Mitigation of Gas Explosions Using Water Deluge

by

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ABSTRACT

The degree of congestion in petro-chemical installations has a strong impact on the strength of possible gas explosions. Model predictions and recent full-scale explosion tests showed that there are situations where the consequences of such gas explosions are unacceptably high. These consequences make it necessary to consider several measures including very expensive ones such as control room relocation or strengthening of control rooms. When the costs are too high also other mitigation methods may have to be assessed. One of these methods is mitigation of gas explosions using water spray systems. Offshore such systems are already in use for this purpose, onshore water curtain systems may be applicable.

The paper gives an overview of recent research into the effects of water spray on the course of gas explosions in congested environments. This paper reports on how water spray affects the course of gas explosions, under which conditions water spray will be effective as a means for explosion effects reduction and how one can design a water spray system to limit the consequences of possible accidental gas explosions. Finally the potential of increase of ignition probability due to the use of water spray will be discussed.

INTRODUCTION

The degree of congestion in petro-chemical installations has a strong impact on the strength of possible gas explosions. Research performed during the last 20 years has revealed the main processes governing pressure development due to gas explosions in congested environments. The understanding of these processes also allowed for the development of models. Sophisticated models based on Computational Fluid Dynamics (CFD) such as FLACS (Hjertager, 1982 and Van Wingerden et al., 1993) and AutoReagas (Van den Berg et al., 1996) seem to be the most promising techniques since they allow for implementation of all physical models necessary for describing the gas explosion processes as realistically as possible.

Using these sophisticated methods investigations were carried out to determine the expected pressure and drag loads due to gas explosions in an example of a type of
petro-chemical installations that are partly enclosed, viz. offshore modules. These investigations showed that there are situations where the consequences of gas explosions are unacceptably high. These findings were recently confirmed during two campaigns of full-scale explosion experiments carried out in representations of offshore modules (Steel Construction Institute, 1998; Al-Hassan and Johnson, 1998). To modify installations in which such potential high pressure gas explosions may arise, measures are necessary such as reduction of the maximum explosion loads (re-arrangement of equipment; increasing and possibly re-distribution of the vent openings considering offshore modules), strengthening of the installation integrity and for onshore plants relocation or strengthening of control rooms. Such modifications involve high costs, sometimes unacceptably high. Therefore also other mitigation methods have to be assessed. One of these methods is mitigation of gas explosions using water spray systems. Offshore such systems may be already available for fire protections, onshore there may water curtain systems for retaining gas clouds after a release.

Recent research into the effects of water spray on the course of gas explosions in congested environments has revealed understanding of the main processes involved. This paper reports on how water spray affects the course of gas explosions, under which conditions water spray will be effective as a means for explosion effects reduction and how one can design a water spray system to limit the consequences of possible accidental gas explosions. Finally the potential of increase of ignition probability due to the use of water spray will be discussed.

THE EFFECTS OF WATER SPRAY ON GAS EXPLOSIONS

The effects of water spray on gas explosions are twofold. Any activated water spray system causes turbulence in the gas mixture which upon ignition of this gas mixture results in an increase of the burning rate. The second effect is a mitigating effect. Due to evaporation of water droplets in the flame burning rates are decreased or it may even be possible to quench the explosion flame. The droplets generated by water spray systems are generally too large to evaporate in the flame. Hence the droplets must break up before entering the combustion area. Such a break-up is possible if the droplets are exposed to strong hydrodynamic forces. These forces do arise during a gas explosion in an unconfined or vented congested environment due to the high flow velocities generated.

**Turbulence generation by water spray systems**
Recent work reported by Van Wingerden and Wilkins (1995) on experiments carried out in a 1.5 m³ box revealed for several nozzle types a burning rate increase of approximately 1.5 to 2.0 times the flame speeds without water spray for propane and 1.4 to 2.3 times the flame speeds without water spray for methane.

An increase of flame speeds was found for nozzles generating relatively big droplets (in the order of 500-1000 µm) and fogging nozzles (droplet sizes in the order of 50-
100 µm). Figure 1 shows an example of increase of flame speeds with distance for various nozzles as a function of the distance from the ignition source.

The experiments indicated that the source of the turbulence generation is related to the bulk flow of water into the box as seen in Figure 2. Further it was noted that the increase of flame speeds appears to be uniformly divided throughout the mixture, indicating that the level of turbulence has been increased uniformly in the entire box and is not limited to areas where the droplets are present. This emphasises once more the fact that the turbulence generation is related to the bulk flow of the water into the box.

