The influence of high degree of turbulence on the near wake of the streamlined cylinder

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Abstract. A method for obtaining high degree of water flow turbulence using semi-cylindrical inserts is shown. The degree of longitudinal turbulence in the flow core of about 20% was obtained under the conditions of the limited size of the working section of the hydrodynamic stand and small overpressure. The PIV method was used to obtain the average characteristics of the near wake behind the cylinder, streamlined by weakly and strongly turbulized flow in the subcritical region. The resulting size of the vortex zone behind the cylinder in the flow with high degree of turbulence is much smaller than in the case of weak turbulence, which is similar to the flow with effective Reynolds number in the region of critical numbers, where the resistance drops sharply.

1. Introduction
Hydrodynamics of flows and their interaction with solids of various shapes are widespread in nature, technologies, and various hydro-and thermal facilities. In many cases, the solid has a cylindrical shape, and the liquid motion is turbulent. Despite the large number of works, studying the features of the transverse streamlining of circular cylinders and their interaction with liquid is of great interest.

Basically, the research focuses on the effect of the turbulence intensity (degree) on the hydrodynamic characteristics and heat transfer of the transverse flow of circular cylinders. Most experimental works are related to wind tunnels, where different grids and gratings are used to increase the intensity of incoming flow turbulence [1]. A method for obtaining the flow with high turbulence degree (10–30%), being a single cell of a two-plane grid with halves of round and square rods, has been demonstrated. Paper [2] provides a brief review and numerically studies the effect of turbulence intensity from 1% to 40% on hydrodynamic characteristics and heat transfer of a circular cylinder, streamlined by a viscous fluid flow with Reynolds number of $4 \times 10^4$. From the results of computational experiments it has been found that the intensity of incoming flow turbulence has a significant effect on all the main characteristics of the streamlined cylinder.

Experimental works with highly turbulized water flow are extremely rare, which is probably due to the possibility of cavitation at high velocities (small static pressures) and limited working areas. In [3], the flow around the cylinder at high Reynolds numbers and a turbulence level of 10% were investigated. Flow turbulization was realized by grids with square cells. It was shown that the increasing level of flow turbulence leads to boundary layer turbulization already at Reynolds numbers of about $10^5$.

In [4], the effect of turbulent intensity on the vibration of an elastic cylinder caused by an axial vertical water flow in the presence of an adjacent rigid cylinder was experimentally investigated. It
was shown that at the level of turbulence of 2.30–2.91% the vibration amplitude of the elastic cylinder increases significantly compared to its analogue at low turbulence (0.71–0.80%).

The conditions of streamlining and the dimensions of vortex zones behind the solids are important for the design of streamlined elements in the hydraulic and engineering devices. Obtaining experimental information for different flow regimes of model objects is important for the construction and verification of mathematical and calculation models.

This paper shows a method for obtaining a high degree of the water flow turbulence (about 20%) at a limited size of the working area and a relatively small overpressure. The flow around a round smooth cylinder in the subcritical region of Reynolds numbers was studied experimentally. The comparative characteristics of the vortex near wake behind the cylinder for low and high turbulence of the streamlined flow have been obtained. In a highly turbulent flow, the size of the vortex zone is found to decrease in comparison with weak turbulence.

2. Experiment

To conduct experimental research the hydrodynamic tunnel of the closed type was used [5]. The working area with a length of 1000 mm and a $150 \times 80$ mm$^2$ cross section (height and width respectively) was equipped with plane parallel transparent walls for optical measurements. The ratio of the flow rate to the cross-sectional area of the working section served to determine the superficial velocity of the incoming flow $u$.

The flow rate was measured using an ultrasonic flow meter with a relative volume error of no more than 2%. The working fluid was tap filtered water.

Velocity fields were measured by the PIV system (Particle Image Velocimetry) POLIS, developed at the Institute of Thermophysics SB RAS and consisting of the programmable sync processor; CCD camera ($2048 \times 2048$ pixels), equipped with a SIGMA lens of 50mm 1:2.8 DG MACRO; and 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 to create a laser sheet.

Experiment control and data processing were carried out using the "ActualFlow" software package, designed to automate the experimental process, data processing and visualization [5]. Polyamide tracers with an average size of 50 µm were used in all experiments.

Before experiments with the changing level of turbulence in the free flow, velocity fields for several flows were measured by PIV in the vertical central section (1000 double images for 12 minutes). The obtained data have shown the presence of nuclei in the free flow with velocity $v_{\text{max}}$ and the boundary layer of about 10 mm on the channel walls. The level (degree) of turbulence of longitudinal velocity component $v_x$ in the free channel flow core was on average $T_u \approx 1.8\%$.

