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Pulsation of Cavitating Vortex Rings in Water

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Abstract—We present the results of experimental investigations of the cavitating vortex rings (CVRs) formed upon throwing a water column (jet) from an immersed cylindrical barrel with a diameter of 20–40 mm and a length of 30–100 mm. The dynamics of the CVR formation and propagation in water in the form of toroidal cavitation bubbles has been studied as dependent on the initial jet velocity. It is established that CVRs shaped as hollow tori are formed at a jet velocity above 2 m/s. At a jet velocity above 6 m/s, the CVRs exhibit radial pulsations, which have been observed for the first time with the aid of optical methods.

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The dynamics of the formation and propagation of cavitating vortex rings (CVRs) in atmosphere have been studied in sufficient detail [1]. Detailed investigations of the propagation of CVRs in water were only carried out for Reynolds numbers $\mathrm{Re} \leq 2 \times 10^3$ at a jet velocity not exceeding 0.3 m/s. Since cavitation processes do not develop under these conditions, questions concerning the nature of CVR formation and pulsation remain unanswered because of a lack of experimental data [2–4]. Buzukov [2] thoroughly studied the peculiarities of the formation and motion of ring vortices with a diameter of $d_0 = 35$ mm generated in water by a jet emitted from the barrel at a velocity from 0.04 to 0.28 m/s and visualized with the aid of a dye. Although CVRs were not observed in experiments [2], it was pointed out that, upon an increase in the velocity of emitted water column, the core of a stained circular vortex could propagate over a distance up to 30–40 calibers of the barrel. Shorygin [3] studied free ring vortices in liquids, which were emitted from a vortex generator with hole diameters within $d_0 = 70$–130 mm and monitored by detecting acoustic emission from moving vortices with the aid of a hydrophone. The observed oscillations of acoustic signals were interpreted as pulsations of the cavitating vortex cavity.

While the dynamics of pulsations in spherical cavitating bubbles has been actively studied for more than a century, including attempts at obtaining nuclear fusion reactions [5], the investigations of toroidal cavitating bubbles (including CVRs) lagged behind because of technical difficulties encountered in their generation and mathematical simulations. In this context, the present experimental work is hoped to provide an impulse toward extensive investigation of toroidal pulsating cavitation bubbles as a promising stable basic system for developing various practical applications.

This Letter presents the results of experimental investigations of hydrodynamic processes accompanying the formation and propagation of CVRs generated by explosion of inflammable gases in cylindrical barrels immersed in water. The hydrodynamic parameters of liquid flows were studied by means of high-speed video recording techniques. Using the elaborated methods of CVR generation and spatiotemporal velocity field monitoring, we have directly observed radial pulsation of CVRs and revealed correlations between some parameters.

The CVRs in water were generated by throwing a water column (jet) from an immersed vertical cylindrical transparent barrel with a diameter within 20–40 mm and a length of 30–100 mm. For this purpose, a barrel immersed in water was partly filled with an inflammable propane–oxygen mixture, which was initiated by electric spark. Combustion of a certain volume of this explosive mixture ensured throwing of a water column downward from the barrel at a preset velocity. As a result, a ring vortex was generated at the barrel muzzle and propagated in the liquid flow direction. The experiments were performed in tap water at atmospheric pressure and a temperature of $t^0 = 24$–25°C. The dynamics of hydrodynamic processes was studied by high-speed shadow video recording techniques. The records were made using a MotionXtra HG-LE camera at a speed of up to 10000 fps. The velocity of liquid motion in the barrel and in the vortex "atmosphere" was measured on tracks of polystyrene marker particles ($\rho = 1.05$ g/cm^3, $d = 100$ μm). Using the experimental arrangement described above, it is possible to study the liquid jet efflux from the barrel in a broad range of geometric and hydrodynamic parameters. The proposed device allowed a water column to be accelerated up to 16 m/s.