The experiments described above show that water spray causes increase of explosion loads when the explosions take place in relatively open, low congested environments.

Mitigation by waterspray
Several investigations have shown that water spray under certain circumstances can reduce explosion effects considerably. The most important studies that were performed in this respect are the studies performed by Acton et al. (1990), Bjerketvedt and Bjørkhaug (1991), Thomas et al. (1991), Catlin et al. (1993), Van Wingerden et al. (1995) and the recent two afore-mentioned full-scale explosion experiments campaigns (Steel Construction Institute, 1998; Al-Hassan and Johnson, 1998). In the majority of these studies water spray was introduced everywhere in the installation used for the experiments. Figure 3 shows an example of two pressure-time histories obtained during experiments performed in a representation of an offshore rig, one without water spray being present and one in which water spray was activated. The Figure demonstrates the positive effect water spray has when the explosion takes place in a congested environment.

There are several possible mechanisms by which water sprays can suppress combustion. The most likely mechanism seems to be that of water droplets acting as a heat sink as a liquid component and after evaporation as a diluent of the mixture. A theoretical approach shows that droplets smaller than 10 µm will evaporate in the flame. Larger droplets as supplied by fire protection systems have to break-up as they are too big to evaporate near or in the flame. The resulting water vapour will dilute the gas mixture resulting in burning rate reduction or even flame quenching. Break-up is only possible for certain minimum hydrodynamic forces acting on the water droplets caused by a flow around the droplets.

A thorough analysis of the experiments reported by Van Wingerden et al. (1995) show that the most effective explosion mitigating water spray systems are those generating either very small droplets (less than 10 µm) or large droplets (larger than 200 µm). Nozzles generating droplets between approximately 20 µm and 200 µm are the least effective systems when considering explosion mitigation. Droplets of approximately 10 µm or smaller will evaporate in the flame directly. Larger droplets will have to break-up into smaller droplets to have an effect as well. The hydrodynamic forces acting on the droplets in an accelerating flow ahead of the flame will cause the droplets to accelerate but if high enough will also cause them to break-up. Small droplets (< 200 µm) will easily adapt to flow accelerations and as a result
will not be exposed to strong hydrodynamic forces that will cause them to break-up. Larger droplets will break-up more easily.

If the hydrodynamic forces acting on droplets are not strong enough, break-up will not occur and mitigation will not take place. In the experiments reported by Catlin et al. (1993) break-up did not occur if the degree of confinement was chosen too high. The increase of flow speeds developed during the explosion under high confinement conditions was too low to cause droplet break-up.

Droplet break-up may occur when a droplet is exposed to a flow resulting in hydrodynamic forces that are stronger than the forces keeping the droplet together, viz. the surface tension. This can be expressed in the Weber number (We):

\[
\text{We} = \frac{\rho v^2 d}{\sigma}
\]

where 
\(\rho\) = density of the gas mixture stream (kg/m\(^3\))
\(v\) = velocity of the gas mixture stream relative to the velocity of the droplet (m/s)
\(d\) = diameter of the droplet (m)
\(\sigma\) = surface tension (N/m)

Several experimental investigations have been performed to study droplet break-up. Examples of such work are the shock-tube experiments performed by Lane (1951) and Hanson et al. (1963). These experiments revealed that break-up occurs when the Weber number exceeds a critical Weber number of \(\text{We}_c = 10-12\). It is emphasised that the difference between the velocity of the gas flow around the droplets and the velocity of the droplet itself is determinant. Recently Van Wingerden and Linga (1997) confirmed these findings. In both steady and transient flows (generated by explosions) water droplets broke up when this critical Weber number was reached.

An example of how a water droplet breaks up when critical conditions are reached is shown in Figure 4. First the droplet is deformed and takes the shape of a disk. The inner part of the disk is subsequently blown into a bag held by a ring-shaped outer part. When the hydrodynamic forces are too high the bag breaks up into a fine mist. These very fine droplets can evaporate in the flame. Van Wingerden and Linga (1997) estimated that of the original mass of the droplet approximately 30% are generating these fine droplets. The remaining 70% of the original mass of the droplet cause larger droplets. Only the fine droplets evaporate in the flame.

