Nonlinear Dynamics of Bubbles with Surfactants

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Abstract: Hugh Flynn pioneered many aspects of cavitational phenomena. He even got a patent on the idea that large bubble collapse could be used for inertially induced thermonuclear fusion. Some researchers currently working in the area of sonoluminescence are asking the same questions. One of the key requirements for confining the energy in the collapse of a bubble is maintaining spherical symmetry. Instabilities, such as Rayleigh-Taylor and Kelvin-Helmholtz, can compromise this requirement. Therefore, it is useful to examine the role of surfactants in conferring stability on the collapse of bubbles. Codes that have recently permitted the description of the superoscillations of liquid drops with surfactants in air (1) can be applied to the case of a bubble in a liquid. The opportunities and methodologies of the numerical method are described.

BACKGROUND

A recent report by Stottlemyer *et al.* (2) described an experiment in which the parameter range for single bubble sonoluminescence (SBSL) (1) was influenced by the presence of surfactants. When a fast-diffusing and sorbing surfactant such as Triton X-100 was added to the water in an amount corresponding to one tenth the critical micelle concentration, it became much harder to cause SBSL and the resulting SBSL was much weaker. However, when the surfactant Bovine Serum Albumin (BSA) was used at its critical micelle concentration, it was possible to drive the bubble harder which in turn caused significantly greater light output (by about 50%).

The differences in the effects due to surfactants can be rationalized by understanding how the two different surfactants affect the surface properties. We have shown in our space shuttle studies of the shape oscillations of drops in air that Triton X-100 greatly lowers the surface tension of water (from 72 to 31 dynes/cm at the critical micelle concentration) while having relatively minor effects on the surface damping, whereas the insoluble surfactant BSA only lowers the surface tension somewhat (to 56 dynes/cm) while increasing the damping by a factor of 17. These results suggest that surface damping in sonoluminescence experiments may delay and lessen the onset of instabilities so that the energy concentrating effects of bubble collapse are not compromised by shape deformation.

Therefore, we asked whether we could understand the role of surfactants in bubble collapse more comprehensively so that we could both choose appropriate surfactants and estimate their effect in enhancing SBSL.

NUMERICAL APPROACH FOR DROP OR BUBBLE MOTION

W. T. Shi *et al.* modified the well-developed the boundary integral method to study the shape oscillations of a liquid drop in air with a superimposed acoustic standing wave (3). Measurements performed on the space shuttle (1) were then compared with predictions, and showed excellent agreement in the detailed shape of greatly deformed drops. More recently Chen *et al.* (4) have extended the theory so that it could be used to predict the viscosities (both dilatational and shear) associated with the surface.

The numerical approach involving the boundary integral method involves a number of assumptions and steps. In particular, the liquid is assumed to be incompressible, Newtonian, and irrotational except in the viscous boundary layer in the liquid, and its bulk properties are unchanged by the presence of the surfactant (since the concentrations are so small). The surface fluid is assumed to be Boussinesq. The surface tension is considered to be homogeneous along the surface except when the deformation (aspect ratio) exceeds 1.1, and then the non-uniformity depends on the assumed rate constants for the particular surfactant. Heat transfer is assumed to take place only at the bubble boundary, as the internal properties of the bubble are assumed to be uniform and governed by adiabatic motion.

APPLICATION TO COLLAPSING BUBBLES

A first attempt at using the boundary integral method for studying the effects on bubble collapse considered the idealized case of an air bubble of a certain size in water (5). No surfactant was assumed. The bubble which has grown to a given maximum size is given a perturbation in shape (which is accomplished by distorting a particular mode by a certain percent). It is then allowed to collapse, and the shape history is computed using the method described above. Shown in Table 1 are the bubble shapes when either the computation stops because two sides of the bubble touch or the minimum volume of the bubble is reached.

TABLE 1. Final bubble shapes for given initial maximum radius

R_{max} (μm)	Percent Deformation at Max. Radius (2nd Mode)	Collapse Time (μs)	Shape, Not to Scale
200	1	19.42	 rebounds
20	1	1.87	 rebounds
20	5	1.84	 calculation stops

In a second series of simulations (6), still with no surfactant, we started with a bubble at a realistic initial size (e.g. 5 μm) and we grew the bubble with an imposed acoustic field. At maximum size we assigned a particular aspect ratio, and then let the bubble collapse. Two sets of results are displayed, one for variable frequency but no shape perturbation, and one for a fixed frequency (30 kHz) and variable pressure or perturbation. It is clear in the second case, for example, that the perturbation compromises the predicted maximum internal temperature, and that the maximum temperature is very sensitive to the acoustic drive pressure.

TABLE 2. Results for no perturbation. Bubble initial size: 5 um; Acoustic pressure: 1.2 atmospheres

Freq (kHz)	Perturb %	Press max (atm)	Temp (K)	Rad max (um)	Rad min (um)	Max vel (m/s)
15	0	92877	8201	49.93	0.360	4227
20	0	50798	6726	39.57	0.412	2520
30	0	22248	5061	29.54	0.494	1305

TABLE 3. Results showing effect of perturbation in one case; frequency of acoustic wave: 30kHz

Initial Radius (um)	Acoust. Press (atm)	Perturb %	Press max (atm)	Temp (K)	Aspect ratio(r/z)	Rad max (um)	Rad min (um)	Max vel (m/s)
5	1.2	0	22248	5061	1.0	29.54	0.494	1305
5	1.2	10	24041	4575	2.144			
5	1.3	0	70304	7493	1.0	39.36	0.384	3321
10	1.2	0	10167	4526	1.0	44.01	1.19	736

ADDING SURFACTANTS

Although far more accurate algorithms exist for spherical bubble motion than those described above, they cannot handle non-spherical collapse or surfactants. The boundary integral method permits us to study the effect of shape deformation on internal properties and also permits the addition of surface modifications (such as in elastic and viscous properties). Current research, to be reported at the ICA/ASA meeting, will present results for the case in which the water has surfactants of various types and concentrations dissolved in it. Then it will be possible to estimate the potential role of surfactants in the suppression of shape instabilities in sonoluminescing bubbles.

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