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EXPERIMENTAL MEASUREMENT AND THERMOCHEMICAL MODELLING OF WATER MITIGATION OF CONFINED DETONATIONS

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ABSTRACT

Explosive detonations in confined spaces result in a long-term quasi-static pressure (QSP), formed due to the repeated reflections of the initial shock wave from the walls of the space. In fuel-rich explosives, secondary combustion (afterburn) of the detonation products and binder ingredients contributes significantly to the total energy release and subsequent pressure change in the space. Placing water around an explosive charge has been successfully used as a method to mitigate QSP, though several potential mechanisms have been proposed on how this reduction is achieved. An understanding of this mechanism is a prerequisite for the creation of fast-running modelling tools capable of predicting mitigated explosive events.

This paper presents experimental data on the mitigation of plastic explosive detonations in an unvented chamber, where the use of air and nitrogen atmospheres is used alongside water-mitigated and unmitigated detonations to investigate the effects of mitigation on afterburn reactions, and the resulting QSP. A simplified thermochemical model of the detonation and afterburn reactions is then used to predict the peak experimental QSP using simplifying assumptions on the explosive composition and reaction products, and an assumptions of an ideal gas EOS.

INTRODUCTION

When high explosives detonate in a confined space, the resulting high-pressure loading can cause severe structural damage and injury. The presence of walls and other obstacles leads to multiple reflections of the initial shock wave within the space, leading to complex shock wave interactions and the development of a long-term, uniform quasi-static pressure, or QSP. The magnitude of this QSP is controlled by the energy and volume of gaseous products released in the detonation, and the overall volume of the space. This process is complicated by the fact that most explosives are fuel-rich, and undergo additional combustion, or afterburn, when the fireball of detonation products interacts with oxygen in the surrounding atmosphere. These afterburn reactions release additional energy which contributes to the QSP in the space [1], but are dependent on sufficient mixing of the detonation products with atmospheric oxygen before the system cools to the point of product freeze-out [2,3]. In cases where a confined detonation poses a significant risk of structural damage or injury, it is desirable to limit the potential energy release, or otherwise mitigate the formation of air shocks and QSP, using additional materials placed around the charge. This includes applications as

diverse as explosive stores, counterterrorism response and extending the capacity of dedicated indoor blast chambers for research purposes.

Water has commonly been used for this purpose, including variations such as water mist and aqueous foams, and in many cases has shown promising results, although there is disagreement on which mechanisms are responsible for the observed pressure reductions. In free-field experiments, Allen et al. [4] showed that surrounding spherical charges of PE4 with water reduced the peak pressure observed, and concluded that this was primarily due to inertial effects rather than heat transfer. Similar experiments by Pontalier et al. [5] with C-4 also showed a reduction in peak pressure when charges were surrounded by water, particularly in the near field, but this was instead associated with heating and vaporisation of the water. Resnyansky & Delaney's [6] experiments with Comp B found that bulk water around the charge was much more effective than a distributed water mist in the space for incident pressure measurements.

In confined experiments, Larsen [7] observed significant decreases in QSP when sealed chambers containing C4 charges were completely filled with an aqueous foam, and showed that this decrease could be accounted for by the sensible and latent heating of the water. Similarly, Kong et al. [8] showed that a water mist inside a sealed chamber could reduce the recorded QSP from TNT charges, although the reductions were more modest due to the lower mitigant masses employed. These reductions were also hypothesized to be due to heating and evaporation of the water, as well as suppression of afterburn reactions due to the resulting temperature drop.

Recent experiments at the University of Sheffield have investigated the contribution of afterburn reactions on QSP by using oxygenated and inert atmospheres to isolate the key mechanisms for PE4, PE8 and PE10 charges [9,10]. Measurements of pressure, and temperature, and chemical analysis of the products were also used to define and validate a simplified thermochemical model which was shown to be very effective for predictions of QSP [11,12]. In this paper we adopt a similar approach to the use of water as an explosive mitigant, using oxygenated and inert atmospheres to assess the effect of water on both afterburn suppression and energy transfer, and adapting the thermochemical model to include these effects.

