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Shock-induced collapse and luminescence by cavities

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Recent observations of the collapse of single bubbles or clouds of cavities trapped within stationary acoustic fields have shown the production of light and these phenomena have been dubbed single- or multiple-bubble sonoluminescence. The experimental observation of the variations in the bubble radius with time, with simultaneous measurement of the light emission from the bubble, shows short pulses of light correlated closely with the point of minimum radius of the bubble. Results will be presented showing experimental observations of light produced from shock-collapsed cavities. The role of shock waves generated within the bubble by the motion of the walls will be discussed with application to the shock-wave hypothesis proposed as one of the mechanisms responsible for sonoluminescence. The likely asymmetry of the process, as recently proposed, and the consequent presence of a high-velocity jet will also be discussed. The effect of such 'hot' cavities within an explosive matrix is investigated and results are presented. The collapse of a single bubble shows that light emission from the explosive matrix is due to reaction caused by hydrodynamic heating by jet impact, *not* due to conduction from heated gas during compression. Similar results are seen in arrays of collapsing cavities. The effects of close, inert particles are discussed and an example is given.

Keywords: bubble collapse; explosive ignition; high-speed camera; sonoluminescence; high-speed jet

1. Introduction

The collapse of single bubbles in liquids has been studied experimentally and theoretically since the end of the last century. The problems of cavitation erosion of ship propellers and fluid machinery resulted in discussion of the role of liquid jets and symmetric collapse by several workers (Cook 1928; Kornfeld & Suvorov 1944). Calculations have highlighted the asymmetric nature of collapse in the case of close rigid or compliant boundaries. These boundaries are not found in single-bubble sonoluminescence (SBSL) experiments where the bubble is held stationary at the centre of a quartz sphere, although stable sonoluminescence (SL) has been reported from bubbles that have migrated from the centre of the cells to the flask walls where they still oscillate in a stable manner and produce light. It is not known precisely where these bubbles sit relative to the wall, but if they were within a few radii then asymmetric collapse would be an inevitability. In their classic study, Benjamin & Ellis (1966) showed that the presence of gravity was enough to induce asymmetry

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in the collapse and that this results in a jet which crosses the cavity and penetrates the rear wall. Such asymmetry has been suggested to be a feature of some of the SBSL experiments (Prosperetti 1997). The asymmetric collapse can also be induced by perturbing one wall of the cavity by sweeping it with a shock wave, so involuting one wall into a jet which crosses the cavity at constant speed and penetrates the rear wall. Such experiments have been reported previously from this laboratory and some single-bubble luminescence will be elaborated below. A feature of the process is that light is always emitted.

The voids present in commercial explosives have long been recognized as a sensitizing agent to shock. The role of bubble collapse was first systematically investigated by Bowden & Yoffe (1952). They ascribed the thermal ignition of the reacting fluid containing the cavity to the adiabatic temperature achieved by trapped gas during the collapse of the cavity. Chaudhri & Field (1974) and Starkenberg (1981) found that heating was the dominant ignition mechanism in situations where large cavities collapsed relatively slowly. Others (Kornfeld & Suvorov 1944) emphasized the role of jet formation in the collapse of bubbles in shock situations but it was photographic work (Benjamin & Ellis 1966) that established these processes. The theoretical effects concerning the role of cavities in explosive ignition and initiation have been reviewed (Frey 1985) yet despite these efforts, the cavity still provides a threat to the safe storage or transport of energetic materials.

There have been several observations of the production of light from a collapsing bubble and also of emission from clouds of bubbles. These observations have been reported since the sixties but have lacked detailed study until recent advances in instrumentation (Walton & Reynolds 1984). Particular interest has been generated by the series of carefully controlled and well-instrumented experiments conducted by Putterman and co-workers at UCLA (Barber *et al*. 1997) from isolated single bubbles. Some features of single-bubble luminescence include observations that relate to the hydrodynamics of the process on the one hand, and to the light itself on the other. A partial review of these categories is presented below.

One of several curious aspects of the phenomenon relates to the small range of parameters within which stable light emission occurs. One of the consequences of this is that, to date, only bubbles with diameters in the range 5–50 μm have exhibited the phenomenon. This fact alone has meant that experimental techniques of high sophistication need to be employed to acquire meaningful data. In particular, the interior of the bubble, which at minimum radius is submicron in diameter, cannot be observed, which means that the position of the source of the light cannot be determined. The dearth of knowledge concerning the bubble-wall shape and details of the gas within have lead to a series of hypotheses as to conditions within the bubble and mechanisms of light production, which will be summarized later. A common feature of these theories is that very few observable consequences may be deduced from them which has kept alive a lively debate.

The observations of the radius histories obtained from Mie scattering experiments indicate that a mode-locking mechanism comes into operation over several periods of the driving field. Light production does not occur, or occurs only weakly in the initial stages but reaches its full intensity when the locked state is attained. In this regime the light is produced within 0.5 ns of the point at which the bubble attains minimum radius and the pulse has a duration of less than 50 ps. The repeatability of the collapse and the production of the flash is also remarkable, having a jitter

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of within 50 ps. The stability of the driving oscillatory field is good in the UCLA experiments and the resultant Q of the bubble is thus of the order of 1000 for their system (Barber *et al*. 1994). The bubble wall achieves radial velocities of the order of 1200 m s^{-1} in the final moments of the collapse (Weninger *et al*. 1996).

Measurements of the spectral content of the light, from a series of these experiments conducted upon a range of gases contained within the bubble, yield featureless spectra (at 1 nm resolution) of varying amplitude according to gas type. In some cases (such as a gas bubble in D_2O) the spectra show a maxima but in others there is only a rising edge (Hiller & Putterman 1995). Black-body, bremsstrahlung or other radiation mechanisms have been assumed in order that some estimates of the gas temperature at the moment of light emission can be made. In general these yield results of the order of 10^4 K (Moss *et al*. 1996). Some effort has been expended in striving for even greater resolution of wavelength in order that some evidence of structure might be obtained. These experiments have as yet only confirmed the flat nature of the spectra. A feature of the measured sphericity of the radiation is a small dipolar term which may result from slight ellipticity in the bubble wall or from asymmetry introduced by jetting.

