Mitigation of Vapour Cloud Explosions – A Review

Kees van Wingerden
GexCon AS
Bergen, Norway

1 Introduction

The potential of devastation of industrial installations, nearby houses and businesses and sadly enough: the potential of fatalities and serious injuries due to vapour cloud explosions is unfortunately still being demonstrated on a regular basis. Recent examples of this potential include the following accidents Buncefield (2005 [1]), Texas City (2005 [2]) and Toronto (2008 [3]), whereas past experiences can be found in overviews published by both insurers [4, 5] and researchers [6, 7].
The majority of research performed in the field of vapour cloud explosions has mainly been addressing two main areas of attention: prediction of the consequences of vapour cloud explosions and trying to understand the main combustion mechanisms governing vapour cloud explosions.
Examples of research into prediction methods include the development of prediction tools for blast generated by deflagrative flames such as similarity methods [8] and 1-D numerical methods (e.g. [9]), the development of simple fuel-air blast prediction methods using such tools as a starting point: Baker-Strehlow-Tang [10], the Multi-Energy method [11], the Congestion Assessment Method [12] and dedicated CFD-codes such as AutoReagas [13] and FLACS [14].
Examples of studies addressing research into governing combustion mechanisms in vapour cloud explosions include those addressing flame instabilities [15, 16], combustion dominated by expansion flow generated turbulence (e.g. [17-20]) and DDT and detonation [21, 22].

Very little attention has however been given to mitigation of vapour cloud explosions, i.e. methods aiming at limiting the consequences of vapour cloud explosions with the exception of siting issues which considers e.g. re-locating control rooms or strengthening these. For siting the aforementioned simple fuel-air blast prediction methods are used. The paper addresses different potential methods to mitigate vapour cloud explosions and highlights research needs to improve or develop these methods further.

2 Design of plant details and layout

Dedicated CFD-based predictive tools such as FLACS [14] developed for describing the combustion process in expansion flow generated turbulence at congestion open up for the possibility of designing industrial sites in such a way that explosion effects are limited. This is possible by e.g. limiting the density of the equipment in installations in combination with limiting maximum flame path lengths, introduction of open areas in between installations and special design details limiting e.g. gas build-up in heavily congested areas by locating such areas at a certain height limiting the possibility of gas-build-up inside these areas for heavy gas releases. The limitation of the density of the equipment in

Correspondence to: kees@gexcon.com

installations in combination with limiting maximum flame path lengths can also be used to avoid the possibility of transition to detonation. In addition these CFD-tools can be used to predict local drag loading on e.g. piping and piping supports. Design of these items to withstand these loads may prevent serious escalation after an explosion.

This mitigation measure is only possible during the design phase of plants and is in practice not feasible anymore once a plant is in operation.

Strong demands need to be put to the predictive tools to design installations as described above using these tools. Due to limitations in computer resources many of the processes ongoing during the fluid dynamics and combustion processes cannot be resolved by the computational grid used. These processes are therefore most commonly described by so-called subgrid models [14]. Subgrid models are used for describing flow resistance by, turbulence generation at and flame folding around geometry details not resolved by the computational grid used. Full-scale experiments investigating the effects of congestion on the course of explosions have shown that small details of congestion have a strong influence on the overall explosion effects [23]. In the light of the importance of small obstructions and the continuous need to use subgrid models these need additional attention, especially flame propagation around subgrid obstructions [14]. Also the combustion models in these dedicated CFD-models need attention. Considering burning velocity models uncertain areas include representation of mixtures of fuels for both laminar and turbulent combustion, the influence of temperature and pressure on laminar and turbulent combustion [24, 25], fuel concentration dependency and modelling of quasi-laminar and turbulent combustion [26, 27, 28], including the effect/possibility of local quenching of turbulent flames. Implementation of DDT or improvement of criteria indicating conditions allowing for DDT [29] is essential for vapour cloud explosion prediction tools.

3 Water Deluge

A very promising technology to limit the consequences of vapour cloud explosions is the use of water deluge. This technology can be used on existing facilities but implies the installation of a water deluge system. Further one needs the availability of large amounts of water upon demand. The water deluge system shall be activated before ignition which would also imply installation of a well-designed gas detection system. The positive impact of water deluge has been documented extensively [30-32]. It has been demonstrated that only droplets smaller than 10-20 μm will affect flame propagation due to evaporation in the flame (in methane-air mixtures). Larger droplets need to break-up before having an impact. Hydrodynamic forces acting on droplets in an accelerating flow will allow droplets to break-up as long as these droplets are not able to adapt to the flow accelerations. Flow accelerations occurring during explosions in congested areas are able to break-up droplets larger than typically 200 μm [32]. A droplet break-up criterion is given by the Weber number (*We*):

$$We = \frac{\rho v^2 d}{\sigma} \quad (1)$$

where ρ = density of gas mixture stream (kg/m3)
v = velocity of the gas mixture stream relative to the droplet (m/s)
d = diameter of the water droplet (m)
σ = surface tension of the water (N/m)

The criterion predicts water droplet break-up when the Weber number We = 10 or larger.