Figure 1 shows a series of sequential shots selected from a typical shadow video record, which illustrates

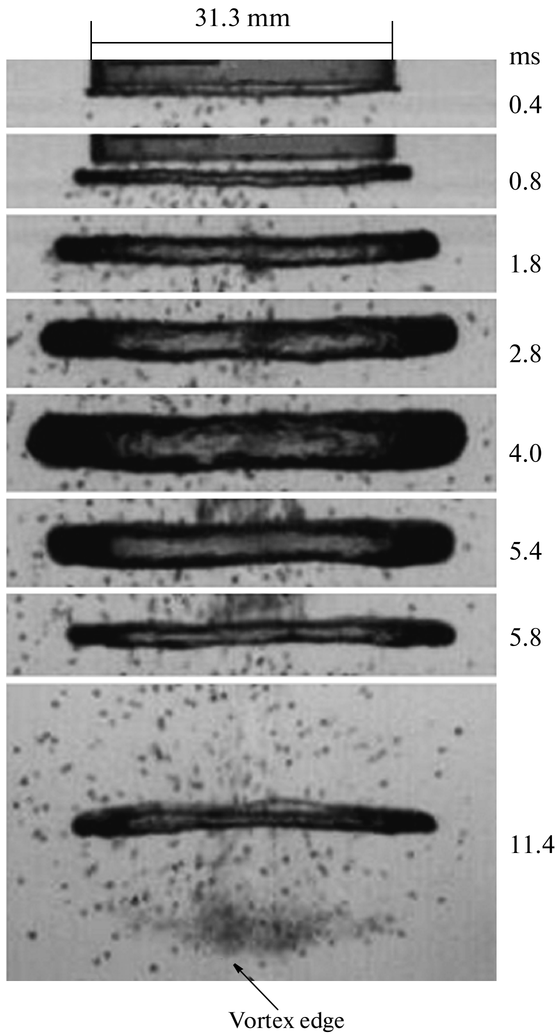

Fig. 1. Selected series of sequential CVR shadow images (V_0 = 11 m/s ± 10%).

the formation and dynamics of a CVR generated by a water column with a height of h_0 = 40 mm emitted from a 47-mm-long barrel with internal diameter d_0 = 29 mm and external diameter D_0 = 31.3 mm. In this record, the water column (jet) velocity at the barrel axis linearly increased in the interval of 0–3 ms to reach 13 m/s. The jet velocity on the barrel muzzle edge at the moment of CVR formation and separation was about V_0 = 11 m/s ± 10%.

Figure 2a presents the results of processing of all shots of the video record shown in Fig. 1 for an experiment with V_0 = 11 m/s(±10%), where $D(t)$ is the distance between CVR external boundaries, $d(t)$ is the diameter of the ring cavity cross section, and $V(t)$ is the velocity of CVR motion in the barrel axis direction. The averaged values of CVR velocity (solid curve) in the interval of 4–16 ms were within 3.5–4.5 m/s.

Figure 2b presents analogous temporal dependences of $D(t)$, $d(t)$, and $V(t)$ for V_0 = 9 m/s (±10%). In this case, the corresponding averaged values of CVR velocity in the interval of 4–16 ms were within 3–4 m/s.

The video record presented in Fig. 1 clearly shows that the CVR expands relative to the barrel caliber to reach D = 1.5 D_0. The CVR then exhibits pulsation with a period of T ~ 1.5 ms. The last shot in Fig. 1 shows the vortex "atmosphere" with a leading front of liquid rotating about the vortex. In this case, the CVR, in terms of [1–3], represents a core of the circular vortex.

The temporal dependences presented in Fig. 2 clearly reveal the process of parametric correlation between the measured characteristics. There is a phase correlation of pulsations of the maximum diameter (D) and the diameter (d) of the transverse cross section of the ring cavity of CVR. Averaged velocity V decreases with increasing CVR dimensions, which is

