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Passive explosion suppression by blast-induced atomisation from water containers

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Abstract

The experimental findings of a combined wind tunnel and field-scale explosion study of blast-induced water release and its effect on blast suppression are reported. The release of water, and its subsequent atomisation, from containers both with open and partly enclosed surfaces, was first studied in a wind tunnel. An array of water containers were then placed at differing positions from the ignition point, together with flame acceleration obstacle arrays at fixed positions, inside a 5.1 m long by 0.3 m^2 cross-section explosion duct. The droplet size and the minimum flame speed necessary for the container array to suppress the explosion were found to depend upon the number of containers in the array and on their shape and size. One particular container array extinguished the flame when placed at any position beyond 1.7 m from the ignition point. When extinction was observed the internal over-pressure was substantially reduced and the external over-pressure completely eliminated. This study suggests a new approach toward passive explosion suppression.

Keywords: Explosion; Suppression; Water; Passive; Blast; Atomisation

1. Introduction

Explosion suppression systems, whether for gas explosions, dust explosions or detonation product gases, all need to disperse the suppressant very rapidly, and in a roughly homogeneous distribution, into the path of the blast and/or combustion front. The suppressant must also be in a very fine particulate form so that it will off-gas, evaporate or absorb heat at sufficiently fast a rate to have the desired suppression effect in its short passage time through the combustion front. If the suppressant is in liquid form, then the suppression system needs to ensure that it is finely atomised as well as dispersed. For example, effective

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Nomenclature

A_W	mean acceleration rate of water from outlet (m^2/s)
C_A	differential air pressure coefficient
C_W	suppressant pressure loss coefficient
C_I	suppressant inertial pressure coefficient
d_p	droplet diameter
D	suppressant outlet hole diameter (m)
H	separation distance between containers in array measured normal to the flow path (m)
L	length of container (m)
N	number of containers per metre measured normal to flow path (m^{-1})
M	number of suppressant outlet holes per metre of container (m^{-1})
ΔP	differential pressure between suppressant outlet and air inlet holes (N/m^2)
S_F	flame speed ($S_F = (8/7)V_A^{max}$, m/s)
Δt	response time of suppressant i.e. time to reach U_W when subject to an approach velocity of V_A (s)
U_W	suppressant outflow velocity at outlet hole (m/s)
U_W^{max}	maximum suppressant outflow velocity before flame arrival (m/s)
V_A	gas velocity incident on containers (m/s)
V_A^{max}	maximum gas velocity incident on containers before flame arrival (m/s)
w	width of theoretical suppressant outflow slot along whole length of container (m)
We	Weber number ($We = \rho_A d_p V_A^2/\sigma$)

Greek letters

α_o	ratio of air velocity passing suppressant outlet hole to that in approach flow
α_I	ratio of air velocity passing air inlet hole to that in approach flow
ε_W	droplet volume concentration in spray blanket
ρ_A	density of incident blast wind (kg/m^3)
ρ_W	density of suppressant (kg/m^3)
θ_W	suppressant volume outflow rate (m^3/s)
σ	Suppressant surface tension (N/m)

droplet sizes for water suppression of premixed gas-air explosions are in the order of 30 μm and smaller [1,2]. The combined requirements of rapid uniform dispersal and fine droplets have resulted in the development of various suppression systems that utilise a high-pressure source to both disperse and atomise the suppressant. Such systems are necessarily active, in that they require a fast response detection and activation system to sense the onset of the explosion and react quickly enough to disperse the suppressant in the remaining, and typically very short, time interval. The installation and maintenance cost of such systems are high in view of the complex electro-mechanical infrastructure required.

Low-pressure suppression systems cannot guarantee to be effective because of the relatively long time (typically a few seconds) required to disperse the suppressant. Two such systems are the “tipping bucket” system used in mines [3] and water spray deluge advocated for use in offshore process modules [4]. Both of these systems rely on the explosion blast wave to both disperse and atomise the suppressant, which is typically water. The “tipping bucket” mine system has the advantage of being passive and responds naturally to the explosion without the need for detection or activation systems. Gas and dust explosions in coal mine shafts, in which there are few obstacles to accelerate the flame, have very long blast wavelengths. Thus, the suppression system experiences blast wind loading for sufficiently long a time to tip the water into the path of the flame before its arrival at the apparatus. In the obstacled environment of offshore process modules, however, the flame acceleration rates can be very fast resulting in explosions with duration of well under 1 s. In contrast, the spray system takes in the order of 10 s from activation to disperse water spray throughout the module. Thus, the policy of using water spray deluge as an explosion suppression strategy offshore, needs to be tied into automatic activation on the detection of gas or fire. Whilst lowering the probability of an explosion, water spray deluge does not, therefore, provide any absolute protection since accidental release of flammable material can disperse, ignite and cause damaging explosions in well under the time taken for the deluge system to activate.

It is the subject of this paper to present the findings of research into a fast response passive explosion suppression system for use with liquid suppressants. The work described was conducted on a 2-year research project in the Department of Chemical and Process Engineering at the University of Sheffield. The Engineering and Physical Research Council awarded the funds to conduct a theoretical and experimental investigation into atomisation from liquid films as a way of suppressing gas explosions. The paper addresses both fundamental and practical issues. The objective is to provide both a scientific and engineering justification for the proposed approach to explosion suppression.

The study began by making a detailed investigation into other relevant technologies. These included water spray deluge for suppressing explosions in offshore modules, high-pressure spray suppression systems for confined explosions, the “tipping bucket” system used in coal mines and air-blast atomisation. Air-blast atomisation is a mature technology used in the majority of gas turbines for producing fine-droplet liquid fuel sprays.

Firstly high-speed cine and flash photography were used to study the response of free-surface liquid films subject to a rapidly rising gas velocity generated by a transient wind tunnel. Their atomisation characteristics were found to be unsatisfactory for explosion suppression. Secondly, various types of liquid container were constructed that protect the liquid from the incident wind except for air inlet and water outlet holes. To understand the response of these containers in an explosion, a simple mathematical theory was developed which is based upon well established aerodynamic and fluid dynamic principles. This theory was helpful in identifying the key design parameters and also provided approximate design calculations. The encouraging results from the wind tunnel trials quickly led to the construction of prototypes for testing in an explosion tube.

Thirdly, field-scale explosion experiments were conducted to determine the suppression effects of the various container arrangements. Being an engineering project, the study also embraced more practical issues concerning the form that a full-scale suppression system might take. Thus, the suitability of construction materials was considered and a water supply system devised. The question of whether salt water could be used is also addressed in the context of maintenance requirements. In addition, installation strategies are also described for tackling three explosion events: (1) extinction of vented flame; (2) external and near-perimeter explosions; (3) interior partially confined explosions.

2. Foreground studies

2.1. Water spray deluge

Water spray deluge is at present the only blast mitigation strategy in use offshore that targets the combustion process. It limits the explosion over-pressure through a combination of cooling and inerting the gas in the reaction and combustion product zones. It is understood that the relatively large spray droplets created by fire nozzles are broken up under the acceleration force of the explosion thus creating finer droplets of the order of 30 μm [1,2]. These small droplets are able to suppress the explosion provided their volume concentrations are sufficient.

These observations have resulted in a patent application [5] for a novel dish-shaped spray (Fig. 1a) designed to generate droplets of the order of 1000 μm diameter. The greater mass of these droplets, relative to those of fire sprays, ensures that they are more readily disintegrated in the explosion and, therefore, effect suppression at lower over-pressures.

Water spray deluge is an “active” system because it requires the presence of gas or flame to be detected some tens of seconds before the explosion. This provides sufficient time to activate the pumps and deluge the module. The short time, however, necessitates that the detection system is automatic thus requiring electro-mechanical actuation. Water spray deluge, therefore, cannot absolutely guarantee that an explosion will be suppressed since it is possible that the gas release and ignition could occur before the deluge system is in full spate.

In the event that the deluge system were activated when an explosion does not occur it could pose its own hazards. By restricting visibility it could inhibit the escape of personnel. It could also increase the likelihood of ignition through water ingress into electrical systems.

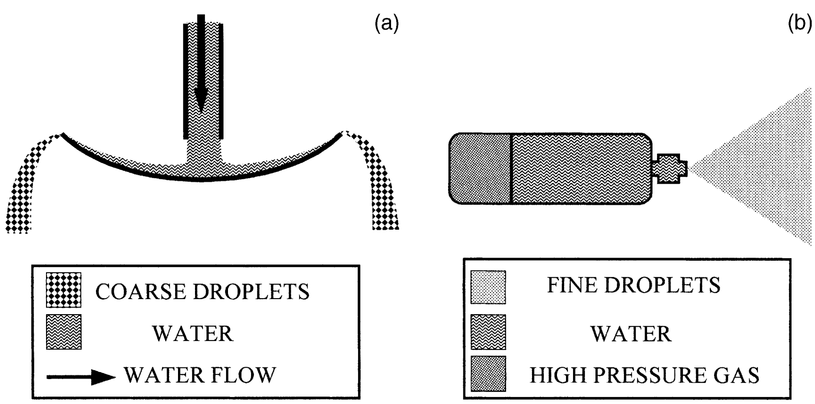


Fig. 1. (a) Curved dish coarse droplet spray; (b) High-pressure fine-droplet spray.

