FORMATION OF A VORTEX RING DURING ASCENT OF A LARGE AIR BUBBLE IN WATER

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The ascent of gas bubbles in liquids has been the subject of numerous experimental and theoretical studies. A review of the literature on this question can be found in [1, 2], for instance. Most attention has been devoted to the study of the ascent of relatively small bubbles ($R_0 \leqslant 3$ cm, $V_0 \leqslant 100$ cm^3). When $R_0 \leqslant 0.1$ cm the air bubble is hardly deformed at all when it ascends through the water. When $0.1 \leqslant R_0 \leqslant 2$-3 cm the bubble changes shape during its ascent, but surface tension forces prevent its breakup. In [3], where the ascent of bubbles with $R_0 \approx 3$ cm was investigated, the main attention was given to a description of the shape of the upper part of the surface and the motion of the liquid around it. The question of breakup of the bubble was not considered. An investigation of the ascent of a bubble with $R_0 \approx 3$ cm ($V_0 = 100$ cm^3) showed [4] that when $t > \sqrt{R_0/g}$ it is converted to an ascending toroidal ring. In [4] the evolution of bubbles with $V_0 = 100$-3000 cm^3 at $t < 2\sqrt{R_0/g}$. was also discussed. The experimental possibilities of the apparatus did not allow observation of the further evolution of large ($V_0 > 100$ cm^3) bubble owing to the wall effect. The largest spherical gas bubbles are formed by an explosion in a liquid [5]. In this case, however, there are great fluctuations of the size of the bubble, which qualitatively alter the picture of its ascent [6]. The present paper gives the results of an experimental investigation of the ascent in water of a large air bubble ($R_0 = 15$ cm, $V_0 = 1.4 \cdot 10^4$ cm^3) which is initially spherical and at rest.

The experimental setup is illustrated in Fig. 1, where 1 is a 16-mm Krasnogorsk motion-picture camera, F = 10 mm; 2 is an 8-mm Ékran motion-picture camera, F = 12.5 mm, in a box for underwater photography; and 3 is a rubber balloon filled with air. The air bubble was formed by puncture of the air-filled rubber balloon with a long needle. The balloon was contained in a fine Kapron net and was held at a distance of 30 cm from the bottom of the 2-m-deep basin. The rubber skin rapidly contracts, releasing the air bubble (this method of bubble formation is similar to that used in [4]). The motion-picture photographs showed that the time of contraction of the skin was less than 0.02 sec. In this time the bubble hardly moves at all. The remains of the skin and the Kapron net have little effect on the ascent of the bubble, since their total surface is much less than the bubble surface. Their effect consists in an initial distortion of the water – air interface. When the bubble ascends to a height $H - H_0 > R_0$, the effects of the net and skin become even more insignificant, since the latter remains at the bottom (H_0 is the initial height of the bubble center).

The ascent of the bubble was photographed with the Krasnogorsk and Ékran cameras at 48 frames/sec. The distance from the walls and bottom of the basin was large enough to exclude their effect on ascent of the bubble. In determination of the geometric dimensions we took into account the difference in the refractive indices of water and air.

Owing to gravitational instability [7] of the water – air boundary the amplitude of the disturbance of the surface on the upper half of the bubble increases. With the passage of time the increase in surface disturbances leads to the breakaway of bubbles of diameter ~ 5 cm from it. As these bubbles ascend they break up into smaller ones and their distribution becomes of a random turbulent nature. When $t \approx 2\sqrt{R_0/g}$ a characteristic toroidal vortex ring, consisting of a mass of bubbles of diameter ~ 1 cm rotating around the axis of the torus, is formed. When the toroidal ring reaches the surface of the water the diameter of the bubbles is ~ 0.1-0.5 cm. Direct confirmation, apart from visual observation, that the toroidal ring consists of individual bubbles was the fact that the volume of the ring was several times larger than the initial volume of the air bubble. At time $t = 10\sqrt{R_0/g}$ the toroid volume $V = 2.4V_0$, whereas the adiabatic increase in gas volume due to its ascent does not exceed 15%.

