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Detonation: Should It Be Included in Hazard and Risk Assessment?

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The current practice in industry in vapour cloud explosions (VCE) assessment is to assume that all VCEs are deflagration. This practice has been in place for nearly three decades. Development of assessment methods has been focussed on predicting the consequence of a deflagration: from simple empirical models to complex models based on computational fluid dynamics. The severity of a deflagration is limited by the amount and extent of congestion such as those present in onshore process plants or on offshore oil and gas facilities.
There have been experiments showing severe deflagrations can transit to detonation. Recent VCE accident investigations on Buncefield in the UK and Jaipur in India concluded that the VCEs involved detonation. There could be more; re-evaluation of past accidents is underway and the indication is that past VCEs classified as deflagration could be detonation. The inclusion of detonation in hazard and risk assessment would identify new escalation potentials and identify critical buildings impacted. This knowledge will allow a more effective management of this hazard.

1. Introduction

The assessment of consequences of a VCE by industry generally involves the identification of congested process area and pipework regions, estimation of the pressure generated in these regions and the decay of this pressure with distance from the region. Research dating from more than thirty years ago provided the basis of this approach, showing that a flame propagating through a flammable vapour cloud engulfing such congested regions could accelerate to high speeds and generate potentially damaging pressures. Industry has developed models that can be used to assess the hazards, ranging from the simpler screening approaches (e.g. TNO GAMES) to detailed Computational Fluid Dynamics.
Implicit in the assessment method described above, VCEs are assumed to be deflagration.
A VCE can be a detonation, which is a more energetic form than deflagration with more severe consequences. A detonation would involve the entire flammable volume, more than the congested volume. This results in a more intensive explosion within the gas cloud and larger overpressure damage footprint than a deflagration.
We believe that detonation VCE is far more common than assumed currently. We found that many VCE incidents produced far higher overpressure damage than deflagration. In the Buncefield accident that we investigated, deflagration was only the first stage of an explosion process that led to detonation (Tam 2011). A process called deflagration detonation transition (DDT). The evidence to support this contention comes from a combination of large scale experimental research, review of evidence from vapour cloud explosion incidents and consideration of how significant quantities of any vapour cloud can be involved in the generation of damaging overpressures. The detailed assessment of the vapour cloud explosions at Buncefield, UK in 2005 and Jaipur, India in 2009 provided the evidence that detonations are realistic events.
Given the conditions of fuel type, fuel concentration and confinement and/or congestion that could result in a severe deflagration, it is difficult to comprehend why detonation would not occur in practice in VCE incidents.
This paper summarises the evidence for DDT and considers why the inclusion of detonation in the assessment of vapour cloud explosion hazards matters. In summary, the methods currently used in the design and location of buildings on process sites are based on an incomplete picture of vapour cloud explosions. This might not have a significant effect in some cases; however in others there is the potential to

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significantly underestimate the explosion hazard. This will result in occupied buildings either being placed in the wrong location or under designed for the explosion threat they are exposed to. This will have a direct effect on the risks to personnel on these sites.

2. Experimental Evidence

One of the main factors determining the severity of a vapour cloud explosion (VCE) is type of gas involved. Ethylene and hydrogen, for example, give rise to higher flame speed and overpressure than normal alkanes such as methane.

DDT and Detonation had been studied over a century and the possibility of detonation is accepted in many accident assessments in confined channels, such as ducts and pipes. The work on DDT in open or semi-confined environment is more recent.

It is known that the factors that may play a role in DDT have some scale dependence (Mercx, 1993, 1997) and as a consequence, preference has been given to large scale experimental studies in partially confined or open congested regions which are common in industrial VCE incidents.

There are two aspects of DDT that need to be demonstrated. Firstly, it needs to be shown that a detonation can be initiated by a deflagration in conditions that are representative of conditions that might occur in reality. Secondly, there is a need to show that this detonation is then sustained, not only through the congested region, but also through any open, uncongested part of the vapour cloud.

Large scale experimental work carried out in a 3 m square test rig measuring up to 45 m in length identified the potential for DDT to occur with propane-air and cyclohexane-air mixtures (Harris & Wickens, 1989). A picture of the test rig is shown in Figure 1a.