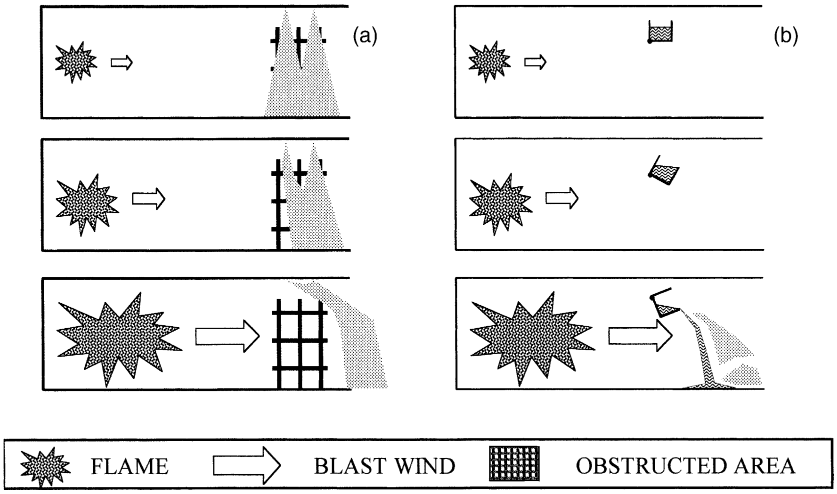


Fig. 2. (a) Displacement of local-area-deluge spray by blast wind; (b) Dispersal and atomisation of water from tipping-bucket coal mine suppression system.

In addition, water spray deluge is not effective for highly confined explosions and, in fact, can lead to higher explosion over-pressures than had the system not been activated [6].

To be effective, water spray deluge must also cover the entire floor area of the module. It is not sufficient to have a local area deluge in the region of greatest concern. The reason for this is because the water spray is displaced by the explosion wind. This effect is shown schematically in Fig. 2a in a hypothetical situation. Here, the whole of the local area spray is displaced to the outer side of the process module before the flame reaches the process plant that the spray was intended to protect. Thus, if a total area deluge strategy is adopted there can be large installation and maintenance costs.

Maintenance can be a particular problem, for example, in a wet salt water system that is constructed from galvanised mild steel [7]. In this case, regular maintenance is required to ensure the spray nozzles do not become blocked by corrosion debris that is present in salt water systems where low concentrations of chlorine are also used to inhibit the build up of marine life.

2.2. High-pressure spray suppression systems

The requirement for fine sprays has resulted in patents for active suppression systems (Fig. 1b) that use either high-pressure gas [8] or super-heated water [9]. These systems are primarily intended for use on confined explosions in which the flame speed is comparatively slow and the spray, therefore, has time to penetrate the flame zone. The same droplet cloud displacement limitations, as described earlier for water spray deluge, would arise with these systems because they generate localised droplet clouds. This is particularly true because the droplet sizes are very small and, therefore, very readily accelerated by the explosion wind.

It is important to recognise that this spray displacement problem is inherent for any explosion in an process module where obstacles cause rapid flame acceleration and result in high blast wind velocities. It is less of a problem in highly confined explosions, at least before the flame is vented, when the flame speeds are comparatively slow. In fact, in such "slow flame" explosions, some beneficial effect may be achieved if the spray system penetrates the combustion product zone after the flame has passed the system. This is because the cooling of the combustion products behind the flame can result in a reduction in the explosion over-pressure.

2.3. Passive explosion suppression in coal mines

By passive it is meant that the presence of the system alone is sufficient to guarantee explosion suppression. The system's natural response to the explosion ensures that suppressant is dispersed and, if necessary, atomised before the flame arrives.

One of the longest established and simplest passive explosion suppression systems is that used in mines [3]. There are various types but they all roughly work in a similar way to the "bucket type". The system simply amounts to having a sequence of water buckets placed at ceiling height along the mine shaft (Fig. 2b). An explosion approaching from the left in the diagram sets up an explosion wind that is able to tip the bucket so that its contents are released before flame arrival. The system relies on there being sufficient time for the water to fall sufficiently far into the path of the explosion wind that the water is atomised either in mid air or, preferably, the water has time to reach the floor where it wets the coal dust. Since a coal dust explosion is primarily fuelled by dust that is whipped up off the floor, then wetting the dust before it becomes airborne provides very effective suppression.

It is important to note that such mine suppression systems are unlikely to have any beneficial effect in a congested process module. The reason is because it takes about 1 s for the bucket to tip and its contents spill. In contrast, an explosion in an offshore module can reach its peak over-pressure in well under 1 s. Thus, the mine suppression system is only effective in mine shafts because the flame acceleration rates in methane–coal-dust explosions are substantially slower than those in the heavily obstacled environment typical of offshore modules.

2.4. Air-blast atomisation

Since small-diameter droplets are necessary to provide effective explosion suppression the principles of air-blast atomisation [10] were also studied. In particular, the pre-filming air-blast atomiser that is the predominant type used in gas turbine combustors. The principles of plane jet and pre-filming air-blast atomisers are shown in Fig. 3a and b, respectively. In the plain jet atomiser, the liquid is injected as a low velocity jet where it is eroded on its perimeter by high-velocity air. In the pre-filming atomiser, the liquid is injected as a film onto the outer surface of the pintle where it is met by high-velocity gas approaching the outlet orifice. The basic physical principle of both is the same. High-velocity gas excites instabilities (technically Kelvin–Helmholtz instabilities) that cause droplets to be stripped from the liquid surface.

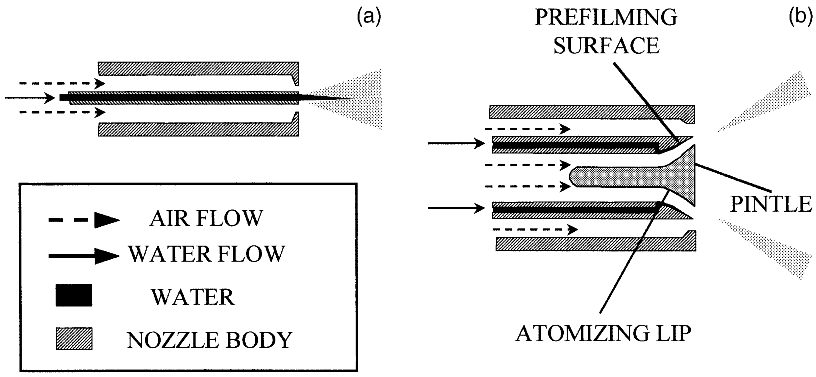


Fig. 3. (a) Plain jet air-blast atomisation; (b) Pre-filming air-blast atomisation.

Whilst the air-blast atomisation process is complex, the droplet diameters produced have a Sauter–Mean that approximately satisfies the constant Weber number atomisation criterion $We \approx 10$. This is consistent with independent research on droplet break-up mechanisms [11]. The droplet size distribution generated by air-blast atomisation process is shown in Fig. 4. Here, the relative velocity of the gas to the liquid film has been related to an incident flame speed. It follows that the mean droplet sizes that would be generated by air-blast atomisation start to reach the size range capable of suppression, defined here as diameters below 30 μm, when the flame speed exceeds 150 m/s. The corresponding mean droplet formation times are substantially less than 0.005 ms and, therefore, many hundreds of thousands of times shorter than the typical duration of an offshore explosion (≈1000 ms). Thus, if it were possible to generate small diameter jets or films of water within the short time interval before flame arrival at a suppression system, then the explosion wind would itself be able to atomise the liquid into sufficiently small droplets to suppress combustion.

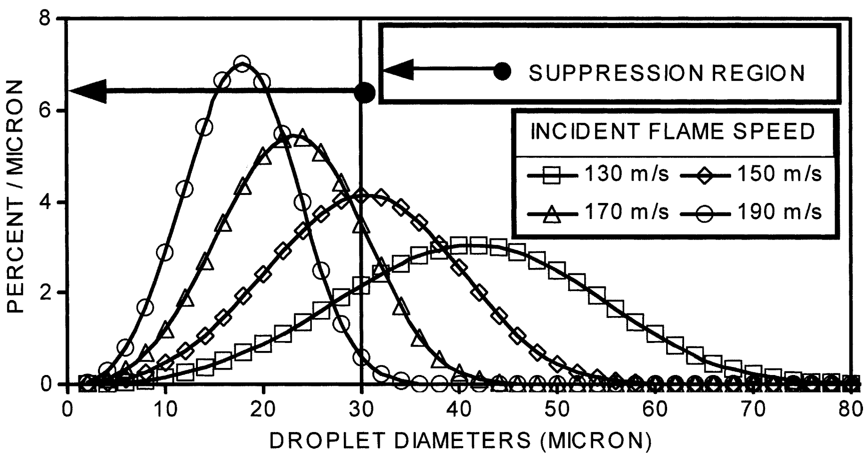


Fig. 4. Droplet size distributions generated by air-blast atomisation for different incident flame speeds.

3. Principles of the proposed system

3.1. Multiple container array

The response time of a suppression system for a congested process module must be very much shorter than the tipping-bucket mine system described earlier. An effective system would need to ensure that water were dispersed across the entire flame path in the order of 10 ms before the flame arrival. To achieve such a short response time the water containers would necessarily have to be small. An array-like arrangement (Fig. 5a) could then be used. Provided all the containers respond quickly enough, a continuous droplet blanket would be formed downstream of the container array (Fig. 5b). If the droplet sizes were small enough and the water volume concentrations high enough, then the flame could not penetrate the droplet blanket.

