The Rayleigh-like collapse of a conical bubble: Measurements of meniscus, liquid pressure, and electrochemistry

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Summary: This paper describes experimental measurements of the collapse of a conical bubble. The apparatus allows ready control of the inertia associated with the bubble collapse, and imaging through a section incorporating both sides of the gas/liquid interface. It also allows measurement of pressure pulses and surface erosion at the centre of the collapse, measurement of the pressure pulses emitted into the liquid when the bubble rebounds, and high speed photography of the bubble wall (giving both measurements of the wall speed, and details of bubble fragmentation). The results are compared with theory. *(Nuffield Foundation supplied undergraduate bursary NUF-UGB98 for T. Bayliss).*

INTRODUCTION

This paper describes an experimental investigation of the collapse of a conical bubble. The apparatus allows control of the liquid inertia, the bubble size prior to and after growth, and the rate of growth. Such control allows accurate establishment of the parameters for the theory (1), which can be tested against direct measurement of the bubble size, the wall speed, and the pressure generated at the cone tip (Table 1). The tip is the effective centre of the collapse, and the geometry will allow sensors to measure not only the pressure, but also to measure via electrochemistry the mass flux and the erosive potential at the centre of the collapse. In addition, the rebound pressures in the liquid, and their propagation speeds close to the bubble wall, can be measured. Finally, sonoluminescence, and the fragmentation and coalescence of the bubble wall, can be monitored.

MATERIAL AND METHODS

The apparatus, and the protocol for use, are described in depth elsewhere (1,2). Essentially, an injected bubble is held by buoyancy at the apex of an otherwise liquid-filled

Experiment can control...	Theory can predict...	Sensors can measure...
Liquid inertia	Input	
Initial (pre-growth) size	Input	Yes
Rate of growth	Isothermal	
Pre-collapse (maximum) size	Input	Yes
	Predicts (adiabatic)	Wall speed during collapse
	Predicts (adiabatic)	Collapse pressure
		Electrochemistry (erosion/species)
		Luminescence
		Rebound pressures
		Fragmentation, coalescence

TABLE 1. The parameters which can be controlled and measured, and which the theory requires or predicts

conical hollow (of half-angle θ=30°). Milled from polymethylmethacrylate (PMMA), the hollow has a circular horizontal cross-section, 60 mm diameter at its base where it connects flush with a steel U-tube. Cone and tube contain degassed water. The length of the water column in the tube determines the inertia associated with the collapse (1,3). At equilibrium, under ~0.1 MPa static pressure, the gas pocket occupies the upper few millimetres of the cone. When the ambient pressure in the U-tube is reduced, the bubble slowly grows. On the sudden release of this partial vacuum, a pressure step propagates down the water column, and causes the bubble to collapse. A schematic of the apparatus is shown in Fig. 1*a*. The range of sensors which can be applied to the collapse is shown in Fig. 1*b*. Details of the transducers, cameras, and light detectors can be found in the literature (1,4).