The experiments involved ignition within partial confinement (shown on the left of the picture) with flame acceleration outside this confinement from 200 m s^{-1} to speeds in excess of 600 m s^{-1} over a distance of just 6 m, resulting in a DDT. This detonation was then sustained through the remaining length of the test rig, even where no pipework obstacles were present.

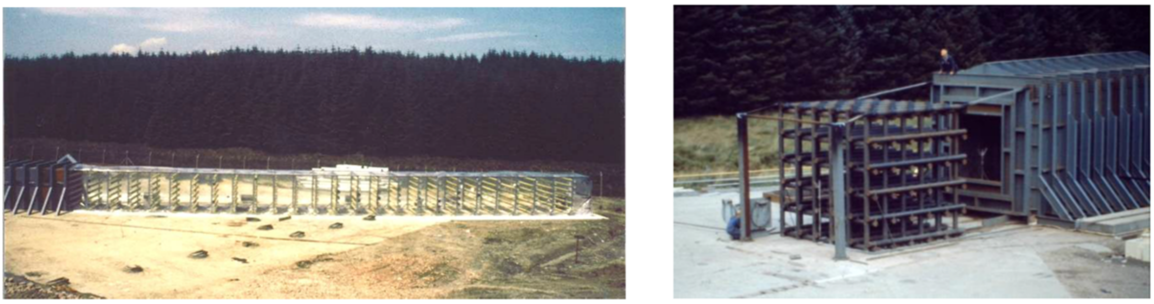

Figure 1: a (left) the 45 m long test rig used to study flame acceleration and b (right) the congestion used in the tests by Tomlin & Johnson (2012)

Experimental studies carried out as part of the EU co-funded explosion projects MERGE and EMERGE (Mercx, 1993, 1997), involved congested regions up to 9 m square and 4.5 m in height. High pressures involving shockwaves were measured at the edges of the congested regions in some ethylene-air and propane-air experiments. These pressures were consistent with the occurrence of a DDT, however this could not be demonstrated conclusively as there was no extended vapour cloud for the detonation to propagate through.

A series of large scale experiments involving the interaction of vented confined explosions with an external region of pipework congestion also showed evidence of DDT and the continued propagation of the detonation through unobstructed vapour cloud (Tomlin & Johnson, 2012). This DDT occurred in both ethylene-air and propane-air experiments (Figure 1b).

More recent experiments, such as one conducted with an ethylene-air mixture engulfing a 9.1m long congested area (Duran, Goodrich and Thomas, 2012) and one with a 30 m long ethane-air vapour cloud engulfing a process pipework region (Pekalski, 2013), showed that DDT occurred and that the detonation continued to propagate through the remaining unobstructed vapour cloud.

2.1 The Buncefield JIP

Experiments have been carried out as part of a joint industry project (JIP) studying explosion mechanisms involved in the Buncefield explosion in 2005. Summary of results have been published (e.g. Tam 2011).

These large scale VCE studies included:

 Experiments examining flame acceleration in propane-air clouds engulfing regions of dense trees and bushes.
 The effects of a detonation on items located within and nearby a propane-air vapour cloud in which a detonation was initiated by a small charge of high explosives.
The eight experiments involving regions of trees examined different densities of trees within regions of at least 30 m in length, 3 m in height and up to 4 m in depth. There was an additional 20 m without any tree to examine the propagation of an explosion emerging from the trees.
DDT occurred in two of these experiments, with the detonation continued throughout the unobstructed part of the cloud. The trees used in these experiments were Alder and had average densities of 3 and 1.5 trees per square metre and flame acceleration was rapid, with DDT occurring within 12m and 21m of flame propagation from a spark ignition for the respective tree densities. The flame speed at the time of DDT was about Mach 2 in both cases.

2.2 Damage Characteristics

The high overpressure and flame speed produced characteristic damage.
Figure 2a compares the damage to cars located within the vapour cloud in the Buncefield incident with damage to a car within the vapour cloud in a detonation experiment. The level of damage is similar and it is notable that the cars in the Buncefield incident were located within an open car park where the damage could not be explained by a pressure from a remote deflagration.
This level of damage cannot be replicated in experiments involving deflagration. The similarity in the damage observed in experiments and the Buncefield and Jaipur incidents extended to instrument boxes, oil filters and oil drums.
The directional effects observed in the incidents were also reproduced in the detonation experiments. Markings on posts and tree trunks within a detonating cloud were on the ‘reverse’ side, as seen in the incidents. In addition, many items were moved in a direction opposite to the direction of propagation of the detonation (Atkinson & Tam 2009). These were also reproduced in advanced explosion modelling (Heidari & Tam 2011).

