

# ON THE CONDITIONS REQUIRED FOR EXPLOSION MITIGATION BY WATER SPRAYS

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## **Abstract**

The paper first outlines why the possible use of water spray as an explosion mitigation technique has been reconsidered in recent years. Examples of previous uses of water sprays for combustion mitigation are then given and observations of relevance to current explosion interests are noted. Finally, results are presented from recent fundamental studies that illustrate and quantify the basic chemical and physical processes by which water spray mitigation of explosions occurs.

**Keywords:** Explosion, mitigation, suppression, turbulent combustion, water sprays

This draft was finally published with additional corrections in Trans I Chem E: Part B - Process Safety and Environmental Protection Vol. 78 pp. 339-354 (2000)

## **INTRODUCTION**

In recent years, following the tragic incident on the Piper Alpha oil platform, there has been increasing interest in the use of water sprays to provide additional explosion protection. For, despite significant improvements in design, layout and management procedures, there still remains a finite possibility that an accidental release of fuel will occur and that an explosion could develop. The use of water sprays has been re-evaluated as they are relatively cheap, require relatively low maintenance and many water deluge systems are already installed. Some operators have sufficient confidence in the beneficial effects of deluge that to have already incorporated them into the overall safety cases made for certain installations. The need to provide replacements for Halons has also prompted renewed interest in water sprays in other applications.

In the present paper the reasons why there is a perceived need for additional means of explosion protection on offshore installations are briefly considered and previous evidence of the potential effectiveness of water deluge is summarised. This is followed by results from recent experimental studies that illustrate and quantify the conditions where water sprays can be effective as an explosion mitigation agent. Some potential disadvantages are also discussed, in particular the possibility of explosion enhancement by spray induced turbulence.

### **THE NEED FOR WATER SPRAY TECHNOLOGY**

Despite significant improvements in the management and operation of installations that process potentially explosive materials there is still a need for explosion protection mechanisms. To ensure continuous safe operation the primary goal for any process is a continual improvement in those factors that minimise the frequency of potentially hazardous explosion events. Currently, attention is given to:

- Operating and management procedures;
- Minimising the occurrence of failures and leaks;
- Continued research into the mechanisms of explosion development;
- Improved plant design and layout.

Despite the significant effort given to implementing the above, there always remains a finite possibility that a hazardous situation could develop and that an explosion might result. It is now well known that several factors can contribute to increased explosion effects and consequences. The most dangerous occurrence is when rapid flame acceleration is observed, where the consequence is the development of damaging internal overpressures<sup>(1,2)</sup>. Flame acceleration is promoted when flame fronts propagate into regions where turbulent flows have developed, for example in the wake of pipes and process vessels. Confinement leads to further pressure increases if the combustion energy cannot be dissipated to the external atmosphere.

Several options exist for reducing explosion overpressures. A standard method is venting through suitably designed weakened areas in the containment walls. However, under some circumstances this may not prove to be a viable method. This could be due to the extreme levels of overpressure generated or physical limitations on vent placement and size. Alternatively, conventional triggered suppressant systems may not be viable as a result of the volumes involved. It is in response to this problem that operators have re-considered water sprays. Water sprays are relatively cheap and in many instances water deluge type systems are already installed. Water sprays can also be deployed more effectively over a large volume, which is not always possible with conventional powder systems where a large number of units may impose weight penalties. Finally, water sprays are not ‘single shot’ protection devices and can be used to provide explosion protection over an extended period of time. Water deluge can be activated on gas detection, potentially inerting the protected volume, whereas triggered systems are activated once an ignition is detected.

A potential disadvantage of water sprays is accidental ignition by a spark following water ingress into electrical fittings. Also, both water and conventional suppression systems can lead to explosion enhancement if they are not effective early enough time. This enhancement is due to the turbulence generated by spray or powder as they are delivered into the volume to be protected. The potential advantages offered by water sprays are however significant and this has prompted a number of research projects on water spray mitigation of explosions, the results of which form the basis of the present paper.

### **PREVIOUS USES OF WATER SPRAYS**

Water sprays and mists have long been considered as means of mitigating fires and explosions and water and foam are still the primary fire fighting agent<sup>(3)</sup> in use world-wide. Their applications include protection during:

- Liquid fuel pool fires
- Storage tank cooling
- Radiation barriers
- Blow-out fires / flame jets
- Hydrocarbon mist and coal mines explosions
- Dilution of flammable mixtures
- Explosions in flammable gaseous mixtures

Whilst not of immediate and obvious relevance, a recent review<sup>(4)</sup> of some of the above applications gives an insight into the potential mitigation mechanisms and effectiveness of water sprays against propagating explosions. Vincent and Howard<sup>(5)</sup> for example investigated the mitigation of combustion of suspensions of fine droplets of heavy hydrocarbons in air (Dowtherm A) and found that water sprays limited fuel concentration to less than the lower flammability limit. They concluded that the sprays ‘scrubbed’ the mist particles away. Watts<sup>(6)</sup> also used water sprays to reduce the concentration of ethylene-air mixtures to below the lower flammability limit. The sprays were effective in this instance because of air entrainment effects, due to water spray motion, but the sprays were ineffective in extinguishing combustion once it

had started. Sprays did however increase the minimum energy required for direct ignition of detonation in the same mixture by PETN, a solid explosive. Thus, even though the source was more energetic, some beneficial mitigation effect was similarly increased.

### **Laboratory Studies**

Small scale experiments have also shown that mists and sprays may also be effective directly against combustion. Sapko *et al.*<sup>(7)</sup> and later Zalosh and Bajpai<sup>(8)</sup> showed that fine water mists can mitigate combustion in two ways. First, fine sprays can inert a gaseous mixture preventing flame propagation away from an ignition source. Second, with sufficiently dense sprays, it is possible to quench an already well established propagating flame. In the latter case the spray density required is significantly greater than that required to inert the same mixture. In both cases a significant fraction of the droplets comprising the spray must be fine enough for them to evaporate within the combustion zone of a propagating flame. For methane air flames, Sapko *et al.*<sup>(7)</sup> estimated the critical droplet diameter to be of the order of 18  $\mu\text{m}$ . Larger droplets also extract latent heat from the reaction products as they continue to evaporate, and may contribute to a longer term reduction in overall pressure and impulse, but they no longer influence the combustion zone.

When applied to small scale explosions, where the combustion front is now turbulent, a significant reduction in impulse was reported by Thomas *et al.*<sup>(9,10)</sup> who mitigated accelerated methane-air flames by water sprays in a 5 m long, 76 mm diameter pipe. More recent work by Thomas and Brenton<sup>(11)</sup> confirmed the findings that mitigation was related to the degree of gas flow acceleration developed in the vicinity of the spray. This finding is consistent with the observations of Watts<sup>(6)</sup>, noted above, that when an energetic PETN source was used the degree of explosion suppression in the surrounding gas was increased, due to the accompanying strong blast wave.



## Reduced Scale Studies

Evidence of the effectiveness of sprays as an explosion mitigant has also been reported from larger scale experimental studies. Acton *et al.*<sup>(12)</sup> observed that water sprays limited overpressures in natural gas-air and propane-air explosions, whilst Bjerketvedt and Bjorkhaug<sup>(13)</sup> obtained reduced explosion severity in a 1/5 scale model of an offshore module when sprays were present. The effectiveness of general area deluge in limiting overpressures in much larger volumes explosions has also been demonstrated<sup>(13,14,2)</sup>, although local enhancement in early pressure time histories are observed in nearly all tests where water deluge is used, even if overall the event was mitigated.