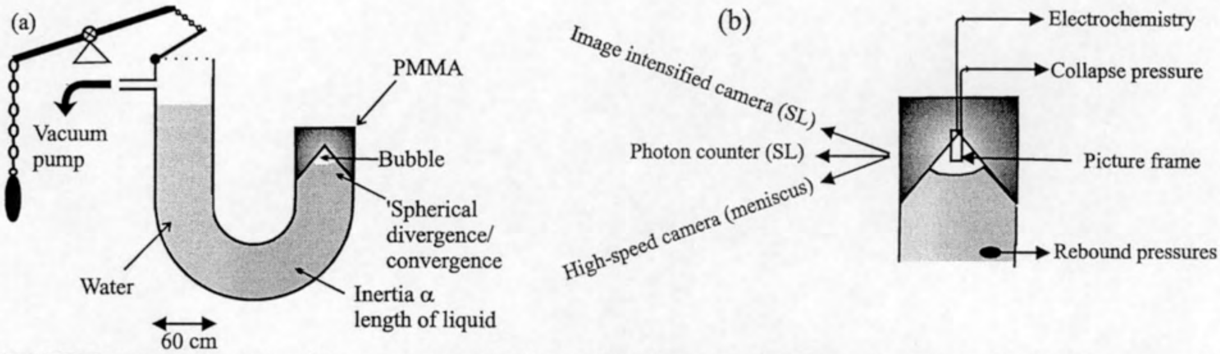

FIGURE 1. (*a*) Schematic of the apparatus. (*b*) The PMMA from which the cone is milled, showing the range of sensors deployed to measure the collapse. The 4 mm × 34 mm box indicates the section which forms the individual frames in Fig. 2.

RESULTS

Figure 2 shows a selection of frames, filmed at 6000 s^{-1}. The cone apex is visible near the top of each frame, the location of which is shown in Fig. 1*b*. Figure 3 shows the simultaneous hydrophone record of the pressure in the liquid, measured 10 cm below the cone apex. Time t=0 corresponds to a trigger signal which causes a single 12 μs flash (which appears as a horizontal line, arrowed in frame 5 of Fig. 2). Having thus synchronised the photographic and pressure records, features can be compared. The collapsing meniscus can be seen entering from the left in frame 232. From the gradient of its path until frame 240, the wall speed during collapse can be measured to be 9±2 m/s, and compared with theory (4). The first collapse ends in frame 243 of Fig. 2 (t=39.7±0.2 ms). This emits a rebound pressure wave which, after propagating 100 mm, is detected by the hydrophone at t=40.7±0.3 ms ('A' in Fig. 3).

Comparison of pairs of timing such as these allows estimation of the spatially averaged propagation speed of the pulse in the liquid between the bubble wall and the hydrophone[4] (here, 100±40 m/s, if the pulse is assumed to leave the bubble wall at the moment of rebound). This can be done for the subsequent rebounds (pressure signals B-D, damping to low amplitude pulsation of the surviving bubble). The meniscus fragments, filling the liquid with small bubbles as the main bubble collapses inwards again (these can be seen mid-frame in frames 290-302). When the bubble rebounds following its second collapse, these disappear as the cone fills with the gas of the expanding main bubbles (frames 304-326).