Apart from the droplet size the mechanism explained above make it clear that apart from the droplet size, the effectiveness of the water spray system will also be dependent on the amount of water present in the air as fine droplets. The higher the water concentration, the more heat will be lost to the water during the flame propagation process and therefore the lower the burning rate will be. The mass of water present just ahead of the flame after the break-up will depend on the water mass present just before break-up. As such the water application rate is an important parameter as well.
APPLICATION OF WATER SPRAY TO MITIGATE GAS EXPLOSIONS

The most apparent areas for application of water spray are offshore modules. A lot of work has been put into showing the beneficial effects of water spray for these installations. The latest full-scale explosion experimental campaign carried out in a module having dimensions of 28 m x 12 m x 8 m showed the potential of water spray: pressures were reduced by a factor 20 in some cases (Al-Hassan and Johnson, 1998). A large variety of tests were performed including the variation of the water application rate and nozzle type. In most cases general area deluge was used which showed the above-mentioned effectiveness. In some tests, however, also water curtains were used including perimeter deluge and dedicated deluge. The latter type is used to cool down specific pieces of equipment such as vessels and appeared not very effective for reducing explosion pressures mainly because it is applied locally only. Water curtains appeared to be less effective than general area deluge even though the same amount of water was introduced in the curtains only as was introduced throughout the entire module for the general area deluge tests. Nevertheless the water curtains had a clear positive effect on the overpressures generated (i.e. a strong reduction).

A reason for water curtains being less effective than general area deluge is the fact that one allows the flame to accelerate in between curtains generating some overpressure whereas general area deluge will not allow for such flame accelerations.

Water curtains can, however, be rather effective onshore as demonstrated by Acton et al. (1990). Tests were performed in a configuration consisting of pipe-racks only. There were no confining structures present. Pressures of up to 3.5 bar were noticed in this geometry for natural gas. When deluge was activated pressures of 0.25 to 1 bar were noticed depending on the type of nozzle that was used in the water curtains. Also here one allows the flame to accelerate in between the curtains but a continuous acceleration process as seen for the dry case is not possible limiting the maximum overpressure generated.

Hence, regarding the large areas covered by onshore plants in comparison to offshore facilities water curtains are a more effective choice than general area deluge. The latter is, however, preferable offshore.

DESIGN OF WATER SPRAY SYSTEMS

General
To be able to use water spray systems the way described above the water spray system must be fully active before ignition has taken place. An activation after ignition e.g. by pressure transducers coupled to a valve in the water spray system is not possible as the water spray system cannot supply water sufficiently fast to respond within the short time that is available. The water spray system should therefore be
activated upon detection of gas by a gas detection system. The consequence is that the water spray system may be activated even though an ignition never takes place. Activation by gas detection puts high demands to the design of the gas detection system.

**Explosion prediction tool with water spray model**

The effects of water spray on gas explosions are dependent on many factors such as the geometry in which the explosion occurs, the properties of the nozzles and water spray system (water application rate, droplet size), nozzle position and even agents added to the water to reduce the surface tension of water. The complicated nature of explosions and the effect water spray has on explosions highlight the necessity of the use of a sophisticated tool to describe these phenomena and to allow for design water spray systems to reduce the consequences of gas explosions. Based on the experimental findings described above a water spray model was developed and implemented in the CFD-tool FLACS. FLACS is a 3-D CFD based tool allowing for prediction of the consequences of gas explosions in complex geometries.

The water spray model implemented in the FLACS-code takes account of all aspects associated with water spray: turbulence generated by water spray systems, droplet acceleration, droplet break-up and reduction of the burning rate due to dilution of the gas mixture with water vapour.

The main input parameters of the model are:
- Average droplet diameter (nozzle dependent)
- Water application rate (nozzle dependent)
- Turbulence generation factor (nozzle dependent)

The latter describes the increase of flame speed due to turbulence generated by the water spray system. The factor has been established experimentally and can be estimated from data related to the nozzle.

When conditions are reached where break-up would occur an immediate effect on the combustion rate is assumed. In FLACS this is translated into a reduction of the local turbulent burning velocity mainly depending on the water application rate (nozzle data).

**Validation of design tool**

The design tool has been validated against many experiments performed at Christian Michelsen Research and British Gas. The most important data sets, however, are the full-scale explosion experiments reported by The Steel Construction Institute (1998) and Al-Hassan and Johnson (1998). The water spray model was tested against these experiments. An example is shown in Figures 5 and 6. Figure 5 shows the rig in which the experiment was performed: a 25.6 m long, 8 m high and 8 m wide rig with closed side walls and open end walls. The rig is highly congested by obstructions representing equipment in an offshore module. Ignition was effected at one of the open ends of the rig. In Figure 6 FLACS predictions are compared to experimental results. A comparison of measured and prediction pressure-time histories are shown for a test without water spray a test in which so-called LDN nozzles were used and a test where MV57 deluge nozzles were applied. The Figure illustrates the drastic pressure reducing effect of general area water deluge. The pressures are reduced by
more than a factor of 10. On the other hand the duration of the pressure pulse is increased. The time of arrival of the pressure pulse is much earlier than without deluge. This effect is mainly due to the turbulence generated by the water spray affecting the early phases of flame propagation.