The stable SBSL described above has only been observed with rare gases present within the bubble. It is found that the light output increases through the series He, Ne, Ar, Xe, and that the intensity is independent of the concentration of rare gas in the bubble. The addition of various alcohols to the liquid can cause variations in the intensity of the light or complete extinction of the emission. Such observations have suggested to some that the bubble wall must play a role in the process.

The liquid medium in which the bubble sits also influences the light-output processes. In particular it seems that only water supports SL (Weninger *et al*. 1995) with all noble gases in the gas bubble. Dodecane supports emission with only Xe within the cavity. This is further evidence of either the role of vapour or of the fluid surface in the light-emission mechanism.

Light emission from clouds of cavities has different properties, and the collapse of a bubble in a cavity cloud is clearly different from the oscillatory system of the UCLA work. In particular, the spectra show structure, and normal spectroscopic techniques can be used to make reliable estimates of temperature. Suslick and co-workers (Zakin *et al*. 1996) have, for instance, shown temperatures of the order of 5000 K for solutions of metal carbonyls, which agree with calculations of temperature (Yuan & Prosperetti 1997). It is useful to consider the differences between single-cavity collapses and collapses in clouds of bubbles in order to differentiate between the emission processes of SBSL and multiple-bubble sonoluminescence (MBSL).

There have been several attempts to construct a model for the SL process and a variety of suggestions have emerged, principally due to the paucity of some experimental details at the smallest bubble diameter in the SBSL case. The most widely discussed of these models is the shock-wave model which has been used to generate extremely high estimates of the temperature in the bubble; of the order of 10^6 K and above (Moss *et al*. 1996). It is important in such calculations to adequately ascribe an equation of state for liquid and gas under these extreme conditions and also to correctly incorporate the hydrodynamics of the bubble-wall motion. The vast majority of these calculations have assumed spherical symmetry throughout the collapse process and in consequence most model a single spherical shock wave launched towards the bubble centre. In some of its details this description is incorrect and

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when one considers those simulations which additionally incorporate inappropriate equations of state, one is left with little that can be plausibly considered as being adequate in any quantitative way. The second hypothesis for SBSL, that of asymmetric collapse, has not been fully modelled to include both the bubble-wall motion and the shocks within. However, Prosperetti (1997) has considered the effects of jet impingement upon the rear surface of the bubble and uses the concepts of 'fracture' of the liquid and solvation of rare-gas atoms into water as explanation for the light emission by fractoemission. Additionally Lepointmullie has hypothesized jet-breakup into droplets, charge separation and subsequent electrical discharge as being responsible for light emission (Lepointmullie *et al*. 1996). An entirely separate explanation for the phenomenon has recently been proposed (Eberlein 1996). This mechanism is based upon quantum electrodynamics and results in the emission of light from the creation of pairs of antiphase photons by the Casimir effect. The phenomenon is relativistic and the mechanism thus requires bubble-wall velocities that are a substantial fraction of the speed of light. Since the mechanism has no basis in bubble dynamics and the theory relies on non-physical values for wall velocities, it will not be further discussed here.

While the bubble-mechanics community have considered single- and multibubble luminescence a rare phenomenon, it is well known in other areas of shock-wave research. The nature of luminescence in these disparate fields is in general poorly understood since the emission has not been considered important relative to the mechanical response or the thermodynamic state of the materials under investigation. Neither is the driving-pressure field oscillatory. However, some of the relevant experimental evidence will be presented below to illustrate some features of various emission processes observed in shock collapse, and emphasis will be placed on the common nature of the observations and upon features of SBSL and MBSL.

2. Experimental

The experiments described below were carried out in a two-dimensional geometry originally used initially to study liquid-drop impact in water (Brunton & Camus 1970; Camus 1971). This geometry allowed observations of jet deviation within the cavities. The technique was adapted to use gelatine sheets into which chosen cavity shapes were punched (Dear 1985). The method has been described elsewhere in more detail (Bourne 1989) and so only a brief description is presented here. The two-dimensional geometry allowed details of processes occurring within the cavity to be viewed during the collapse. The sheet was cast from a 12% by weight mixture of gelatine in water and was of thickness 3 mm and density 970 ± 50 kg m^{-3}. The prepared gel slab was then clamped between glass or polymethylmethacrylate (PMMA) blocks and spacers were butted against the free surfaces to prevent lateral releases from reducing shock pressure from the sides.

Plane shock waves were introduced into the sheets by the impact of a rectangular phosphor–bronze flyer plate of weight 5.5 g. The plate was fired down a rectangular bore gas gun. The flyer travelled at 150 m s^{-1} and induced a shock of pressure 0.26 GPa in the gel. The shock wave easily overcame the weak polymeric bonding in the gel, which flows in a manner indistinguishable from water.

In other experiments, an aquarium was adopted to index match the gelatine. It was given sufficiently large dimensions that the curvature of the shock front became

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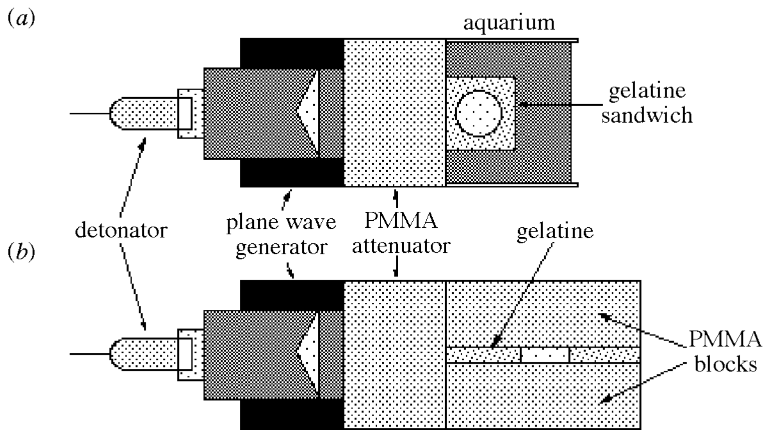

