Cavitation streamlining of a round cylinder in the critical range

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Abstract. The paper presents experimental results on the transverse cavitation streamlining of a circular cylinder by a turbulent water flow in the critical range of Reynolds numbers determined on diameter. Using the PIV method, averaged velocity fields are obtained. Their vector patterns serve to determine the lengths of the reverse flow and the distance between vortices in the near wake behind the cylinder. The presence of a minimum of spatial characteristics of the vortex zone for the initial cavitation modes is shown. Initial cavitation, transient modes, and developed cavitation are determined for different flow rates. The beginning of cavitation is found to depend on the Reynolds number. With smooth decrease in static pressure in front of the cylinder, critical anomalous phenomena, probably related to the rearrangement of cavitation modes, are detected in very narrow range. Vortex shedding from the cylinder surface is found to occur quasi-periodically despite the possibility of simultaneous shedding and breakdown of vortices.

1. Introduction
Despite the simple geometry, the flow around a circular cylinder is extremely complex and depends on the streamlining mode. An analysis of the literature demonstrates that most of the works devoted to the round cylinder streamlining are associated with the flow of gas and, less often, with a liquid. Compared with a non-cavitating flow, there are relatively fewer experimental studies on the cavitation streamlining of a transverse circular cylinder [1–3], including in the critical region [4, 5]. The interest in and the relevance of research in the critical range of Reynolds numbers (Re ≈ (1–4)×10^5) result from significant structural changes in the flow near the streamlined cylinder, which are very sensitive to factors such as the level of turbulence, blocking of the working channel, the ratio of length to diameter, and surface roughness [6].

Flow conditions and the size of the vortex wake behind the bodies are important for designing the placement of streamlined elements in technological structures. In addition, to construct and verify modern computational and mathematical models describing the occurrence and development of cavitation, it is necessary to obtain experimental information for various flow modes of model objects [7].

This paper deals with experimental studies of cavitation streamlining of a round steel cylinder by a turbulent water flow in the critical region with Reynolds numbers Re ≈ (2.4–3.0)×10^5 using the PIV (Particle Image Velocimetry) method.
2. Experimental technique

A closed-cycle water tunnel of the Novosibirsk National Research State University was used for experimental research. Perpendicular to the side walls of a rectangular working area with a cross section of 0.08 × 0.15 m (width × height) there was a round steel cylinder with a diameter \( d = 0.026 \) m (figure 1) with a relative roughness \( R_a/d \approx 6.2 \times 10^{-5} \) (\( R_a \) is the arithmetic mean deviation of the profile). The water flow was directed from left to right. The walls of the working area were equipped with viewing windows for optical measurements.

The cylinder was streamlined with a constant volume flow rate, which was measured using an ultrasonic flow meter with a relative volume error of no more than 2%. The PIV POLIS system developed at the Institute of Thermophysics SB RAS was used to measure velocity fields. It consists of a programmable synchronizing processor; a dual solid-state nd:YAG laser with a laser radiation wavelength of 532 nm (pulse energy of 25 mJ, pulse duration of 10 ns, and pulse repetition rate of up to 1.3 Hz) with focusing and cylindrical lenses to create a laser sheet; CCD cameras with a resolution of 2048×2048 pixels; mirrors – the main one at the bottom and an additional one at the top – that serve to "cut" a certain section of the studied area in the central part of the working area. Figure 1 shows the main elements of the POLIS, the location of the cylinder, and pressure and temperature measurements.

Measurements and control of pressure and temperature before and after the cylinder were carried out by pressure and thermal resistance sensors, respectively, with an error of no more than 0.5%. The working fluid was filtered tap water with separation of 5-micron particles. The air content in the stand did not change during the experiments. All experiments used polyamide tracers with an average size of 50 microns.

![Figure 1. Experimental techniques.](image)

Control over the experiment and data processing were performed using the "ActualFlow" software package, designed for experiment automation, data processing and visualization. The instantaneous velocity fields were calculated using an iterative cross-correlation algorithm with continuous displacement and deformation of the elementary calculation cells and 75% overlap of the calculation regions. For more information, see [8].

