CUMULATIVE STREAMS DURING THE IMPACT COLLAPSE OF CAVITIES IN THIN LIQUID LAYERS

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High-speed motion-picture photography has been used to study the dynamics of the impact-induced collapse of air-filled bubbles in thin layers of various liquids. The circular surface of the bubble is disruptive in an arbitrary manner during the collapse, and high-velocity cumulative streams arise. The stream parameters have been measured as functions of the initial experimental conditions.

Knowledge of the course of physical processes accompanying the collapse of bubbles in thin liquid layers during impact is extremely important for a correct understanding of the reasons for the various phenomena which occur. For example, errosion of solid surfaces bounding a liquid layer has been observed when the surfaces are drawn apart and then rapidly pushed back togehter [1]. Under similar experimental conditions, it has been observed that when surfaces move into a layer of a previously uniform liquid one can directly photograph the appearance of cavitation bubbles, which rapidly collapse as the surfaces approach [2]. One reason which has been advanced for the destructive effect of cavitation is the interaction with the solid surface of the high-velocity cumulative liquid streams formed during the collapse of cavitation bubbles [3, 4]. The appearance of cumulative streams during collapse of bubbles in thin liquid layers of explosives was recently demonstrated by Bowden [5].

Despite the well-known progress in experimental studies of asymmetric collapse of bubbles in liquids, we know of no systematic information about the interaction of the cumulative streams formed during the collapse with solid surfaces in the liquid as a function of various external factors. With such information available for even the extremely simple case of liquid collapse in thin liquid layers during impact, one can estimate the contribution of this interaction to the dynamics of the various subsequent events.

We used high-speed motion-picture photography to study the collapse of air bubbles formed in thin liquid layers (thickness $h_0 = 0.2$–1.0 mm) between the flat surfaces of two cylindrical rollers which are made to collide (Fig. 1). The rollers are mounted vertically and coaxially, one above the other.

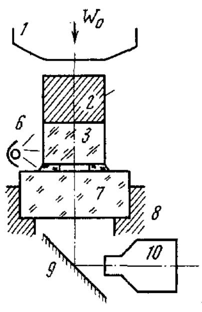

Fig. 1

The lower roller 7, 30 mm in diameter and 25 mm thick, is made of K-8 optical glass; the upper roller, 3 of Plexiglas, has a diameter 2R of 19 mm and a height of 20 mm. The ends of the rollers are polished. Their common axis passes through the center of the bubble 5, which is circular in shape with a diameter $2r_0$ equal to 5 or 10 mm. The bubble height corresponds to the thickness of the liquid layer 4. The air pressure in the bubble is atmospheric. The test liquids were an aqueous solution of glycerine, VG 7/93 (wt. %) ($\rho_0 = 1.24$ g/cm^3 and $\mu = 3$ p) and nitroglycerine ($\rho_0 = 1.6$ g/cm^3 and $\mu = 0.3$ p).

On the upper rollers there is another steel roller 2, of the same size, which transfers the impact from a falling weight 1 (5 kg in mass) to roller 3. The drop H = 5-80 cm was chosen so that the initial impact velocities W_0 varied from 1 to 4 m/sec. In all the experiments, the characteristic times for the impact of the weight with the liquid layer $\tau = h_0/w_0$ were much greater than the time characteristic of

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhicheskoi Fiziki, Vol. 11, No. 2, pp. 148–151, March-April, 1970. Original article submitted October 8, 1969.

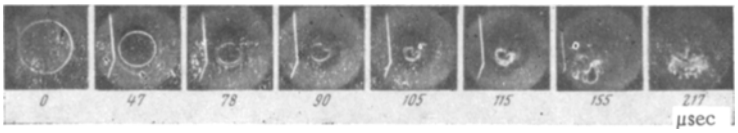

Fig. 2

the collapse of the bubbles of the corresponding size. The bubble collapse was photographed during the impact by a ZhLV-2 high-speed motion-picture camera 10. The illumination was by an IFK-120 flash lamp 6 at the side of the rollers.

Figure 2 shows a series of motion-picture frames demonstrating the collapse of an air-filled bubble 10 mm in diameter in a 0.5 mm-thick layer of VG 7/93 glycerine-water solution, caused by a weight falling from 20 cm (initial impact velocity of 2 m/sec). The labels on the frames show the time in μsec, reckoned from the beginning of the bubble collapse. As these photographs show, at some point during the collapse the circular shape of the bubble surface is disrupted and becomes unstable; here individual surface regions acquire a velocity higher than that of other regions. As a result of this transient process, cumulative liquid streams arise which subsequently collide with the opposite side of the bubble surface at 70 m/sec. The final frames in Fig. 2 show that after the impact of the stream, the bubble breaks up into many smaller bubbles which gradually are carried away by the liquid flow toward the periphery of the rollers.