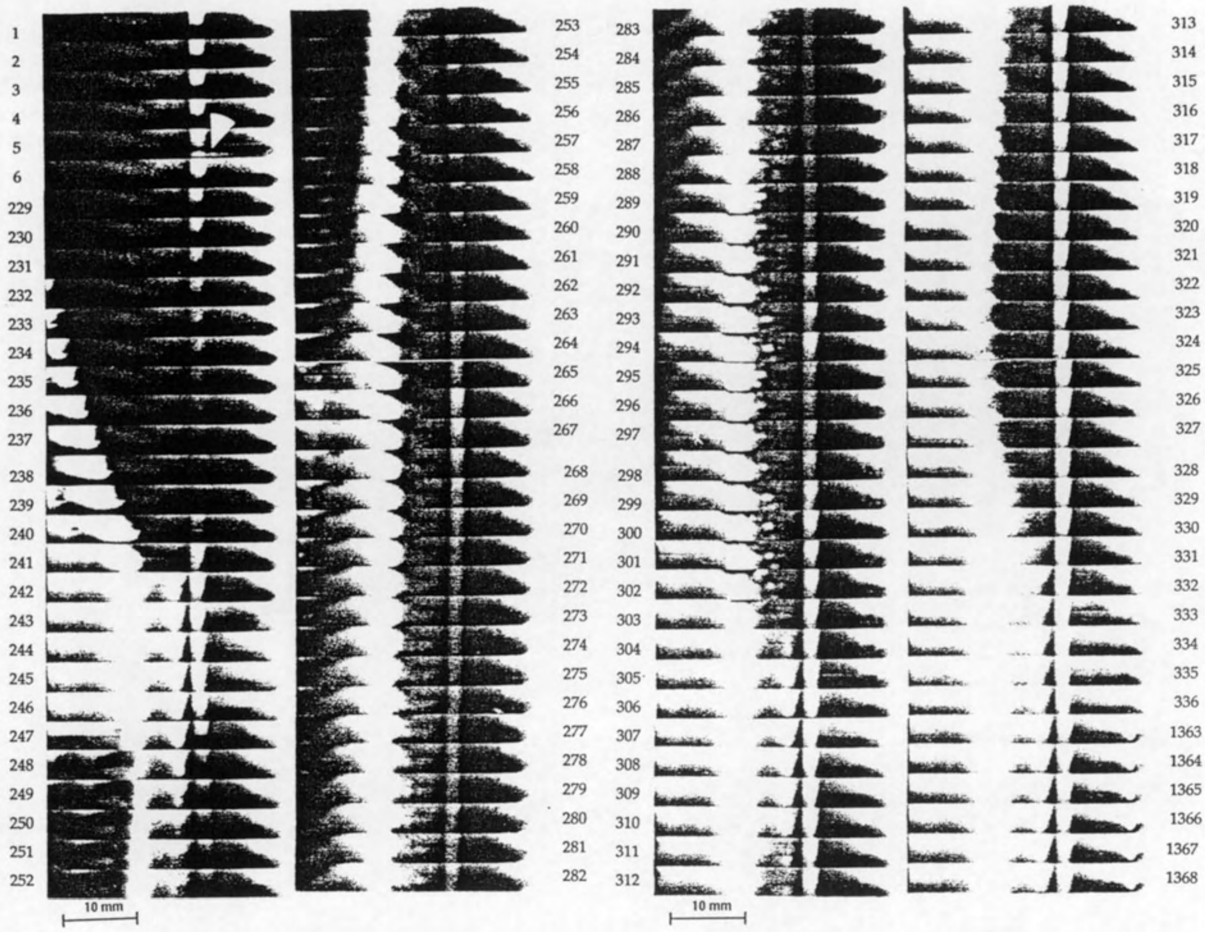

FIGURE 2. A selection of frames from a consecutive sequence, filmed at 6000 f.p.s.. Each frame occupies the 4 mm-wide region indicated in Fig. 1*b*., rotated by 90°. Hence the cone tip can be seen as a dark shadow in the lower right of each frame. Just prior to collapse, the meniscus was R_i =60±5 mm from cone tip; after the collapse and subsequent bubble oscillation/fragmentation/coalescence features had ceased, there was a spherical bubble of diameter 1.7±0.05 mm (=$2R_f$) remaining close to cone tip. The device contained 1050 ml degassed water (h_i=37.1 cm). (Symbols relate to theory of Leighton *et al.* (1)).

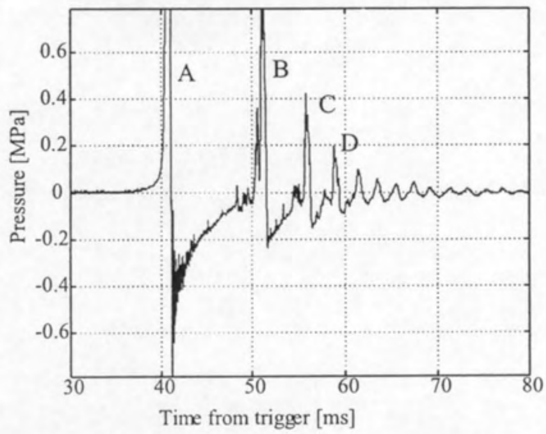

FIGURE 3. Plot of the hydrophone signal (triggered at t=0) recorded 10 cm below the cone apex for the collapse filmed in Fig. 2. Rebound pressure emissions are labelled.