It can be seen that the FLACS simulations qualitatively tell that the pressures will occur much earlier with deluge than without. LDN nozzles give the earliest arrival, MV57 nozzles thereafter. FLACS also predicts the pressure reduction very well for both types of nozzles as well as the double peak indicating that also the physics are well represented.

The code was also used for predicting the effects of using water curtains as reported by Al-Hassan and Johnson (1998) with satisfactory results indicating that the FLACS code also can be used for designing water curtain systems for e.g. onshore plants.

IGNITION PROBABILITY

The beneficial effects of water spray has now been widely accepted and the existence of design tools has made it possible that this technique is now becoming more and more popular to mitigate explosions on offshore installations. In spite of this, however, there are still oil companies who are hesitating to start using this mitigation technique offshore. There may be several reasons for this such as the fact that the water that is used offshore is often seawater and the associated corrosion problems may be unacceptable from a maintenance point of view. The most often heard reason, however, is the fact that water spray may cause ignition of the gas cloud.

Savage (1996) reported on two accidental explosions caused by ingress of water into electric equipment resulting in sparks. These accidents highlight the necessity of using waterproof electric equipment when applying water deluge to reduce the consequences of gas explosions. Use of proper electric equipment and maintenance of this equipment will take away this ignition hazard.

A second source of ignition could be electrostatic discharges. A study reported by Hearn and Jones (1995) shows that discharges from charged clouds (lightning discharges) are not possible. Another source could be water slugs caused by water collected near the roof on a ledge or generated by the nozzles themselves. When such a slug falls down it is charged by collection of charged droplets. A slug on a sledge may also be charged by induction due to a charged water droplet cloud. Proper design of especially the nozzles will avoid such discharges in offshore facilities. Hence the only remaining possibility would be charging of non-earthed objects by charged water particles falling onto these objects. The water itself running from these objects would normally assure a sufficient earthing but there may be certain situations where this does not happen. Good earthing of all larger objects will avoid such electrostatic discharges. In this connection it should be mentioned that in all experimental campaigns performed by Christian Michelsen Research and British Gas an accidental ignition has never occurred.

CONCLUSIONS
Experiments have shown that water deluge activated by gas detection before ignition can reduce the consequences of gas explosions considerably. Water deluge will however not work under all conditions as the effect of water spray on gas explosions in congested environments is twofold:
- Turbulence generated by the water spray will cause an increase of explosion effects
- When hydrodynamic forces acting on droplets are strong enough to cause droplets to break-up mitigation of gas explosions is possible

As a result one should investigate for each application whether water spray will work and design the system in an optimal way. For this purpose a model has been developed and implemented into the FLACS-code, a 3D gas explosion simulator. The model describes the effects of initial turbulence, droplet acceleration and break-up and reduction of burning rates due to evaporating droplets.

The code has been validated against available experimental results including full-scale experiments for investigation of the effects of water spray. The experimental results were reproduced well.

The higher risk of ignition due to use of water spray can be reduced by adequate measures regarding use of electric equipment and avoidance of electrostatic discharges.

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![Graph](image)

**Figure 1** Flame speed as a function of distance in propane-air mixtures for four different nozzle types (Van Wingerden and Wilkins, 1995).
Figure 2 Maximum flame speed in propane-air mixtures as a function of the water application rate of various nozzle types (Van Wingerden and Wilkins, 1995).
Figure 3 Pressure-time histories obtained during two explosion experiments performed in a representation of an offshore module: one without water spray being activated and one where water spray was activated (Bjerketvedt and Bjørkhaug, 1991).

Figure 4 High speed recordings of droplet break-up (Van Wingerden and Linga, 1997)
Figure 5  View of 8 m wide, 8 m high and 25.6 m long high congestion module used during the BFETS, Phase II project.

Figure 6  Comparison of FLACS predictions and results from three different tests performed in the module of Figure 5, one dry test and two tests in which general area deluge was applied using LDN and MV57 nozzles respectively.