## Preliminary Conclusions

Based on the above observations, the following general conclusions can be drawn. First, for sprays and mists to be effective as mitigating agents, quenching combustion and thus limiting further overpressure development, it is necessary for droplets to evaporate within the combustion zone of a propagating flame, Simple analytical calculations<sup>(7)</sup> show that individual droplets must be of the order of only a few tens of microns in diameter. Droplets continue to evaporate after they have passed through the flame but the subsequent cooling of the products is not sufficient to cause flame quenching nor give sufficiently fast reduction in overpressure. Despite this observation, sprays with large droplet size distributions (of the order of millimetres) *have* been shown to be effective. This combined with earlier findings lead to the inescapable conclusion that some form of droplet fragmentation process must occur.

The break-up of sprays in high speed flows has been the subject of significant research effort over the years, some of it concerned with the detonation of clouds of flammable droplets<sup>(15,16)</sup>. In the detonation case a fine flammable mist is formed rapidly following aerodynamic break-up. In

a complementary study, Thomas *et al.*<sup>(17)</sup> showed that water droplets could mitigate an established gaseous detonation, as the water mist residue cooled and quenched chemical reaction. The preceding studies were both based on existing knowledge on the aerodynamic break-up of water sprays behind steady planar shock waves. Explosion flows however are transient, the pressure and gas flow velocity generally increase with time, and only limited data exists on the behaviour of droplets in such flow fields.

### **Issues Identified**

Bases on the above, several questions now arise when attempting to quantify the possible extent of explosion mitigation by water sprays. First, what quantity of sprays of given size distributions are required to quench propagating flames? Second, under what conditions will sprays with large size distributions undergo aero-dynamic break-up to give the fine mist characteristics required for combustion mitigation? Third, to what extent will the process of introducing the sprays provide a means of aggravating an explosion if it is not effective as a mitigant?

### **COMBUSTION IN SPRAY GENERATED TURBULENCE**

When any water spray is activated some fraction of its momentum is transferred to the ambient gas and, inevitably, will give rise to turbulence in the gas phase. This can arise due to droplet motion through the gas, which can leave turbulent wakes, or viscous interaction of the bulk gas flow with obstacles or the vessel walls *etc.* As the combustion rates of flammable gases are known to be a function of the gas phase turbulence intensity, see for example Abdel-Gayed *et al.*<sup>(18)</sup>, this could present an unacceptable situation if the rates of combustion were unduly exacerbated by spray induced turbulence. Thomas and Brenton<sup>(19)</sup> as well as Wingerden and Wilkins<sup>(20)</sup> have conducted short series of experiments to investigate the degree of flame

acceleration in methane- and propane-air flames as they propagated through volumes into which water sprays were continuously discharged.

### **Small Scale Experimental Studies**

Brenton and Thomas<sup>(19)</sup> conducted experiments in a vessel 2.40m high, 0.30m wide and 0.21m deep container, shown in Figure 1. The nozzles used were a range of small and medium sized industrial nozzles manufactured by Lurmark. Equi-spaced clusters nozzles were used to try to ensure uniform spray densities. Spray droplet size distribution parameters<sup>(21, 22)</sup> were measured at several locations below the spray injection plane using commercial Dantec particle dynamics and Malvern particle size analysers. These measurements indicated sprays with mean droplet diameter,  $D_{10}$ , of the order 100-350  $\mu\text{m}$ . The authors however noted significant discrepancies between the measurements from the two techniques, an issue also discussed by Lefebvre<sup>(22)</sup>. A typical spray size distribution is given in Figure 2 (a). Data from both Malvern and Dantec systems, obtained at various distance below one of the sprays used for the present tests are shown in Figure 2 (b), where the size parameter plotted is  $D_{32}$ , the ratio of droplet volume to surface area. Data for all of the present sprays are summarised on Table 1. Vertical velocity measurements, mass flux and droplet spacing and number density are shown in Table 2.

Wingarden and Wilkins<sup>(20)</sup> used a 1.5  $\text{m}^3$  cubical container and sprays with mean droplet diameters ranging from 40-800  $\mu\text{m}$ . Droplet sizes in this case were based on manufacturers data. In both experiments the spray was allowed to establish for five to ten seconds before the spark was ignited and the subsequent flames observed using video cameras. Typical flame velocity measurements obtained by Thomas and Brenton<sup>(19)</sup> are presented in Table 3. In general a three fold increase in flame front velocity was obtained when water sprays were active. This result was confirmed by the observations of Wingarden and Wilkins<sup>(20)</sup>. Visually, the unsprayed flame

fronts had thin smooth profiles whereas the sprayed flame fronts were thicker and brighter, yellow as opposed to blue, in a manner characteristic of turbulent flames.

The Reynolds number,  $Re = \rho uL/\mu$ , is widely used to characterise fluid flows. Here  $\rho$  is the fluid density,  $L$  a characteristic length scale and  $\mu$  the dynamic viscosity of the fluid, velocity  $u$ . As an example, for pipe flows with  $Re < 2000$  are normally laminar and above this they become turbulent. In the experimental configuration shown in Figure 1 two length scales can be used. The first is characteristic of the vessel and the second is the dominant droplet diameter in the spray. Reynolds numbers based on the droplet size computed by Thomas and Brenton<sup>(19)</sup> are given in Table 4. These are small but of the order where disturbance in wake flow can occur<sup>(23)</sup>.

The Reynolds numbers based on the vessel width were however an order or so greater than those required for turbulence in pipe flows, see Table 4 again. Further evidence in support of the dominance of large scale turbulence came during a test<sup>(19)</sup> where the spray was run for five seconds and then stopped. A further five seconds elapsed before ignition, by which time the vessel was clear of spray but flame acceleration was still observed. Finally, both studies included predictions of turbulent burning velocities that were in good agreement with the experimental measurements, see Table 4 for example. Both investigations used published correlations<sup>(18, 24)</sup> for turbulence intensities based on the bulk gas flow.

## **AERODYNAMIC BREAK-UP OF DROPLETS**

### **Previous Studies**

A number of previous studies exist on the aerodynamic break-up of droplets and these have been combined in an extensive review by Pilch and Erdman<sup>(25)</sup>. These authors also presented correlations of critical conditions for the onset of break-up, in terms of initial droplet diameter,

liquid surface tension and density and gas flow velocity relative to the droplet. These combine in the Weber number,

$$\text{We} = \frac{rv^2 \rho_g}{\sigma_l} \quad (1)$$

where  $r$  and  $\sigma_l$  are the droplet radius and surface tension and  $v$  and  $\rho_g$  are the gas velocity and density respectively, which can be correlated with the various break-up modes that have been observed.

