

Dynamics of cavitation clusters and vortex rings in water

V. Teslenko A. Drozhzhin R. Medvedev
v_s_teslenko@hydro.nsc.ru

Abstract

This work deals with the results of experimental investigation of vortex cavitation processes developing in pulse pushing of a water projectile from flooded cylindrical tubes of diameters 20-40 mm into water. The dynamics of cavitation development on the cylinder cut and the propagation of cavitation vortex rings (CVRs) in water depending on the velocity of water pushing are investigated. Having the form of hollow torus, stable CVRs have arisen at velocity of water piston (jet) more than 2 m/s. At jet velocities more than 6 m/s, radial pulsations of CVR have been first recorded by optical methods.

1 Introduction

The dynamics of formation and propagation of vortex rings in atmosphere are studied in details [1]. The problems of formation and motion of CVRs in water remain unsolved. Many papers including those on collapse of cavitation bubbles and dynamics of bubbles in underwater explosions of chemical substances are devoted to dynamics of pulsations of spherical bubbles. The problems of formation and pulsations of cavitation ring bubbles are underinvestigated [2, 3]. This work presents the results of experimental investigating the processes of formation and dynamics of CVRs in water with optical recording of hydrodynamic parameters on the cut of CVR generator.

2 Experimental set-up

Generation of vortex rings in water was performed by pushing a water projectile from clear cylindrical tubes of diameters 20-40 mm and lengths 30-100 mm flooded vertically in water. The first frame of Fig.1 shows the experimental set-up. A clear cylindrical tube located in water was filled with combustible propane-oxygen mixture, which was ignited by a high-voltage spark. Combustion of specified portions of gas mixture provided pushing out of water column from the tube accelerating up to required velocity. Here on the tube cut, a ring vortex was generated. The vortex propagated downwards.

This experimental set-up makes it possible to perform investigation of liquid outflow from the tube in a wide range of geometric and hydrodynamic parameters. The device permitted to accelerate the water column up to 16 m/s. The experiments were performed at atmospheric pressure and temperature of tap water was $t^0=24-25^0$ C. The dynamics of hydrodynamic processes was studied by using a high-speed recording. The recording was performed by the camera "MotionXtra HG-LE" at frame frequency up to 10 000 frames per second. The liquid velocity both in the tube and vortex was measured by tracks of polystyrene particles ($\rho = 1.05$ g/sm³, $d=100$ mkm).

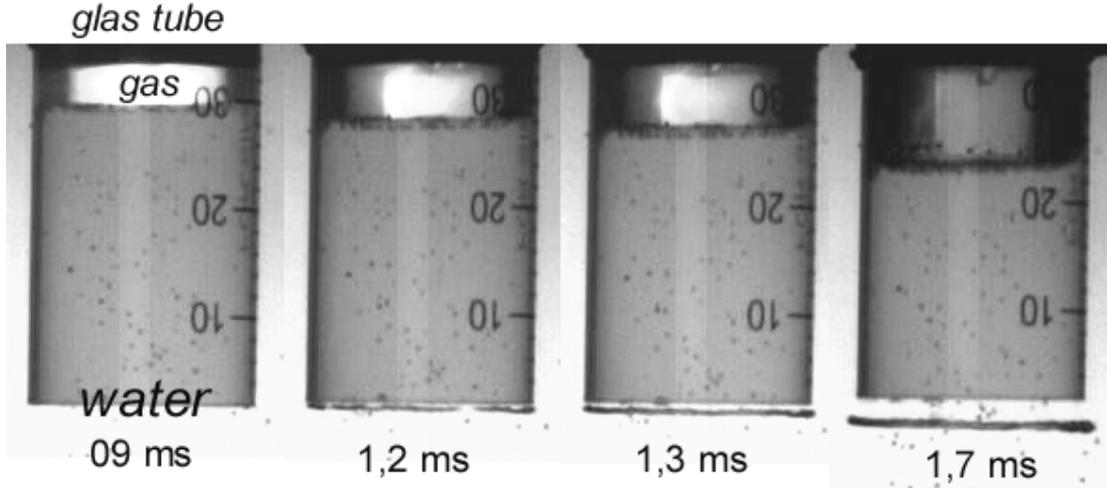


Figure 1: The scheme of experimental set-up and record of initial stage of CVR formation.