Figure 1. (a) Plane-wave generator with aquarium. The water impedance matches the fluid gelatine, avoiding the need for glass blocks which shatter, obscuring the experiment and destroying the confinement. (*b*) The experiment with transparent blocks cemented to the gap. Schlieren photography is used to image density variations. In other experiments a flying plate is used to introduce a shock.

important and masked some of the details occurring within the cavity. However, sequences showed clear evidence of jetting at high velocities. The shock was introduced using a plane-wave lens and a calibrated inert gap to separate explosive from aquarium. The experiment was carried out in a water-filled aquarium of dimensions $40 \times 40 \times 40\,\mathrm{mm}^3$. In a second geometry, the gelatine sheet with punched bubble is sandwiched between two further sheets, isolating a disc-shaped cavity of depth 3 mm and diameter 6 mm. The experimental configurations are shown in figure 1. The wave was not completely planar as it exited the PMMA gap and so the collapse was observed from the side through a curved shock front. This distorted certain details of the collapse.

The two-dimensional collapse of a cavity in an emulsion explosive was attempted using the same experimental arrangement as that used for the gelatine configurations described earlier (figure 1*b*). A 3 mm thick layer of an emulsion explosive of composition described in table 1 was contained between two 25 mm thick PMMA blocks. PMMA spacers were placed against the free emulsion surfaces to prevent any attenuation of the shock by releases. Cavities were introduced by punching holes in the sheet in a similar way to the gelatine sheets. The complete assembly was bonded with PMMA cement to a plane-wave generator. High-speed framing photography at microsecond framing rates recorded the light emitted by the ignited sites. No external lighting was used except where stated.

The interaction of the shock with the cavities was photographed using Hadland Imacons 790 and 792 at framing-rates ranging from 2×10^5 to 5×10^6 frames per second and streak rates from 200 ns to 1 μs mm^{-1}. Shocks were visualized using a two-mirror schlieren apparatus. The flash source employed was a QArc Xenon QCA5 tube which delivered 100 J in *ca.* 100 μs. The flash and camera were triggered from a Hadland three-channel delay generator by the flyer-plate cutting an infrared beam at the end of the gun barrel in the first series of experiments, and by light emitted from the detonator in the second.

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Table 1. *Composition of emulsion explosive*

component	weight %
ammonium nitrate (AN)	66.71
sodium nitrate (SN)	13.34
water	11.34
oil (various)	2.28
waxes	3.87

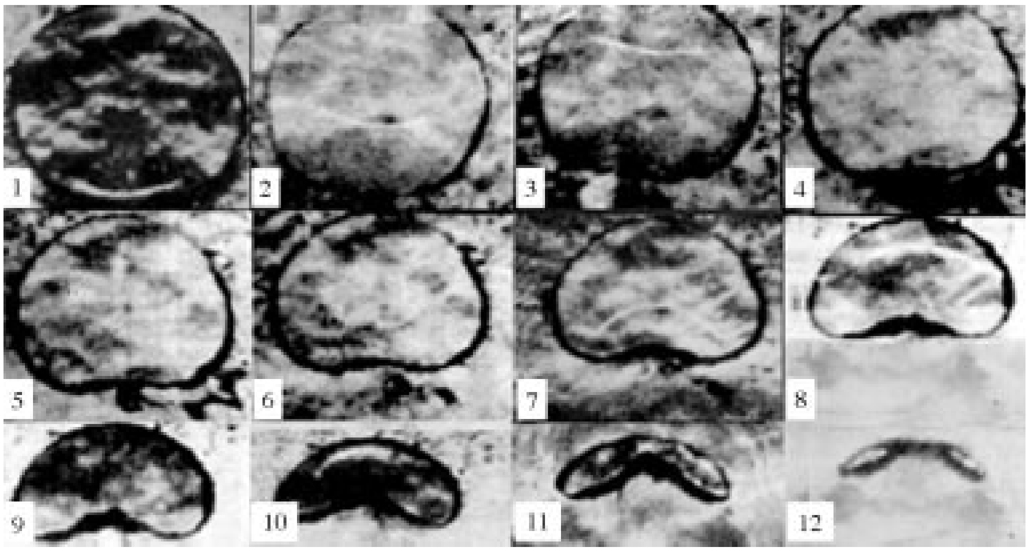

Figure 2. Twelve frames taken from several sequences showing the collapse of a 12 mm diameter air-filled cavity by a 0.26 GPa shock. The cavity is punched into a gelatine sheet which is impacted from beneath to introduce the shock. Schlieren visualization is used to see the shock in the gas. The frames are 10 μs apart.

3. Results and discussion

Figure 2 shows a sequence in which a 12 mm disc cavity collapses in a gelatine matrix. The matrix has been impacted with a rectangular flyer and the calculated shock pressure (from the measured impact velocity) was 0.26 GPa. The sequence is made up from several experiments in which various timing delays were introduced to investigate different parts of the process. In the montage shown in the figure, each frame is 10 μs apart. The exposure time was 200 ns, which freezes the collapse details. The cavity initially contains air under standard conditions. The incident shock enters the first frame from below and is half the diameter up the cavity at the moment the frame was captured. The schlieren system was adjusted to have maximum sensitivity for waves running in the gas so that the shock in the liquid is seen less distinctly. Nevertheless, it is out of view by the second frame. The dappled appearance of the gas is believed to be disturbance caused by weak compression waves running ahead of the incident shock due to an air blast travelling in the gun ahead of the projectile that induced the shock.