CONFINED DETONATION EXPERIMENTS

Confined detonations were carried out inside a 275L blast chamber, as shown in Figure 1. The walls of this 1m long steel pipe were fitted with pressure transducers to measure QSP, and additional valves to allow control over the initial atmosphere. In experiments where a nitrogen atmosphere was used, the pipe was evacuated with a vacuum pump before introducing the nitrogen. Further details on the experimental methodology and instrumentation are available in [9]. In unmitigated experiments, spheres of plastic explosive were supported on a fiberglass mesh between two steel rods, and initiated using a nonelectric detonator. For experiments with water as a mitigant, the explosive charge was placed inside a thin-walled glass bauble, which was then filled with the appropriate water mass, as shown in Figure 1. Two plastic explosives were used in these tests: PE10 (84% PETN, 16% binder) and PE4 (87% RDX, 13% binder). Both explosives are highly oxygen deficient.

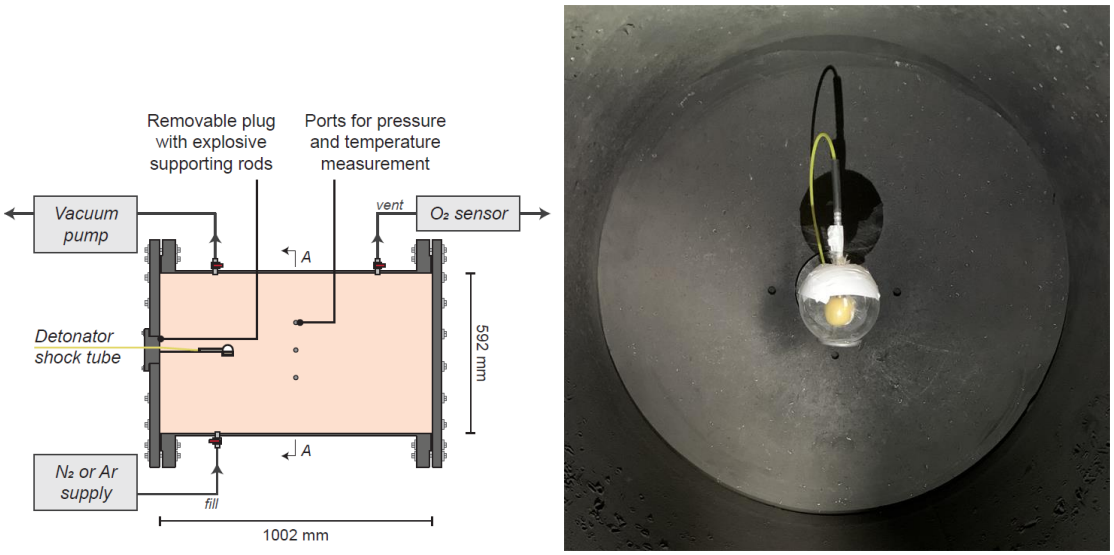

Figure 1: The 275L confined blast chamber (left), which incorporates control over the initial atmospheric gases and pressure measurement ports. Glass baubles (right) were used to surround charges with a measured quantity of water as a mitigating material.

Spherical 20g charges of PE10 were tested in an air atmosphere without the addition of mitigation, and then with 40g and 200g of water in a bauble surrounding the charge (two and ten times the charge mass, respectively). Each of these experiments were then repeated in a nitrogen atmosphere, where no additional oxygen would be available for secondary afterburn reactions. The results of these experiments are shown in Figure 2, where the same data is presented on two different timescales to emphasise the first few shock measurements and the overall QSP development in the chamber.