Lane<sup>(26)</sup> provided an early summary of studies of droplet shattering in streams of air. For drops with diameters ranging from 0.5 to 5.0 mm a relationship ( $v^2d = \text{constant}$ ) was observed to hold between droplet diameter and the critical relative flow velocity required for break-up. Later Hanson *et al.*<sup>(27)</sup> observed a critical Weber number of 3.6-71 for bag type break-up and for water obtained a value of  $0.45 \times 10^6$  for the constant in the equation by Lane, using the strictly incorrect combination of  $v$  in  $\text{ms}^{-1}$  and  $d$  in  $\mu\text{m}$ . More recent work has been summarised by Pilch and Erdman<sup>(25)</sup>, much of it of relevance to explosion mitigation but with one important difference. In the majority of previous experiments the droplets were subjected to instantaneous changes in the ambient gas velocity behind a shock front. In an explosion however the droplet is more likely to experience a flow that accelerates as the explosion evolves. Under these conditions, different modes of break-up may be observed. Pilch and Erdman<sup>(25)</sup> may unfortunately not have considered fully some aspects of the work by Lane<sup>(26)</sup>. The latter noted the difference in modes of break-up between drops in steady streams of air and those exposed to transient blasts. Lane also noted that transient flows could bring about the same mode of break-up at a lower velocity than a steady flow. Less work on droplet dynamics in transient flows has been reported, see for example

Temkin and Mehta<sup>(27)</sup>. In more recent studies, Thomas and Brenton<sup>(19)</sup> and Yates<sup>(28)</sup> considered droplet motion in transient flows and verified the validity of an existing break-up criterion.

### Simple Model For Droplet Dynamics

Using a simple analytical model Thomas and Brenton<sup>(19)</sup> predicted droplet acceleration in one-dimensional gas flows, due to drag forces resulting from the velocity difference between the droplet and gas. The velocity term used was the instantaneous relative velocity  $v_r$  between the gas phase the droplet and the local instantaneous gas density,  $\rho_g$ . The force  $F$  acting on the droplet, of radius  $r$ , is then given by the usual drag law

$$F = \frac{1}{2} \rho_g v_r^2 C_d A \quad (2)$$

where the area  $A$  is the projected droplet area,  $\pi r^2$ , and  $C_d$  a drag coefficient. The instantaneous droplet acceleration and displacement were then obtained by integrating the droplet equation of motion using a simple Runge-Kutta routine.

The expression for the drag coefficient  $C_d$  was based on correlations of measured values for spheres as a function of Reynolds number,  $Re$ . The exact expression used was that given by Wallis<sup>(29)</sup>,

$$C_d = \frac{24}{Re} (1.0 + 0.15 Re^{0.67}) \quad (3)$$

In this way, it was possible to obtain information on droplet acceleration, instantaneous velocity and displacement. More importantly, for the present interest, information was available on the instantaneous velocity difference between the gas and the moving droplet that allows an instantaneous Weber number to be computed.

To illustrate the likely behaviour of droplets in an accelerating flow they first investigated with gas flow where the rate of acceleration was constant. However, as rate of change of gas pressure is the primary variable measured in experiments, a fixed rate of change in the gas pressure was also considered with the time resolved change in the gas velocity computed from the standard relationship for finite amplitude waves in one dimension

$$v_g = \frac{2c_0}{\gamma - 1} \left(1 - P^{\frac{\gamma-1}{2\gamma}}\right), \quad (4)$$

where  $v_g$  is the gas velocity,  $c_0$  is the velocity of sound speed in the gas and  $\gamma$  the ratio of principal specific heats. The pressure  $P$  is normalised to atmospheric pressure.

What emerged was that for any given droplet size and a steady rate of gas flow acceleration, droplets are accelerated until they attain an acceleration equal to that of the gas. At this point a constant velocity difference (and hence steady drag force) exists between the drop and gas flow. The time taken by droplets to accelerate to a steady velocity is also an important parameter and this time increases as the droplet diameter is increased, due to the increased mass and inertia of larger droplets. From these transient velocity histories, examples of which are shown in Figure 3(a), it is then possible to derive instantaneous Weber numbers based on the relative velocity between the gas flow and droplet. The time-resolved Weber numbers developed under the conditions shown in Figure 3(a) are presented in Figure 3(b).

### **Critical Rates Of Acceleration**

One consequence of the above analysis is that, for the same gas flow, small droplets will not achieve large values of Weber number, as they accelerate rapidly to match the gas acceleration. The maximum Weber number exhibited by the droplets thus increases as the diameter is

increased and this provides a means of identifying a possible critical condition for the onset of droplet break-up. In shock studies<sup>(25)</sup> a Weber number of 12 is found to define the boundary beyond which fragmentation is observed to occur. In Figure 4, the time required to attain a critical Weber number value of 12 is plotted as a function of a theoretical rate of pressure rise for range of droplet diameters in accelerating flows. The result is a series of curves, each of which defines a boundary at each rate of pressure rise below which droplets of certain sizes *will not* break-up. Below the curves, the critical Weber number condition of 12 is never attained. These results also indicate the time to onset of break-up for any given condition. As an example, for break-up of a 0.2 mm droplet to occur in less than 5 milliseconds requires a rate of pressure rise of the order of  $100 \text{ bar s}^{-1}$ , whereas the onset of break-up is predicted for a 4 mm droplet at some  $15 \text{ bar s}^{-1}$  after the same time period has elapsed. A similar plot for water droplets with added surfactant is reproduced in Figure 5. A slight shift in critical conditions is suggested, resulting in slightly lower critical values for rate of pressure rise when surfactant is used compared to water alone.

### **Experimental Study**

In addition to simple calculations, a parallel experimental programme was also undertaken<sup>(11, 28)</sup>. Droplets in free flight were synchronised with a transient expansion flow in a one-dimensional. Direct visualisation of the droplets using macro-cine methods allowed the conditions for break-up to be determined. Examples of video and cine images obtained of the break -up of 4 mm droplets are shown in Figure 6 and 7. These show catastrophic break-up in Figure 6 and a much slower near critical case, Figure 7. The larger droplets were initially of the order 4 mm. In Figure 7, which also had 2% added surfactant, a 2mm droplet is also visible initially. From such observations, data on the occurrence or otherwise of break-up within given times can then be

compared with theoretical predications. These results are reproduced in Figure 8, where good agreement can be seen. A critical Weber number of 12 thus appears to hold for both steady and transient flows.

### **Simulated polydisperse sprays**

In addition to single droplet tests, the response of simulated sprays has also been investigated<sup>(28)</sup>. These were generated using a brass manifold crudely drilled with 21 equi-spaced holes in a 3×7 pattern. Water flow to the manifold was controlled by a solenoid valve and the expansion fan initiated when spray was detected at the base of the observation window. A rapid onset of spray break-up into fine mist was again observed, see Figure 9. Both single droplet and simulated sprays thus indicate that break-up of large droplets (several millimetre diameter) can occur in under 10 ms and that significant fine mist can be produced over the same time scale. These times are also relatively short compared to the duration of explosions in large volume enclosures.

## **QUENCHING OF LAMINAR COMBUSTION**

As described in the preceding sections, it is now known that that significant aerodynamic shattering of large droplets can occur in explosion flows and that mitigation by water sprays during explosions is probably due to the quenching of combustion by the residual mist. However, before the potential effectiveness of these residues can be estimated, there is a need to understand their interaction with flames and to quantify the optimum characteristics required to quench a propagating flame. Thomas and Brenton<sup>(11)</sup> first reported the results of such a study, based on calculations using the Sandia flame code<sup>(30,31,32)</sup>, to investigate the limits of water vapour and droplet concentration below which a laminar methane-air is incapable of self-sustained propagation.