Pre-measurement of the velocity field in a free flow using the PIV method in a vertical central section for various flow rates shows that the velocity profile has a constant velocity core (the boundary layer on the channel walls being 10–12 mm) with a turbulence level of the longitudinal velocity component in a free single-phase flow of the order of 1%.

3. Results and discussion

The geometric parameters of two-phase vortex structures in the near wake of the cylinder were determined using averaged (2000 double images for 25.5 minutes) vector velocity fields. The average flow characteristics show the passage of an antisymmetric pattern of alternating vortices, the averaged
image of which gives the configuration of two symmetrical vortices. It has been found that just behind the cylinder there is a forming region with oppositely rotating vortices: one is rotating clockwise (from the upper part), and the other is rotating counterclockwise (from the lower part). Between the vortices, the liquid moves in the opposite direction to the main flow. Along the axis of symmetry of the near wake, the average velocity of the reverse flow varies non-monotonically: it is equal to zero on the rear surface of the cylinder and in the end of the region of reverse flows (the distance between these points is the length of the reverse flow \( l_i \)), and it is maximum approximately in the middle part.

Table 1 below presents the main average characteristics of vortex structures behind a streamlined cylinder in initial cavitation modes (stages) for different cavitation numbers at relatively close Reynolds numbers, the same velocity \( u_\infty \approx 9.8 \text{ m/s} \), temperature \( t \approx 25–27^\circ\text{C} \), and pressure \( p_\infty \approx 112–130 \text{ kPa} \). Reynolds numbers were calculated on the cylinder diameter \( d \) and the velocity in the core of the free flow \( u_\infty \). The cavitation number \( \sigma = 2(p_\infty - p_i)/\rho u_\infty^2 \), where \( p_\infty \) is the static pressure in the flow before the cylinder; \( p_i \) is the saturated vapor pressure at a given temperature; and \( \rho \) is the density of water.

| Table 1. Parameters of average vortex structures behind a streamlined cylinder. |
|------------------|-----------------|-----------------|-----------------|-----------------|
| Re number \((10^5)\) | 2.84 | 2.82 | 2.91 | 2.95 |
| Cavitation number, \( \sigma \) | 2.27 | 2.63 | 2.65 | 2.70 |
| Reverse flow length, \( l_i(d) \) | 0.65 | 0.48 | 0.60 | 0.57 |
| Distance between the centers of vortexes, \( \Delta y_i(d) \) | 0.37 | 0.25 | 0.32 | 0.29 |

Table 1 shows the presence of a minimum of vortex zone parameters for \( \sigma \approx 2.63 \). In [9], on a high-speed cavitation stand with a smooth steel cylinder, a minimum resistance for \( \sigma \approx 1.94 \) was obtained in the range of Reynolds numbers from \( 1.26 \times 10^5 \) to \( 3.2 \times 10^5 \). The beginning of cavitation corresponded to \( \sigma_i \approx 2.21 \).

Using the PIV POLIS equipment, the cylinder streamlining is studied at a pressure decrease in the stand for free flow rates \( u_\infty \approx 8.3 \text{ m/s}, 9.2 \text{ m/s}, 9.8 \text{ m/s} \) from non-cavitation to developed cavitation modes. The beginning of cavitation in our case corresponds to detection of the separation of gas bubbles from the surface of the cylinder, as well as the noise caused by cavitation, during visual observation and in photos obtained with the help of a CCD camera. Experiments with pure water and in the presence of tracer particles for a flow with \( \text{Re} \approx 3 \times 10^5 \) and parameters \( u_\infty \approx 9.8 \text{ m/s}, t \approx 27.4^\circ\text{C} \), and \( p_\infty \approx 130 \text{ kPa} \) have shown that the presence of particles did not act on the beginning of cavitation processes.

It has been found that in the temperature range of \( 25.1–27.9^\circ\text{C} \) for \( \text{Re} \approx 3.0 \times 10^5 \) \((u_\infty = 9.8 \text{ m/s})\) the beginning of cavitation corresponds to \( \sigma_i \approx 2.70 \), for \( \text{Re} = 2.83 \times 10^5 \) \((u_\infty = 9.2 \text{ m/s})\) \( \sigma_i \approx 3.05 \), and for \( \text{Re} = 2.4 \times 10^5 \) \((u_\infty = 8.3 \text{ m/s})\) \( \sigma_i \approx 3.15 \). It has been revealed that the beginning of cavitation may depend on the Reynolds number in the critical region with turbulence of the boundary layer, which is sensitive to the profile deviation in this range.