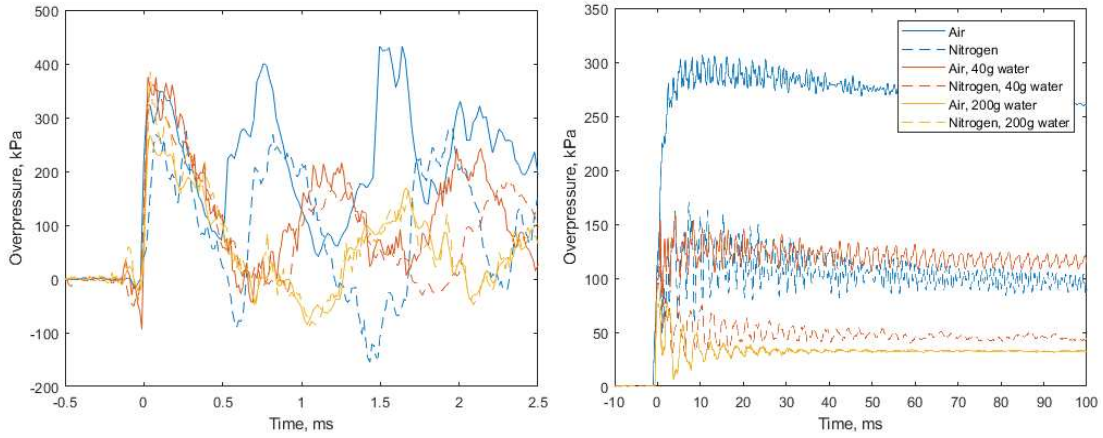

Figure 2: Overpressure measurements for 20g PE10 in air and nitrogen atmospheres, and with 40g and 200g water mitigation. The early time graph (left) highlights differences in the first few measured shocks, while the resulting QSP is shown on the right.

The difference in QSP for the bare charges in air and nitrogen atmospheres represents the contribution of the afterburn of the detonation products and binder, which is around

58% of the total overpressure in this case. This additional energy release is visible in the first few measured shocks, which increase in magnitude and arrive more quickly in the air atmosphere, but decrease in magnitude in the inert nitrogen atmosphere. As previously reported [9], the onset of afterburn has been associated with the reflection of the initial shock with the wall of the chamber, which forces mixing of the atmospheric oxygen with the partially combusted detonation products. At this scale afterburn reactions appear to be complete within 10–20ms.

Compared to the base case in air, the addition of 40g of water (two times explosive mass) around the charge decreases the observed QSP by 58% in air, and by 82% in nitrogen. The difference between the two atmospheres indicates that afterburn reactions are still occurring, and this is again visible by the difference in the timing and magnitude of the first few shocks: the second and third shocks in air are of higher magnitude and return more rapidly than in nitrogen, indicating further energy release. Notably, the first shock in both atmospheres is of a similar magnitude to the base case in air, and so the energy transfer to the water appears to occur after the interaction with the chamber wall, indicating a thermal mechanism. Increasing the water mass to 200g (10 times explosive mass) decreases the observed QSP by 89% compared to the base case in air. This is consistent across both the air and nitrogen atmospheres, indicating that afterburn is no longer occurring, presumably because the temperature in the chamber has dropped below the auto-ignition temperature of the detonation products.

Further experiments were performed with 50g spheres of PE4 in an air and nitrogen atmospheres, both without mitigation and 100g of water in a bauble surrounding the charge (two times the charge mass). The results of these experiments are shown in Figure 3. Comparison of the air and nitrogen atmospheres without mitigation again shows that afterburn accounts for around 57% of the total overpressure observed. The addition of 100g of water decreases the QSP by 73% in air, and 83% in nitrogen compared to the base case in air, and so some afterburn is still present. This is again observable by comparison of the first few recorded shocks, which also appear to show a reduction in the first shock, unlike the PE10 experiments.