Obtaining a high level of turbulence in the water flow is complicated by the possibility of cavitation on the turbulator, which can violate the homogeneity of the flow behind it. Often the working area of the stand has limited dimensions, which also imposes certain restrictions.

In our case, the source of increasing the flow turbulence was a turbulator, being a single cell of a two-plane grid, consisting of horizontal and vertical inserts (semi-cylinders) with a height of 22 mm and 12 mm, respectively, and with a rounding radius of 10 mm and a width of 20 mm, mounted on a stainless steel frame with a thickness of 4 mm. The turbulator was installed in the working part of the channel at a distance of 0.2 m from the confuser. The flow clogging over the cross-sectional area was about 60%.

The effective size of the turbulator cell was determined from the equality of the areas of the real open part and the effective grid of the square section. The size $M = 68$ mm. For flow rates $Q \approx 100–150$ m$^3$/h at distance $x = 4M$ from the turbulator in the flow core, the degree of turbulence was $T_u = 18–20\%$.

The cylinder (center) was installed at distance $x = 4.55M$ from the turbulator. Figure 1 shows the scheme of the experiment with the cylinder streamlined in a highly turbulent flow. Perpendicular to the side walls of a rectangular channel there was a round cylinder with diameter $d = 26$ mm. The cylinder was streamlined by the water flow with a constant volumetric flow rate.
pressure and temperature before the cylinder were carried by overpressure and thermal resistance sensors with an error of no more than 0.5%.

Figure 1. Scheme of the experiment: 1 – flow; 2 – double pulse Nd:YAG laser; 3 – mirror; 4 – CCD camera; 5 – working section; 6 – mirror; 7 – turbulator; white dots – tracers.

3. Results and Discussion

Figure 2 shows the average (2000 double images for 25.5 minutes) fields of the longitudinal velocity $v_x$ when the steel cylinder is streamlined by a turbulent flow in the central part of the channel.

![Velocity field $v_x$: (a) – Re = 7.6×10^4 (without turbulator), (b) – Re = 7.0×10^4 (with turbulator).](image)

For low and high turbulence of the flow, the pressure before the cylinder $p \approx 146$ kPa and the temperature $t \approx 21$°C. The water flow rates were approximately the same $Q \approx 115$ m$^3$/h. The Reynolds number $Re = v_{max} \cdot d/\nu$ ($\nu$ is the kinematic viscosity of water).

Figure 3 presents comparative graphs of turbulent stresses for the flows of low (solid line) and high (dotted line) degree of turbulence, streamlining the cylinder. Here $\tau = -\rho u_x u_y$ is the turbulent stress ($u_x$, $u_y$ are the corresponding pulsations of the longitudinal $v_x$ and transverse $v_y$ velocity components and $\rho$ is the water density); and $q = \rho u^2/2$ is the average dynamic head of the incoming flow. Graphs were built after the processing (averaging) of 2000 double images.
Figure 3. Relative turbulent stresses: (a) – corresponds to $x/d$, at which the velocity of the reverse flow behind the cylinder is maximal, (b) – $x/d = 1.2$. Solid line – flow around the cylinder without turbulator ($Re = 7.6 \times 10^4$), dotted line – with turbulator ($Re = 7.0 \times 10^4$).

In figure 3(b), the difference between the points of the graph curve exit to the zero vertical from above and from below allows estimating the transverse size of the vortex zone of the near wake ($\Delta y_w$) behind the cylinder. For low turbulence flow $\Delta y_w \approx 1.75d$, and for high turbulent one $\Delta y_w \approx 1.25d$. The table shows the main average characteristics of the reverse flow between the vortices in the near wake of the cylinder.

|                | $Re \times 10^4$ | Length of reverse flow $l(d)$ | Maximum velocity of reverse flow $v_{max}(u)$ |
|----------------|-----------------|-------------------------------|---------------------------------------------|
| Without turbulator | 7.6             | 0.75                          | 0.36                                        |
| With turbulator    | 7.0             | 0.48                          | 0.19                                        |

The parameters of reverse flow in the near wake are close to the values obtained in [6] when the cylinder is streamlined by a flow with weak turbulence with $Re = 2.84 \times 10^5$, where $l_r \approx 0.46d$, and $v_{max} \approx 0.17u$.

Conclusions
A passive method for obtaining the flow with high turbulence degree in a subcritical region has been demonstrated. With the turbulator in the flow, the length of the reverse flow and the distance between the vortices in the near wake of the streamlined cylinder has decreased more than one and a half times, compared to the effect of the weakly turbulent flow.

It is shown that a high degree of turbulence in the flow leads to an increase in the effective Reynolds number up to that in the critical region.

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