## Burning Velocity Calculations

The Sandia Premix flame code is a one-dimensional model for calculating the properties of steady laminar pre-mixed flames. Thomas<sup>(33)</sup> has recently extended this to include a more accurate model for droplet motion and heat, mass and momentum transfer between the droplets and gas. A simple drag law was used in the droplet equation of motion while the droplet evaporation rate was given by a simple '*d squared*' law

$$d^2 = d_0^2 - kt \quad (5)$$

which allows the instantaneous rate of mass loss due to evaporation at any time  $t$  to be computed from a droplet diameter  $d$ , initial diameter  $d_0$ . This is a simple formulation to implement but, as is shown by Sirignano<sup>(34)</sup>, provides a model of droplet evaporation that compares favourably with other more complex models.

To allow the evaporation rate to reflect the local conditions through the flame, Thomas<sup>(33)</sup> used a dynamic formulation<sup>(35)</sup> for the evaporation rate constant  $k$ , given by

$$k = \left( \frac{8\lambda}{\rho_l c_p} \right) \ln \left[ 1 + \frac{c_p}{L} (T_f - T_s) \right] \quad (6)$$

where  $\lambda$  and  $c_p$  are the gas thermal conductivity and heat capacity,  $\rho_l$  the liquid density,  $L$  the latent heat of vaporisation and  $T_s$  and  $T_f$  are the surface and flame temperatures respectively. All of these parameters were computed as part of the flame solution. The influence of pure water vapour gave a quenching limit in agreement with published data. The burning velocity decreases as the fraction of water vapour dilution increases and the water vapour limit of 25% is consistent with the experimental value of 26.5% reported by Coward and Gleadall<sup>(36)</sup>. A more detailed

investigation of the influence of humidity on natural gas-air mixtures was reported recently by Dlugogorski *et al.*<sup>(37)</sup>.

### **Influence of droplet size and number density**

Using the analysis described above burning velocities of stoichiometric methane-air flames were computed<sup>(33)</sup>, including a loss term based on the individual evaporation histories of increasing initial number densities of monodisperse droplets. The calculated burning velocities for a range of droplet sizes and number densities are summarised in Figure 10. Other calculations showed that the contribution to the reduction in burning velocity from heat transfer was significant in the pre-heat and exothermic reaction zones and that the addition of water vapour from evaporating droplets had a much less marked effect. Lentati and Chelliah<sup>(38)</sup>, who undertook computations for counterflow flames, observed that 15  $\mu\text{m}$  droplets were the most efficient, with the maximum droplets evaporation occurring at the plane of maximum rate of formation of radicals.

### **Alkali Salts**

Thomas<sup>(33)</sup> also studied the influence of potassium chloride solutions on flame quenching. Table 5 shows the results of flame calculations for increasing molar fraction of KCl in water for droplets of initial diameters 10 and 20  $\mu\text{m}$  and two loading densities. A definite influence on burning velocity was observed, arising from the influence of alkali salts (Na, K *etc.*) on reactions involving the OH radical. Unfortunately little experimental data exists in this area. Zheng<sup>(39)</sup> and Zheng *et al.*<sup>(40)</sup> recently demonstrated changes in extinction limits when NaCl solutions were used in counter-flow flames and Mitani and Niioka<sup>(41)</sup> also observed further reductions in burning velocities in ethylene flames when salts were added to water mists.

## Comparison With Analytical Models

Finally, Thomas<sup>(33)</sup> has compared burning velocity predictions with an analytical model for flame inhibition by inert dust and sprays developed by Mitani<sup>(42,43)</sup>. Although in apparently reasonable agreement, the analytical and Sandia solutions diverged for larger and smaller droplets.

Proust<sup>(44)</sup> has also compared experimental data of droplet evaporation with flame extinction criterion based on the work of Joulin<sup>(45)</sup>. A reasonable correlation of variations in burning velocity with parameters characterising the mists was found. Some of these data are reproduced in Table 6 but only a limited comparison with the predictions of Thomas<sup>(33)</sup> is possible. The experimental burning velocity data gives estimated droplet loading densities some ten times less than the numerical predictions for mono-disperse droplets.

Proust<sup>(44)</sup> also noted a significant disagreement between the theoretical predictions<sup>(45)</sup> and a small number of measurements of quenching limits. The theory of Joulin predicted limits at larger mean droplet diameters and lower number densities than was observed in experiments. A probable cause for the apparent failure of the Joulin model is that it does not allow for particle evaporation. Experimentally, quenching was obtained at loading density of the order 0.4-0.5 kg m<sup>-3</sup> and droplet Sauter mean diameters smaller than 40 µm. These give critical droplet number densities in excess of  $1.0 \times 10^{10} \text{ m}^{-3}$ , now of the same order of magnitude as the predictions of Thomas<sup>(32)</sup>. It is worth noting however that Proust observed the flames became unstable in many experiments and this may explain variations between the two experimental data sets.

## MITIGATION OF SMALL-SCALE EXPLOSIONS

The results described in the preceding sections have identified the potential contributions of various physical and chemical process to explosion mitigation. The existence of critical

conditions below which mitigating effects would not be obtained have been identified, with the main controlling factor being the degree of gas flow acceleration generated ahead of the combustion front. To investigate the effective of the relevant physical processes, under conditions closer to practical explosions, further tests were undertaken to monitor spray dynamics in response to propagating methane-air explosions in a 175 x 250 mm cross section tube. The aim was to monitor whether break-up criterion obtained from the laboratory studies were valid in an accelerating one-dimensional explosion flow.

### **Experimental Details**

The experiments were performed in a rectangular flame tube, configured as shown in Figure 11(a). The internal cross section of the tube was 175 x 275 mm with an overall length of the order of 5.32 m. A central section was fitted with three pairs of opposing glass windows that allowed optical access across the shorter side. A 0.247 m diameter 1 m long driver section ignited at the closed end was used to provide the source of accelerating flow fields in the test section. The acceleration was promoted by the slight change in cross-sections and accelerated further in some tests by the use of a grid plate inserted at the area change.

A high speed video camera was used to monitor the spray motion (typical camera frame rate was 1,000 frames per second). This visualisation was achieved either by direct observation of emission or by back lighting the window section using halogen lamps and observing any attenuation caused by the sprays. Pressure gauges, photo-diodes and thermocouples were used to monitor pressure and flame front development. The diagnostics deployed was varied during the course of the testing with a move away from photo-diodes for flame detection to the use of thermocouples. Also used was a novel combined laser diode-photodiode pair. Located in diametrically opposing ports, the laser illuminated the diode and spray could be detected as it

attenuated the transmitted laser beam, resulting in a *decrease* in the photodiode signal. At the same time, the diode could detect flame arrival by the attendant *increase* in emission. The various sensor locations used during the tests are summarised in Table 7.

To promote the development of explosion overpressures a grid was inserted between the 0.247 mm diameter tube and the rectangular section. The gas mixtures were prepared by a recirculation method with the methane added as required to give the desired final mixture gas concentration. An A.D.C. infra red absorption analyser was used to sample the resulting gas mixture and determine the exact methane concentration. This method of producing the test mixture required a fully closed tube. Therefore, before each test, a swinging axe-head was released which ruptured a paper diaphragm at the end of the tube away from the ignition point allowing flame propagation towards an open end.