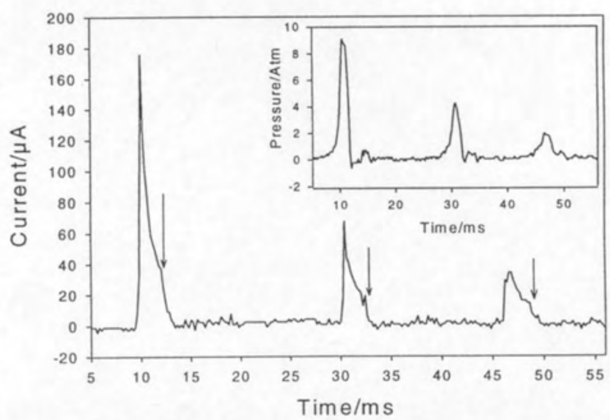

FIGURE 4. Simultaneous current and pressure profiles. Working electrode: stainless steel and frame acting as the CE/RE. Electrode potential held at 0.25V. Solution: 0.1 mol dm^{-3} KNO_3 (room temperature).

Figure 4 shows the simultaneous rebound pressure and current (taken to relate to the reformation of an oxide layer at the cone tip following its removal by the erosive collapse). However, the re-oxidation signal is interrupted by the re-expansion of the bubble (arrowed in Fig. 4). This essentially isolates the working electrode from the reference/counter: the cell resistance rises, dramatically reducing the applied potential and essentially stopping the re-oxidation reaction. Changing target can reduce this effect. Figure 5 shows the re-oxidation current observed for an aluminium target and the simultaneous liquid pressure. The re-oxidation current was mainly associated with the first collapse of the bubble. However, Fig. 5 shows that more than one re-oxidation transient (A and B) can be observed.

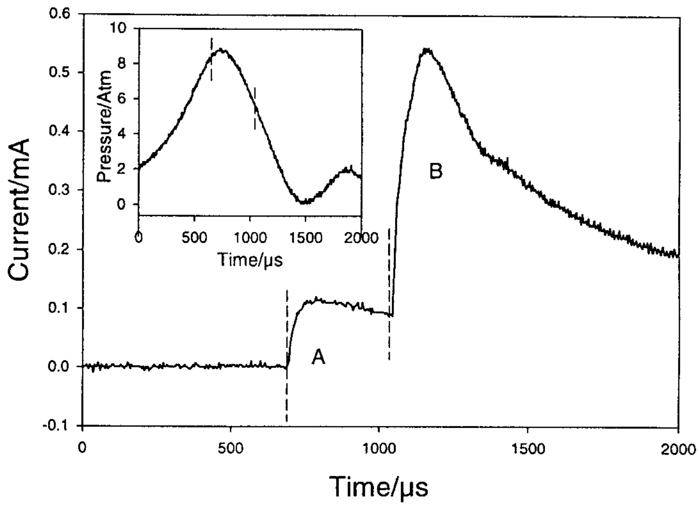

FIGURE 5. Simultaneous current and pressure profiles, showing two erosion events. The potential of the aluminium was held at +0.75V vs. the steel body RE/CE. The bubble was grown from *Rc*=10 mm to 36 mm before collapse. The dotted lines on both plots indicate times of electrochemical events, taking into account propagation time of pulse to hydrophone.

CONCLUSIONS

The apparatus produces inertial collapse of a gas pocket. The bubble size prior to growth, the size prior to the first collapse, and the inertia associated with the collapse, can all be readily controlled. The liquid and gas pressures can be monitored, and measurements made of the gas chemistry and luminescence. Photography allows measurement of wall collapse speeds, fragmentation and re-coalescence, and estimation of the sound speed close to the bubble wall. Although the theory assumes adiabatic behaviour during collapse, the predictions are in agreement with high-speed photographic observations of the collapsing meniscus, and with the output of pressure transducers. That is not to say that the theory models the collapse with high accuracy, but only that there is agreement within the limits of the observations.

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