Numerical and experimental study of shock-driven cavity collapse

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Abstract. A study is presented of the interaction of a shock wave with gas cavities cast in a hydrogel. Simulations are conducted using a front-tracking approach, whereby Lagrangian hypersurfaces are used to model the interface between different materials. These 'fronts' are overlaid on an Eulerian grid which is used to model the bulk flow. Results are compared to an experimental investigation, in which a light gas gun is used to create ~600 MPa shock waves in hydrogel blocks, within which air cavities have been cast. Experimental results are presented, including temporally resolved measurements of light emission. Comparison between experimental and simulated results shows good agreement.

1. Introduction
The collapse of cavities or bubbles by shock waves in fluids is a common occurrence in nature and technology, with applications ranging from shock wave lithotripsy through to cavitation damage and the sensitisation of explosives. Numerous studies of this process[1, 2] have shown that the impact of a shock wave on a cavity leads to the development of a high-speed jet. This jet propagates across the cavity and strikes the far wall, compressing a section of gas to high temperatures and pressures, and leading to the formation of a strong water hammer shock in the liquid. The action of the jet causes the remains of the cavity to form a torus, in which further regions of high temperature and density are formed. Of particular interest, it has been shown experimentally that this process leads to two distinct bursts of light emission from the cavity[3]. These bursts of light have been correlated with the impact of the jet on the leeward cavity wall, and the collapse of the toroidal cavity remains.

2. Methods
2.1. Numerical Methods
Simulations in this work are conducted using a front-tracking methodology[4]. This method uses Lagrangian hyper-surfaces or 'fronts' to model contact discontinuities between different materials. These fronts are overlaid on an underlying Eulerian mesh, which is used to model the bulk flow. The fronts break the simulation up into a number of separate regions and act as a set of boundary conditions, across which ghost cell extrapolation is performed. The propagation of waves between components is completely handled by the update to the position of the fronts. This method effectively eliminates numerical diffusion of the interface; this is a key challenge in modelling problems such as shock-driven cavity collapse. A stiffened polytropic equation of state is used to model the hydrogel, and the air is modelled as an ideal gas. Simulations are conducted using rotationally-symmetric coordinates. For a more comprehensive description of the methods used in this work, the reader is referred to[2, 5].
2.2. Experimental Methods

The experimental methods used in this work build upon previous research on the subject, in which a single-stage gas gun or explosives were used to create shock waves in gelatin blocks into which cylindrical cavities were cast[1]. Figure 1 shows the experimental setup used in this study. A 70 mm bore single-stage light-gas gun is used to accelerate projectiles into an aluminium striker plate, behind which a hydrogel block is placed. Shock waves (pressure ∼600 MPa) are created in the gel block, which go on to collapse spherical cavities cast within the block. The projectile used consists of a 50 mm diameter, 15 mm deep mild steel disk, which is placed within a nylon sabot. The gas gun is capable of accelerating this projectile, which has a mass of approximately 450 g, to velocities of up to 700 ms$^{-1}$. The aluminium striker plate seals a vacuum chamber placed over the gun barrel, allowing the barrel to be evacuated prior to the shot to a pressure of approximately 0.8 Torr. The hydrogel used for the target is made by dissolving 0.5 % by mass gellan gum (Sigma Aldrich) in deionised water heated to 90 °C, with 0.05 % CaCl used as a setting agent. This mixture is allowed to cool before being poured into moulds to set. Half-spherical depressions are cast into the walls of two gel blocks, which are then joined together to form spherical cavities within the combined block. By this method, complex multi-cavity arrangements are easily implemented. Completed gel blocks are of depth 42 mm, width 50 mm and height 50 mm. Cast cavities are of diameter 5 mm.

Imaging of cavity collapse is conducted using a SimX16 high speed camera (Specialised Imaging Ltd., UK). This camera is capable of capturing 16 frames at a maximum frame rate of 200 Mfps. Images may be backlit using a 200 W pulsed diode laser (Cavilux SMART, Cavitar Ltd., Finland). Any light emission from cavity collapse is focussed through a series of beamsplitters on to 3 photo-multiplier tube modules (PMTs, Hamamatsu H11526-20-NF), each of which is filtered to detect a particular wavelength of light. The wavelength of these filters (405 nm, 460 nm and 760 nm) are chosen such as to avoid the 640 nm central wavelength of the laser. This setup is calibrated using a Bentham CL6 II calibrated light source.
3. Results

The impact of a 600 MPa incident shock wave on a single spherical cavity is shown in Figure 2. The top half of the images show the experimental results found using the setup of Figure 1, while the bottom half shows the results of a matching simulation. The simulated results are shown using a plot of the magnitude of the gradient of the density, giving a numerical representation of the experimental result, in which large gradients in density appear as dark lines. The images show a central section of the gel block, with the gas cavity positioned 10 mm from the aluminium striker plate. The shock wave propagates across the images from left to right, and the times shown are relative to the time of shock impact on the cavity. Although the high-speed jet is not visible in the experimental images, its formation may be inferred from other phenomena, such as the water hammer shock formed by the impact of the jet on the leeward cavity wall. Also clearly seen in the experimental images is the expansion of the rarefaction wave, formed in the liquid by the impact of the shock wave on the cavity. Comparing the simulated and experimental results, there appears to be reasonable agreement in the formation and propagation of these features between the two result sets.

Light emission from the collapse of the cavity as recorded by the PMTs is shown in Figure 3. Times shown are as in Figure 2. As can be seen, the light emission is divided into three distinct bursts. Analysis of shock propagation in the experimental images suggests that the first peak
corresponds to the impact of the high-speed jet on leeward cavity wall, while the second and third peaks correspond to the collapse of the toroidal cavity remains. This gives a difference in time between the impact of the incident shock on the cavity and jet impact of 3.4 $\mu$s. This compares to an equivalent simulated time difference of 4.1 $\mu$s. Currently our best estimate for this 20% discrepancy relates to the difficulty in obtaining an accurate equation of state for the hydrogel, at the conditions relevant to this experiment. Comparing the relative amplitudes of the PMT traces, the light emission can be seen to be significantly more intense at shorter wavelengths. These relative amplitudes are consistent with the cavity emitting light as a black body, with peak temperatures of approximately 20,000 K. More detailed analysis will be required to improve the accuracy of this result.

4. Conclusion
This paper has presented initial results from an investigation into the interaction of an incident shock wave with air cavities cast in a hydrogel. Comparison has been made between experimental and simulated results, with reasonable agreement shown. By using an array of photomultiplier tubes, it has been shown that under the influence of the incident shock wave, cavities collapse and emit bursts of light. This light is concentrated into three distinct peaks, with the intensity of the light greater in the ultraviolet than the visible.

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