Sprays could be introduced into the tube through a maximum of three pairs of nozzles in the window section. For the initial tests, only one port was used. The nozzles used were six clusters of three Lurmark Fn 4.0 nozzles delivering 44 litres  $\text{min}^{-1}$  and or six single Lurmark Fn 17 nozzles delivering 51 litres  $\text{min}^{-1}$ . They were supplied with water or water/surfactant mix by a pump which produced pressures up to 700 kPa. Droplet size distributions and volume fractions were measured *in situ* and the measured distributions are summarised in Tables 8 and 9. The three measuring positions were all 145 mm directly below a nozzle in the centre of the spray and positions 43 mm, 53 mm and 63 mm to the side of the centre line.

Three pairs of nozzle heads were used, placed in staggered opposition along the longest sides of the tube. The sprays on opposing walls were staggered so that they did not impinge directly but gave alternating series of sprays fans along the tube. This is shown schematically in Figure 11 (b). This configuration was chosen because the interaction of opposing sprays at the mid point of

the tube creates areas where the spray coverage is poor, see Figure 11 (c). The extended sprays were located at four different location along the tube, as shown in Table 10. The water sprays, when used, were activated five seconds prior to ignition, which was effected by a spark at the closed end of the tube. Further details can be found in Yates<sup>(28)</sup>

### **Experimental Observations Of Spray Dynamics And Mitigation**

The majority of the tests were with the coarser Fn 17 water sprays without surfactant. The maximum pressure rises quoted are always based on records from the gauge closest to the centre of the spray.

Typical pressure records with and without sprays obtained at gauge positions 1, 3 and 4 are shown in Figure 12. In Figure 12 (a), for 10.1 % methane in air, with Fn 17 spray in operation, four phases may be identified. First, a gradual pressure rise occurs due to combustion in the ‘driver’ volume. This is followed by a rapid pressure rise as the flame propagates through the area change. The pressure pulse can also be seen to propagate along the tube. Rapid mitigation then occurs and there is a sudden fall in pressure. This rapid pressure drop was observed in all tests where mitigation occurred. The pressure increase after 200 ms is due to heat transfer to the gauges, which gives rise to an apparent pressure increase due the thermo-electric effect. Pressure records obtained in a test with 10.7% methane in air are shown in Figure 12 (b). Here the first two phases are observed again but, without a spray in use, the second pressure rise is greater than in the mitigated test. Also visible on these records is a second pressure rise, easily seen a double pressure pulse on the final gauge. This is caused by pressure generated from an external explosion propagating into the tube. The maximum rates of pressure rise measured at gauge location 2 were  $1.2 \text{ bar s}^{-1}$  for the 10.1% test and  $21.5 \text{ bar s}^{-1}$  for the unmitigated 10.7% methane test. A test at 8.25% methane was mitigated at a pressure increase of  $22.5 \text{ bar s}^{-1}$ . A test at 7.0%

methane was similarly mitigated at *ca.* 6.5 bar s<sup>-1</sup> whereas a test at 7.6% was not, when the maximum rate of pressure rise was *ca.* 2 bar s<sup>-1</sup>. The corresponding pressure records for the latter two tests are shown in Figure 13. The different times of occurrence of the first peak pressure reflects the increased flame speed in the 7.6% and clearly illustrate the importance of the initial flame acceleration events on the likelihood of mitigation. The oscillations seen for the 7.6% test are due to acoustic oscillations within the tube.

With the coarser spray at the second spray location a tests at 6.6% was mitigated, with a limited pressure rises of 1.2 bar s<sup>-1</sup> whereas. A test at 7.6 % methane was not however mitigated whilst a test at 8.0% was. The corresponding rates of pressure rise were 3.3 and 15.2 bar s<sup>-1</sup>. Outputs from the laser diode-photodiode pair are shown in Figure 14 (a) and (b). There is clear evidence of flame emission with the 7.6% test, indicating flame propagation along the entire tube. At 8.0% however there is no evidence of flame arrival. When the Fn 17 spray was replaced by the Fn 4 nozzles, Figure 14 (c), there was clear evidence of attenuation and hence of significant quantities of spray arriving at the end of the tube, in this case with 8.3% methane and a maximum rate of pressure rise of *ca.* 30 bar s<sup>-1</sup>.

When the spray was moved to the third location a 6.7% methane-air mixtures quenched and no temperature rise was observed at the final thermocouple location. Also, there was no evidence of flame emission in the window on the video sequence. For 7.5 % methane, combustion did propagate through the spray although there was little evidence of excessive pressure at the end of the tube and low flame emission at the end laser-diode gauge. For tests at 8.2% and 9.5 % the combustion was extinguished in both cases. The laser-photodiode sensor shows increased spray at the end of the tube for the 9.5 % test. The general trends were again as shown in Figure 14. The rates of maximum rates of pressure rise measured during these tests were 14.4 bar s<sup>-1</sup> for the

8.2% test and  $26.7 \text{ bar s}^{-1}$  for the 9.5 % test. The corresponding value in the 7.5% tests was ca.  $8.3 \text{ bar s}^{-1}$ .

With the spray at the fourth and furthest location a test at 10 % methane was obviously quenched and distinct evidence of spray break-up was observed on the video. At 7.9% significant spray motion was observed on the final laser-photodiode sensor and a small temperature decrease was measured by the co-located thermocouple. At 6.7 % spray arrival was again inferred from the laser-photodiode record but in this case there was clear evidence of flame propagation along the entire length of the tube. The measured rates of pressure rise were 24, 6.3 and  $3.8 \text{ bar s}^{-1}$  for the 10%, 7.9% and 6.7 % mixtures respectively. With the introduction of the grid, the rates of pressure rises at mixture compositions comparable to two of those in the previous section were 95, 1.6 and  $2.6 \text{ bar s}^{-1}$  for 9.8 %, 6.7 % and 6.9%. For the lower methane concentrations the rates of pressure rise were significantly less, see Figure 15. In both cases spray arrival at the end of the tube was observed. In the 6.9% cases no emission is seen over the recording time whereas there is an indication of emission for the 6.7 % tests. The increase in output signal after initial spray arrival coincided exactly with an increase in output from the final co-located thermocouple.

The addition of surfactant had little significant effect in this configuration. The pressure and laser-photodiode gauge were generally very similar to those obtained with water only. With the spray at the fourth location, mitigation was observed by the end of the tube for an 8.7% methane in air mixture, see Figure 16 (a). This plot shows the outputs for the emission/attenuation sensor located at the end of the tube, as well as the corresponding thermocouple output. Whilst spray is detected, there is no evidence of flame. However, at a methane concentration of 6.9%, Fig 16 (b), there is now no mitigation despite the appearance of mist.