This concept motivated our first transient wind tunnel experiments in which we used small open-topped water trays (Fig. 6a) subjected to the velocity ramp shown in Fig. 6b. High-speed cine film showed the response of the tray water to be like that in Fig. 7. A wave starts to form on the leading edge of the tray that grows in size as the gas velocity increases. At still higher velocities, water droplets are stripped from the wave crest and at some point the drag resistance causes the wave to be pushed backwards from the leading edge. The formation of the wave is apparently a necessary precursor before finer droplets are generated. The atomisation process, however, is very unstable and the droplet sizes too large for effective explosion suppression. The system also has a very practical flaw in that wave formation would also be readily excited by naturally occurring wind thus causing water to slop out of the trays. Consequently, the system would require continuous refilling, cause a lot of wetting in its near vicinity and could not guarantee the presence of sufficient water at the time of the explosion. Our research was, therefore, directed to the enclosed-type of container to which this paper principally refers.

3.2. Water release from enclosed containers

The objective was to exploit the pressure differences on the outer surface of the container, caused by the passage of the blast wind. The small size of the containers envisaged suggested that the dynamic response of the neighbouring air could be assumed to be quasi-steady. Thus, the outer surface pressure distribution at an instant of the explosion would correspond to that if the container were placed in a steady approach flow of the same velocity. This problem has been addressed extensively for an aerofoil.

In its simplest form, we could envisage a container like that in Fig. 8 with near cylindrical bow and a slim tail. With an approach gas flow of velocity V_A (m/s) with density ρ_A (kg/m^3), this container would produce surface gas velocities of $\alpha_o V_A$ at the upstream hole and $\alpha_I V_A$ at the downstream hole. Here, $\alpha_o \approx 2$ and $\alpha_I \approx 1$, respectively. Bernoulli's law then states that the pressure difference between the two surface points is given by ΔP (N/m^2), where

$$\Delta P = \tfrac{1}{2}\rho_A C_A (V_A)^2. \quad (1)$$

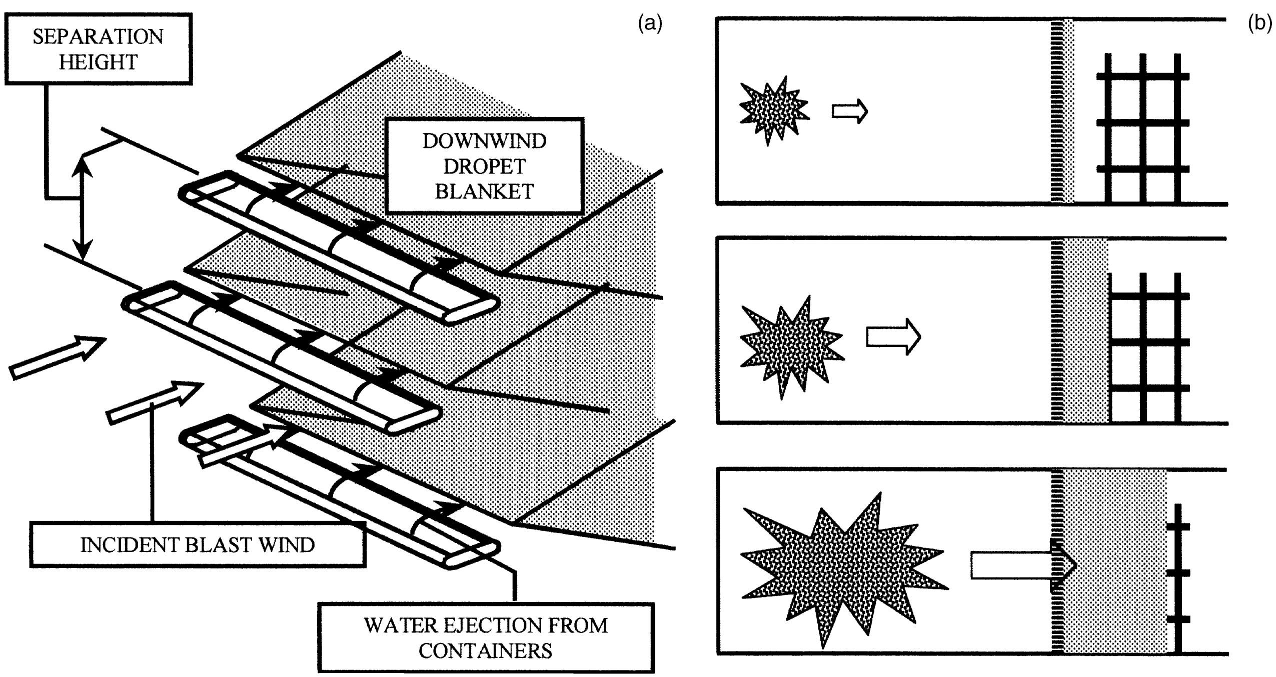


Fig. 5. (a) Container array and downwind droplet dispersal; (b) Formation of droplet blanket downwind of container array.

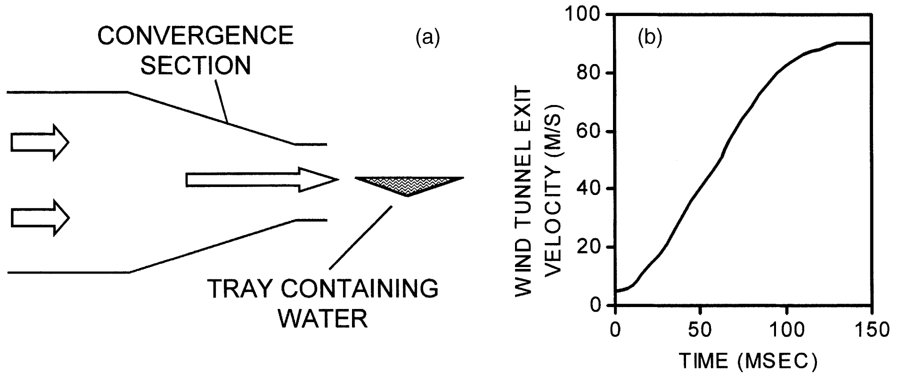


Fig. 6. (a) Free-surface water container at outlet of convergence section of transient wind tunnel; (b) Velocity of transient blast wind generated by wind tunnel.

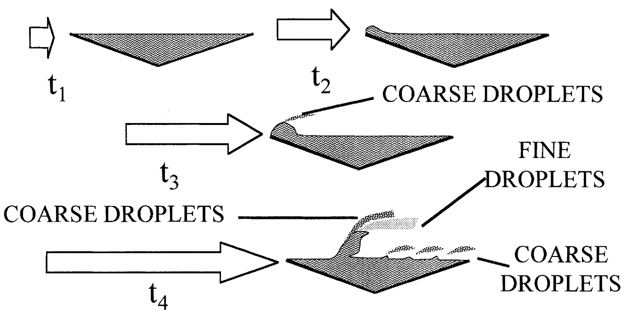


Fig. 7. Wave and droplet formation on the free-surface of a water container under transient wind loading.

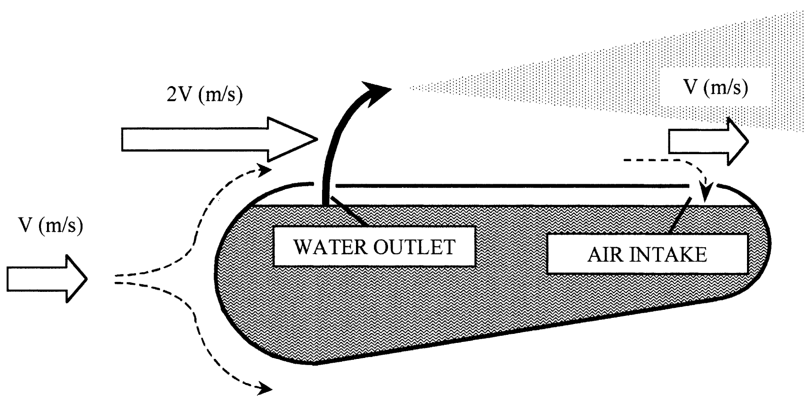


Fig. 8. Aerofoil cross-section container showing suppressant outlet and air inlet.

C_A is the differential air pressure coefficient given by

$$C_A = \{(\alpha_o)^2 - (a_I)^2\} = 3. \tag{2}$$

Thus, if we take C_W to be the steady state pressure loss coefficient for liquid flow out through the upstream hole, then

$$\Delta P = \tfrac{1}{2}\rho_W C_W (U_W)^2, \tag{3}$$

where ρ_W is the density of the suppressant and U_W its steady outflow velocity. Equating Eqs. (1) and (3), it follows that

$$U_W = \left(\frac{\rho_A C_A}{\rho_W C_W}\right)^{1/2} V_A. \tag{4}$$

Thus, the volume outflow rate of suppressant (θ_W, m^3/s) from one container is approximately equal to

$$\theta_W = wLU_W, \tag{5}$$

where L (m) is the length of the container measured at right angles to the container's cross-section and w (m) the width of the theoretical slot-shaped suppressant outlet route.