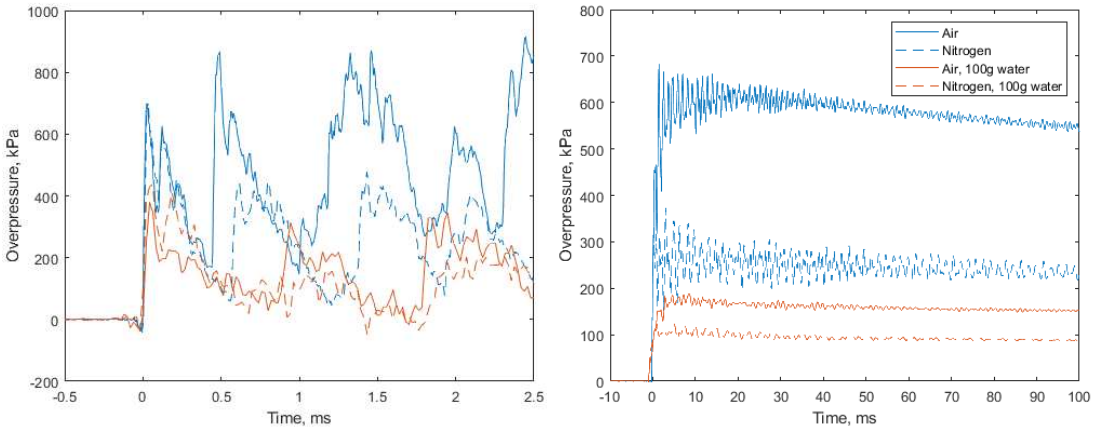

Figure 3: Overpressure measurements for 50g PE4 in air and nitrogen atmospheres, and with 100g water mitigation. The early time graph (left) highlights differences in the first few measured shocks, while the resulting QSP is shown on the right.

THERMOCHEMICAL MODELLING

The results from the experimental trials appeared to show that reductions in QSP due to a water mitigant were due to the transfer of heat from the detonation products to the water, and so this theory was also assessed using a thermochemical analysis of the experiments. A simplified thermochemical approach [11,12] was previously shown to consistently predict QSP for plasticised explosives (PE4, PE8, PE10) to within 3% of experimental values for both air and nitrogen atmospheres. While full details are available at these references, the model calculations involve:

1. The initial internal energy of the atmosphere in the confined volume;
2. The reaction products and energy release due to detonation, and afterburn as allowed by the atmospheric oxygen;
3. The temperature change in the final gas mixture based on the change in its internal energy and its heat capacity, and the resulting pressure change (QSP).

Simplifying assumptions include the use of an ideal gas equation of state, Kistiakowsky–Wilson rules on detonation product formation, selection of representative hydrocarbon chain lengths for binder oils, and the selection of methane and carbon as products of binder pyrolysis reactions when oxygen is not available for afterburn. Temperature-dependent heat capacities are used for all reaction products.

To include the effect of heating the water on the QSP prediction, an additional step was introduced to include the heat capacity of the water as part of the final temperature change calculation. Assuming full mixing of the water with the atmosphere in the chamber, thermal equilibrium is sought between the final gas mixture and the water, and liquid water is converted to vapour when its boiling point is reached. This is similar to the approach adopted by Larsen [7] for aqueous foams, except with the addition of a pressure-dependent boiling point and latent heat of evaporation for water, and a temperature-dependent heat capacity for water vapour. Equilibrium is complicated by the fact that any additional water vapour produced will alter the moles of gas present and the mean molar heat capacity, and so the fraction of liquid water converted to vapour must be identified. This is solved using a bisection method to minimise the error between the energy released by the explosion reaction(s) and the energy required for a particular fraction of water vapour production. This energy requirement includes sensible heating of liquid water from ambient conditions to boiling point, the latent heat of evaporation, and sensible heating of the vapour, and an additional calculation loop refines the values of these based on the final predicted pressures.

The updated model demonstrates three zones of pressure/temperature behaviour dependent on the mass of water used, and an example is provided in Figure 4 for the case of 20g PE10 in the 275L chamber. Here it is assumed that no afterburn occurs, and that the energy available is that from detonation of the explosive and pyrolysis of the binder as above.