These frames show the typical pattern of bubble collapse under these experimental conditions. Only a few remarks should be made to supplement these photographs. Frequently, especially at low impact velocities, one may observe the nearly simultaneous appearance of two or even three cumulative streams.

As they move, the streams generally interact with each other; the result is either an intensification or an attenuation of the effect on the bubble walls. In particular, a collision between the two streams moving at a right angle or in opposite directions from opposite sides of the bubble results in the destruction of the streams and the subsequent formation of many very small bubbles. If the effect of the cumulative stream on the wall of the collapsing bubble is not sufficient to, say, shatter the bubble, the air compressed in the bubble turns out to have a large effect on the subsequent collapse. In certain experiments, especially with small bubbles, we were able to observe a pulsation of the bubble – its contraction to an extremely small size (a greater than tenfold decrease in radius), its subsequent expansion due to the energy of the air compressed in it, and finally a repeated contraction.

Figures 3 and 4 summarize the experimental dependence of the relative bubble radius r/R on the time t (in microseconds), reckoned from the beginning of the bubble collapse (R = 9.5 mm is the radius of the upper roller). The data in Fig. 3 refers to bubbles having an initial diameter of ≈ 10 mm for various nitroglycerine-layer thickness: 1.0, 0.5, and 0.25 mm, for curves 1-3 respectively. The weight velocity at the instant of impact is 2 m/sec (H = 20 cm). Figure 3 also shows for comparison time dependences of the radius of a bubble having an initial diameter of ≈ 5 mm and a thickness of 0.5 mm (curve 4) and 0.25 mm (curve 5) in nitroglycerine and that of a bubble 10 mm in diameter and 0.5 mm thick for a glycerine-solution layer (curve 6) with the same initial weight velocity. Each curve corresponds to results averaged over 5-10 separate experiments. Figure 4 shows dependences of r/R on t (μsec) for bubbles 10 mm in diameter in a nitroglycerine layer 0.5 mm thick; curves 1-3 correspond to wave velocities of 1, 2, and 3 m/sec, respectively.

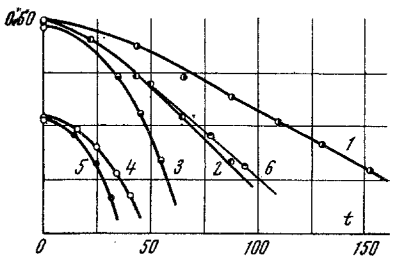

Fig. 3

From the results in Figs. 3 and 4, one can estimate the characteristic bubble collapse time t_+ by extrapolation of the r/R curves to the t axis, and one can estimate the average bubble-boundary velocity u = dr/dt at the end of the final stage of the collapse, when "permanent" surface deformations appear and cumulative streams arise. The latter estimate is based on a graphical differentiation of the corresponding t dependences of r/R.

The results of this analysis (table) show that the collapse time of a bubble of given diameter for a given initial impact velocity increases with increasing liquid-layer thickness. As the characteristic liquid-layer impact time $\tau = h_0/w_0$ increases, the collapse times also

TABLE 1

Experiment	VG 7/93 (wt. %)	Nitroglycerine								
	0	1	2	3	4	5	6	7	8	9
w_0, m/sec	2	1	2	2	2	3	3	4	2	2
h_0, mm	0.5	0.5	1.0	0.5	0.25	0.5	1.0	1.0	0.5	0.25
r_0/R	0.485	0.49	0.49	0.49	0.48	0.51	0.49	0.51	0.27	1.27
u, m/sec	40	20	.25	45	100	90	40	60	85	120
t_+, μsec	130	265	205	120	70	75	135	95	50	40
h_0/h_*	1.47	1.82	1.47	1.49	1.67	1.50	1.4	1.38	1.21	1.48
r/r_*	2.31	4.92	3.92	2.59	1.85	2.62	3.15	2.98	4.98	3.57
v, m/sec	80	25	40	100	180	150	75	150	150	300
P, kbar	1.75	0.75	1.15	2.65	5.2	4.5	2.0	3.8	4.35	8.3

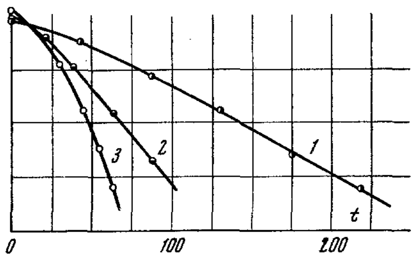

Fig. 4

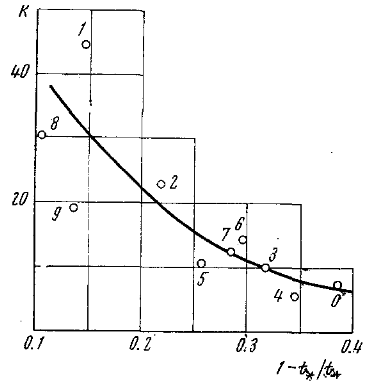

Fig. 5

increases. The opposite dependences are observed for u. As the table shows, marked difference (an order of magnitude) in viscosity coefficients has little effect on the bubble collapse time under these experimental conditions.

