SMALL-SCALE STUDIES OF WATER SPRAY DYNAMICS DURING EXPLOSION MITIGATION TESTS

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Results are presented from small scale tests of the mitigation of methane-air explosions in a 5 m long 76 mm diameter explosion tube by water sprays covering a 500 mm long central section of the tube. By varying the length of an initial accelerating section, explosions with a range of flame velocities and associated rates of pressure rise could be generated.

The dynamic response of the sprays to the explosion induced flows was monitored and the success or otherwise of the sprays in mitigating the explosions was noted. The preliminary findings suggest that a minimum explosion severity is required before sprays with initially relatively large mean droplet sizes (of the order 200-500 microns) are effective. The sprays become effective when the gas flow acceleration rates are sufficient to maintain a sufficient velocity differential between the spray and the gas phase so that droplet break-up occurs, in a manner similar to that observed for abrupt shock acceleration of sprays.

Key words: Explosions, flame acceleration, water sprays, mitigation.

INTRODUCTION

Despite the proven success of water sprays in suppressing gaseous explosions, several aspects of the phenomena are still poorly understood. Decisions regarding the effectiveness of deploying spray suppression systems on operating plant cannot be made in an informed manner until these uncertainties are resolved. One of these uncertainties is the behaviour of the sprays during an explosion event.

It is now widely accepted that explosion mitigation by water arises because of the extinguishing effect of fine droplets on the combustion process that provides the energy source during an explosion. Some of the sprays used in explosion studies to date, however, have mean droplet sizes significantly greater than those required to cause extinction of the combustion process. Unless a large proportion of the spray is sufficiently fine - which has been shown not to be true by droplet sizing carried out on deluge sprays - the mitigation process must also depend on a physical break-up process, reducing the large droplets to a much finer mist. Such a mechanism is well understood for strong explosions, where shock waves are formed. Less clear is the nature and time-scale of the corresponding process during less violent explosions.

The present paper reports results from small scale tests of the mitigation of methane-air explosions in a 5 m long 76 mm diameter explosion tube. Various water sprays were generated over a 500 mm long central section of the tube. A range of explosion severities could be generated, as evidenced by increasing rates of pressure rise and flame velocities, by varying the length of profiled liner in the tube, which promotes flame acceleration.

Measurements are presented of the dynamic response of the sprays to the explosion induced flows and of the subsequent extent of any mitigation and some implications for the applicability of such sprays as large scale mitigation devices are considered.

PREVIOUS EXPERIMENTAL STUDIES

Water sprays have a long history of use in the protection of plant from fire. Recently, Jones and Thomas[1] reviewed some of the previous applications that were of relevance to gaseous explosions. Apart from potential applications in coal-mine explosions, relatively little work has been done on the mitigation of unconfined gas cloud explosions. The initial work concerned detonation. For example, Gerstein *et al.*[2] mitigated sub-atmospheric detonations in a 60 cm diameter, 90 m long pipe with water spray rings placed at a separation of 1.5 m. Carlson *et al*[3]. rapidly attenuated detonations in hydrogen-air, but were astonished to find that the initial flames were accelerated by the sprays. There was evidence of pressure reduction, which was attributed to the mechanical shattering of the water droplets. Thomas *et al.*[4] suggested that the mechanism responsible for detonation quenching was the formation of a micro-mist, by boundary layer stripping, allowing more rapid vaporisation.

Small scale gaseous explosions studies were reported by Jones *et al.*[5] who studied the effects of sprays on accelerated flames in a 76 mm diameter tube. They observed that the effectiveness of the water spray increased as the flame velocity increased, with the reduction in impulse significantly greater than the reduction in peak pressure. In a comparable cubical volume they observed flame acceleration, attributed to gas phase turbulence due to the spray.

On a larger scale Acton *et al.*[6] demonstrated the ability of water sprays to limit flame speeds and overpressures in natural gas-air and propane-air explosions. They used standard offshore pendant type nozzles and medium velocity deluge nozzles and obtained pressure reduction from 780 to 280 mbar in a representative offshore module. Bjerkedvedt and Bjorkhaug[7] used standard nozzles in a 1:5 scale model of a typical offshore module. They also observed competing effects: Flame acceleration during the initial phase with mitigation during the later phase of combustion. Similar results were reported recently by Catlin *et al*[8].