### **Correlation Of Mitigation With Pressure Data**

Based on the tests outlined in the previous sections, rates of pressure rise have been computed and plotted as a function of mixture concentration. This data is shown in Figure 17. Also indicated on this plot is whether the explosion was mitigated (closed symbols) or whether flame propagated to the end of the test section (open symbols). From this data it is possible to conclude that mitigation was observed in all of the present tests if the rate of pressure rise was in excess of some  $10 \text{ bar s}^{-1}$ . As an example, assuming a one-dimensional flow and using the appropriate gasdynamic relationship, this correspond the gas accelerating to  $50 \text{ ms}^{-1}$  in 20 ms whilst the pressure increases to 0.2 barg.

Figure 18 presents data on the observation durations and the influence on break-up, as a function of rate of pressure rise. The  $10 \text{ bar s}^{-1}$  limit condition is again seen. Also re-plotted on this figure are the theoretical predictions presented previously in Figure 4. Curves for mono-disperse droplets of diameter 0.4 mm, 1.0 mm and 2.0 mm are included. The best agreement appears to be with the 2 mm droplet data. The Sauter mean diameter of the Fn 17 spray used was of the order of 0.39 mm and the mean diameter was of the order 0.12 mm. A typical droplet size histogram for this spray is shown in Figure 19 where a few droplets as large as 0.8 mm were recorded

## DISCUSSION

### **Criterion for Aerodynamic Break-up**

The role of aerodynamic break-up process in explosion mitigation by water sprays has now been demonstrated unequivocally and mitigation is intimately linked to droplet acceleration characteristics. This is directly linked to the local acceleration of the gas and related droplet acceleration. If the relatively velocity between the gas and droplet is such that a Weber number of 12 can be obtained and maintained for a sufficient time then droplet break-up will occur. This prediction appears to agree well with laboratory observations of critical break-up conditions. In

small scale transient explosions however the break-up and mitigation appeared to occur more easily. This might be due to errors in the size distribution measurements or alternatively because break-up eventually occurred over the slightly longer time scales developed in the small scale tests. The laboratory measurements and theoretical predictions would thus provide a conservative break-up and mitigation criterion.

One outstanding issue is the size of the mist residue. Unpublished photographic evidence that suggests the mist is less than a few microns in size, an inference supported by the extremely rapid acceleration of the residue once it enters the free gas stream. The short duration and relatively high mist densities have not allowed direct measurements by laser diagnostic techniques up to the present.

Acceleration of the fine residue was also clearly evident in the present small scale explosion tests, where mist residue was advected rapidly to the end and out of the test section. In practical explosions this could be significant if the break-up occurs too early and the potential mitigant is vented out of the volume to be protected before the combustion front arrives.

### **Flame Quenching Efficiency of Water vapour And Mono-Dispersed Droplets**

Both water vapour and water sprays can be effective in mitigating combustion. For mono-disperse droplets the critical number densities obtained from the calculations of Thomas<sup>(32)</sup> are summarised in Table 11. The experimental limit reported by Coward and Gleadall<sup>(36)</sup> of 26.5% water vapour in a molar methane-air mixture equates to  $0.21 \text{ kg m}^{-3}$  of vapour in the fuel-air mixture. The limit indicated by predictions of laminar flame quenching by  $10 \text{ }\mu\text{m}$  droplets however requires a critical loading density is of the order of  $0.06 \text{ kg m}^{-3}$ . It would appear therefore that, for droplets with diameters of up to  $20 \text{ }\mu\text{m}$ , a constant spray density of  $0.06 \text{ kg m}^{-3}$  results in extinction. As the droplet size increases further, to  $100 \text{ }\mu\text{m}$ , the spray mass density (and

corresponding volume fraction) increases by an order of magnitude. These measurements are consistent with the experimental results reported by Zalosh and Bajpai<sup>(7)</sup>, for lean hydrogen-air mixtures where the critical loading densities were in the range 0.1 to 1.0 kg m<sup>-3</sup> for droplet in the range 20 to 100 μm. Loading densities of 0.08 kg m<sup>-3</sup> gave a 50% reduction in burning velocity<sup>(8)</sup> in atmospheric ethylene-air for microns sized droplets. For pure vapour, the limiting concentration equates to 0.23 kg vapour per kg of air, compared to 0.05 kg per kg of air for droplets. Thus droplets appear to be more effective than pure vapour.

### **Turbulent flames**

It is important to note that the limit calculations for droplet number densities were made for laminar flames. For turbulent flames the flame front surfaces are highly convoluted. The effects that this flame front turbulence has on the predicting quenching limits is not known. Even assuming that the turbulent flame front is still composed of small laminar elements, termed laminar flamelets, the repeated passage of the flame boundary over droplets variations will alter the effective droplet residence time. Alternatively, the turbulent flame may be assumed to have a much wider overall exothermic reaction zone than that found in a laminar flame. This thickening might lead to increased residence times and might perhaps explain the increased effectiveness of smaller diameter sprays in transient explosions described above. It should also be noted that studies with counterflow flames<sup>(38-40)</sup> have shown that laminar flame fronts are more susceptible to strain and that this could be a beneficial aspect of turbulent flames. If the laminar flamelet concept holds.

Increase in turbulent combustion velocities and associated overpressures are virtually inevitable as sprays are introduced into large volumes. The existing studies all suggest that an increase in burning velocity of some three times the velocity without sprays are generally for observed.

Whether mitigation occurs is then dependent on the local rates of velocity increase and the related droplet acceleration rates. As the acceleration of gas flows in explosions is dependent on local levels of congestion and confinement, this potential effectiveness of water sprays will thus be extremely geometry dependent.

### **Incorporation Into CFD Models**

Predictions of the likely onset of aero-dynamic break-up of droplets should be possible with advanced computational fluid dynamic (CFD) codes if accurate gas velocity data, spray size distributions and loading densities are available. The use of a critical Weber number of 12 appears to be appropriate. Inferences from pressure data alone are not sufficient in complex three-dimensional geometries and the local gas velocities and densities must be used.

### **Effectiveness In Practice**

Finally, in practice, water sprays can be effective at a large scale. This can be seen in Figure 20, which illustrates the increased efficiency of overpressure reduction obtained when suitable water sprays were used in recent large scale JIP experiments simulating an offshore platform configuration<sup>(46)</sup>. The efficiency was defined as the ratio of the reduction in overpressure to the pressure in the corresponding dry test. Despite the limited number of test available the results shown an encouraging trend with increasing mitigation when sprays were used, as the corresponding 'dry' explosion severity increased.

## **SUMMARY OF CONCLUSIONS**

One-dimensional calculations of the influence of droplet evaporation on the extinction limits of stoichiometric methane-air flames permit mitigation criteria to be estimated for mono-disperse sprays. For realistic polydisperse sprays, the major contribution to extinction will come from

those droplets with diameters less than 50  $\mu\text{m}$  and the work highlights the need for accurate characterisation of poly-disperse sprays, in particular of that fraction below 30  $\mu\text{m}$ .

The effectiveness of water sprays in practical explosions is linked to the initial explosion severity. The controlling physical mechanism is the relative acceleration of droplets compared to the accelerating gas flow. Larger droplets ( $>1\text{ mm}$ ) can thus be very effective due to their larger inertia, whereas smaller droplets accelerate to match the gas flow. The slower acceleration of larger droplets leads to increased instantaneous velocity differences between the gas and droplets, which can then be incorporated into a mitigation criterion based on the non-dimensional Weber number. A critical Weber number of 12 gave good agreement for transient flows of droplets under laboratory conditions. A similar behaviour was found to hold for small-scale transient explosions in methane-air. From a theoretical standpoint the use of surfactant appears to offer some potential additional benefit but this was not evident in practice. It may be that the effect of the surfactant on foaming during the injection process may counteract any other benefits. The addition of alkali salts, such as a brine, should also improve the effectiveness of mitigation and limited laboratory data exists to support this view.

