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Sectioning of Potential Explosion Domains to Reduce the Severity of a Vapour Cloud Explosion

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Medium scale vapour cloud explosion experiments demonstrated that the severity of a vapour cloud explosion (VCE) can be reduced substantially by initiating counter fires within a vapour cloud as soon as a developing flame can be detected within the vapour cloud. For instance, experiments with two simultaneous ignitions at opposite sides of the used symmetrical test rig resulted in explosion pressures which were reduced by a factor of three to five compared to single point ignition at one side.
A later re-analysis of the test findings drew the attention to a flame acceleration mechanism, which had been known before, but its contribution to the severity of a VCE had not been fully appreciated. The generally accepted theory is that flame acceleration occurs as the flame passes obstacles. In addition to that, the contribution of the expanding combustion gas has been found to play a paramount role as well.
A big part of the strong reduction of the explosion severity with two-point ignition could be related to the fact that the two developing flames were acting against each other, creating a kind of expansion barrier against each other. This prevented the expanding combustion gas to push into the rig, which otherwise would have added to the flame speed.
In the past, walls in a congested area had been assumed to increase the severity of a VCE. The test findings suggest, however, that barriers could be implemented in a way such that they slow down the acceleration of a flame front.
It is expected that such barriers can be effective in particular when they are installed perpendicular to the anticipated direction of flame front acceleration. Process equipment is typically installed in rows 8 to 15 m wide, often extending over a length of more than 50 m, with access corridors at both sides. Horizontal equipment such as drums and heat exchangers are typically arranged perpendicular to the longitudinal direction.
For such an arrangement, a flame can be assumed to accelerate preferentially in the longitudinal direction, perpendicular to the obstacles in its way, and to speed up as it passes gaps between and below equipment, pushed through the gaps by the expanding gas behind. By closing such gaps or by installing barriers, the longitudinal hot gas expansion could be partly suppressed and its contribution to the flame speed would be reduced substantially. In addition, the barriers would force the hot gas to vent towards the uncongested space aside and above the equipment and they would force the flame front to “take a detour” around the barriers. Together, these effects would reduce the burning rate.
Hence, properly arranged barriers are expected to subdivide larger congested domains into smaller explosion cells, where less severe explosions occur. Because of the time needed for the flames to proceed from one cell to another, the pressure waves from these cells would be spread out over time, resulting in a lower overall explosion pressure, but continuing over a longer time period.

1. Introduction

In 2012, ExxonMobil conducted a series of medium scale explosion experiments at the test rig of BakerRisk at their Box Canyon facility in Texas, USA (Malik et al.). The experiments demonstrated that the severity of a

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vapour cloud explosion can be reduced substantially by initiating counter fires within the vapour cloud immediately after an incipient flame can be detected within the cloud.
The experiments did not fully support the initial expectation that the reduction of the explosion pressures would correlate to the number of ignition sources in the test rig. A big step change was observed from one to two simultaneous ignition points, but no further improvements were observed when adding more ignition points.
Eventually, these effects could be explained satisfactorily by taking into account the hot and cold gas flow patterns imposed by the expanding combustion gas (Baron et al.).
A later re-analysis of the test results pulled the attention further to the role of the expanding combustion gas. Its contribution to flame acceleration depends on the flow resistance created by the surroundings. Based on these new considerations, it appears possible to slow down flame acceleration by implementing barriers to influence the flow pattern of the expanding hot gas.
It is recognized that physical barriers may also interfere with the dispersion of a released vapour. This aspect needs to be taken into account, of course, but is not discussed here.

2. Explosion experiments

Medium scale explosion experiments were conducted on a 7.80 x 7.80 m test rig containing 784 vertical tubes of 50 mm diameter and a height of 1.8 m, arranged in a square pattern. The test rig was charged with a stoichiometric propane-air mixture which was contained by a plastic film and homogenized by fans prior to ignition.