An air shock, which appears as a white line, can be seen travelling through to

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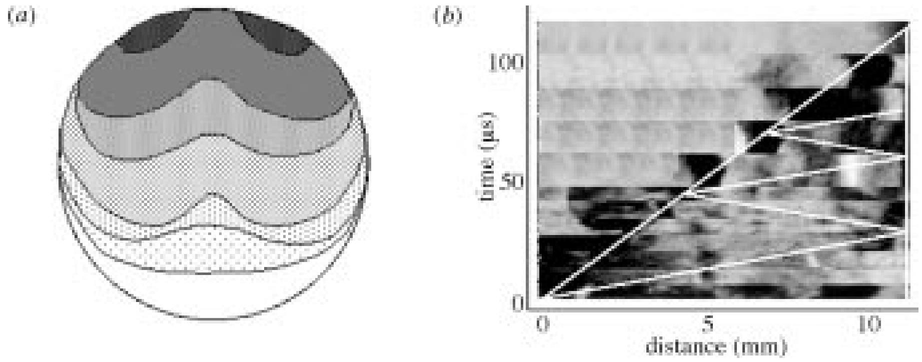

Figure 3. (*a*) Rear-wall positions are shown for the collapse of figure 2. (*b*) A distance–time diagram is constructed using central axis information taken from the images of figure 2. The rear surface and air shock are indicated by white lines superposed over the images.

reflection in frame 4. Its radius of curvature increases as it travels. This process is believed to result from compression waves travelling laterally from the confining cavity walls as the shock enters the converging downstream part of the cavity. After reflection in frame 4, the shock returns as a dark line since it refracts light from the front onto the knife edge of the optical system. It is thus more difficult to observe but, nevertheless, reflection by frame 7 has rendered it white once more, and the shock has assumed a shape influenced both by its initial conditions and the new deformed upstream wall shape from which it has reflected. Further reflections occur through the sequence, but by frame 10 the shock is strengthening rapidly as the walls approach one another.

The microjet begins to form as a sinusoidal instability visible in frame 2 and developing in amplitude by frame 3. By frame 4 it is of sufficiently large amplitude that a jet proper forms and travels across the cavity to impact the downstream wall between frames 11 and 12. The area around the impact site experiences high transient pressures of order 0.1 GPa at this time. Penetration of the jet into the downstream wall leads to the formation of two linear vortices, which further work has shown to travel off downstream in the flow. The jet impact isolates two lobes of trapped highly compressed gas visible in frame 12. These regions are those in which considerable heating occurs and it is from these that light emission is observed, as shown using image intensifiers at these pressures (Dear *et al*. 1988) and which may be seen directly with stronger collapsing shocks (see below). It is believed that the light emission is principally due to the adiabatic heating of the gas and that the shock temperatures achieved do not result in light emission visible with this apparatus.

Figure 3*a* shows the outer wall of the collapsing cavity of the previous figure and figure 3*b* shows an x–t plot for the collapse that is overlaid on parts of the sequence. Figure 3*a* shows the extremely smooth nature of the jet formation in large cavities and relatively low shock pressures. The form of the cavity wall is taken every other frame and it can be seen here that the wall has begun to involute 40 μs after impact. The jet proper crosses the cavity at a uniform velocity and penetrates to form the two isolated lobes seen at the downstream wall. In a real three-dimensional cavity, this structure would clearly be a toroidal cavity remnant containing the high-temperature adiabatically heated gas. In other work, the volume (and in this two-dimensional geometry, the area) of the disc-shaped cavity has also been shown to

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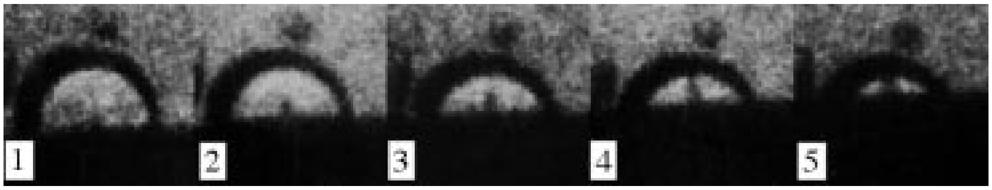

Figure 4. A high-speed jet travels across a 6 mm cavity under a 1.88 GPa shock from a plane-wave generator. The jet travels at *ca.* 5 km s^{-1}.

decrease linearly with time (Bourne & Field 1991). Figure 3*b* is formed by cutting strips from the central axis of each of the frames in the previous figure. The strips represent conditions down the central axis for each frame of the sequence and when stacked may be used to construct a distance–time diagram for this interaction. The shock in the liquid is not shown, as its velocity is orders of magnitude higher than other speeds considered. However, white lines have been superposed over the pictures to indicate the downstream and upstream wall positions as well as the shock within the gas. The downstream wall velocity is *ca.* 0.1 mm μs^{-1}, while the air shock waves travel at *ca.* 0.5 mm μs^{-1}. Clearly, the wall of the cavity travels at a lower speed than the particle velocity induced by the shock in this case.

The aquarium adopted to index match the gelatine was of sufficiently large dimensions that the curvature of the shock front became important and masked some of the details occurring within the cavity. However, some sequences show clear evidence of jetting at high velocities.

Figure 4 shows a jet moving at *ca.* 5 mm μs^{-1} across a 6 mm cavity. The incident shock pressure in the water was 1.88 GPa and the shock was introduced using an explosive plane-wave lens. Such 6 mm diameter cavities collapsed in *ca.* 3 and 2 μs at pressures of 1.88 and 3.49 GPa, respectively, and 12 mm cavities were found to take 7 μs at 1.88 GPa. This would indicate a jet velocity of *ca.* 1.7 mm μs^{-1}. Collapse times were not better resolved since the resolution of the measurement was limited to the framing rate of 1 μs and jets were masked by the shocks.

It is clear from figure 4 that jet impact in this case occurred at the downstream cavity wall before the incident shock had arrived at the same position. This resulted in a situation where the shock resulting from the impact will travelled ahead of the collapsing shock. Chaudhri *et al.* (1983) have observed a similar phenomenon when a 9.5 mm hollow aluminium sphere in water was collapsed with a strong shock from a pentaerythritol tetranitrate (PETN) charge. In figure 5, frame 1 of Chaudri *et al.* (1983), a hemispherical shock can be seen propagating ahead of the incident shock.