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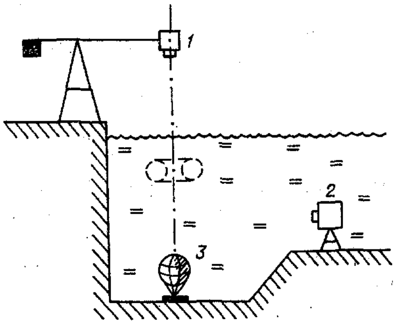

Fig. 1

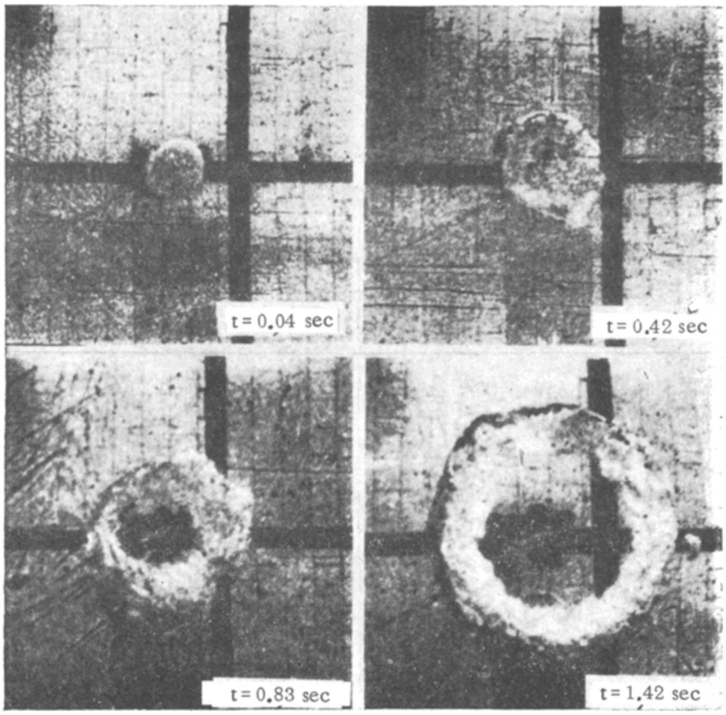

Fig. 2

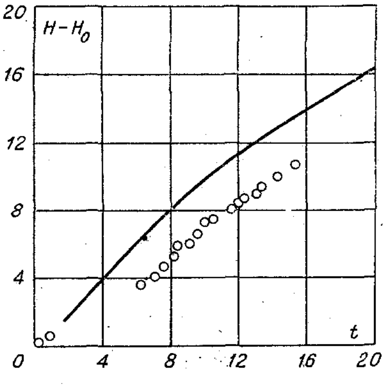

Fig. 3

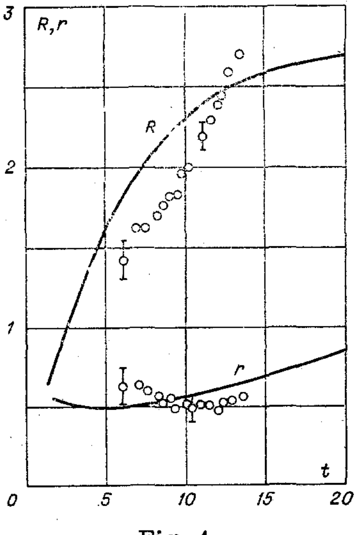

Fig. 4

The general picture of formation and development of the vortex ring is illustrated in Fig. 2 (view from above, picture taken with camera 2).

Plots of the height of ascent $H(t)$, measured from the initial position of the bubble H_0, and of the large $[R(t)]$ and small $[r(t)]$ radii of the torus are shown in dimensionless form in Figs. 3 and 4. The scale of measurements of the linear dimensions was R_0, and the time scale was $t_0=\sqrt{R_0/g}$. The error in determination of R and r was ~10% on the average and was due mainly to irregularities of the edge of the toroidal ring.

For comparison with experiment Figs. 3 and 4 show the results of calculation of $H(t)$, $R(t)$, and $r(t)$ from the phenomenological model [8] (continuous line).

In the calculation corresponding to the case of an external medium of constant density we took a set of dimensionless parameters, similar to that used in [8]: $t'_0=0.12$; $\xi=1.29\cdot10^{-3}$; $\gamma_0=0.2$; $R'_0-r'_0=0.596$; $H'_0=0.0076$; $V'_0=0.128$; $v'_0=0$; $\alpha=0.055$; $\beta=0.5$; $C_X=0.4$; $\theta=\text{const}$; $\rho_1=\text{const}$ (notation as in [8]). The satisfactory agreement of the theoretical and experimental data indicates the reasonable choice of empirical constants in the model.

The tendency toward divergence of the calculated and experimental relationships $R(t)$ becomes appreciable at $t/t_0 \gtrsim 12$, when the water surface affects the ascent of the ring. This effect leads to slower ascent and more rapid expansion of the vortex ring than in the case of an unbounded medium, for which the model in [8] is applicable.

The stability of the obtained results when the initial conditions were altered was experimentally confirmed. In particular, we changed the point of puncture of the balloon skin (at the top and on the equator) and the mesh of the Kapron net (3 × 3 cm, 6 × 6 cm). The qualitative and quantitative agreement of the results of these experiments when $t > t_0$ indicates that the ascent of the vortex ring is almost independent of the initial conditions.

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