The mean suppressant volume concentration (ε_W) downwind of the apparatus can then be estimated from the following equation by assuming the droplets are carried on the wind and disperse to form a uniform mixture

$$\varepsilon_W = \frac{\theta_W}{V_A L H}, \tag{6}$$

where H (m) is the separation distance between the containers measured at right angles to the direction of flow. Combining Eqs. (5) and (6), the mean suppressant concentration can alternatively be expressed in terms of the number of containers per metre N (m^{-1}) as

$$\varepsilon_W = \frac{\theta_W}{V_A L H} = (Nw)\left(\frac{U_W}{V_A}\right). \tag{7}$$

Further combining Eqs. (7) and (4), it follows that

$$\varepsilon_W = Nw\left(\frac{\rho_A C_A}{\rho_W C_W}\right)^{1/2}. \tag{8}$$

Note that the suppressant volume concentration ε_W is independent of the explosion wind and is dependent only upon the geometry of the container array. Note also that the theoretical slot width of w can be replaced by a row of holes with diameter D (m), of which there are M (m^{-1}) per meter, where

$$w = \tfrac{1}{4}\pi M D^2. \tag{9}$$

A key design requirement is to ensure that the suppressant has a sufficiently short response time Δt (s) to the explosion wind. An explicit formula for Δt can be determined as follows. The response time, Δt, is defined as the time taken for the suppressant to accelerate from rest to its steady outflow rate. First express Δt in terms of the average acceleration rate A_W (m^2/s) of the suppressant, namely

$$\Delta t = \frac{U_W^{max}}{A_w}, \tag{10}$$

where U_W^{max} is the maximum value of U_W, just before flame arrival at apparatus, which in turn is related to the pressure difference ΔP acting across the suppressant by

$$\Delta P = C_I \rho_W w A_W, \tag{11}$$

where C_I is the non-dimensional inertia coefficient of the suppressant, which is of the order of unity, and which depends upon the geometry of the container. Thus, combining Eqs. (10) (11) and (4) gives

$$\Delta t = 2C_I \left[\frac{\rho_W}{\rho_A}\left(\frac{C_W}{C_A}\right)\right]^{1/2}\left[\frac{w}{V_A^{max}}\right], \tag{12}$$

where w (m) is the width of the theoretical slot-shaped suppressant outlet route and V_A^{max} the maximum value of the incident blast wind velocity V_A just before flame arrival at the containers.

To obtain a very approximate estimate for the response time of a typical container assume that the ratio of the pressure coefficients is of order unity, namely $C_W/C_A \approx 1$, and the inertia coefficient of the order of 10, namely $C_I \approx 10$. Assuming $\rho_W = 1000\,kg/m^3$, $\rho_A \approx 1\,kg/m^3$ and $w \approx 0.001\,m$ it follows that the time Δt between the container being subject to an impulsive change in its incident gas velocity, and the liquid reaching its steady state flow rate, is approximately $\Delta t \approx 0.7/V_A^{max}$ (s). It follows that Δt is very much shorter than the duration of the explosion and in fact, it is approximately equal to the time taken for a freely propagating flame (whose flame speed S_F is approximately related to V_A^{max} by $S_F = (8/7)V_A^{max}$) to cross the 0.8 m immediately in front of the suppression array.

It is a key design requirement to ensure that the response time Δt is short enough for the type of explosion under consideration. The principal factors determining the response time are the magnitude of the aerodynamic and hydrodynamic pressure-drop coefficients (C_A, C_W) and the inertial coefficient (C_I). C_A is increased by shapes that cause the airflow to stagnate near the air inlet and for the air pressure to be below ambient near the suppressant outlet. Keeping C_W and C_I as small as possible requires that the flow route for the suppressant is as loss-free as practicable and the mass of liquid that needs to be accelerated to achieve the required outflow is kept to a minimum.

3.3. System characteristics

The particular characteristics of this system can be summarised as follows:

1. Passive: responding to the blast wind alone.
2. Short response time: 10 ms and smaller determined by container size and shape.
3. Droplet sizes are determined by the wind velocity incident on the container at the time of flame arrival. A minimum incident gas velocity of between 150 and 170 m/s is required for the droplets to be small enough to cause suppression.

4. The release of droplets is continuous creating a droplet blanket on the downwind side of the device.
5. Suppression is caused local to the apparatus and not far downstream of it. This allows optimal placement of limited number of suppression screens.
6. The duration of the continuous droplet release is determined by a trade off between number of holes per container and the container volume.
7. Droplet concentrations are determined by having an adequate number of outlet holes per unit area of blast wind cross-section. This is achieved by a trade off between the spacing distances between containers and the number of outlet holes per container.
8. Droplet concentrations are additive, thus more containers further downstream increase the droplet concentration on their downwind side.

4. Types of container

4.1. Leading edge spoiler

A spoiler was attached to the aerofoil-shaped container (Fig. 9a). This spoiler amounted to a narrow plate with holes which was angled approximately at 45° to upper surface of container set back slightly from the upstream row of container holes. The spoiler has the following three effects:

1. The incident air stream is partially stagnated which leads to a pressure head of approximately $+(1/2)\rho_A(V_A)^2$ at the upstream holes.
2. A vortex is set-up in the wake of the spoiler causing a low-pressure region that extends as far as the downstream row of holes. Thus, the pressure difference between the two rows of container holes is larger than in the design without spoiler and the rate of liquid expulsion is also larger. High-speed video of the response of this type of container in the transient wind tunnel shows a water jet leaving the downstream row of holes that is dragged backwards into the recirculation zone (Fig. 9a). The water jet eventually meets the high-velocity air passing through the holes in the spoiler to cause fine atomisation.

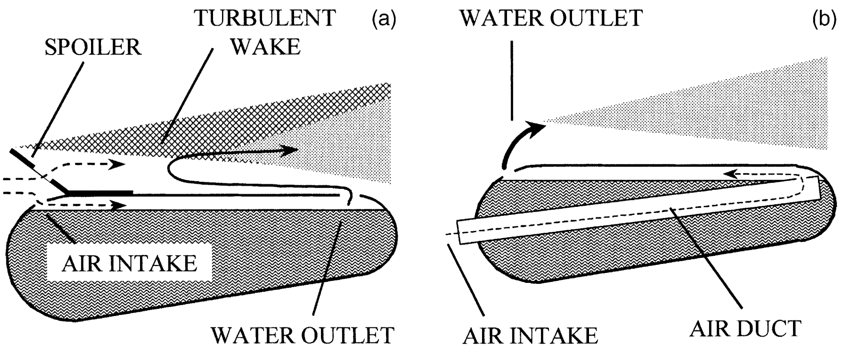


Fig. 9. Container with (a) leading edge spoiler and (b) stagnation point air intake.

3. The combined effects of the turbulence generated by the gas jets penetrating the spoiler and the eddies being shed in the wake of the spoiler cause rapid dispersion and mixing of the droplets with the downstream wind. This shortens the distance downstream of the device at which the droplet volume concentrations become sufficient for suppression.

4.2. Stagnation point air intake

In this design (Fig. 9b), the stagnation air pressure on the leading edge of the container is piped through its interior to the downstream end immediately above the suppressant. Thus, the air intake and liquid outlet are located at the same end of the container. The pressure differential driving the liquid is thus intensified being $+(1/2)\rho_A(V_A)^2$ at the air intake and $-(1/2)\rho_A(2V_A)^2$ at the suppressant outlet holes. This corresponds to a differential air pressure coefficient of $C_A = 5$.

Wind tunnel observations show that this configuration is able to generate a liquid jet that is ejected vertically upwards from the leading edge holes and well away from the upper surface of the container. This jet is simultaneously bent over in the crosswind and atomised. The dispersion of the droplets is caused by free stream turbulence together with the instabilities in the vicinity of the atomisation zone.

4.3. Pivoted self aligning

A design that combines the principle of the wind vane with the container described in Section 4.2 is shown in Fig. 10. In this case, a filled container can be pivoted about a point close to its centre of mass so that it hangs in a vertical orientation without the contents draining away. When subjected to an explosion wind the container will self align with the flow direction. The position of the pivot can be chosen so that the container remains stable under natural wind loading. This system, therefore, ensures that the containers are optimally aligned to the explosion wind. The one system can protect against flame encroachment from any direction. It is also able to change direction during the course of the explosion.

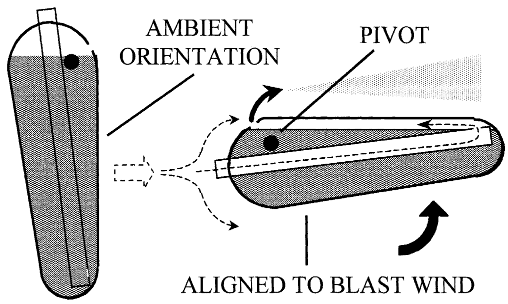


Fig. 10. Pivoted container showing self alignment with blast wind.

5. Experimental set-up

5.1. Explosion duct

An explosion rig was built at the department's remote test site at Buxton, Derbyshire (Fig. 11). The explosion duct was constructed from aluminium sections to make a 5.1 m long smooth walled duct with a square (0.3 m × 0.3 m) cross-section (Fig. 12). The duct was purge-filled with a premixed methane–air mixture from the closed ignition end. Gas concentration was monitored continuously at both the closed and open ends of the duct.

Fig. 11. Close-up of explosion duct showing vent cover that falls to ground immediately before ignition.