In the sequence of figure 2, the gas shock progressively gains strength through the sequence as the upstream and downstream walls approach one another and compressive waves travel inwards along the shock front from the rigid cavity sidewalls. This causes high shock temperatures, and, since the Mach number of the shock will not be uniform along its length, there will be variations in temperature across the front (Lesser & Finnstrom 1987; Leighton 1994). In the final stages of collapse, the shock front will have a highly non-uniform shape (see, for example, frame 7 of figure 2) and will make many transits, especially between the rapidly closing jet tip and the far cavity wall. In a violent collapse the jet velocity may sufficiently exceed the flow-particle velocity so that the gas may not be able to escape sideways into the lobes

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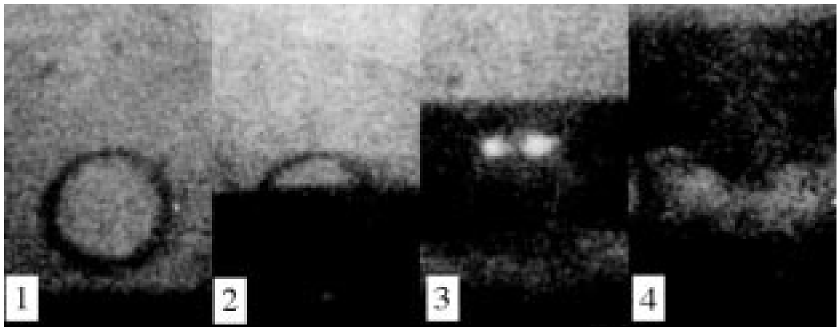

Figure 5. A 1.88 GPa shock wave interacts with a 6 mm cavity.
Luminescence is seen to occur in frame 3.

which form in frame 11, and a hot packet of gas will be trapped at the point of jet impact.

A sequence is shown in figure 5 in which a cavity collapses in gelatine. Four frames from the original sequence are reproduced in the figure. The interframe time is 2 µs. In frame 1 the bubble can be seen with the shock entering from below. In frame 2 the shock has travelled across over half of the cavity and collapse has started. In frame 3, the shock has obscured the entire area of the cavity. However, the shocked remnant and a reflected shock in the liquid are visible behind the shock front. Two bright areas of emitted light are visible. In frame 4 the collapse has been completed and the rebound shock is visible moving into the fluid and centred on the jet impact site. The observed collapse gives a jet velocity of *ca.* 2 mm μs^{-1}, which is similar to the 12 mm cavity jet velocity calculated above. The dark band of material appearing from the bottom of frame 4 is spalled PMMA from the plane-wave lens. Luminescence was also observed from 3 and 12 mm cavities collapsed under the same shock regimes. When the shock pressure was reduced to 0.49 GPa, no luminescence was observed with camera apertures adjusted for a Xe flash. The two flashes originate from the two isolated lobes of gas discussed earlier and correlate in position with these.

The same experiment was repeated at a higher framing rate and the results are presented in figure 6*a*. The interframe time is 0.2 µs and the exposure time is 40 ns per frame. In frame 2, a single flash of light is observed. In frame 3, this is not seen. However, indeterminate structure can be observed in a similar region. In frame 4, two less-bright regions are seen. In figure 6*b*, the positions of the flashes of light are shown schematically in relation to the original position of the cavity wall. Analysis of the position of the light flashes indicates that the bright flash, J, observed initially, is positioned midway between those observed in frame 4. The source of this initial luminescence is believed to be the violent shock heating of a pocket of gas trapped between the jet and the far cavity wall at the moment before impact. The jet then impacts and as the lobes, L, are isolated and compressed the gas pockets in frame 4 begin to luminesce. The duration of temperatures sufficient to cause gas luminescence can be estimated to be about a microsecond.

SL from cavities created by acoustic fields has been discussed by many authors (for a review see Leighton 1994). For water a continuum spectrum of wavelengths shifted to the blue has been observed. The spectral-intensity distribution can be fitted to that of a black-body radiator with a colour temperature of 8800 K (Dear *et al.* 1988). The postulated mechanisms by which the luminescence occurs are radiation from

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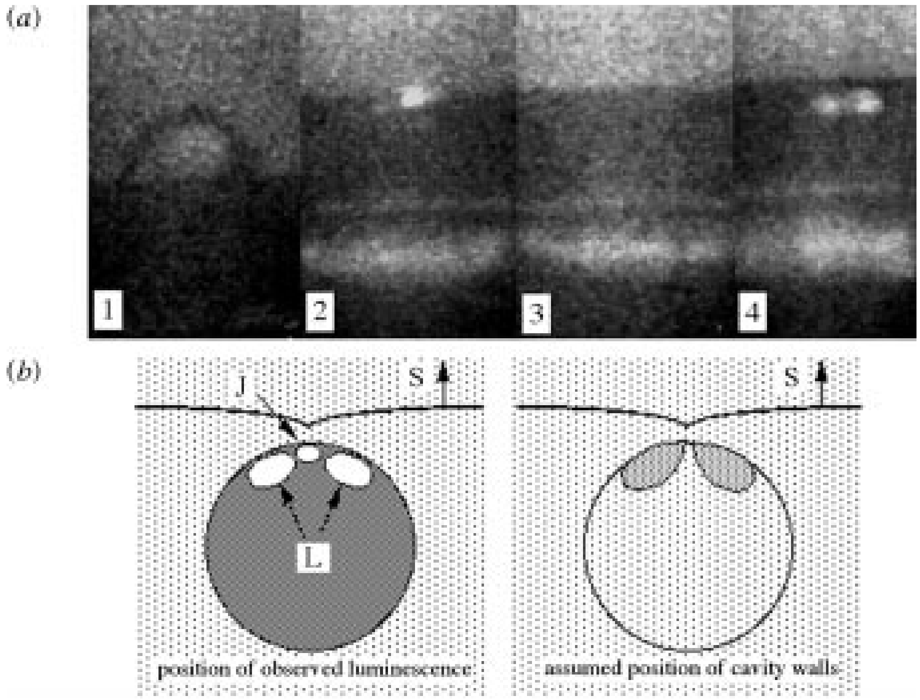

Figure 6. (a) The luminescence event of figure 5 is seen in more detail. Frame 1 is halfway through collapse. Frames 2–4 are taken at jet impact and are sequential and 200 ns apart. The luminescence occurs only here and is observed to consist of two events J and L, defined in the schematic figure (b). The sequence is taken with an Imacon 790 and uses schlieren photography.

the thermally excited ionized contents, or chemiluminescence arising from reaction involving photons. These reaction steps might include recombination of radicals, for instance

$$OH^{\bullet} + H^{\bullet} \rightarrow H_2O + h\nu. \quad (3.1)$$

Many other such schemes are possible but insufficient evidence has been presented as yet to determine the processes occurring exactly. Some workers (Dear *et al.* 1988) attributed the luminescence (observed in 3 mm collapsing cavities in gelatine using an image intensifier to time average the light emission) to 'free-radical creation and radiative recombination', which is presumably a similar mechanism to that discussed above.