To be of practical significance, the mechanism of explosion mitigation must lead to a reduction in the explosion overpressure and several possible means can be identified. One is the direct reduction in overpressure due to heat abstracted from combustion products. This effect has been observed but is only effective in the region where the inerting agent is located and is not generally considered to be of significance over explosion time scales. The main mechanism must therefore be related to combustion extinction. When considering the possible influence of water sprays, the main extinction routes must involve, to varying degrees, either a dilution of the mixture concentration to render the mixture below the lower flammability limit or heat abstraction from the pre-heat and combustion zone so that the combustion front temperatures and reaction rates are reduced to the point where the reaction front is no longer self-sustaining

When the water spray mitigation of gaseous explosions is considered the existing experimental findings indicate that the latter is the more likely mechanism. However, when the initial spray characteristics are examined, and likely evaporation models tested, it does not seem possible to effect this quenching as the overall evaporation rates are insufficient for large droplets (greater than 20 microns) over the relevant combustion time scale[9]. This indirectly confirms the inference from other experimental findings that a secondary physical process is required, which fragments the initially large droplets to a size range where they can act directly and efficiently on the combustion reactions.

AIMS OF THE PRESENT STUDY

Although the basic mechanisms whereby explosion mitigation occurs have been identified, the dominant extinction mechanism is still unclear. Also, the physical break-up mechanisms are not well characterised for typical sprays in transient explosion flow-fields. Much work has been reported in the literature on droplet break-up, under a wide variety of conditions, for example by Pilch and Erdman[10]. However little attention has been given to the response of sprays and droplets when placed in a gradually accelerating flow.

In the present series of tests the work of Thomas *et al.*[5] has been repeated, but with particular emphasis placed on monitoring the motion of the water spray and of any potential correlation with the flame velocity as it approaches the spray location. The present studies further extend the previous work in that significantly lower flame acceleration rates were investigated, with a view to identifying minimum explosion flow conditions, below which it was suspected that mitigation would not be observed.

EXPERIMENTAL DETAILS

The experimental configuration used comprised an initially closed stainless steel tube of internal diameter 76 mm and length 5 m. The tube could be fired open-ended by removing the end cover immediately prior to ignition. This was formed from two 2 m long sections, each containing ports for gauge placement. A further 1 m long section, which could be fitted with three pairs of diametrically opposed nozzles could be placed at the mid-point of the two 2 m sections. Using ports located in this section a 50 cm long water spray could be formed using three diametrically opposed and impinging water sprays Each nozzle pair was located 10 cm apart at distances of 2.11, 2.21 and 2.31 m from the initiating spark. The general arrangement is shown schematically in Figure 1. Natural flame acceleration in the tube could be enhanced by placing profiled cylindrical Duralumin liner with a length of up to 1.95 m in the section prior to the spray.

Flame propagation was monitored by wall mounted, light-sensitive detectors. These were formed from coupled pairs of diametrically opposed light emitting diodes (LED's) and photo diodes, located 2.21, 2.56 and 3.05 m from the spark source. They were thus capable of detecting attenuation of the partially collimated LED output due to the presence of fragmented water spray and also increased light output due to the passage of a combustion front. An additional photodiode was placed 1.93 m from the spark. Kistler pressure gauges monitored pressure histories as flames propagated down the tube, placed at distances of 1.93 and 3.35m from the spark. For the majority of tests discussed in the present paper, a 0.4 m long accelerating section was used.

EXPERIMENTAL RESULTS

To date, the majority of the acceleration tests have been undertaken with six Delevan BIM8 spray nozzles mounted as diametrically opposing pairs. Droplet size distribution measurements, based on an analysis using a MALVERN particle sizer are presented in Figure 2. The analysis also indicates a Sauter mean diameter for the spray of the order of 110 microns.

Typical pressure records obtained in explosion tests with methane-air for a 0.4 and 1.0 m lengths of accelerating section can be compared with the records obtained with no accelerating section in place from Figures 3(a)-(c).