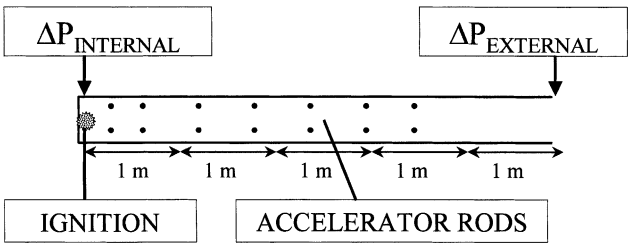


Fig. 12. Explosion tube showing location of pressure transducers and accelerator rods.

Leakage from the open end was prevented to within seconds before ignition by a polycarbonate hinged vent cover (Fig. 11). Upon release, the vent cover falls to the ground under its own weight. Ignition was achieved by discharging a capacitor through a spark plug mounted at the centre of the closed end. The voltage induced by the discharge current was used to trigger a computer-controlled data logger. Pressure measurements were taken by two Meclec piezo-electric transducers mounted flush to the closed end plate and in the sidewall within a few centimetres of the open vent. Additional logging channels were used to collect photodiode voltage outputs mounted at windows along the side of the rig. This enabled the flame passage times at these positions to be measured accurately. Thus, the pressure measurements recorded the internal and external overpressures.

5.2. *Flame accelerators and container array*

Steady flame acceleration was achieved by using a series of accelerators along the duct (Fig. 12). Each accelerator had two rods (6 or 8 mm diameter) mounted in thin steel-sheet holders. The thin steel holders presented very small cross-sections to the flame and, therefore, the only perturbations in pressure and flame speed were a direct consequence of the accelerator rods and not the holders. The same holders were used for the suppression containers so as to ensure that their effects on the flame could be readily determined from the pressure trace. This ensured that the flame's interaction with each accelerator could be associated with a change in curvature of the pressure–time trace. Hence, the average flame speeds between accelerators could be accurately determined from pressure recordings alone. The photodiode measurements primarily served to prove the adequacy of the pressure data for determining flame speed. The number of accelerators and/or the diameter of the rods were varied to achieve different rates of flame acceleration and, thereby, control the incident flame speed on the suppression containers. A maximum of seven accelerators were used. These were placed at 0.3, 0.6, 1.2, 1.8, 2.4, 3.0 and 3.5 m from the ignition point (Fig. 12). The container array was placed at varying positions along the duct but in particular at distances (Δx, m) from the ignition point of 2.5, 1.9, 1.7, 1.5 and 1.3 m, four positions of which are shown in Fig. 13.

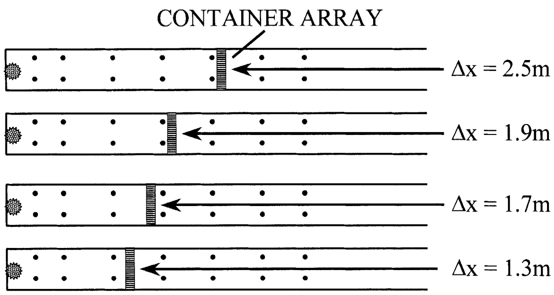


Fig. 13. Locations of the container array amid the accelerators.

6. Explosion trials

6.1. Minimum flame speed for suppression

The first phase of tests employed varying numbers of accelerators and one suppression array of three (Fig. 14a) 35 mm aerofoil-type containers (Fig. 14b). Experiments were done both with (wet) and without (dry) water in the containers. Thus, the effect of water released from the containers could be assessed directly from the pressure measurements. It was established (Fig. 15a) that with an incident flame speed of 80 m/s the water droplets caused the explosion over-pressure to increase. This was calculated to correspond to a mean droplet diameter of 125 μm. That the combustion rates were enhanced by these droplet sizes is consistent with independent findings [12]. By increasing the incident flame speed to 128 m/s, thus generating a mean droplet size of 49 μm, a significant suppression effect was observed (Fig. 15a). A further increase in the incident flame speed to 170 m/s, corresponding to a droplet size of 27 μm, gave rise to distinct suppression.

6.2. Effect of droplet volume concentration

In these experiments, a staggered array of 12 (Fig. 16a) 20 mm aerofoil shaped containers (Fig. 16b) was employed. By changing the number of liquid outlet holes per container (Fig. 16b), the water droplet concentration in the wake of the container array was varied. All the holes had 1.5 mm diameter. A nominal outlet hole-separation of 18 mm ($1 \times$ holes) was chosen and the separation then varied between 36 mm ($(1/2) \times$ holes) and 9 mm ($2 \times$ holes). The more effective suppression was observed for the highest water volume fraction ($2 \times$ holes), marked by the more rapid fall in over-pressure, after the flame interacts with the containers, shown by arrows in Fig. 15b. Here, the time-origin of the pressure traces has been artificially chosen to aid comparison.

6.3. Effect of leading edge spoilers

Spoilers made from aluminium sheet, into which holes were drilled, were designed so that they could be clipped onto the basic aerofoil-shaped container (Fig. 17a). Twelve containers were mounted into the suppression array (Fig. 17b). A base-line experiment was first conducted without the container array (WITHOUT) and with five accelerators in the positions shown in Fig. 12. The corresponding internal (IN) and external (OUT) over-pressures, shown in Fig. 18a–d, enable the effects of the container array to be judged. The container array was placed at five positions along the duct. Rapid suppression of the internal over-pressure occurred for container array positions $\Delta x = 2.5$, 1.9 and 1.7 m, respectively (see Fig. 18a–c). When the containers were moved closer to the ignition position than $\Delta x = 1.5$ m the incident gas velocity was insufficient to cause any appreciable suppression. As a result, the suppression array acted as an additional accelerator that drove the explosion over-pressure above that of the nominal case (Fig. 18d). Importantly, in all the cases when internal suppression was observed the external over-pressure was completely removed (Fig. 18a–c). This has been attributed to extinction of the flame inside the duct. The absence of the flame is clearly evident in high-speed video taken of the venting gas. The absence of the container

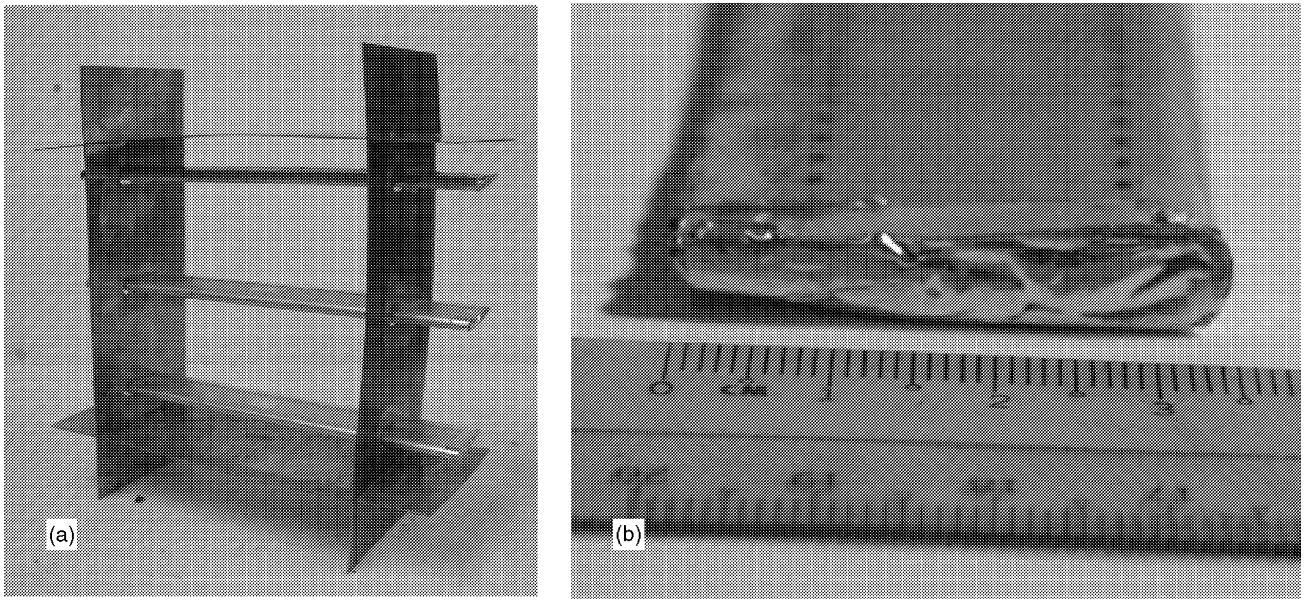


Fig. 14. (a) Three-fold array with 35 mm aerofoil-shaped containers; (b) Cross-section of 35 mm aerofoil-shaped container.