Reported experiments show that the effect of water deluge on flame propagation can be twofold: flame accelerations due to turbulence generated by the water flow if the water droplet break-up criterion is not met; mitigation if the criterion is met. Large-scale experiments show that maximum explosion overpressures generated by vapour cloud explosions in a congested area may be reduced by a factor of 20 or more (maximum overpressures of 10 bar or more were reduced to 0.5 bar or less) [23]. Models to predict the consequences of water deluge as included in FLACS [14] give satisfactory results in spite of their simplicity [33]. To improve the model more information needs to be developed regarding the mechanisms of initial turbulence generation (in relation to the water flux into the protected area and dimensions of the protected area itself), water droplet break-up dynamics and how to improve the efficiency of the breaking-up (e.g. using additives) and the influence of water droplets on flame propagation depending on the water droplet size and water droplet concentration. The latter needs to be investigated for several fuels. Some initial results on water droplet break-up dynamics are presented in Figures 1 and 2 [34]. Figure 1 shows an example of droplet break-up in a steady flow. This type of break-up (known as bag-jet break-up) occurs at Weber number of We = 17 – 30. At lower Weber number break-up occurs according to the inverted bag break-up mechanism (here the central pillar of the bag-jet mechanism as seen in Figure 1 fails).

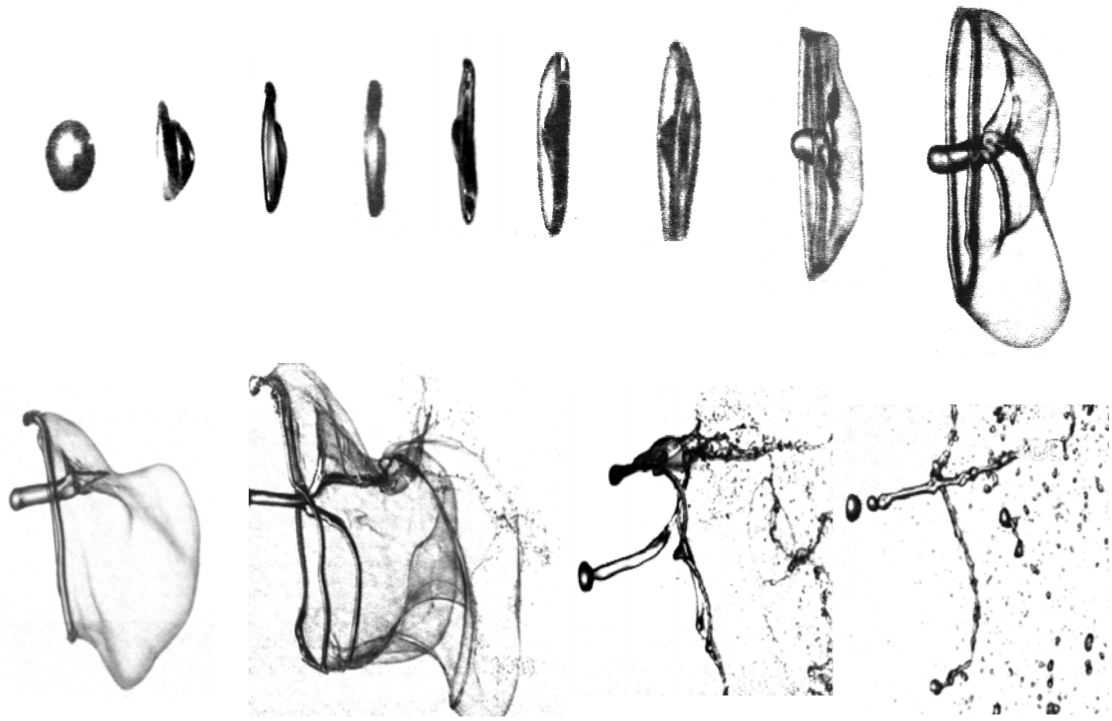

Figure 1. Water droplet break-up mechanism (type inverted bag-jet break up). Measured in 30 cm x 30 cm cross-section wind tunnel. Initial droplet size 4.2 mm. Steady flow of 15 m/s. [34].