## **ACKNOWLEDGEMENTS**

The experimental tests performed at Aberystwyth were undertaken variously by John Brenton, Alwyn Jones, Sian Jones, Gwyn Oakley and Mark Yates and their significant contribution is gratefully acknowledged. Access to the PDA Droplet Sizing equipment at the Department of Mechanical Engineering, Cardiff University, was by kind arrangement with Dr. Phil Bowen. Financial support for this work was forthcoming at various times from British Gas, EPSRC and

Marine Technology Directorate (GR/K19969), Mobil North Sea and UK HSE Offshore Safety  
Division.

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| Spray       | Water Pressure (kPa) | PDA D10 ( $\mu\text{m}$ ) | Malvern D10 ( $\mu\text{m}$ ) | Mean D10 ( $\mu\text{m}$ ) | Velocity ( $\text{ms}^{-1}$ ) |
|-------------|----------------------|---------------------------|-------------------------------|----------------------------|-------------------------------|
| 6×3/8Fn7.5  | 350                  | 309                       | 150                           | 230                        | 1.14                          |
| 15×1/8Fn0.8 | 525                  | 165                       | 169                           | 167                        | 0.93                          |
| 15×1/8Fn1.6 | 450                  | 335                       | 100                           | 217                        | 1.99                          |
| 15×1/8Fn3.2 | 350                  | 347                       | 96                            | 222                        | 2.27                          |
| 15×3/8Fn6.3 | 280                  | 311                       | 188                           | 250                        | 2.35                          |

Table 1 Mean of number average droplet sizes and droplet velocities at a point 1m below the sprays

| Spray       | D10 ( $\mu\text{m}$ ) | Flux ( $\text{kgm}^{-2}\text{s}^{-1}$ ) | Number density ( $\text{m}^{-3} \times 10^{-6}$ ) | Volume Fraction (%) | Droplet spacing (mm) |
|-------------|-----------------------|---|---|---------------------|----------------------|
| 6×3/8Fn7.5  | 230                   | 4.20                                    | 60  | 0.037               | 2.59                 |
| 15×1/8Fn0.8 | 167                   | 2.30                                    | 232   | 0.057               | 1.63                 |
| 15×1/8Fn1.6 | 217                   | 0.53                                    | 219   | 0.172               | 1.65                 |
| 15×1/8Fn3.2 | 222                   | 2.61                                    | 201   | 0.151               | 1.71                 |
| 15×3/8Fn6.3 | 250                   | 2.33                                    | 119   | 0.097               | 2.03                 |

Table 2 Mean droplet size, droplet fluxes, volume fractions, spacing and number densities at a point 1 m below each spray.

| Spray   | CH <sub>4</sub> in Air (%) | Mean Flame Velocity ( $\text{ms}^{-1}$ ) |
|---|----------------------------|--|
| no spray  | 9.3                        | 0.92                                     |
| no spray  | 10.2                       | 0.98                                     |
| 15×Fn6.3  | 9.6                        | 1.96                                     |
| 15×Fn6.3  | 10.0                       | 2.44                                     |
| 15×Fn3.2  | 9.2                        | 2.05                                     |
| 15×Fn1.6  | 9.5                        | 1.96                                     |
| 6×Fn7.5   | 9.4                        | 1.70                                     |
| 6×Fn7.5   | 9.5                        | 1.94                                     |
| 15×Fn0.8  | 9.3                        | 2.23                                     |
| 6×Fn7.5 - extinction event                      | 9.3                        | 0.26                                     |
| 15×Fn6.3 - spray terminated 5s before ignition. | 9.7                        | 1.78                                     |

Table 3 Summary of average measured velocities for spray accelerated flames.

| Spray         | D <sub>10</sub><br>( $\mu\text{m}$ ) | Spray<br>velocity<br>( $\text{ms}^{-1}$ ) | S <sub>t</sub> /S | Re<br>Tube | Re<br>Droplet |
|---------------|--------------------------------------|---|-------------------|------------|---------------|
| 6 × 3/8Fn7.5  | 230                                  | 1.1                                       | 4.4               | 18 800     | 17            |
| 15 × 1/8Fn0.8 | 167                                  | 0.9                                       | 5.1               | 15 300     | 10            |
| 15 × 1/8Fn1.6 | 217                                  | 2.0                                       | 4.7               | 32 800     | 29            |
| 15 × 1/8Fn3.2 | 222                                  | 2.3                                       | 4.4               | 37 400     | 32            |
| 15 × 3/8Fn6.3 | 250                                  | 2.4                                       | 1.9               | 38 700     | 38            |

Table 4 Calculation of Reynolds numbers for different sprays and two characteristic lengths

| Diameter ( $\mu\text{m}$ )         | 10    | 10    | 20    |
|------------------------------------|-------|-------|-------|
| Number density ( $\text{m}^{-3}$ ) | 2e+09 | 2e+10 | 2e+09 |
| Molar fraction KCl                 |       |       |       |
| 0.00                               | 0.400 | 0.368 | 0.391 |
| 0.01                               | -     | 0.361 | -     |
| 0.02                               | -     | 0.356 | 0.379 |
| 0.04                               | 0.393 | -     | 0.369 |
| 0.06                               | 0.396 | -     | 0.364 |
| 0.08                               | -     | -     | 0.360 |
| 0.1                                | 0.392 | -     | -     |

Table 5 Computed laminar burning velocities ( $\text{ms}^{-1}$ ) for water droplets of the given number density and diameter containing various molar fractions of KCl.

| Droplet Sauter Mean<br>Diameter ( $\mu\text{m}$ ) | Loading Density<br>( $\text{kgm}^{-3}$ ) | Droplet number<br>density ( $\text{m}^{-3}$ ) | m    |
|---|--|---|------|
| 60  | 0.02                                     | 1.8e+08                                       | 0.79 |
| 120   | 0.02                                     | 2.2e+07                                       | 0.78 |
| 200   | 0.12                                     | 2.9e+07                                       | 0.73 |
| 260   | 0.075                                    | 8.2e+06                                       | 0.81 |
| 290   | 0.87                                     | 6.8e+07                                       | 0.64 |
| 320   | 1.09                                     | 6.4e+07                                       | 0.68 |
| 500   | 1.27                                     | 1.9e+07                                       | 0.62 |

Table 6 Variations in ratio, m, of reduced laminar burning velocity to the un-perturbed laminar flame velocity. Experimental data after Proust [42]

| Sensor | Pressure |      |      |      | Photodiode |      |      |      | Laser-<br>photodiode | Thermocouple |   |   |                     |
|--------|----------|------|------|------|------------|------|------|------|----------------------|--------------|---|---|---------------------|
|        | 1        | 2    | 3    | 4    | 1          | 2    | 3    | 4    | 1                    | 1            | 2 | 3 | 4                   |
| Test   |          |      |      |      |            |      |      |      |                      |              |   |   |                     |
| 1-47   | -0.17    | 0.53 | 2.64 | 4.78 | 0.53       | 1.45 | 2.33 | 4.78 | 4.78                 |              |   |   |                     |
| 1-18   |          |      |      |      |            |      |      |      |                      |              |   |   | N/A                 |
| 19-31  |          |      |      |      |            |      |      |      |                      |              |   |   | 0.53 N/A 2.33 4.78  |
| 32-47  |          |      |      |      |            |      |      |      |                      |              |   |   | 0.53 1.45 2.33 4.78 |