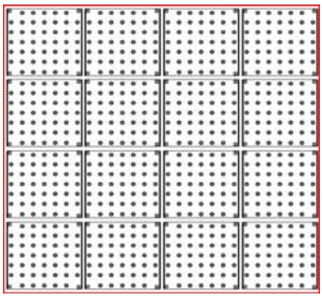

Figure 1: Arrangement of obstacles, top view

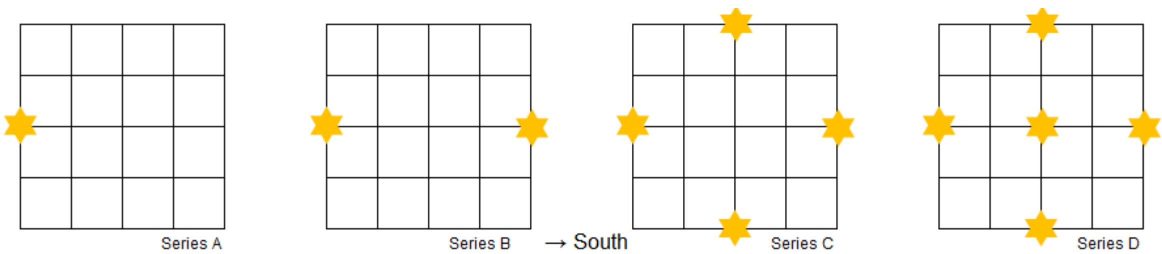

Figure 2: Ignition locations of experiments A, B, C, D

3. Test results

Figure 2 shows the ignition locations of 4 sets of experiments. Table 1 shows explosion pressures measured in these experiments at 15, 30 and 60 m from the test rig. For the single point reference experiments, Series A, pressures are shown in the direction of flame acceleration from North to South and also averaged over all measured directions. For the other experiments, only averaged pressures are shown.

Table 1 Far field peak pressures for explosion experiments A-D

Distance from centre of rig	Average Peak Pressure (psig)				
	Series A N → S 1 ign. point	Series A Average 1 ign. point	Series B Average 2 ign. points	Series C Average 4 ign. points	Series D Average 5 ign. points
15 m	1.03	0.65	0.18	0.21	0.60
30 m	0.47	0.30	0.10	0.11	0.31
60 m	0.29	0.16	0.05	0.06	0.17

For the single point ignition Series A, strong directional effects were observed. The pressures in the direction of flame propagation were more than 50 % higher than the average pressures over all directions. The pressures observed in Series B, C and D varied less than 25 % over the different directions.
When comparing the averaged values only, a reduction of the explosion pressure by a factor of about three was observed for the experiments B and C versus Series A. Thereby, the pressures from the four point ignitions were slightly higher than from the two point ignitions.
The addition of a fifth ignition point at the centre in Series D increased the explosion pressure back to values similar to those of the single point experiments.

4. Explanation of results

Figure 3 and Figure 4 below are showing snapshots of one experiment of the A-series and one of the B-series at the moment when the explosions had reached their highest intensity.

Figure 3 above shows a snapshot of the fully developed flame during single ignition point experiment A03, 340 msec after ignition at the left side.

Figure 4 above shows the fully developed flame during 2-ignition point experiment B01 at 370 msec after simultaneous ignitions at the left and at the right sides

In the A-series, the flame apparently propagated so quickly during the final phase of the explosion, that the bulk of the fuel burned off within a short time interval, resulting in high explosion pressures. The snapshot shows almost the complete volume under the plastic film still at high temperatures.
In the B-series, a symmetrical flame pattern can be observed with flames being pushed out of the rig from both sides, with a less intense flame in the centre region. Combustion appears to proceed over a longer time than in the experiment A; it seems that there is still unburnt gas below the plastic film in the centre region.

The differences between experiments A and B can be explained by two mechanisms:

1. In configuration A, the number of rows of obstacles in the path of flame propagation is twice as high as in configuration B. Flames are known to accelerate each time they pass an obstacle due to the wrinkling of the flame front and due to the turbulence created, both effects increasing the flame front area and hence the burning rate.