Frey (1985) presents a model in which initiation of a solid explosive occurs by single-cavity collapse. His work is based on an early analysis (Carroll & Holt 1972) of the collapse of a cavity in an incompressible elastic–plastic medium. He identifies several contributions to temperature rise in the explosive. Assuming, in the most general case, that a gas-filled cavity is situated in a material with elastic–plastic behaviour, then the following contributors to temperature rise may be identified:

(i) gas-phase heating;

(ii) hydrodynamic effects resulting from the compressibility of the material;

(iii) inviscid plastic work done overcoming the yield strength of the material; and

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(iv) viscoplastic work depending on the viscosity of the material.

The results of Frey's model show various features of the collapse process. Hydrodynamic heating will be significant when the strength or viscosity of the medium is insufficient to prevent the radial collapse from being violent enough to cause high-speed jetting. In the symmetric case, very high radial velocities will increase temperatures. Viscous heating will dominate over that generated by inviscid–plastic work in several circumstances. However, viscous heating is usually limited since as temperature increases the viscosity decreases, thus reducing the importance of these mechanisms.

The strong dependence on initial radius results in heat dissipation away from the collapse site being negligible for all save the smallest cavities. For cavities greater than 1 μm in diameter the collapse will be complete before conduction effects begin to operate and thus the gas will not have had any chance to significantly heat the surrounding matrix. Initial gas pressure and subsequent pressurization is important only when collapse can occur without solid deformation. This will be the case in many liquid systems and in specialized situations, for instance when the gas trapped at the end of an artillery shell is compressed (Starkenberg 1981). In a similar model, Butler *et al*. (1989) add the chemical decomposition of the material of the void to a Carroll & Holt (1972) analysis. This results in a rapid radial deceleration of the walls due to the pressure of the gases in the void produced by decomposition. Temperature at the gas–explosive interface can rise to 1000 K before thermal runaway occurs in the gas phase.

In light of the above, it is not surprising that workers ascribe many different mechanisms to initiation in their systems. Mader's work for small cavities in nitromethane (Mader *et al*. 1967) can be explained in terms of a primarily hydrodynamic model, while that of Chaudhri & Field (1974) (where large cavities are placed in a low-viscosity liquid against single crystals of a primary explosive of high thermal conductivity) can be regarded as a gas-heating ignition. Ignition in shocked large cavities can thus be assumed to be the result of hydrodynamic heating in the jet-impact area and adiabatic heating from the compressed gas. These assumptions are based on the high-pressurization rate produced by the plane-wave generator, the large cavity dimensions and the absence of any strength and low viscosity in our matrix material.

Cavity collapse may occur in fluids containing other particles of varying impedance. In explosives it is possible to add aluminium particles to aid reaction next to ignition sites produced by collapsing cavities. The presence of varying impedance-partners affects the collapse and the subsequent temperature that the cavities will attain. An example is shown in figure 7 where the collapse of a 3 mm cavity placed downstream of a 3 mm lead disc is shown.

In this configuration the particle shields the cavity from the incident shock, resulting in markedly reduced collapse times and jet velocities. A 0.26 GPa shock is introduced by a flyer plate and enters each frame from below. The interframe time for the sequence of figure 7*a* is 2 μs. The incident shock, *S*, has entered in frame 1 and can be seen diffracted around the particle. A reflected compressive shock, *C*, can also be seen. In frame 3 the release from the cavity can just be seen in the fluid upstream of the cavity. From frame 2 onwards, a darkened area is seen to develop at the downstream stagnation point of the cylinder. This emits a wave, starting in frame 4, which propagates outward through frames 5 and 6. There is seen to be some structure (see the left-hand edge) at the wavefront. The dark speckled areas seen in

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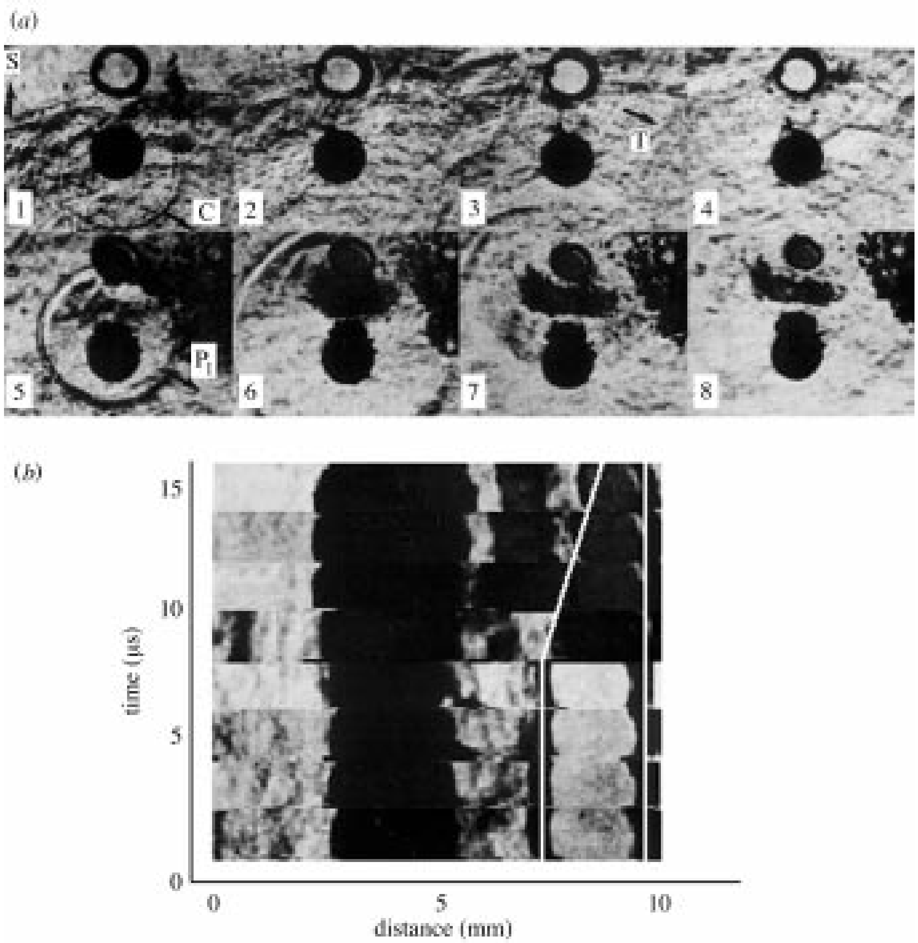

