EXPERIMENTAL AND NUMERICAL STUDY OF TEMPERATURES IN CAVITY COLLAPSE

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Abstract. The temperature of the gas enclosed in a cavity collapsing as the result of the passage of a shock wave has been the subject of much previous interest. We consider the ability of this collapse to ignite an explosive medium in which the cavity is placed. Both jet impact and hot gas ignition mechanisms are considered. A series of experiments have been conducted in which a cylindrical cavity has been collapsed under shock. This geometry has the advantage of allowing details of the interior gas to be studied. A further series of experiments has been conducted to ally this disc-shaped geometry with a spherical cavity using two novel arrangements. The development of these tests has addressed the temperature increase within the cavity. The gas content can be varied to include chemically reactive gases content so that the combustion can also be used as a temperature diagnostic. For jet impact studies we use nitromethane as the liquid and measure ignition directly. The series of experiments has been coupled with numerical modelling of the multi-material shock interactions as well as the combustion of the diagnostic gases, both in the design and validation stage.

INTRODUCTION

The collapse of a gas void within a reactive material has the potential to start local burning leading to partial reaction or run to full detonation (1). There are three main features of the collapse that provide a means for ignition. The first is the formation of the high-speed jet and elevated velocities in the convergent flow around the wall of the cavity. This gives rise to heating in viscous materials (2). The second is the shock-heated region at the point of jet impact in an asymmetric collapse (3). The third is the compression of the gaseous or vapour content of the cavity (4). These effects have been studied (5) and an experiment, showing examples of each of these modes of heating giving rise to local reaction is described below. Once ignited, a burning front may be quenched or may accelerate so that a transition to detonation may occur according to the confinement of the material.

There is evidence of sensitization of material and also of associated shock-heating of the impacted explosive. Mader has modelled shock-induced hot spots (3, 6). He has shown the process of jets impacting in a local high-pressure area, followed by compression of material followed by heating. His models have not required a gas-filled bubble to achieve the necessary ignition temperatures. This mode was considered by Kang et al. (7). Clearly, in materials with viscosity and/or strength there is also friction between and shear within moving explosives to consider. In a visco-plastic material, work is done at internal interfaces leading to heating and the formation of a melted layer at the edge of a pore at which surface burning may start (8). These effects may be summarized by stating that low viscosity and small bubbles decrease sensitivity.

The size of the cavity will determine which mechanism gives rise to heating that may ignite the matrix. Flow is favoured at the smallest scale, and gas compression and jet impact at the largest. In the following work, larger cavity diameters are considered as they are experimentally easier to visualize.
EXPERIMENTAL

The experiments described were carried out in two and three-dimensional geometries. A disc shaped cavity allowed observations of jet formation, shock and reaction within the cavities. A prepared gel slab with introduced cavity was then clamped between glass or polymethylmethacrylate (PMMA) blocks and plane shock waves were introduced into the sheets by the impact of a flyer plate from one of the RMCS gas guns. In other experiments the shock was introduced using an explosive plane wave lens and a calibrated inert gap. In some experiments a 3 mm thick layer of an ammonium nitrate (AN) emulsion explosive (described in 9) was contained between two, 25 mm thick PMMA blocks. High-speed framing photography at microsecond framing rates recorded the light emitted by the ignited sites. Schlieren was used to visualize the shock in some experiments whilst no external lighting was used for the AN experiments where reaction occurred.

![Figure 1](image1.png)

**Figure 1.** In a), a 12 mm cavity collapses in gelatine. In b), an array of four 5 mm cavities (in two rows of two) collapses under a shock of gap pressure 8 GPa.

Figure 1 a) shows six frames taken from a sequence in which a 12 mm cavity containing air is collapsed by a 0.3 GPa shock. In frame 1 the incident shock has entered the sequence from below and has crossed two thirds of its diameter. An air shock can be seen travelling away from the downstream wall at the acoustic velocity of air. The micro-jet begins to form as an instability in frame 2 and subsequently travels across the cavity to impact the downstream cavity wall. Frame 5, taken 60 μs after frame 1, is representative of an intermediate stage of the collapse where the air shock has reflected from the involuted upstream wall and travelled back across the cavity. After jet impact, two lobes of compressed gas are trapped in the closure. As the jet penetrates the downstream wall, a pair of linear vortices subsequently form and travel downstream in the following flow.

Figure 1 b) shows the collapse of a 2x2 square array of cavities (which are all 5 mm in diameter) by a shock of amplitude 8 GPa entering an emulsion. The initial cavity positions are shown as white circles and the interframe time is 1 μs. The shock enters from below and runs over the rear of the cavities. There is a small amount of light emission from the bubble rear walls when the shock meets the first row. The voids close between frames 1 and 2 and the material ahead of each can be seen reacting in frame 3. The sites produced by the first row still react with that to the right persisting for the longest time but no accelerating reaction occurs. In frame 4 the second row of cavities starts to collapse with the burning site to the right immediately ahead of the point of jet impact. The bulk of the explosive ahead of the cavity reacts in frame 6. The diffracted shock can clearly be seen as a dark band to the rear of the left-hand site. In the sequence presented, hotspots have been formed, but the criterion for a propagating reaction has not been met so that the sites die. This may be due to their short duration and to the lack of adequate confinement.