2. In experiment A, the combustion gas can expand in all directions. Initially, there is little resistance to backwards and sideward venting, away from congestion. As the flame penetrates into the test rig, the flow resistance to backward venting increases and the resistance to forward venting decreases, so that the flame front gets pushed forward more and more, accelerating the flame front and increasing turbulence. By contrast, in experiment B, forward venting of the combustion gas towards the centre of the test rig gets impeded by the expanding gas from the combustion cell at the opposite side.

The effects in experiment C are very similar to those in Series B except that lateral venting of the combustion gas also gets impeded by the gas expansion in the adjacent combustion cells. As a result, a higher pressure develops in the centre of the test rig, which adds to the “far distance pressures” observed outside of the rig.
By adding the fifth ignition point at the centre of the test rig, the flame acceleration distance nominally gets cut in half. Despite of this shorter acceleration path, an increased explosion pressure is observed compared to experiments C.
The increased explosion intensity can be satisfactorily explained by the role of combustion gas venting. The hot gas expansion at the centre ignition point occurs in the same directions as the flame propagates. From the moment of ignition on, the flame front is pushed radially outwards by the hot combustion gas, adding to the flame speed and increasing turbulence around the obstacles. The flames originating from the external ignition locations are slowed down by the expansion wind from the combustion cell in the centre. As a result, the centre explosion cell expands over a major part of the test rig volume, dominating the other flames.

5. Modelling of multi-ignition experiments by sectioning of test rig

The ignition at multiple ignition points creates multiple explosion cells. Assuming ideal symmetry in the testing configurations, the symmetry planes between these cells can be assumed to almost behave like solid walls. In Figure 5, these symmetry planes are illustrated for Series B, C and Series D. Configuration B is approximated by two rectangular explosion cells with three open sides and constrained by a fictitious wall on one side. Configuration C is sectioned into four triangular explosion cells with two fictitious walls arranged along the diagonals and one open side with the ignition point in the middle. Configuration D can be approximated the same way as C, but with two ignition points within each section.

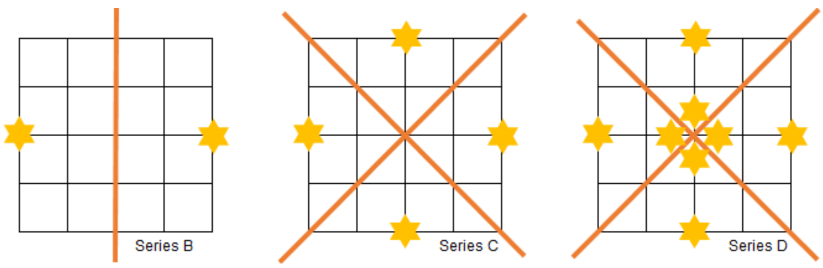

Figure 5: Sectioning of explosion cells for multi-ignition point experiments B, C and D

These fictitious walls are creating some degree of artificial confinement within the congestion. Often, there is a perception among safety engineers that partial confinement would directionally increase the severity of a vapour cloud explosion. This is apparently not the case for configuration B and C, with the ignition points at the edge of the congestion. Based on the test results, however, the partial confinement does increase the explosion severity in the D-experiments with one of the ignition sources located at the inner corner of the quadrant. Similar phenomena have been reported in the literature (Bjerketvedt et al.).

6. Opportunities for practical application

The new conclusion from the test results (and also from literature) is that barriers in the way of a vapour cloud fire can act either as means to speed up flame propagation or to slow it down, depending on the arrangement relative to the flame front.

Barriers suppressing backwards venting of the expanding combustion gas tend to speed up the flame front, barriers preventing forward venting contribute to reduced flame acceleration.

Based on these considerations, it should be possible to implement physical barriers within a process area in such a manner that the contribution of combustion gas venting to flame acceleration is minimized.

As a simple example, Figure 7 illustrates the flame propagation through a typical arrangement of heat exchangers in a process area. The smaller cloud contour indicates the original size of the vapour cloud. The larger dotted cloud contour indicates the dimensions of the hot gas after combustion. The density of the arrows is indicative of the flame speeds.

It can be expected that the flame accelerates every time it passes through the gaps between the stacked heat exchangers.