Water break-up dynamics were studied in both steady and accelerating flows (the latter generated by an explosion). The droplet distribution after break-up indicates that only 33 % of the original droplet results in small droplets potentially contributing to mitigation. The duration of droplet break-up is approximately 30 ms.

4 Flame inhibitors

Recently an alternative suggestion was made, viz. the use of flame inhibitors by either injection into the flame directly (post-ignition detection) or by injection into the developing flammable gas cloud upon pre-ignition gas detection.

The potential of the use of flame inhibitors was investigated experimentally on both laboratory scale (in a 20 l sphere) and medium scale in a 50 m^3 congested vented enclosure. The 20 l sphere experiments were used to derive fundamental combustion properties in the presence of flame inhibitors. The medium-scale experiments investigated the potential of using this technology in reality both as a pre- and post-ignition agent [35, 36]. Especially the use of flame inhibitors as a pre-ignition agent appears very effective. Results of experiments using flame inhibitors as a pre-ignition agent (potassium carbonate) performed in the 50 m^3 congested vented enclosure are shown in Figure 2 for several hydrocarbon gases. Reference tests without inhibitor are performed for comparison.

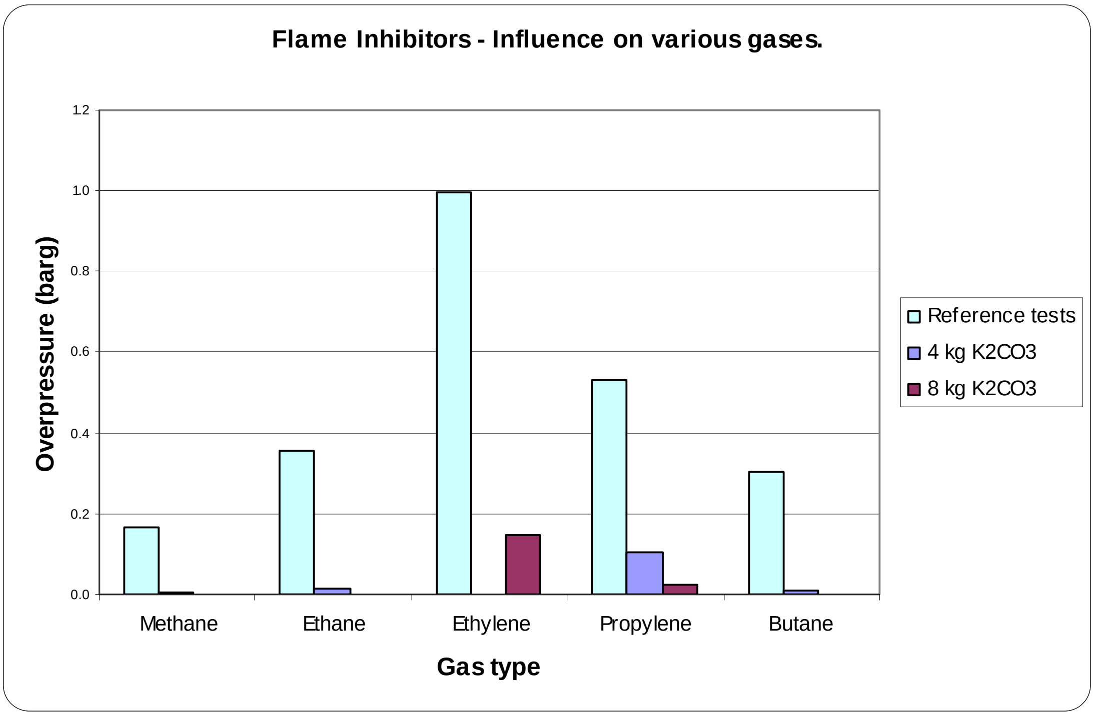

Figure 2. Peak explosion pressure in the 50 m^3 module for a series of hydrocarbon fuels using potassium carbonate as an inhibitor. The quantity of inhibitor was varied and ignition was effected 2 s after inhibitor injection.

The experiments revealed a big dependency of the efficiency of flame inhibitors on the gas concentration: flames in lean mixtures can be quenched using relatively low concentrations whereas flames in rich mixtures are much less affected. This needs to be understood better. A practical means for injecting flame inhibitors into released clouds as a pre-ignition agent or into flames when applied as a post-ignition agent needs developed.

5 Conclusions

The paper argues that more attention should be given to mitigation of vapour cloud explosions. This is possible through design of (petro-) chemical facilities using CFD-based prediction tools, activation of water deluge upon gas detection or application of flame inhibitors both as a pre-ignition or post-ignition agent. Several recommendations have been given regarding research and development to improve the prediction tools and the mitigation measures of water deluge and injection of flame inhibitors.

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