NUMERICAL

This study considers low (ca. 0.3 GPa) and high pressure (ca. 3 GPa) shock impact on cavities of order 10 mm in diameter (relatively large for explosives). In the lower pressure regime the temperature of the gas in the collapsed cavity is deemed to be the main concern whilst in the higher pressure regime jet impact is seen as the more important feature when considering the likelihood of explosive ignition. The geometry of the problem is shown in fig. 2.

![Figure 2](image2.png)

**Figure 2.** Schematic of model system.
Details of the behaviour of this system have been modelled using a 2D, multi-material Eulerian hydrocode. A variety of material models are available and these are introduced in the sections below.

**FIGURE 3.** a). Closure and jet penetration for the low pressure collapse of a 12 mm diameter cavity shocked to 0.3 GPa. In b), the simulation tracks both shocks and the cavity walls. Fig. 3 a), shows details of the final stage of the collapse of the 12 mm cavity of Fig. 1 a), collapsing under a shock of magnitude 0.3 GPa. As will be seen, the code predicts the form of the walls and the interface between gas and liquid well. The position of shocks is also shown leading to regions of high pressure and temperature. Other experimental work has shown the presence of luminescence from the enclosed interior gas soon after the jet impacts (9).

**FIGURE 4.** Collapse of 6 mm cavities under 2 GPa shock waves. The first frames show initial cavity positions. In a), interframe time is 1 μs, whilst it is 0.2 μs in b). In c) temperature distribution in lobes of gas is shown.

Fig. 4 shows the collapse of a 6 mm cavity by a 2 GPa shock photographed at two different framing rates (interframe times of 1 μs for a. and 0.2 μs for b.). Frame 1 of each sequence shows the initial cavity position. There are two bright flashes of light in frame 4 of the slower sequence which are shown in greater temporal detail in b). First, a single flash occurs in frame 3 that fades until the two regions of luminescence are seen in frame 4. It is interesting to note the similarity with sonoluminescence where the source of light is believed to be weak bremsstrahlung radiation.

To explain these effects, different approximations for the equation of state of air have been investigated. Ideal gas calculations show local gas temperatures peak at around 4000 K for an impact speed of 200 m s\(^{-1}\). It is expected that air chemistry might be important under these conditions and thus the calculation is repeated with a seven-species air model including electron production.

**FIGURE 5.** Collapsed bubble shape with electron concentration superimposed.

The distribution of electron density at the time of peak temperature is plotted in Fig. 5 and the regions of maximum intensity coincide with the observed light emission sites.

The gas chemistry model in the code was additionally employed to consider reactive gases in the cavity. Strong shocks exist within the bubble and (as Ball et al. (10) have recently shown) adiabatic collapse models will significantly underestimate the peak temperatures. The simulation of Fig 4 c), shows the temperature distribution in the lobes at the end of collapse showing high values at a central position at the time of jet impact followed by further elevated values in the trapped lobes at later time as seen in the sequence.

Shock waves of higher pressures will naturally produce higher gas temperatures in the collapsed cavities (ca. 35,000K for a steel flyer plate impacting at 1000 m s\(^{-1}\)) but these exist only for short periods of the order of 200 ns. Here, the main mode of ignition of a reactive medium is the heating at the point of jet impact in the surrounding fluid. This ignition source occurs well before peak gas temperature is achieved. For a spherical bubble a 100 m s\(^{-1}\) plate impact results in a 4000 m s\(^{-1}\) jet speed. For a cylindrical bubble this speed reduces to ca. 3200 m s\(^{-1}\). The RMCS gun can impact energetic materials and it is planned to fire into...
nitromethane (NM) containing well-defined cavities. Simulation of these experimental studies requires an Arrhenius kinetics model for nitromethane within the hydrocode. This analysis was fitted by Cook et al. (11) from bullet impact studies and thus is well suited to jet impact.

**FIGURE 6.** Temperature in Nitromethane showing ignition location compared with collapsed bubble.

Fig. 6 shows contours of temperature in the NM near to the state of minimum bubble volume. The darkest shading corresponds to 2600 K and shows the locus of ignition of the NM after jet impact in relation to the collapsed bubble.

Fig. 7 shows qualitative comparison of a) a 6 mm cavity collapsing under an 8 GPa shock in an AN emulsion explosive and b) a simulation of a 10 mm cavity collapsing in nitromethane under the conditions of Fig. 2.

**FIGURE 7.** Experiment and simulation of large (6 mm) cavity collapsing in an AN matrix. Light is due to reaction. Interframe time 1 μs. b) Temperature field around a cavity collapsing in NM showing similar reaction sites.

The temperature in the cavity reaches high values only towards the end of the collapse and although there is reaction in the vapour within the cavity as the jet is close to impact, it is the temperature and pressures generated at the jet impact site itself that causes ignition of the surrounding fluid. The same feature is seen for the NM simulation. High temperatures of thousands of K are generated in the collapsing cavity but it is the jet impact that gives rise to the main ignition.

**SUMMARY**

A range of experiments and simulations has illustrated an approach adopted to understand the formation of hot spots in reactive media by the collapse of cavities. Experiments have illustrated features of the shock collapse of large (mm sized) cavities in spherical and cylindrical form to observe details occurring within the cavity. A numerical scheme with suitable representation of liquid and included gas has been developed and has been shown to reproduce the wall geometry, the included gas behaviour (including the electron density consistent with observed luminescence) and the temperature field within the bubble. Further experiments have been described to probe the temperature field that is present with particular regard to the ignition of energetic materials.

**REFERENCES**