The spaces between the equipment stacks can be regarded as partially confined spaces which are ignited by the flame front passing through the gaps from the left side. The expansion of the burning gas then causes some pressure increase between the equipment, pushing the flame further through the next gaps at an increased speed.

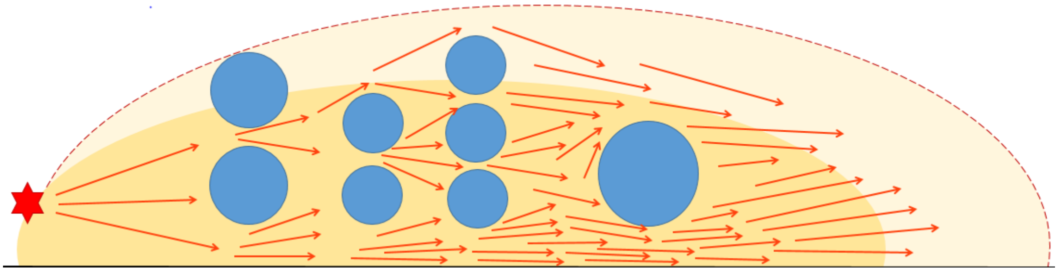

Figure 7: Flame propagation through an arrangement of heat exchangers

Figure 8 illustrates the same equipment configuration, but with vertical barriers installed in the gaps below and between the stacked exchangers. Lateral flame acceleration through the gaps is prevented by the barriers. Instead, the flames need to pass over the top of the stacks, then burn downwards into the space between the equipment. The expanding combustion gas is venting mainly towards the uncongested space above the equipment and therefore does not interfere much with the flame front.

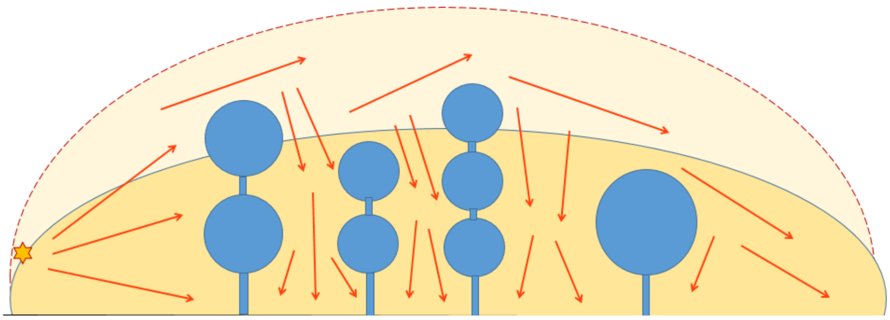

Figure 8: Flame propagation through an arrangement of exchangers with vertical barriers between the shells.

7. Conclusions

Previous explosion tests conducted by ExxonMobil confirmed that it is possible to reduce the severity of a vapour cloud explosion by igniting the bulk of the vapour at multiple locations in a timely manner, i.e. before the initial flame can spread over the bulk of the vapour cloud.

A re-analysis of the test results is pointing towards another way of slowing down a vapour cloud explosion by implementing physical barriers which suppress the contribution of the expanding combustion gas to flame acceleration. Barriers can also act to interrupt the path of flame propagation requiring the flame front to follow a “detour”, which may result in less generation of overpressure.

The effectiveness of a barrier depends on its arrangement relative to the location of the expected ignition point and to the likely flame path. A set of general principles can be deduced from the observations:

a. In partly confined spaces, flame speed is not supported by the expanding combustion gas when the flame burns from the edge towards the confining walls. Barriers should be placed such that they act against displacement of the (cold) flammable cloud ahead of a potential flame front.

b. Ignition of a vapour cloud near a wall or inside of a partly confined space will result in the combustion gas to push the flame front forward, adding to the flame speed. Confinement near potential ignition sources should be avoided.

c. A flame burns more slowly downwards than it does upwards, in part, because the floor acts akin to a “confinement wall”. In addition, the low density hot gas tends to vent upwards, creating a draft which pulls some of the flammable cloud along with it.

d. Barriers could be effective to reduce strong flame acceleration within congestion by closing gaps between equipment in the likely flame path.

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