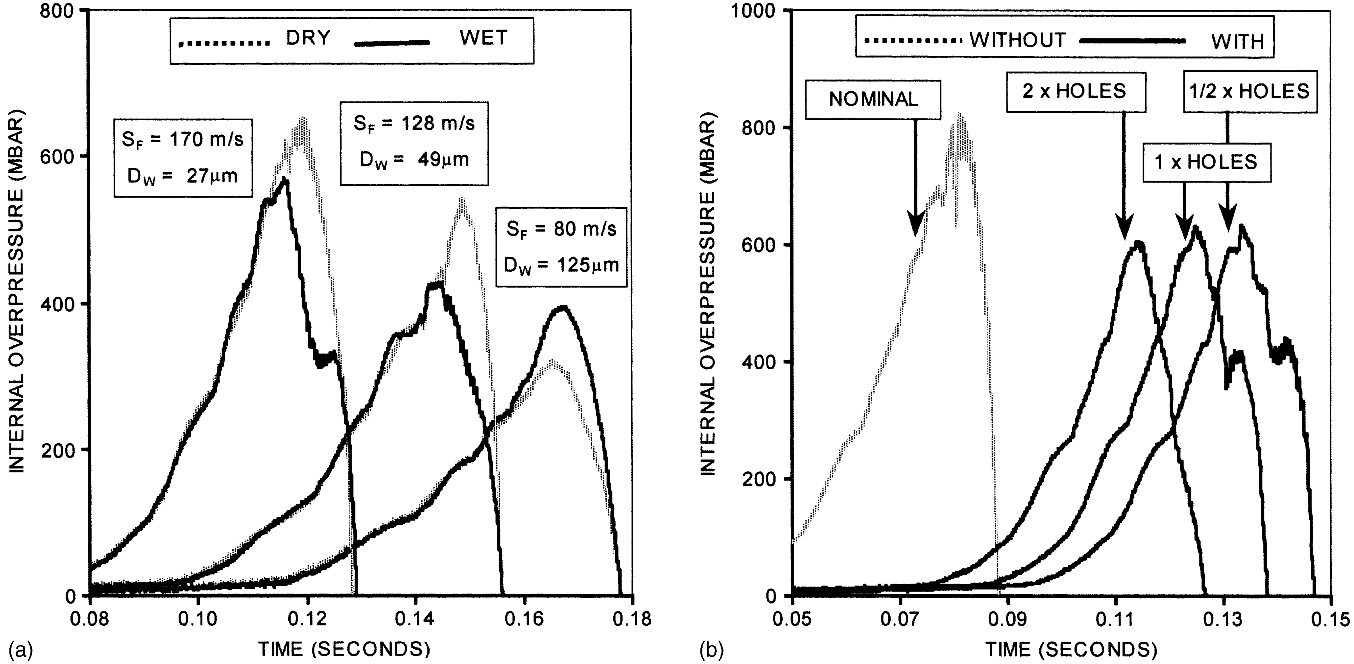


Fig. 15. Suppression effects registered on the internal over-pressure. Effects of the (a) incident flame speed and (b) number of water outlet holes.

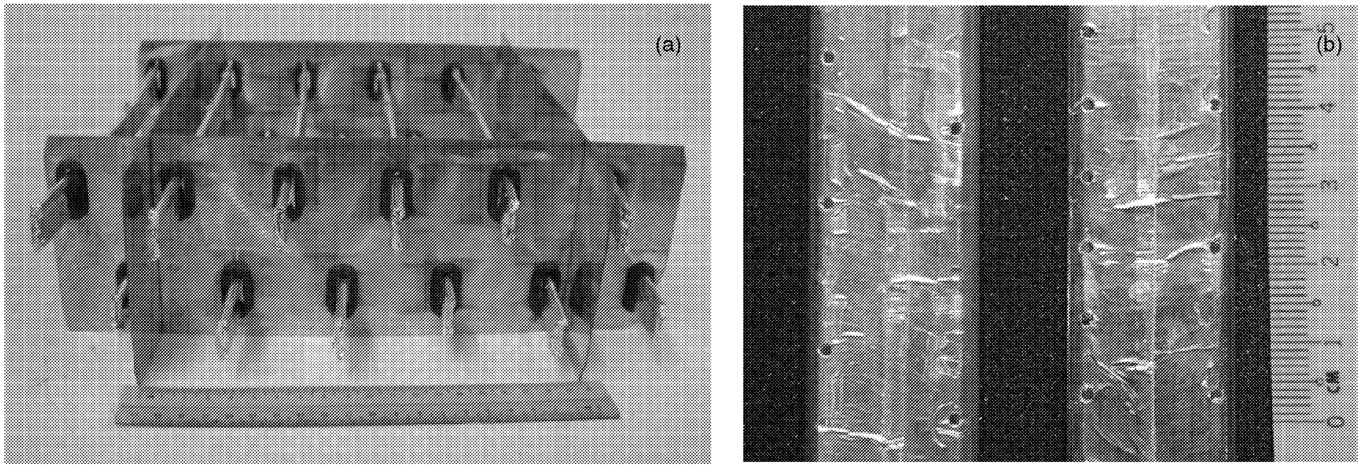


Fig. 16. (a) Twelve-fold array with 20 mm aerofoil-shaped containers; (b) Upper surface of two 20 mm aerofoil-shaped containers showing suppressant outlet holes on left and air inlet holes on right.

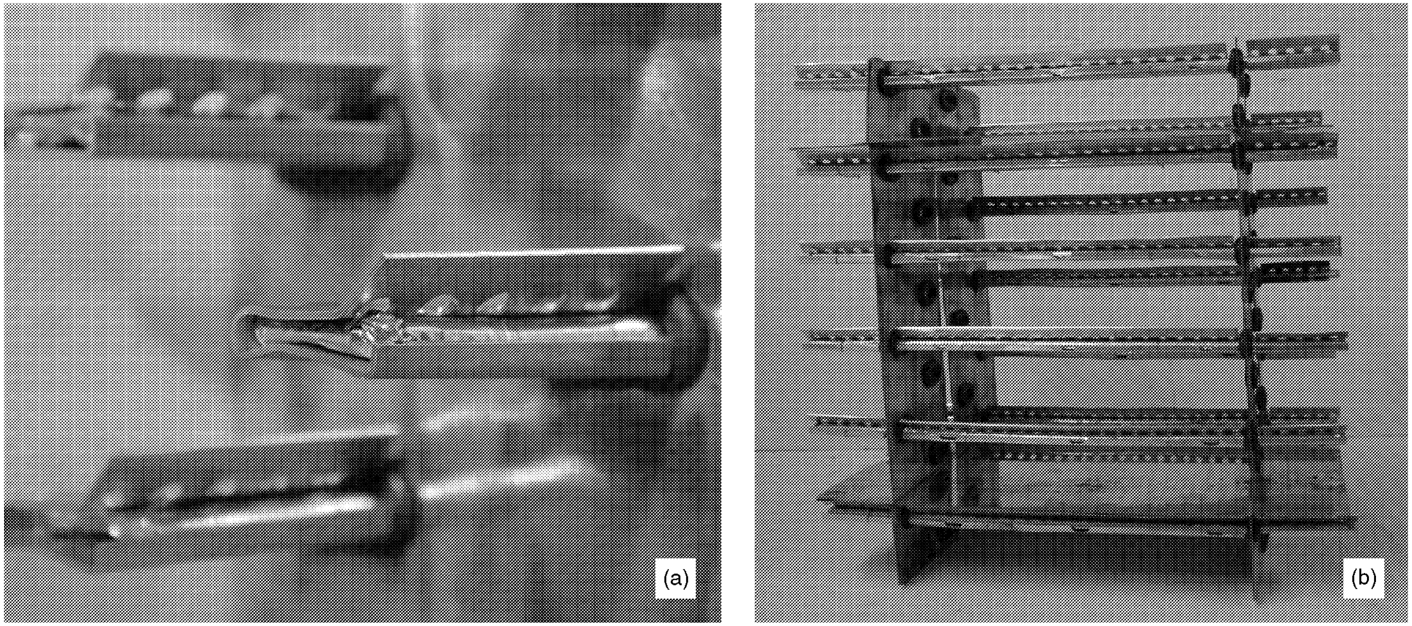


Fig. 17. (a) Aluminium spoilers clipped to 20 mm aerofoil-shaped containers; (b) Twelve-fold array with clipped-spoiler container array.