The corresponding photodiode records are shown on Figure 3(d)-(f). In these the decrease in signal strength clearly shows the motion of the water spray ahead of the flame front. The photodiode output, located some 0.8 m downstream of the spray injection point is reduced as the spray obscures the emission from the light emitting diode but increases as the flame front reaches the gauge at a later time.

The use of LED photodiode pairs thus provides a convenient means of estimating spray acceleration, whilst the corresponding pressure records could provide an estimate of the associated gas velocity based on simple wave theory and isentropic compression of the gas.

A total of 56 tests were carried out with no spray present in the tube and a 112 tests with spray present. In 56 of the tests with sprays in use, extinction was observed. The range of flame velocities observed varied from 7 to 146 ms^{-1} for the dry tests and from <1 to 233 ms^{-1} for the wet (with spray) tests.

Given the relatively large number of tests undertaken, it is not possible in the present paper to discuss in detail all of the individual results obtained and some further analysis is still outstanding due to the number of permutations that were investigated. An initial analysis has however identified certain significant trends, based on measurements of maximum spray and flame speeds, which are summarised below.

Dry (no spray) Tests:

1. Highest flame speeds were recorded just rich of the stoichiometric mixture ratio.
2. Faster flame speeds were recorded in open tubes than in closed tubes with the same number of accelerating sections.

Spray Tests:

3. There was no obvious correlation in any case between flame speed and spray speed.
4. All extinctions took place when the flame was within a moving spray.

5. Low-speed flames were difficult to extinguish, high speed flames were usually quenched.
6. Extinction was generally preceded by an increase in flame speed, as the flame entered the spray.
7. Extinction was most likely to be observed in lean or rich flames. Stoichiometric flame speeds recorded when quenching was observed were low in comparison to those recorded in the dry case.
8. Extinction was more likely to occur at moderate spray speeds.
9. In some cases, the spray acceleration was sufficiently fast that the flame did not catch up with the spray slug over the length of the test section.
10. When the flame overtook the spray, the flame speed was highest within the spray, that is the flame accelerated as it passed through the spray. This tended to happen in cases of low flame speeds and low spray speeds.

DISCUSSION

The summary remarks made above, based on the present results, are in general agreement with the accepted theories for explosion mitigation by water sprays. Flames are extinguished by a spray due to cooling below the auto-ignition temperature. This is done most effectively by droplets which will evaporate completely during transit through the flame front and absorb their latent heat of vapourisation from the flame. It has been estimated by Sapko *et al.*[9] that droplets smaller than 18μm will do this in a typical turbulent flame. As water droplets from deluge systems are usually of the order of a several hundred microns in diameter, they will be ineffective unless some mechanism can reduce the mean size of the droplets by two orders of magnitude between their injection into the system and their inclusion into the flame front. As we have already seen, such a reduction is possible if the droplets are shattered by viscous forces in an accelerating gas flow.

Although the present tests are on a small scale, the experiments go some way to showing that flow accelerations and velocities thought to be necessary to induce droplet shattering can be produced during a methane-air explosion, without shock formation. They also indicate that a minimum flow acceleration and critical Weber number for the droplet is required for the process to be effective: no extinction took place in less violent flows.

To illustrate this, let us consider three specific tests, two with spray and a third control without. Further, two of these tests (control and spray) were at methane concentrations of 10.3 and 10.5% respectively. The third test was with 8.2% methane. The light emission/absorption records from these tests are presented for comparison in Figure 4 for four monitoring locations.

The upper trace in each plot is the control no spray case. The middle is the 10.5% with spray test and the lower trace the 8.2% with spray case. Without spray, the flame is observed to propagate through the region with a flame speed of the order of 10-20 ms^{-1}. With the spray, at this concentration, the incident flame speed, determined using a further gauge, was observed to be of the order 30-40 ms^{-1}. This increase is attributed to the turbulence induced by the spray injection process. As expected a lower incident flame velocity is observed with the lower 8.2% methane mixture with spray, of the order 15-20 ms^{-1}.