2.3 In Summary

In summary, there is ample evidence from large scale experimental studies that DDT can occur in a VCE and that once initiated, the detonation can continue through unobstructed regions of the cloud. In all cases, DDT occurred after flame speeds in excess of the ambient speed of sound had been generated. The interaction of shock waves generated by such flame speeds with the flame is probably a key aspect leading to DDT.
The experimental evidence essentially relates to propane, ethane and ethylene mixtures. There is no direct evidence of DDT in experiments conducted with natural gas-air mixtures, though there is some indirect evidence of limited DDT when the author examined the data in full scale experiments conducting using offshore geometries.

3. Past Accidents

After the Buncefield accident investigation and the start of the Buncefield JIP that we started to review past accidents for the possibility of a detonation having occurred.

3.1 Buncefield, UK, 2005

The Buncefield incident in 2005 (BMIIB, 2006) provided a considerable amount of evidence related to the effects of a vapour cloud explosion in a large pancake vapour cloud. The evidence included damage to items such as cars, oil drums and instrument boxes within the vapour cloud. Figure 2a shows the comparison of damage in cars observed in the Buncefield incident and those in detonation tests. In addition, directional indicators in the form of bent posts, scoured paintwork and displaced items were present throughout the vapour cloud, even in large unobstructed areas. Analysis of the evidence combined with modelling studies led to the conclusion that the Buncefield vapour cloud explosion could not have been caused by a deflagration in congested areas alone and had involved DDT, with the C-J detonation propagating through much of the vapour cloud (Buncefield Phase 1, 2009)

3.2 Jaipur, India, 2009

A second similar vapour cloud explosion occurred in Jaipur, India in 2009 (Johnson 2012). The evidence of severe pressure damage and directional indicators was spread throughout the vapour cloud. Examples of the damage and directional indicators are shown in Figure 2b. The level of damage observed at Jaipur requires pressures of several bar and is consistent with the damage caused by the passage of a detonation. Again, most of these areas had little or no congestion that could sustain a deflagration leading to the conclusion that there had been a DDT, with most of the cloud undergoing detonation.

Figure 2: a (left) damage to car in the Buncefield incident and in experiments and 2b (right) directional indicators and pressure damage observed in Jaipur incident.

3.3 Port Hudson, USA, 10

The VCE incident at Port Hudson, Missouri, occurred in 1970. A propane cloud was ignited in a rural area, generating severe explosion damage (NTSB, 1971). No pipework congestion was present; however, the cloud engulfed buildings and wooded areas.

The Port Hudson incident was reported to involve a detonation of the propane vapour cloud and shared many characteristics with the Buncefield explosion, including the same pattern of directional indicators within the cloud. In an analysis of the Port Hudson incident (Burgess & Zabetakis, 1973) it was stated in relation to the damage inside the Port Hudson cloud, “We think that it is significant that the wind direction was everywhere opposite to the postulated direction of the detonation” (‘Wind direction’ in this case is taken to be the implied direction of the gas flow associated with the propagating detonation.). These are exactly the same types of directional indicators observed at Buncefield and Jaipur.

3.4 Ufa, Russia, 1989

A propane cloud produced by a pipeline failure was ignited by passing trains (Makhviladze and Yakush, 2002). There were widespread directional indicators throughout the vapour cloud in the form of fallen trees which lied in a direction pointing to a small area. These were viewed at the time as being due to the wind generated by a rising fireball, but are entirely consistent with the event being caused by a detonation of the cloud.

3.5 Flixborough, UK, 1974

The Flixborough incident involved a VCE of a cloud of cyclohexane in a chemical plan. This is unlike the above incidents which occurred in region where severe VCE had not been expected.

Research is underway to assess the VCE in Flixborough. While we cannot be certain that a detonation occurred, the conditions for a DDT were met. Preliminary results showed that the overpressure within the plant was high; this confirms the finding of Hoeist (1975) who concluded the overpressure inside the plant was several bars. Figure 3 showed a picture of a crushed oil drum taken at Flixborough, and for comparison those observed in Buncefield. This can be compared with that observed in Jaipur (Figure 2b). Further, the far field overpressure indicated that the volume of flammable gas cloud involved in producing this high overpressure was larger than the congested volume which was enveloped by the vapour cloud.