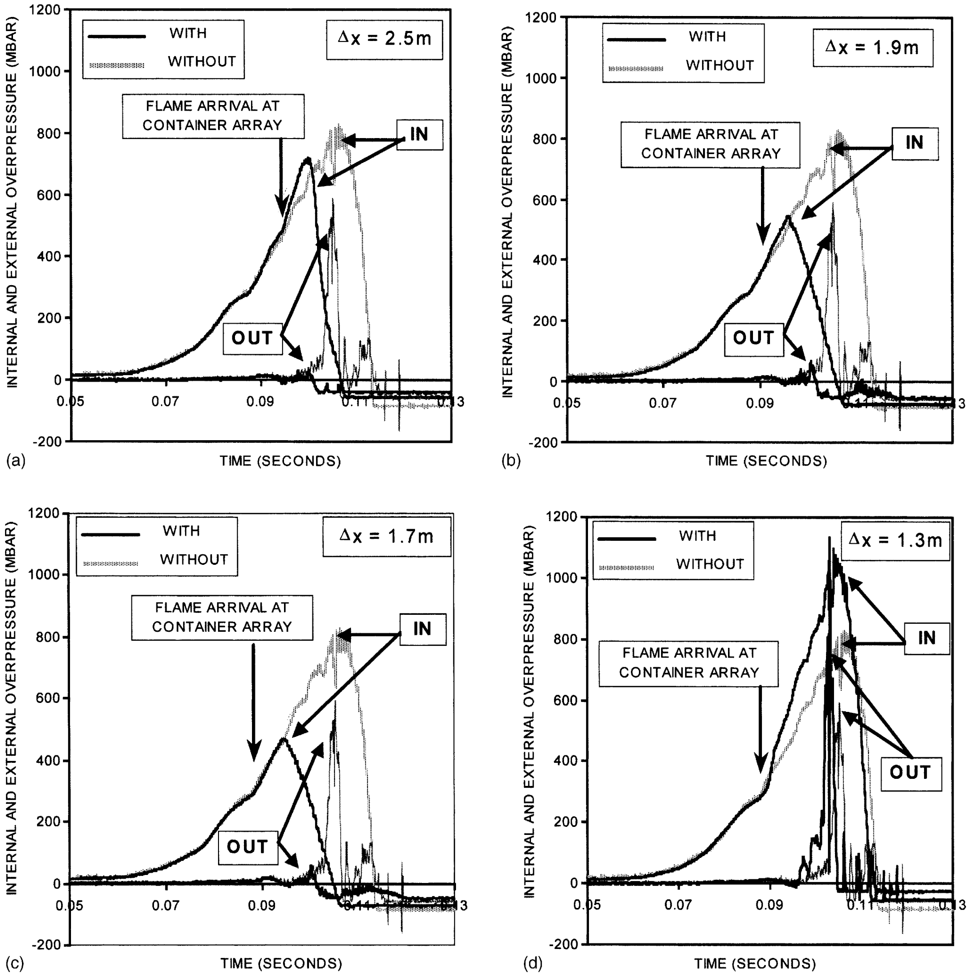


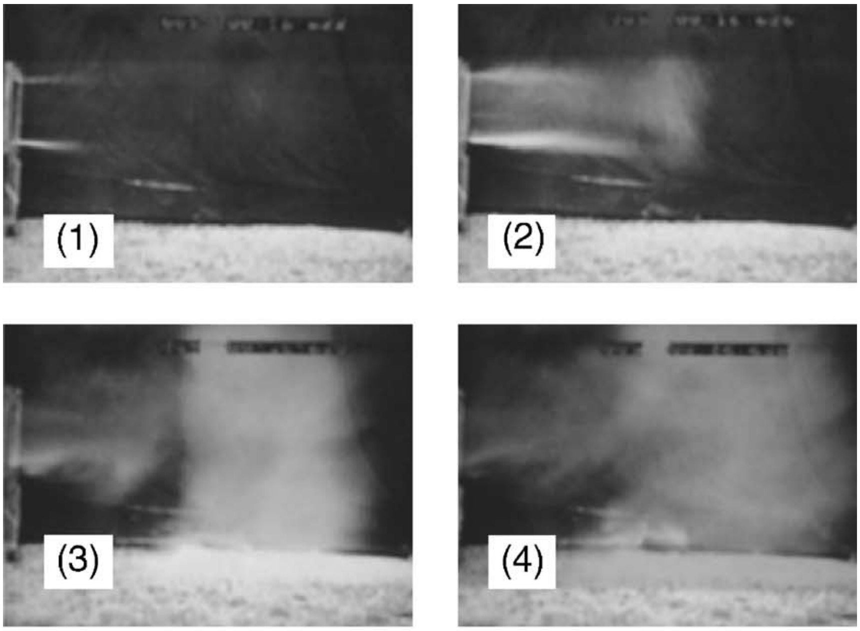
Fig. 18. (a and b) Overlaid internal and external over-pressures with and without clipped-spoiler suppression array for $\Delta x = 2.5$ and 1.9 m; (c and d) Overlaid internal and external over-pressures with and without clipped-spoiler suppression array for $\Delta x = 1.7$ and 1.3 m.

array was marked by a large flame-ball outside the vent (Fig. 19a) and the presence of the array by venting of what appeared to be a fine-droplet cloud (Fig. 19b).

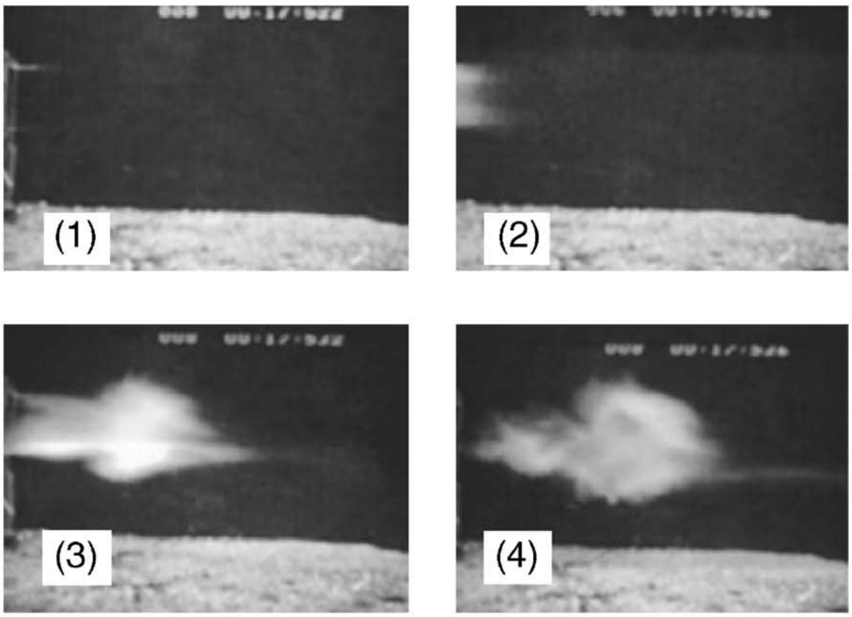
7. Placement strategies for different explosion event

7.1. Extinction of vented flame

The proposed suppression system is suited to extinguishing vented flame. Although venting limits confined explosion over-pressure, it simultaneously produces a very high-velocity



(a)



(b)

Fig. 19. (a) High-speed video frames showing (a) external explosion when suppression array is absent, and (b) vented droplet cloud when suppression array is present.

jet of unburned gas, followed by flame, which can cause a substantial external explosion. Such an external explosion is of particular concern if it occurs within plant or confinement. The placement of the proposed suppression system in the vent region (Fig. $20a_1$) would both inert the gas vented through it and prevent external ignition. The minimum internal over-pressure at which suppression would occur at the vent is below 200 mbar. The relationship of this minimum internal over-pressure with the vent coefficient is shown in Fig. 20b. Here, the vent coefficient is defined as the ratio of the vent area (A_{VENT}) to that of the process module wall in which it is located (A_{MODULE}). The relatively long duration of the venting process would, however, require that the container depletion times are appropriately long, which can be achieved by suitable choice of container volume.

7.2. External or near-perimeter explosion

A similar strategy to that described earlier would also apply at, or in the near vicinity of, the perimeters of open modules (Fig. $20a_2$). Here, external explosions or high venting velocities through plant could give rise to particularly high over-pressures. In all of these situations, the location at which the suppression system should be placed is clearly defined, since the blast wind direction is outward. Thus, a fixed horizontal container system may well suffice. There is the possibility that the system could be mounted just outside the process module thus removing the need for structural modification. In this case, the system could be designed to serve doubly as protective wind cladding.

7.3. Interior partially confined explosion

Neglecting the effects of drag resistance caused by obstacles on the explosion wind, an unconstrained steady flame in tube, cylindrical and spherical geometries (Fig. 21a) generates the peak explosion over-pressure shown in Fig. 21b. Kuhl et al. [13] determined this relationship between over-pressure and flame speed for a flame propagating steadily in a domain of infinite extent.

Thus, if we assume that a suppression system is effective for incident flame speeds between 150 and 170 m/s then Fig. 21b indicates that the maximum over-pressure when the suppression system is present is dependent upon the flame geometry. In fact, the peak-suppressed over-pressure is approximately 600 mbar for tube-like geometries, 330 mbar for cylinder-like geometries and 250 mbar for an unconstrained spherical flame. Note that in the experiments described in Section 6.1 the peak over-pressure corresponding to 170 m/s was approximately 600 mbar (Fig. 15a) and, therefore, in good agreement with Kuhl et al.'s theory.

Since ignition could occur anywhere, it is not known from which direction the flame will approach the suppression system. Thus, in order to arrest flame acceleration before unacceptable pressures are reached, it would be necessary to cage the explosion domain (Fig. $20a_3$). In this way, the propagation distance of the flame to the suppression system could be minimised. This requirement can be readily satisfied where the process plant is arranged in separate areas. The same requirement is more difficult to ensure when the system is retrofitted to a module that is heavily congested with process plant. The grating-floor areas