The nature of the light scattering from spherical droplets is such that little attenuation is observed by the light emitting diode/photodiode detector pair for the initial spray generated by the nozzles. It is not possible therefore to make any definitive statement on the nature of the spray in the vicinity of the injection point during the time of flame passage at these locations. However, that there is significant motion and break-up of the initial spray can be inferred from the attenuation observed on the lower two detectors in figure 4(d), which indicates a significant translation of the spray along the tube, together with evidence of a high fraction of small scattering particles (size range < 30 μm). For the 10.3% test, there was no evidence of the flame surviving passage through the spray, or its residue. The behaviour of the 8.2% is less clear, but there is some suggestion of a marginal flame propagation through the spray. This behaviour was typical of the lower flame acceleration cases. Weaker mixtures exhibited less acceleration that led to less spray break-up and hence limited mitigation. The corresponding pressure records are shown in figure 5 for the two gauge locations used, at 1.95 and 3.05 m.

In both cases the furthest gauge from the spark registers a lower peak pressure. This reflects the decay of the transient pressure pulse generated by the flame acceleration in the initial profiled section. The effect of a water in reducing the pressures after the flame interacts with the spray can be seen clearly.

The influence of the flow field on the spray behaviour can be deduced from traces 3(e) and 3(f). As the gas velocity can be related to the local pressure field, the increased pressure (and hence gas flow velocity) in the corresponding pressure traces (3(b) and 3(c), gives rise to greater fragmentation. This is evidenced by the increased scattering and attenuation of the LED source incident on the photodiode. A lower rate of pressure rise can be directly linked to the lower attenuation in the spray, due to slower gas phase acceleration and lower consequential fragmentation.

Any spray acceleration will be due to drag forces acting on the droplets. The controlling parameters in this case will be the drag coefficient C_d, the projected area of any droplet and the instantaneous relative velocity between the droplet and the gas flow. If the gas phase acceleration is relatively slow, the droplet acceleration rate is such that a lower velocity differential exists between the drop and the gas velocity. This can be demonstrated easily by simple integration of the appropriate equation of motion. For a given drop size, the larger the gas acceleration rate, the greater the velocity differential between the phases. It is speculated that this can be linked to critical break-up criteria, in a manner analogous to the criteria for shock flow break-up of droplets, where the velocity differential is established instantaneously. Further work on individual droplets is required to ascertain whether the same break-up criteria, based on Weber number or equivalent, are still appropriate for the gradually accelerating flow case.

CONCLUSIONS

The present small scale tests have demonstrated that the mitigation of subsonic methane-air flames in a one-dimensional pipe can be brought about using large mean diameter water sprays. Significant spray motion and fragmentation has been observed due to drag induced by the gas dynamic flow. For low rates of flame acceleration no mitigation was observed indicating that critical spray acceleration rates must exist.

The results provide qualitative evidence to support the hypothesis concerning spray fragmentation based on critical gas flow acceleration rates. Further work should be directed to monitor more closely the acceleration of sprays and single droplets in transient accelerating flows. One parameter of significant interest is the appropriate value of drag coefficient. Previous shock studies have suggested a value of the order 2 or higher, however, for gradual acceleration, where the droplet is still essentially spherical the classic value of the order 0.5 might be more appropriate. Direct measurements of gas phase velocities should also be attempted, allowing critical Weber numbers for droplets subjected to accelerating flows to be studied.

ACKNOWLEDGEMENTS

Financial support for this work from UK HSE Offshore Safety Division is gratefully acknowledged under contract Matsu/8473/2937. JRB also acknowledges financial support under a British Gas Research Scholarship.

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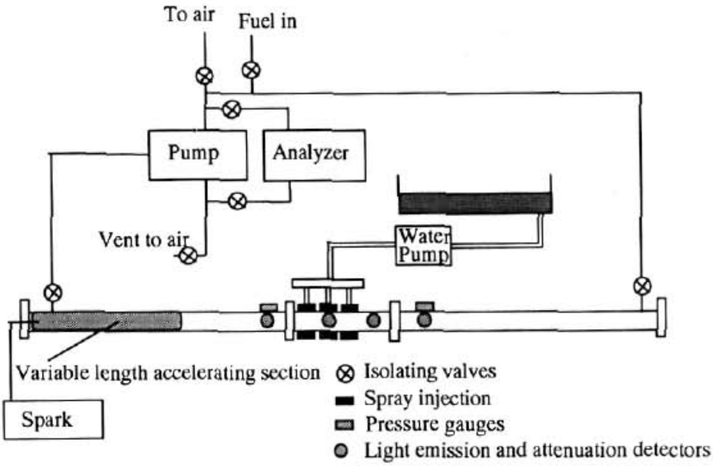