In [4] for a smooth brass cylinder \((R_d/d \approx 2.1 \times 10^5)\) with the relative length of the cylinder \( l/d \approx 2.1 \) and the channel clutter \( d/h \approx 0.18 \) \((h \text{ is the height of the working section of the channel})\), the value of \( \sigma_i \approx 2.72 \) is given in the temperature range of \( 6.8–9.0^\circ\text{C} \) for \( \text{Re} = (2.83–3.27) \times 10^5 \). In [1] for a brass cylinder with \( R_d/d \approx 6 \times 10^5 \), \( l/d \approx 6.5 \) and \( d/h \approx 0.15 \) for \( \text{Re} = 6.4 \times 10^4 \) the beginning of cavitation corresponds to \( \sigma_i \approx 3.72 \).

Two anomalous states with periodically amplifying/weakening cavitation wake and increasing noise and vibration are observed in a narrow pressure range. The first abnormal state \((\sigma_i)\) probably corresponds to the transition from film to cloud cavitation, when the periodic increase/decrease of the cavitation wake (approximately 2 times) occurs at a frequency of about 0.5–1 Hz, while the bubble film covers the entire cylinder in length, including the boundary layer on the walls of the working area. The second anomalous state \((\sigma_i)\) corresponds, perhaps, to a transition to vortex cavitation, with periodic emissions of cavitation structures occurring at a distance of approximately \( 20d \). After
abnormal phenomena, noise and vibrations are significantly reduced. For example, for $Re \approx 2.8 \times 10^5$ and temperature $t \approx 24.6^\circ C$, these states correspond to the cavitation numbers $\sigma_1 \approx 2.38$ and $\sigma_2 \approx 1.7$. For the range of $Re = (2.45-2.75)\times10^5$ and $t \approx 23-24.2^\circ C$, the first anomalous state corresponds to $\sigma_1 \approx 2.36-2.38$. In this range, the beginning of cavitation corresponds to close values of $\sigma_i$.

The study of the cavitation flow around the cylinder has proved the existence of several types of separation flows behind the cylinder in the near wake [10]. Figure 2(a) shows the formation of two vortices on one side of the cylinder, and figure 2(b) illustrates the simultaneous symmetrical formation of a pair of vortices on opposite sides of the cylinder.

![Figure 2](image1.png)

**Figure 2.** Patterns of cylinder streamlining at $Re \approx 3\times10^5$ and varying degrees of cavitation intensity: (a) – $\sigma \approx 2.00$; (b) – $\sigma \approx 1.61$.

With developed cavitation, the structure of the flows behind the cylinder is very different depending on whether there are particles in the flow or not. Figure 3 shows photos of the flow around the cylinder at the same Reynolds number $Re \approx 3\times10^5$ and the cavitation number $\sigma \approx 1.60$ in the case of pure water (left) and water with tracers (right). In pure water, large bubbles appear, as in normal boiling, and in a stream with tracers, the particles attach to the bubbles, as in flotation.

![Figure 3](image2.png)

**Figure 3.** Cavitation flow around the cylinder: (a) – pure water; (b) – water with tracers.

**Conclusions**

A PIV study of the initial cavitation modes has revealed a minimum of average geometric parameters in the near cylinder wake. This is probably due to the transition from bubble to film cavitation mode.

The beginning of cavitation is found to depend on the Reynolds number. The surface roughness and structure, probably, play a great role, especially in the critical area where the boundary layer is turbulent and the cylinder resistance changes dramatically. The study of the cylinder streamlining patterns under developed cavitation has shown the existence of several types of separation flows behind the cylinder in the near wake, including the simultaneous shedding of a pair of vortices, as well as their destruction, although on average, over a long period of time, the separation of vortices occurs quasi-periodically.
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