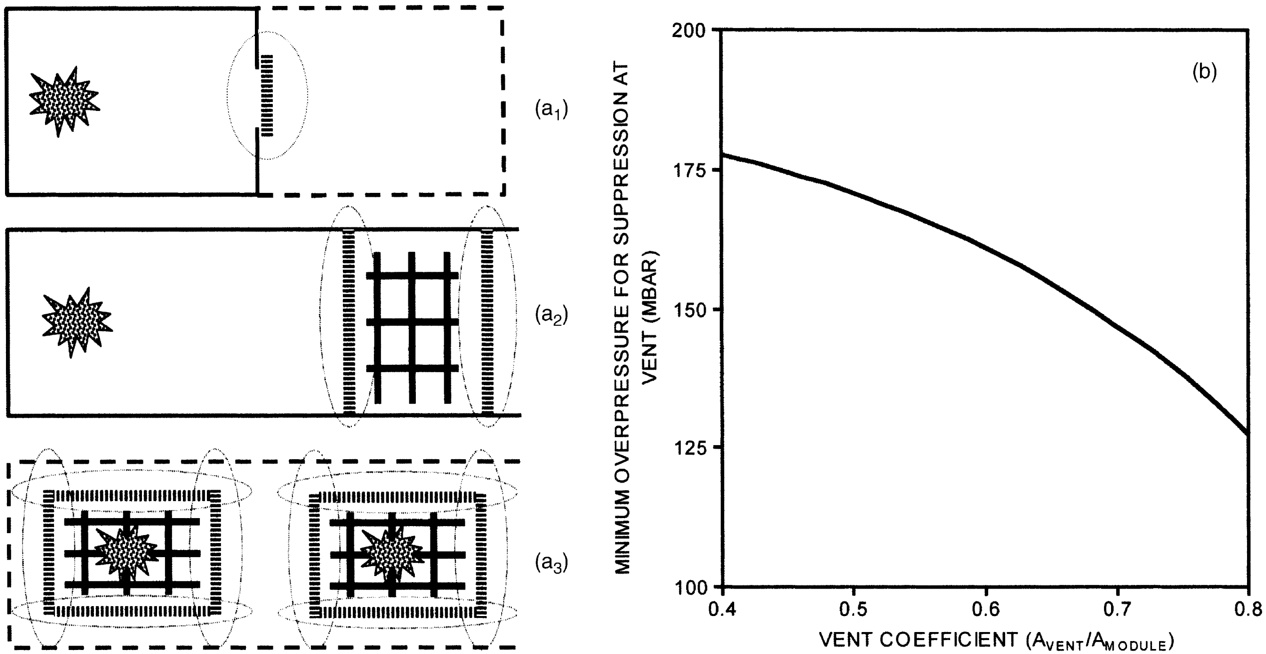


Fig. 20. (a) Placement strategies for suppression screens: (a_1) vented flame, (a_2) external explosion, (a_3) internal partially confined; (b) Minimum confined explosion over-pressure for suppression to occur at vent.

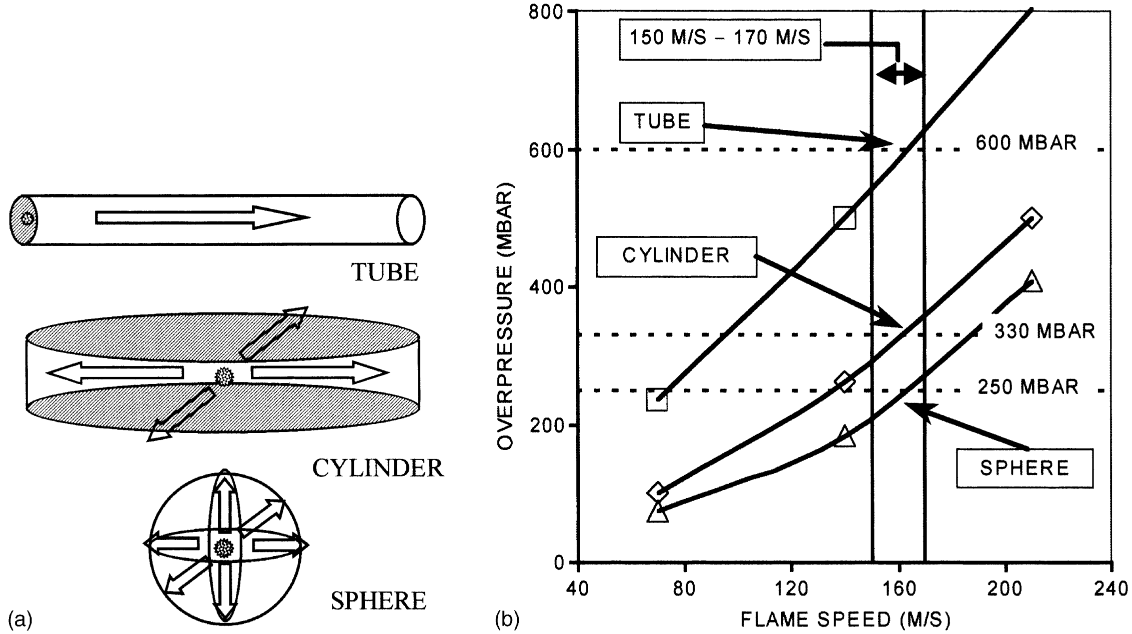


Fig. 21. (a) Flame geometries used in Kuhl et al.'s calculation; (b) Relationship between explosion over-pressure, flame speed and flame geometry showing 150–170 m/s suppression region.

separating mezzanine levels, however, may provide suitable mounting positions if vertical flame propagation is to be suppressed.

8. Installation in process modules

8.1. Water replenishment

Under ambient conditions the principal cause of water loss from the suppression system will be due to natural evaporation through the air inlet and water outlet holes. If exposed to high natural wind velocities, this could possibly lead to some extra loss. Thus, a water supply system only needs to provide slow replenishment rates that could, therefore, be gravity fed. Such a system is shown in Fig. 22, in which the water is allowed to cascade down the hollow frame to fill catchment buckets. The buckets in turn feed water horizontally sideways into the suppression containers. The system shown also has header and sump tanks that provide local water storage.

8.2. Water type

The water would need to be free of debris so that it does not block the water outlet and air inlet holes. If the system were able to have a fresh water supply then corrosion could be minimised. Maintenance problems would arise when seawater is used as for offshore fire water systems. However, a maintenance procedure for this explosion suppression system need not require a lot of manual effort and adjacent equipment need not be bagged. Since the system is necessarily wetted in its nominal mode then, if seawater were used, corrosion and marine life would need to be minimised. This should be possible by suitable choice of materials that can resist corrosion by saline and chlorine solutions, the latter being necessary to inhibit the build up of microbial and marine life.

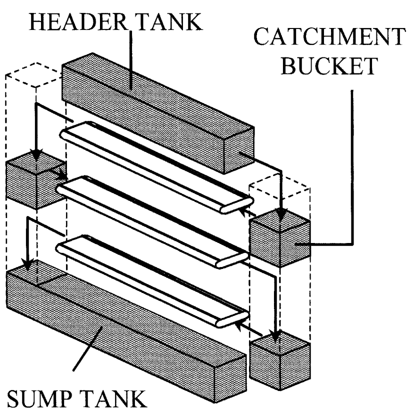


Fig. 22. Gravity-fed water supply system for containers in suppression screen.

8.3. Materials

Should the system need to withstand substantial fire loading, then this would exclude the possibility of using plastics that otherwise would be sufficiently strong and non-corrosive. If metals were used, then the presence of water would constrain temperature rise under fire loading. The metals that could be used depend upon the water quality. Fresh water systems could be constructed from mild steel whereas for saltwater systems it may be necessary to consider super-duplex steels or copper–nickel alloys. The latter have an established record for use in offshore fire water systems, with an installation cost little greater than flame resistant fibreglass [7].

8.4. New design versus retrofit

The proposed suppression system offers versatility when designing a new process plant. Its placement could be chosen specifically to address the most probable explosion scenarios. Retrofit necessarily poses more problems but could be made practicable by the comparatively lightweight of the system. In addition, the shape of the container array is arbitrary and could, therefore, be moulded around plant. Note that an unbroken droplet blanket must be presented to the flame or else it could penetrate and sustain the explosion. Nonetheless, access routes could be provided through the container array.

9. Discussion

9.1. Robustness

The proposed system has simplicity and is robust. An important consideration is the lack of need for precision or sophistication in the manufacture. The numerous experiments conducted to date have shown that the system remains operative even when the containers incur minor damage. It is not necessary that the water be brim full for a spray to be generated. Thus, satisfactory response characteristics can be ensured against the ever present risk of minor damage, whether during installation or through engineering operations. The passive response characteristics of the system remove the need for associated detection and activation devices whose integrity during an accident poses additional problems.

9.2. Scaling and design

The suitability of the proposed system for use in full-scale plant would need to be assessed in larger-scale experiments than reported here. It should be emphasised, however, that the scaling issues are the ones associated with the explosion and not the suppression device. Each implementation of the system would require careful design. The principal concerns are the response time of the containers, the number of suppressant outlet holes and the stacking separation in the container array. These parameters are difficult to quantify a priori by theoretical analysis alone, but can be readily determined through a combination of laboratory and limited small-scale explosion experiments. By incorporating a range of container sizes, it should, however, be possible to design one suppression system to be effective under a wide range of possible explosion scenarios.

9.3. Extinction of vented flame

The implementation of the proposed system for extinguishing vented flame should be considered in the widest sense. There are many sorts of confined explosion scenario, for example in compressor houses where over-pressure is limited by means of a low failure-pressure vent. The venting process, however, produces high-velocity flammable gas and flame jets that pose their own particular hazard. The proposed suppression system has the potential of eliminating the escalation in an explosion that such a strong ignition source could cause. Moreover, this additional safe-guard is achieved by simply mounting a suppression device on the explosion-side of the vent so that the failure of the vent initiates the flow of escaping gas through the container array.

10. Conclusions

This paper has presented a series of investigations into the passive suppression of explosions using water containers. The concepts have been justified both theoretically and experimentally in laboratory and field-scale experiments. The study has also considered a number of practical issues of installing such a system in full-scale process plant. The results support the engineering feasibility of using such a system. Before being considered for implementation at full-scale, however, the proposed concepts would require experimental demonstration at a larger scale than reported here and preferably in a representative geometry.

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