3 Experimental results

Figure 1 illustrates the frames of shadow record of initial stage of CVR formation on outlet cut of the clear tube. Figure 2 shows the example of shadow record of dynamics of CVR formation and propagation in pushing the water column of height $h_0 = 40$ mm from the tube of length 47 mm, inner diameter $d_0 = 29$ mm and outer diameter $D_0 = 31.3$ mm. For this record the velocity of water column (jet) at the tube axis increased linearly up to 13 m/s in a time 0-3 ms. At the moment of formation and separation of CVR, the jet velocity was within the interval $V_0 = 8 - 12$ m/s.

All dynamic parameters of CVR depend on velocity V_0 ; therefore, the values of V_0 in presented results are determined for the moments of CVR formation and separation from the tube. We take the values V_0 and h_0 as initial parameters of CVR formation and propagation.

The records in Figs. 2 and 3 illustrate that formed CVR expands with respect to the tube cut up to diameter $D = 1.5 \cdot D_0$ and pulsates with period $T \sim 1.5$ ms. The last frame of the record in Fig. 2 shows “atmosphere” of vortex with leading edge of liquid rotating around CVR. According to terminology in [1, 2], in this case CVR is a nucleus of the vortex ring.

Figure 3 presents the dependencies of parameters D and d on time from the data processing results of complete record in Fig. 2. ($V_0 = 11$ m/s, $\pm 10\%$): $D(t)$ is a distance between outer boundaries of CVR, $d(t)$ is a diameter of cross-section of CVR cavity. It follows from the data in Fig. 3 that D and d correlate with respect to time. The average values of velocity of CVR motion along the generator axis at time periods 4-16 ms were within the interval 3.5 – 4.5 m/s. Figure 4 shows the dependencies $D(t)$ and $d(t)$ for $V_0 = 9$ m/s ($\pm 10\%$). Thus, the average values of velocity of CVR motion at time periods 4-16 ms were within the interval 3 – 4 m/s.

It follows from the data in Figs. 3 and 4 that in decreasing V_0 the values $D(t)$, $d(t)$ and the period of CVR pulsations decrease. Further decrease of V_0 leads to disappearance of observable CVR pulsations, i.e., CVR is observed but pulsations are indistinguishable. At jet velocities 2 – 3 m/s only thin lines in the form of a bubble necklace with distances between the bubbles are observed. When the jet velocity increases, bubbles coalesce along the axis of toroidal ring and the formation of cavitation ring occurs with increase of D

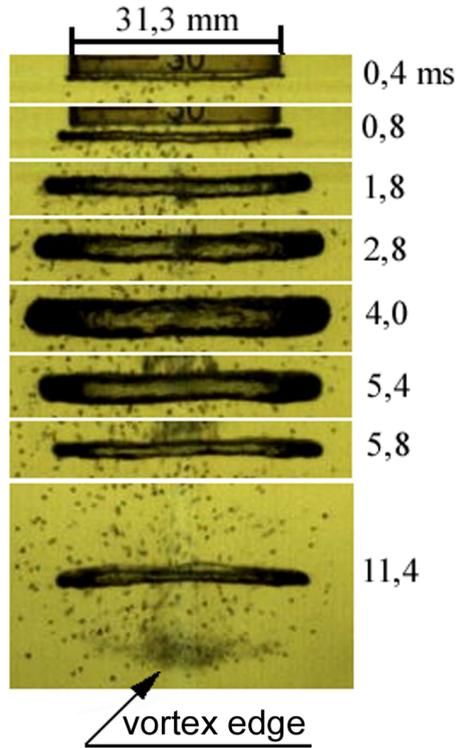


Figure 2: Sampling frames of shadow record of CVR ($V_0 = 11 \text{ m/s}$).

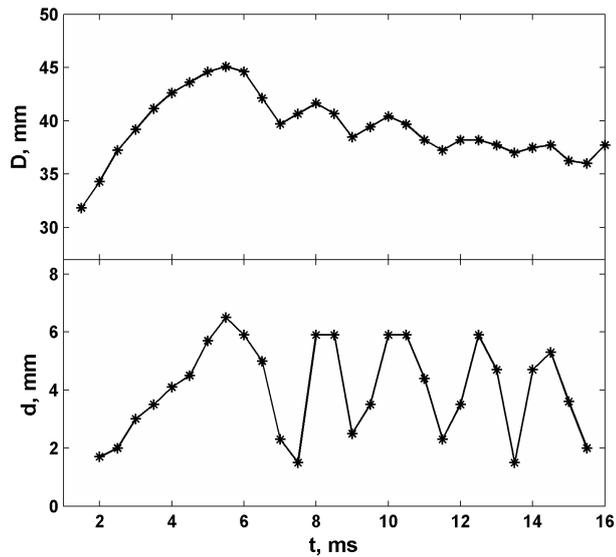


Figure 3: Dependencies of the distance between the outer CVR boundaries (D) and the diameter of cross-section of CVR cavity (d) on time for $V_0 = 11 \text{ m/s}$.