Figure 7. A 3 mm cavity placed downstream of a 3 mm lead disc collapses under a 0.26 GPa shock. The shock comes from below and the interframe time is 2 μs: (*a*) the framing sequence is shown with the shock indicated as S, the compressive and tensile shock reflections as C and T and a wave travelling in the confining blocks as P_1; (*b*) an x–t diagram for the collapse along the central axis.

the right-hand portion of frame 5 are regions relieved by a release wave from the free gel slab surface.

The speckled appearance of this dark region may be due to small cavities formed at the fluid–glass interface. This disappears as the wave runs across this area. It will also be noticed that the wave is not apparently diffracted by the lead disc as one would expect for a bulk wave. It is thus thought that this wave runs at the interface between the fluid and confining blocks and that the energy in the wave is associated with the shedding of vortices from the downstream portion of the particle. Such waves can be regarded as a consequence of the pseudo-two-dimensionality of the experimental configuration.

The region of relieved pressure between cavity and particle can be seen as a dark area in frames 6–8. The structure apparent is an indication of the turbulent nature

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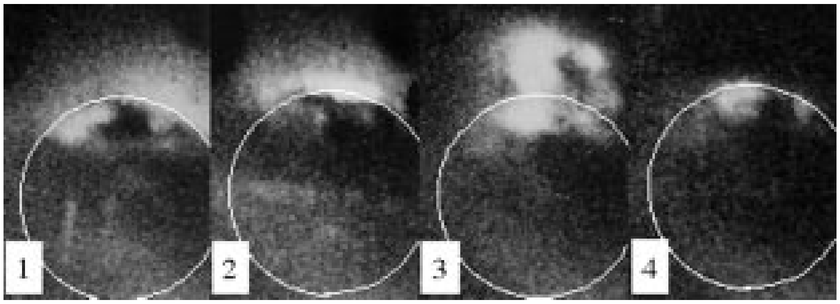

Figure 8. The collapse and reaction of an 8 mm cavity punched into a sheet of emulsion explosive. The shock pressure is 5 GPa and the interframe time is 1 μs.

of the flow behind the shock (each variation in intensity is a variation in refractive index in the medium). It should be noted that the dark areas of stagnation present in these gelatine experiments have also been observed under the same experimental conditions using tap water as the surrounding fluid.

Figure 7*b* shows a streak sequence constructed as before by stacking images down the central axis of the impact. The lead disc can clearly be seen as a dark rectangle to the left-hand side, whereas the cavity is seen on the right-hand side. The collapse is delayed by 6 μs by the presence of the lead disc. Further, the movement of the downstream cavity wall is slowed to *ca.* 0.15 mm μs^{-1}. The lead particle shows an expansion in the size of the dark region. This is due to the flow behind the shock around the disc, which results in the formation of a stagnation point and the shedding of a vortex from the downstream flow between cavity and disc.

The slowing of the collapse in this manner is likely to reduce ambient temperatures in the contained cavity gases. It should be noted, however, that an equivalent geometry has been studied in which the shock was allowed to run over the cavity first. In this geometry it is possible to achieve a shorter collapse than in the isolated cavity, as the lead particle reflects some of the shock back to the upstream wall resulting in the acceleration of both walls towards one another. In complex geometries, light emission will be greater than an isolated cavity in the latter case and reduced in the former. Thus, real fluids with particles within may be expected to contain a range of geometries and thus a range of light emission levels. The results of several of these collapses have been contrasted and presented elsewhere (Bourne & Field 1992). In the limit of concentration reducing to the point that the cavity/particle distance is such that the time for a particle to communicate its presence becomes greater than the collapse time, then cavities will behave as in the isolated case.

The collapse times and jet-impact pressures associated with the shocks introduced by explosives and discussed above were 5 and 8 GPa. This produces collapse times of the order of 2–3 μs in an inert medium, and jet velocities of 5–6 km s^{-1}. This would imply transient jet-impact pressures of 4–5 GPa lasting for approximately half a microsecond. It is of interest to gauge the effect that such a shock and such a cavity-collapse jet impact might have upon an array of cavities placed in an explosive medium. To this end, cavities were collapsed in the emulsion explosive matrix described above. Shocks were introduced with explosive plane-wave lenses. The emulsion was opaque and so no flash-lighting was used; any light picked up by the camera was due to emission from reacting emulsion in the visible range. The emulsion was