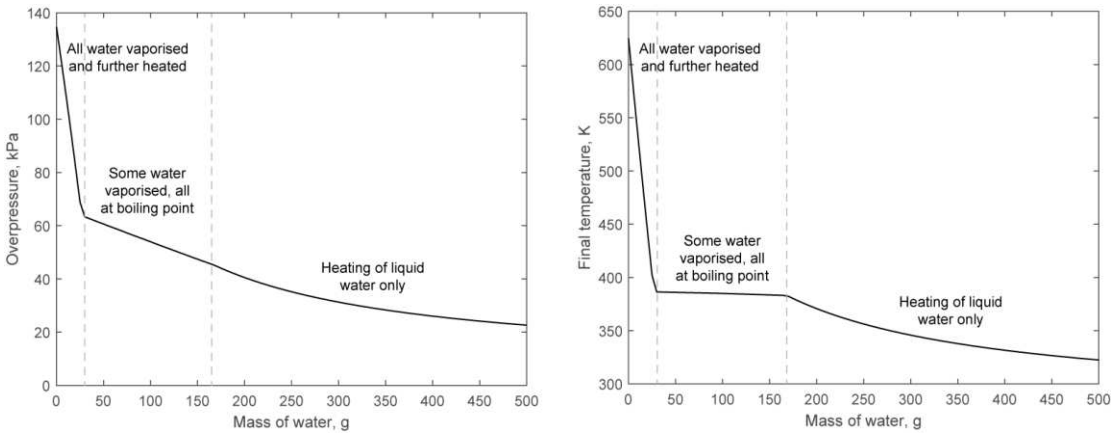

Figure 4: Thermochemical model predictions of water mitigation effects on QSP (left) and temperature (right) assuming no afterburn occurs, for a 20g PE10 charge in a 275L chamber filled with nitrogen.

The three zones of behaviour are as follows:

1. When low masses of water are placed around the charge (<30g, or <1.5 times the charge mass in this example), there is sufficient energy available to raise all of the water to boiling point, to vaporise all of the water, and to further heat the resulting steam. The final temperature and pressure of the system drop rapidly as the water mass is increased.
2. Between 30g and 170g of water (between 1.5 and 8.5 times the charge mass in this example) there is sufficient energy to raise all of the water to boiling point, but only partially vaporise it, and the vaporised fraction decreases as the mass of water is increased. The temperature of the system is capped at the boiling point throughout this zone.
3. When large masses of water are placed around the charge (>170g, or >8.5 times the charge mass in this example), there is insufficient energy available to bring the water to boiling point, and the system reaches equilibrium at a lower temperature. In the limit the temperature remains at ambient conditions, and the pressure increase is solely due to the increased moles of gas in the volume following the explosion reactions.

Figure 5 shows a comparison of the experimentally measured QSP and the thermochemical model predictions of water mitigation effects, with assumptions of full afterburn and no afterburn. The experiments performed in an inert nitrogen atmosphere closely follow the “no afterburn” model predictions for both PE10 and PE4, indicating that the pressure reduction is primarily due to heat transfer to the water mitigant and the resulting phase changes. In an air atmosphere, the experimental results showed that some afterburn does occur at low water masses (e.g. 2 times explosive mass) and so the results for these experiments lie between the “no afterburn” and “full afterburn” model predictions. Experiments with 20g PE10 and 80g or 200g water (4 or 10 times explosive mass) are both well represented by the “no afterburn” assumption, and so it appears that afterburn reactions are effectively quenched at a point between 2 and 4 explosive masses of water for the current arrangement. Further analysis of the thermochemical model predictions of temperature may allow more a more generalised approximation of this afterburn quenching to be built in to the calculations for lower mitigant masses.