This will be reported in due course.

Figure 3: Observed damage showing the crushed pattern in oil drums in Flixborough (right) and Buncefield (left). Both sets of drum had been exposed to fire, the tell-tale stress mark showed that they had been exposed to high pressure compression loading.

4. Discussions

4.1 Detonation and DDT

The experimental evidence demonstrates that DDT is possible given flame speeds in excess of the ambient speed of sound and also that flame acceleration to these speeds can be rapid.

A detonation is not particularly sensitive to concentration variations within the cloud provided they are within the detonable range. Pressure energy will therefore be contained within a single shock wave propagating away from the vapour cloud. Even if a concentration fluctuation outside the detonable range is encountered in the vapour cloud, the detonation is likely to be able to go around or above or below the non-detonable area and continue to propagate. In contrast, a deflagration traveling at sub-sonic speeds encounters such fluctuations, its speed will change. This would produce oscillatory pressure pulses as the flame repeatedly speeds up and slows down. The pressure energy would therefore not be contained within a single pressure pulse and would consequently give low peak overpressure as the pressures decay away from the cloud.

4.2 Characteristics of the above incidents

The Jaipur, Buncefield incidents involved low lying dense vapour clouds spread over a large area with significant parts of the cloud containing no obstacles. This type of cloud will show evidence of detonation much more clearly as:

• High levels of pressure damage throughout the cloud, including the open areas, cannot be explained by deflagrations in the more limited congested areas.

• The mechanism that results in the directional indicators, expansion of combustion products in the opposite direction to the detonation, will be more evident.

The Flixborough incident involved a flammable cloud with an even aspect ratio. When a hemispherical cloud is ignited centrally, the reverse directional indicators would not occur.

4.3 Assessment of pressure decay from a pancake cloud

The Buncefield JIP (SCI 2014) produced a relatively simple relationship for assessing pressure away from the flammable cloud. It is a correlation from the simulation and experimental data and related to depth of the cloud only:

$$P = 6.571\,.\left(\frac{H}{\Delta R}\right)^{0.975} \tag{1}$$

Where:

H the height of the flammable gas cloud (m)

P Overpressure at ΔR from the edge of the cloud.

ΔR distance from the edge of the cloud (m)

Please note that the above correlation was obtained from one cloud height. This may not be valid for others. Research is ongoing to develop a generalised correlation.

4.4 Existing Guidance

It is a routine part of the design of new facilities, and operation of existing facilities, that vapour cloud explosion hazards are assessed in order to determine where onsite buildings can be located and define the pressure loading that the buildings should be able to withstand. The assessment of the potential for explosions to cause offsite damage is also part of the design process and can be a requirement for land use planning.

The assessment methods are defined within guidance (API (2009), CIA, (2010)) and are based around the size of the congested regions and the strength of the deflagration that could be generated within that region. Design and location of buildings can be based on either consequence calculations or they can be risk based. Where a risk based approach is used, the return period used to define the 'design event' is often specified as once in 10,000 years.

If vapour clouds produced by accidental releases do not extend significantly beyond the congested region, then an approach based on the congested region may well be adequate. However, where a vapour cloud can extend well beyond the congested region, which is more likely for denser than air fuels released in calm conditions, then the possibility of DDT can significantly change the potential consequences.

5. Conclusions

The current widely used assumption that detonation cannot occur is not supported by experiments or assessment of incidents in the industry. The inclusion of detonation in hazard and risk assessment would identify new escalation potentials and identify critical buildings impacted. This knowledge will allow a more effective management of this hazard.

Current guidance and standards address deflagration only. We suggest that they are updated to highlight the potential for DDT. This update could provide guidance on:

- The types of fuels where DDT is possible.
- The conditions required to produce DDT.
- The types of conditions where DDT may make more difference to design decisions.
- Methods to be used in the definition of design loads for occupied buildings and critical structures.

In addition, the interpretation of evidence present after a vapour cloud explosion needs to be improved. Guidance should be provided based on the research work carried out in the wake of the Buncefield incident.

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