For an idea of the size of the bubble at the instant of collapse, t_*, for which the spherical surface becomes unstable, we show in the table the values of r_0/r_* and h_0/h_* which characterize the contraction of the initial radii r_0 of the bubbles and their heights, respectively. The h_0/h_* values were calculated from $h_*/h_0 = 1 - t_*/\tau$, found under the assumption of a constant weight velocity w_0 during the bubble collapse. This may be assumed because the mass of the weight under our experimental conditions was several orders of magnitude greater than the mass of the liquid layer. As the table shows, h_0/h_* remains relatively constant for all the bubbles studied (1.47 ± 0.16). On the other hand, (r_0/r_*) depends on the initial experimental conditions; in a certain sense, the (r_0/r_*) values characterize in this case the instability of the surface of the coaxial bubbles. Figure 5 shows the dependence of the limiting bubble contraction $K = (r_0/r_*)^2 h_0/h_*$, at which contraction the circular symmetry of the collapse is disrupted, on the quantity $1 - t_*/t_+$. The labels in Fig. 5 correspond to the experiment numbers in the table.

We also measured the velocity of the cumulative streams arising during the collapse, but since the stream velocity was not strictly constant in magnitude or direction in the various experiments, these measurements were not very accurate.

Kozyrev [6] observed a similar behavior during the collapse of cavities produced by an elastic discharge in a liquid. Table 1 shows the measured stream velocities V, averaged over several experiments, for the corresponding initial cavity dimensions and weight impact velocities.

For various practical reasons, it is important to know the parameters of the mechanical effects of the cumulative streams on the walls of the collapsing bubbles and on the solid surfaces bounding the liquid. The dynamic pressures arising during the interaction of the streams with the bubble walls were estimated on the basis of the known bubble velocities v, the bubble-boundary velocities u, the densities ρ_0, and the impact adiabat for the liquid. The latter was adopted in the form suggested in [7], so that the final version of the equation used to calculate the pressure during the stream impact was

$$p = 0.5\ \rho_0(u + v)\ [1.2\ c_0 + 0.85\ (u + v)]$$

where c_0 is the sound velocity in the liquid, calculated from Raoult's rule for organic liquids (see [7]). For nitroglycerine we have c_0 = 1750 m/sec, and for VG 7/93 aqueous solution of glycerine we have c_0 = 1900 m/sec. The calculated P values are shown in the table.

Analysis of the data in the table shows that under our experimental conditions a decrease in the thickness of the liquid layer and an increase in the impact velocity of the weight are accompanied by an increase in velocity of the cumulative streams during the bubble collapse and in the liquid pressure during interaction with the bubble boundaries. These stream parameters also increase with decreasing initial bubble diameter. We note that the dynamic pressure in the solid surfaces adjacent to the liquid can be easily estimated on the basis of the impact adiabat for the solid material.

These experiments have established that the impact collapse of bubbles in thin liquid layers due to relatively weak mechanical effects (impact velocities in the range 1-4 m/sec) is accompanied by the formation of cumulative liquid streams which move at relatively high velocities (≈ 100 m/sec).

The interaction of the streams with the boundaries of the collapsing bubbles generates comparatively high dynamic pressures (of the order of several kilobars), above the breakdown strength of many solids. It chould be noted, however, that such high pressures exist only relatively briefly in a liquid, for a time of the order of $t^\circ \approx h/c$, where h is the thickness of the liquid layer and c is the sound velocity in the liquid. For h ≈ 0.2-1.0 mm and for c = 2000 cm/sec, we have $t^\circ \approx$ 0.1-0.5 μsec. After this time, the pressure during the impact of the stream decreases rapidly, to a value of the order of a few hundred atmospheres, calculated from the familiar relation for an incompressible liquid:

$$p_0 = 0.5\ \rho_0(u + v)^2.$$

Nevertheless, if the bubble collapse occurs under operating conditions permitting a repetition of the effects, the streams may ultimately destroy the solid surfaces.

We note that in the experiments with an explosive liquid, explosion phenomena were observed under certain conditions after the collision of the streams with the bubble boundaries.

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