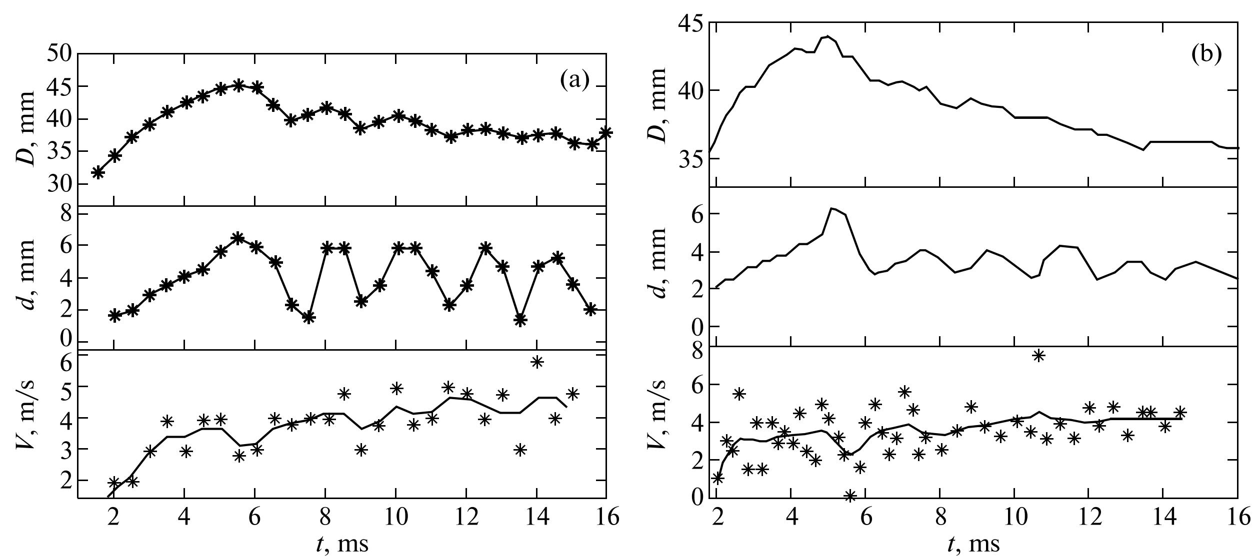

Fig. 2. Temporal variation of CVR parameters $D(t)$, $d(t)$, and $V(t)$ for (a) V_0 = 11 m/s (±10%) and (b) V_0 = 9 m/s (±10%).

especially clearly manifested by the first pulsation observed in the interval of 5–6 ms.

The data presented in Fig. 2 clearly demonstrate that a decrease in V_0 is leads to a decrease in $D(t)$, $d(t)$, and the period of CVR pulsations and, eventually, to vanishing of the observable pulsations (i.e., CVRs are observed, but pulsations are not detected). At an initial jet velocity of 2–3 m/s, only thin threads are observed in the form of a necklace of disconnected bubbles. As the jet velocity increases, the bubbles coalesce along the axis of the toroidal ring and a cavitating ring is formed with increasing d, but no significant radial pulsations are observed. Noticeable radial pulsations of CVRs are observed at initial jet velocities $V_0 > 6$ m/s.

The velocity of jet emitted from the barrel, for which cavitation at the barrel muzzle is first observed, was within $V_0 = 2$–3 m/s. This threshold corresponded to Reynolds numbers $\mathrm{Re}_0 = V_0 d_0/\nu > 2 \times 10^4$, where ν is the viscosity of water at $t^0 = 25°\mathrm{C}$. The further increase in the velocity of emitted water column ensures the formation of stable CVRs in the form of cavitation toroids.

The threshold of cavitation onset can be determined in terms of cavitation number ε determined from the Bernoulli law as $\varepsilon = P_0/\rho V^2$, where P_0 is the hydrostatic pressure, ρ is the liquid density, and V is the liquid flow velocity. In the case under consideration, the cavitation number is within $\varepsilon = 21$–22, which is about ten times greater than the value obtained for the formation of a "cavitating vortex" [6]. The results obtained in [6] likely played the role of retarding factors in CVR investigations, since the "cavitating vortices" were obtained in oil at jet velocities of ~100 m/s for a liquid column height of 10 mm and a barrel diameter of 15 mm, which was a rather complicated technical solution. It should also be taken into account that the "cavitating vortex" studied in [6] had a spheroidal shape, while we are considering a cavitating ring as a core of the circular vortex [1]. Using the velocity of a water column (jet) emitted from the barrel, we have established the threshold parameters for cavitation processes and the formation of stably pulsating CVRs. Note that CVRs were formed both in the presence of polystyrene particles and in pure water. There were no significant differences in the dynamics of CVR formation in pure water and in water with polystyrene particles.

In concluding, we have developed a relatively simple method of CVR generation in water that is based on throwing a water column accelerated to a velocity up to 16 m/s by explosion of a gas mixture in cylindrical barrels. It was experimentally demonstrated that CVRs in water appear at a velocity of liquid jet efflux from a barrel above 2–3 m/s at a cavitation number of $\varepsilon = 21$–22 and a Reynolds number of $\mathrm{Re}_0 > 2 \times 10^4$. Using optical methods, radial pulsations of CVRs were directly observed for the first time at a jet velocity above 6 m/s.

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