) kPa.

The component \(\bar{u}_x'^2\) has a two-lobe structure with a maximum values localized near \(x/d = 1.0\) and located from \(y/d = \pm 0.125\) to \(y/d = \pm 0.2\) relative to the axis of symmetry when the pressure decreases.
from 150 kPa to 120 kPa. The component \( \bar{u}_y^2 \) has a one-lobe structure with a maximum value on the longitudinal axis approximately from \( x/d = 1.2 \) to \( x/d = 1.4 \) when the pressure decreases from 150 kPa to 120 kPa.

Shear stresses and turbulent kinetic energy were investigated. The normalized turbulent kinetic energy \( k_e = \frac{1}{2} \left( \bar{u}_x^2 + \bar{u}_y^2 \right) / \frac{1}{2} \bar{u}_c^2 \), evaluated from the normal stresses, exhibits a saddle structure with the maximum values \( k_e \approx 0.22 \) located on each side of the wake centerline at \( x/d \approx 1.0 \) and \( y/d = \pm 0.14 \) to \( y/d = \pm 0.17 \) when the pressure decreases from 150 to 120 kPa. The transversal size of the vortex zone of the wake \( \Delta y_w \) is determined as a distance between the points where the value \( \tau / \bar{u}_c^2 \) is found to be null \( \tau = -\bar{u}_x \bar{u}_y \) represents the Reynolds shear stresses) for \( x/d = 2.0 \) below and above the symmetry line \( (y/d = 0) \). As the pressure decreases, \( \Delta y_w \) increases from \( 1d \) \( (p = 150 \text{ kPa}) \) to \( 1.1d \) \( (p = 130 \text{ kPa}) \) and \( 1.2d \) \( (p = 120 \text{ kPa}) \), respectively.

It is shown, that the maximum values of the shear stress and turbulent kinetic energy in the wake of the cylinder are located near the center of the vortices, the position of which depends on the pressure in the flow.

4. Conclusions
An increase in the size and kinematic characteristics, distributions of stresses and turbulent kinetic energy with decreasing pressure was shown in the wake behind a cylinder. This can be associated either with a change in the thickness of the air plastron in the surface folds, which entails a change in the surface structure, or with the phenomenon of nanocavitation on surface structures due to the diffusion of air from the water flow. It is possible that this Reynolds number corresponds to a crisis of resistance, then, by changing the pressure, we can control the crisis phenomena in the flow around a hydrophobic cylinder.

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