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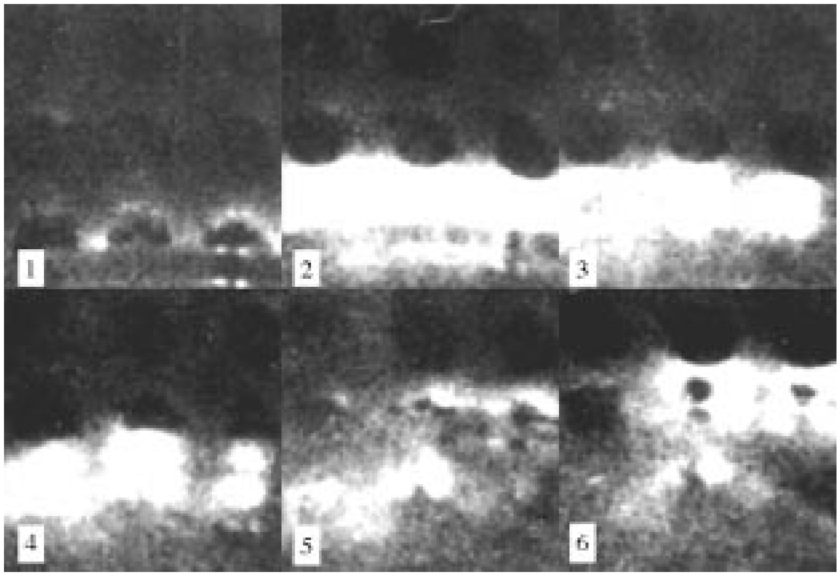

Figure 9. The collapse of a rectangular array of nine 5 mm cavities in an unsensitized emulsion. The incident shock starts collapse of the first cavity row in frame 1 and jet impact occurs between frames 1 and 2. The material downstream of the first row ignites in frame 2 and these sites persist for 3–4 μs, convecting in the flow behind the shock up to frame 6. The sites are found in material ahead of the shock. The interframe time is 2 μs.

sufficiently insensitive that the same material, shocked without the addition of cavities, produced no reaction behind the shock front.

Figure 8 shows the collapse of an 8 mm diameter air-filled cavity subject to a shock of 5 GPa. The interframe time is 1 μs. The shock enters frame 1 from below and runs up the frames. The position of the cavity wall is indicated by a white line drawn over the frame. The shock is over halfway across the cavity in the first frame and the jet crossing the cavity can be seen as a dark pointed region about to hit the cavity wall. There is emission of light from the trapped lobes of gas on either side of this jet, with the lobe to the left having the brighter appearance. It is not clear whether material is reacting to produce this light or whether this is further indication of luminescence from trapped gas, as seen in figures 5 and 6. Certainly, the gas will contain an explosive vapour which will favour reaction, and, additionally, it is likely that its temperature will have exceeded the ignition threshold for this material. There is, however, less light emitted from the explosive itself in this first frame. On the right-hand side of the jet-impact zone there is more light output, suggesting that bulk reaction may be starting. The light output is correlated with the heat conduction into the matrix from the heated gas across the cavity wall since light emission dies away with distance from here.

In frame 2, the jet-impact zone (which is at the highest pressure) shows the brightest light output. This indicates the strong role of the shock heating that must occur at this point in accelerating reaction. In frame 3, the reaction spreads back into the material, filling the now-closed cavity and into the material ahead of the downstream wall. By frame 4, the reaction has reduced but remains strongest around the jet-impact site. The matrix reacts but does not liberate energy sufficiently to ensure

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that the reaction spreads. Thus detonation conditions are not satisfied by such a cavity. Nevertheless, the conditions are similar to cavity-induced hotspots close to critical conditions.

Similar features can be observed in the interactions of shock waves with a rectangular array, which is presented in figure 9. An array of nine 5 mm cavities is collapsed with a 5 GPa shock. Again these cavities are air-filled. The interframe time is 2 μs. In figure 9, the shock can be seen entering frame 1 from the bottom. The cavity on the right of the first row shows two points of light on the shock front. These are the refracted images of two reacting sites, or of compression of hot gas around the jet (as in figure 5). Note that there is a second shock with the same pair of bright spots behind the main shock. This is a release running from the point at which that part of the main shock that runs in the confining PMMA blocks meets the free surface. The material ahead of the point of jet impact reacts in frame 2 and the sites persist until frame 6. Clearly, the main reaction sites are within the bulk explosive between cavity sites and not in vapour within the cavities, and there is also cooperative burning from adjacent sites not seen for the isolated cavity of the previous figure. The sites appear characteristically kidney-shaped. The second row is nearing the end of collapse in frame 5 and by this time the second row is approaching the end of its collapse. The main shock has left the array by this stage, since in arrays of cavities the collapse of downstream rows is controlled by the collapse of the first row and the shocks sent out as they close (Bourne & Field 1991). Reaction is beginning in the most central cavities by frame 5 at the jet-impact site. In frame 6 the sites grow in the central and right-hand cavities. The lifetime of the sites in such an array is *ca.* 8 μs. However, the life of reaction sites may be limited by a high void-concentration, which reduces the quantity of fuel available at the jet tip.

4. Conclusions

The collapse of single cavities and arrays of cavities subject to impacts from induced shock waves has been presented for a range of cavity sizes, shock pressures and reactive and non-reactive media. In order to study processes occurring within the cavity during this process, the three-dimensional cavities were simulated by discs cut from a thin gelatine sheet that was shocked by impact from a projectile from a gas gun or by shocking using an explosive plane-wave lens. Such sheets were confined by clamping them between thick transparent blocks so that a two-dimensional collapse was approximated. The cavities collapsed in all cases by involution of the upstream wall to form a jet which crossed the cavity and impacted the downstream wall. At this point a high pressure was generated in the surrounding matrix. The jet velocity depended in a nonlinear manner upon the shock pressure and the cavity diameter. Previous work (Dear *et al*. 1988) has shown, using image intensifiers, that even at relatively low shock pressures, photons are emitted during collapse. At some of the pressures used in this work, light emission exceeded that transmitted through the transparent medium from the high-power flash used in these experiments. The mechanism may be related to the SL observed recently by other workers although the cavity collapse is more violent here.

Additionally, high temperatures in the gas contained within the cavity lead to heat conduction into the surrounding fluid which, if potentially reactive, may ignite. Experiments were performed to test this hypothesis and indeed an emulsion explosive

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was ignited by a collapsing cavity. Additionally, the reaction could be related to the impact region about an impacting jet rather than due to heat conduction around the entire cavity periphery. Thus the effects of conduction limit the influence of the transient high temperatures that a collapsing cavity can induce.

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