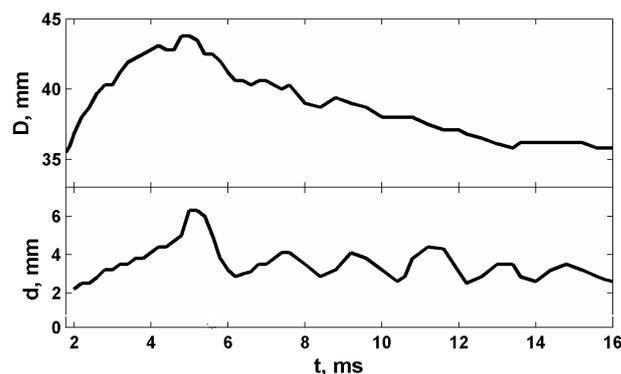


Figure 4: D and d versus time for $V_0 = 9$ m/s.

and d . No visible radial pulsations are observed. At jet velocities $V_0 > 6$ m/s observable radial pulsations of CVR arise.

4 Analysis of the results

The velocity of water flow pushed out from the tube, at which cavitation processes on the tube cut become observable, was within the interval 2-3 m/s. This threshold corresponded to the Reynolds numbers $Re_1 = V_p \cdot d_0 / \nu > 2 \cdot 10^4$ (here V_p is a velocity of water piston on the cylinder cut, d_0 is the inner diameter of cylinder and ν is water viscosity at $t^0 = 25^0$ C). Further increase of velocity of water piston pushing provides the formation of stable CVRs in the form of cavitation torus.

The threshold of cavitation arising may be estimated by the parameter of cavitation number (ε) according to the Bernoulli law ($\varepsilon = P_0 / \rho \cdot V^2$, where P_0 is a hydrostatic pressure, ρ is a liquid density and V is a velocity of liquid flow). In our case, the value of cavitation number is within the interval $\varepsilon = 21-22$ that is different by an order of magnitude from the values obtained before for “cavitation vortex” in [4]. The results of work [4] may have been an inhibiting factor in investigation of CVR since in this work “cavitation vortices” were obtained in oil at jet velocities ~ 100 m/s for the oil jet of length 10 mm pushed out from the tube of diameter 15 mm that was a relatively complicated technology. Here it is to be taken into consideration that in [4] “a cavitation vortex” of spheroid type was obtained and studied, but in this case a cavitation ring is considered as the nucleus of ring vortex. In [5], we studied in detail “the peculiarities of formation and motion of ring vortices in water” for generator of vortices of diameter $d_0 = 35$ mm at velocities of water flow from 0.04 up to 0.28 m/s. The record of vortices was performed by using dyes. In these experiments CVR was not recorded. However, the author notes that when the velocity of pushed water column increased, the nucleus of the ring vortex with dye propagated to distances up to 30-40 tube diameters. In [2], “free ring vortices in a liquid” for generators of vortices of diameters $d_0 = 70 - 130$ mm were studied. Acoustic radiation from moving vortex was recorded by using the hydrophone. Recorded pulsations of acoustic signals were interpreted as pulsations of cavitation vortex cavity. In this work, direct measurements of radial pulsations of CVR are performed by using shadow speed recording. By using the developed method, the record of the field of liquid flow velocities was performed on a space-time scale. By parameters of jet velocity the threshold parameters of formation of stable and radially pulsating CVRs are found out.

5 Conclusions

1) A relatively simple method of CVR generation by using pushing of cylindrical water column accelerating up to 16 m/s by exploding gas mixtures in water is developed.

2) It is shown experimentally that CVRs arise at velocities of liquid outflow from the cylindrical tube more than 2-3 m/s, with cavitation number $\varepsilon = 21-22$ and the Reynolds number $Re_1 > 2 \cdot 10^4$.

3) By using the speed record, direct measurements of radial pulsations of CVRs in water have been first performed.

Acknowledgements

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Vyacheslav S. Teslenko, Lavrentyeva ave. 15, Novosibirsk, Russia

Aleksey P. Drozhzhin, Lavrentyeva ave. 15, Novosibirsk, Russia

Ruslan N. Medvedev, Lavrentyeva ave. 15, Novosibirsk, Russia