Table 7. Summary of the location of the diagnostic sensors. All distances are in metres relative to the area change in the tube.

| Position | Surfactant | D <sub>32</sub> (μm) | D <sub>10</sub> (μm) |
|----------|------------|----------------------|----------------------|
| 1        | N          | 259                  | 115                  |
| 2        | N          | 248                  | 121                  |
| 2        | N          | 255                  | 113                  |
| 3        | Y          | 211                  | 118                  |
| 2        | Y          | 269                  | 131                  |

Table 8. Dantec PDA measurements of Sauter Mean Diameter, D<sub>32</sub>, and Mean diameter, D<sub>10</sub>, for the Lurmark Fn 4.0 clusters. 18 nozzles, 44 litres per minute

| Position | Surfactant | D <sub>32</sub> (μm) | D <sub>10</sub> (μm) |
|----------|------------|----------------------|----------------------|
| 2        | N          | 386                  | 188                  |
| 3        | N          | 403                  | 220                  |
| 3        | Y          | 395                  | 214                  |
| 2        | Y          | 376                  | 199                  |

Table 9. Dantec PDA measurements of Sauter Mean Diameter, D<sub>32</sub>, and Mean diameter, D<sub>10</sub>, for Lurmark Fn 17 spray. 6 nozzles, 51 litres per minute.

| Position | Start (m) | End (m) |
|----------|-----------|---------|
| 1        | 0.3       | 0.8     |
| 2        | 0.8       | 1.8     |
| 3        | 1.2       | 2.2     |
| 4        | 2.3       | 3.3     |

Table 10. Approximate physical extent of the sprays at the four locations used. The distances are all relative to the change in flame tube cross-section.

| Droplet Diameter<br>( $\mu\text{m}$ ) | Number. density<br>( $\text{m}^{-3}$ ) | Volume Fraction | Loading Density<br>$\text{kgm}^{-3}$ |
|---------------------------------------|--|-----------------|--------------------------------------|
| 10                                    | 1.1e+11                                | 0.6 e-4         | 0.06                                 |
| 20                                    | 1.2e+10                                | 0.5 e-4         | 0.05                                 |
| 30                                    | 6.5e+09                                | 1.0e-04         | 0.1                                  |
| 50                                    | 2.5e+09                                | 1.7 e-4         | 1.7                                  |
| 100                                   | 8.0e+08                                | 4.2 e-4         | 4.2                                  |

Table 11 Summary of mono-disperse spray characteristics at critical number densities for inhibition

## Figure Legends

- Figure 1 Schematic diagram showing the general experimental arrangement used for the low velocity flame acceleration tests.
- Figure 2 a) Droplet size distributions measured using MALVERN analyser 1 m below spray and b) comparison of the size parameter  $D_{32}$  obtained with MALVERN (●) and DANTEC PDA (■) droplet measurement apparatus at various distances below the spray.
- Figure 3 Plots showing a) predicted increase in droplet velocities as a function of time in response to an accelerating gas flow (no symbol) and b) time resolved plots of corresponding Weber numbers. Droplet diameters: ◆ - 0.2 mm, ▲ - 0.4 mm and ■ - 1.0 mm
- Figure 4 Predictions of the time required to attain a Weber number of 12 as a function of rate of gas pressure rise for a range of water droplet diameters: ● - 4 mm, ▲ - 2 mm, ■ - 1 mm, ◆ 0.4 mm, ▼ - 0.2 mm.
- Figure 5. Predictions of the time required to attain a Weber number of 12 as a function of rate of gas pressure rise for water (solid symbols) and water plus 2% surfactant (open symbols) for two droplet diameters: ● -0.4 mm and ■ - 2 mm.
- Figure 6 Sequence of video images showing catastrophic break-up of a 4 mm water droplet.  $\Delta t$  - 1 ms.
- Figure 7 Sequence of cine film images showing near critical break-up of 2 and 4 mm water droplets with added surfactant,  $\Delta t$  - *ca.* 12 ms.
- Figure 8 Plot of residence times of droplets in expansion flows indicating whether droplet break-up occurred in that time. Droplet diameters: ● - 1.4 to 2.1 mm and ■ - 3.8 to 4 mm. Solid symbols - complete break-up, shaded symbols - partial break-up and open - no break-up in the time.

- Figure 9 Sequence of cine film images showing rapid fragmentation of a simulated water spray  $\Delta t$  - *ca.* 1.3 ms.
- Figure 10 Variation in computed burning velocities as a function of droplet number density for a range of initial droplet diameters ( $\mu\text{m}$ ).
- Figure 11 Schematic of the 275 mm x 175 mm explosion tube showing a) 0.247 mm diameter explosion driver, window section and gas handling arrangements, b) vertical section on AA showing the relative positions of spray heads used to promote more uniform distribution to avoid c) view from B of unwanted spray collision and the creation of voids if spray pattern shown in (b) is not used. Overall spray length *ca.* 1 m.
- Figure 12 Pressure histories from gauges 1, 3 and 4 for a) test at 10.1% methane in air with spray Fn 17 at location 1 and b) test at 10.7 % methane in air with no spray.
- Figure 13 Pressure histories from gauges 1 and 2 for tests with spray Fn 17 at location 1. a) 7% methane in air, no mitigation and b) 7.6 % methane in air with mitigation.
- Figure 14 Output from laser-photodiode pair with spray Fn17 at location 2 a) 7.6% methane in air showing flame arrival and no mitigation, b) 8.0 % methane in air with mitigation and c) spray Fn 4 and 8.3% methane showing significant spray arrival.
- Figure 15 Plots of a) overpressure in the vicinity of the spray and b) output from laser-photodiode gauge. Spray location 4. Solid line - 6.9% methane no mitigation, dashed line 6.7% methane with mitigation.
- Figure 16 Output from emission/attenuation gauge and thermocouple located 4.78 m from the area change. a) 8.7% methane with mitigation b) 6.9% methane with no mitigation. Tests with 2% surfactant and Fn 17 nozzles.
- Figure 17. Variation in measured maximum rate of pressure rise as a function of methane composition. Solid symbols - mitigation, open symbols - no mitigation. Both accelerated and un-accelerated tests.

Figure 18 Variation of observed duration of overpressure for various rates of pressure rise. Solid symbols - mitigation, open symbols - no mitigation. Solid lines are predicted critical conditions presented in Figure 4; Droplet diameters - upper -0.4 mm, middle - 1 mm, lower 2 mm.

Figure 19. Typical droplet distribution for the Fn17 nozzles.

Figure 20. Plot of pressure control efficiency  $(P_{dry}-P_{wet})/P_{dry}$  indicating decrease in maximum explosion pressure  $P_{wet}$  when sprays were used relative to the corresponding dry tests, maximum pressure  $P_{dry}$ .