Figure 1 Schematic of experimental configuration used for initial spray displacement tests in a 76 mm diameter explosion tube

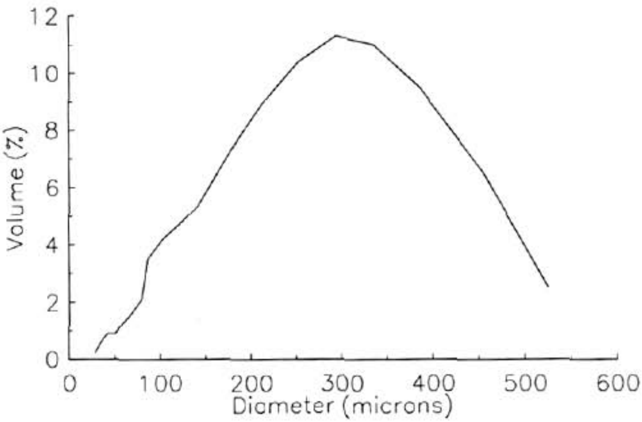

Figure 2. Typical distribution obtained for Delevan BIM8 nozzles

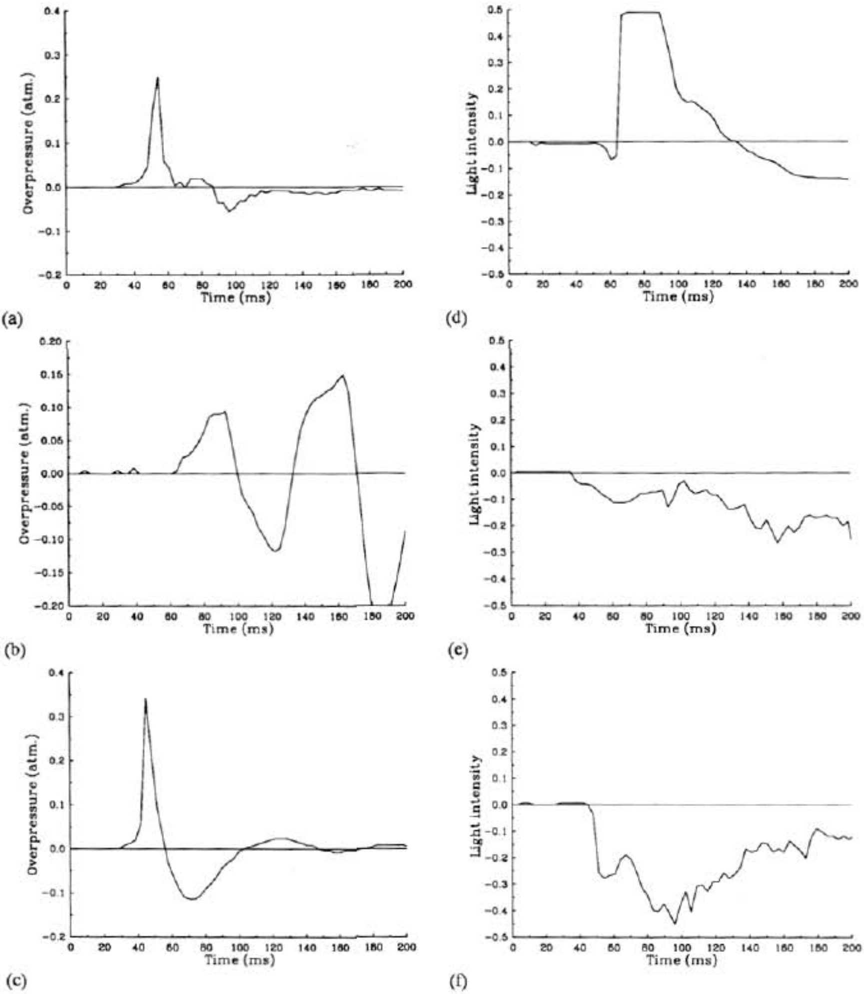

Figure 3. Pressure (left) and photo diode outputs (right) showing spray motion and flame propagation obtained with and without accelerating section in place. a) and d) 1.0 m accelerator, no spray; b) and e) 0.4 m accelerator, spray; c) and f) 1.0 m accelerator, spray.