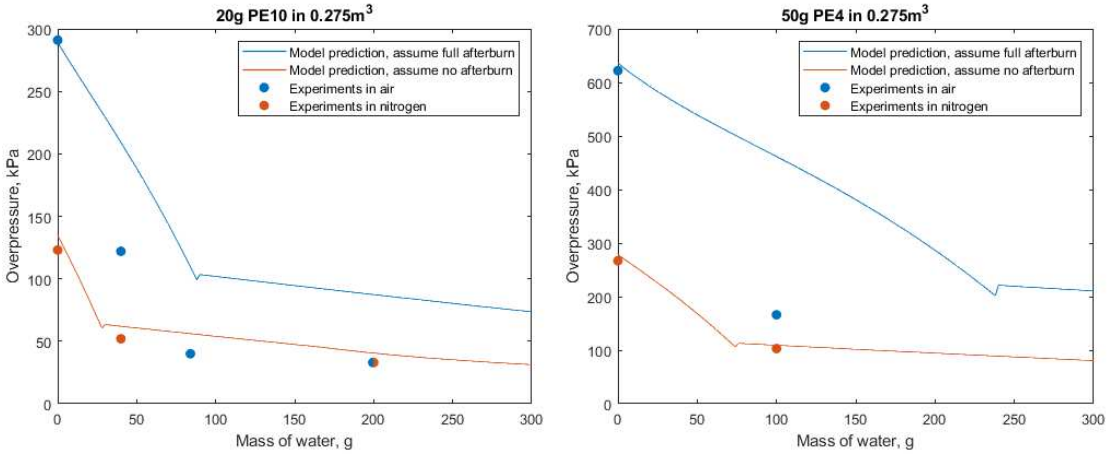

Figure 5: Comparison of experimentally measured QSP and thermochemical model predictions of water mitigation effects, with assumptions of full afterburn and no afterburn, for 20g PE10 (left) and 50g PE4 (right).

CONCLUSIONS

Quasi-static pressure measurements of PE10 and PE4 charge detonations were performed in a 275L chamber with air and nitrogen atmospheres to assess the mitigation effect of surrounding the charge with varying masses of water. The use the oxygenated air atmosphere and the inert nitrogen atmosphere allowed an independent assessment of the mitigation effects on the energy release from afterburn reactions, and the energy transfer from the detonation products. QSP reductions of up to 89% were observed for experiments with a water to charge mass ratio of 10. At these high mass ratios identical results were recorded in air and nitrogen atmospheres, indicating that afterburn reactions were not contributing to the energy release in the space. At a water to charge mass ratio of two, higher pressures were observed in the air atmospheres than in nitrogen atmospheres, showing that afterburn reactions were still contributing to the energy release at lower mitigant masses. In the majority of mitigated experiments in both atmospheres, the first shock was of a similar magnitude to the base case in air, and so the energy transfer to the water appeared to occur after the interaction with the chamber wall, indicating a thermal mechanism.

To assess this mitigation mechanism further, a thermochemical analysis of the experiments was performed by adapting a model that had been previously validated for confined plastic explosive detonations in air and nitrogen atmospheres. Assuming full mixing of the confined atmosphere with the mitigant, the model allows for the sensible and latent heating of the water, and includes the resulting liquid/vapour mixture in the heat capacity calculations used to predict the final temperature and pressure. Model predictions assuming no afterburn reactions were in very good agreement with the experiments performed in a nitrogen atmosphere, confirming that the pressure reduction is primarily due to heat transfer to the water mitigant and the resulting phase changes. Experiments in air atmospheres with lower water masses lay between the model predictions for “full afterburn” and “no afterburn” assumptions, indicating that

partial afterburn was occurring, while afterburn was fully quenched at higher mitigant masses.

Further analysis of the thermochemical model predictions of temperature and pressure at lower water masses may allow more a more generalised approximation of the partial contribution of afterburn to be built in to the model. This will be particularly useful for assessing the effectiveness of other two/three-phase aqueous mitigants, such as foams and granular systems, on oxygen-deficient explosives in confined spaces. We also intend to use this model baseline alongside experimental trials to assess other effects such as the limits of the "full mixing" assumption for the mitigant and chamber atmosphere, and how mitigants perform when it is not possible to completely surround the charge.

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