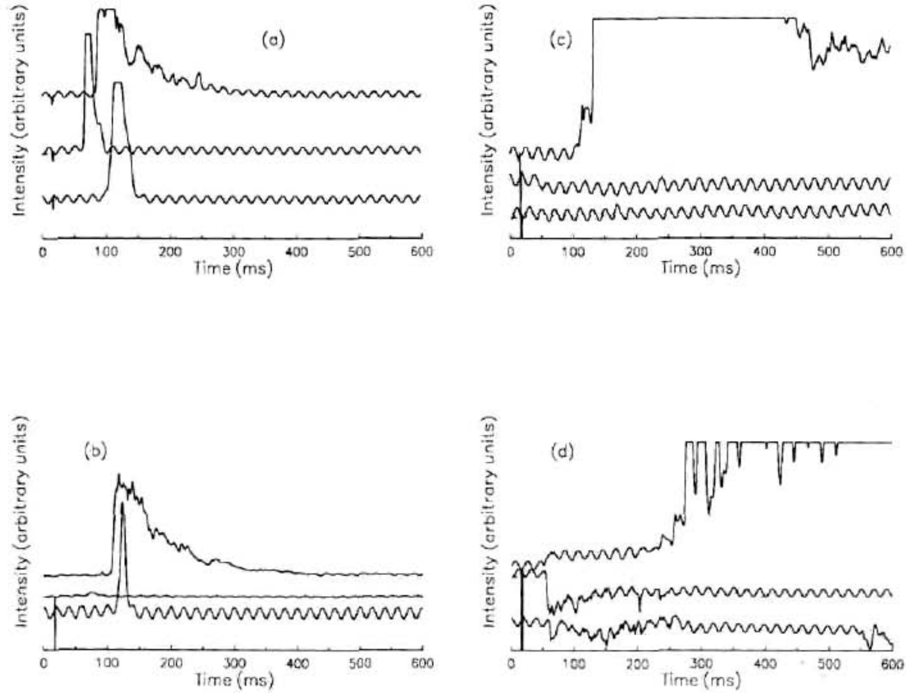

Figure 4 Light intensities measured at four locations a) 1.93 b) 2.21. c) 2.56 and d) 3.05m from the spark. Upper trace - no spray 10.3 % CH_4; middle trace - 10.5% CH_4 with spray; lower trace -8.2 % with spray.

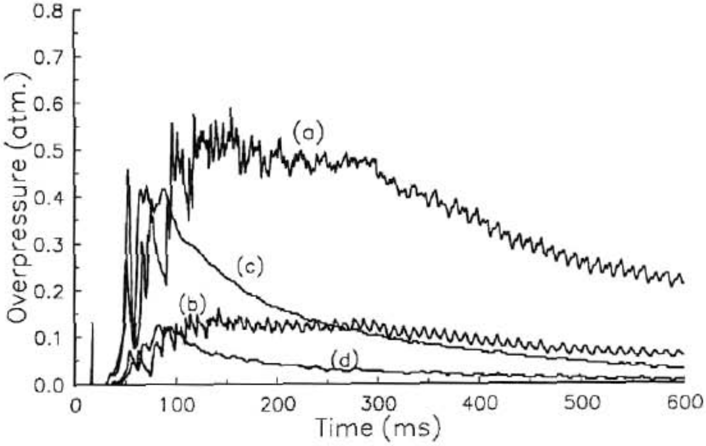

Figure 5. Comparison of two pressure gauge records, upstream and downstream of the spray location, with and without the spray. Without spray - (a) and (b); with spray (c) and (d). Gauge locations relative to spark - (a) and (c) - 1.95 m; (b) and (d) - 3.05 m; Spray centre 2.21 m.