The Acceleration of Flames in Tube Explosions with Two Obstacles as a Function of the Obstacle Separation Distance

Abstract

The separation distance (or pitch) between two successive obstacles or rows of obstacles is an important parameter in the acceleration of flame propagation and increase in explosion severity. Whilst this is generally recognised, it has received little specific attention by investigators. In this work a vented cylindrical vessel 162 mm in diameter 4.5 m long was used to study the effect of separation distance of two low blockage (30%) obstacles. The setup was demonstrated to produce overpressure through the fast flame speeds generated (i.e. in a similar mechanism to vapour cloud explosions). A worst case separation distance was found to be 1.75 m which produced close to 3 bar overpressure and a flame speed of about 500 m/s. These values were of the order of twice the overpressure and flame speed with a double obstacle separated 2.75 m apart. The profile of effects with separation distance was shown to agree with the cold flow turbulence profile determined in cold flows by other researchers. However, the present results showed that the maximum effect in explosions is experienced further downstream than the position of maximum turbulence determined in the cold flow studies. It is suggested that this may be due to the convection of the turbulence profile by the propagating flame. The present results would suggest that in many previous studies of repeated obstacles the separation distance investigated might not have included the worst case set up, and therefore existing explosion protection guidelines may not correspond be derived from case scenarios.

1. INTRODUCTION

The interaction of the explosion induced unburnt gas flow with obstacles results in the generation of turbulence downstream of the obstacle and the acceleration of the flame when it reaches this turbulence. Extremely fast explosion flames can be generated by this mechanism giving rise to severe overpressures. Understanding and prediction of these phenomena is of concern to process industries, and in particular in assessing the risks and designing suitable protection and mitigation measures against vapour cloud explosions.

The intensity and spatial distribution of the turbulence downstream of the obstacle are determining factors of the severity of the explosion and speed of flame acceleration. For a single obstacle or for a congested area that can be treated as a large porous structure the region of major concern in explosion hazards is the region of maximum turbulence which is shown to occur at some distance downstream of the obstacle grid. In an explosion scenario the maximum burning rate (and therefore the highest rate of generation of overpressure) will occur at the position of maximum turbulence intensity and most of the work has focussed on quantifying global flame acceleration and...
maximum overpressure through obstacle groupings, rather than detailed analysis of flame propagation through the individual elements of the congested region.


The separation distance (or pitch) between two successive obstacles or rows of obstacles is an important parameter in the acceleration of flame propagation and increase in explosion severity. Whilst this is generally recognised, it has received little specific attention by investigators. The influence of obstacle separation distance on gas explosion severity from the above experiments could not be quantified because of the fixed pitch that was used.

The limited research on the effect of obstacle separation distance was shown experimentally to have influence on the gas explosion severity (Moen et al. 1980; Moen et al. 1982; Harrison and Eyre 1987; Zeeuwen et al. 1983; Wingerdenet et al. 1990; Johnson et al. 1991; Mercx 1992; MERGE, 1994; Gubba et al. 2008; Rudy et al. 2011 and Vollmer et al. 2011). Surprisingly, in all of the above studies no justification was given as to the obstacle separation distance used, except for Harrison and Eyre (1987). The authors’ initial inter-grid spacing was based on the wind-tunnel experiment of Baines and Peterson (1951) on peak turbulence intensity where maximum overpressure and flame speed occurred.

The amount of turbulence generated is dependent upon the flow velocity and the geometry of the confinement. There is very little data on the turbulence generated in transient flows so we have to rely on data from steady state unreacting flow studies.

Additionally, most measurements of obstacle (generally grid plates) induced turbulence have been made well downstream of the obstacle, in the turbulent decay region, where the turbulence is isotropic i.e. 40-50 hole diameters downstream of the grid (Comte-Bellot and Corrsin 1966). This is well beyond the region of interest in the explosion hazards field since the maximum combustion rate generally takes place within a distance of 3 to 20 obstacle-hole diameters from the obstacle (Phylaktou and Andrews, 1991).

Measurements of the turbulence intensity, $u'U$, in the region immediately downstream of the grid are scant and only limited data could be found from cold flow wind tunnel studies (Baines and Peterson, 1951; Robinson and Kovitz, 1975; Checkel, 1981). An example of these near grid measurements of turbulence is reproduced in Fig. 1 from the work of Baines and Peterson (1951). This is a plot of the turbulence intensity (measured on the centre-line of the grid holes) as a function of the axial distance normalised by the characteristic grid-scale $b$ ($b$ is defined as the width of the solid material between the grid holes).
Fig 1: Variation in turbulence intensity produced by perforated plates against the downstream distance from the plates (Baines and Peterson, 1951).

It shown that the turbulence intensity increases downstream of the grid, it reaches a maximum value some distance after it, and it then begins to decay at a more or less steady rate over a relatively long distance.

From the above plot it is evident that there is an “optimum” spacing for obstacles where each successive obstacle is placed just after position of peak turbulence so that it “sees” the maximum flame speed. This would in turn be expected to cause the maximum possible turbulence downstream of that obstacle and therefore overall would cause the fastest possible acceleration to the highest possible flame speed and hence highest overpressure. Conversely if the obstacle spacing is larger or smaller than the optimum, then flame acceleration would not be as severe and the limit cases (too near or too far) the effect of repeat obstacles would be minimal.

It is the aim of this work to systematically vary the obstacle separation distance in order to identify the worst case interaction distance and relate this to the cold flow turbulence generation and decay profile.

2. EXPERIMENTAL SET-UP
An elongated cylindrical vessel 162 mm internal diameter made from nine flanged sections, 8 of them of 0.5 m length each and one section 0.25m in length (total nominal length of 4.25m. The test vessel was rated to withstand an overpressure of 35 bar. The test vessel was mounted horizontally and closed at the ignition end, with its open end connected to a large cylindrical dump-vessel with a volume of 50 m³. This arrangement enabled the simulation of open-to-atmosphere explosions with accurate control of both test and dump vessels pre-ignition conditions.

Fig 2.Experimental set-up. (a) Schematic diagram, (b) Photograph

Two orifice plate obstacles of 3.2 mm thick steel plate and 30% blockage were used in the test vessel. The obstacle scale, b, (0.03m) was considered to be the nominal width of the solid material between holes (using the same definition as Baines and Peterson (1951) \( b=M-0.95d \), where M is mesh size and d the diameter of the hole) for multi-hole grids, based on notional large grid plate with multiple holes of size and blockage ratio equal to the single hole actual obstacle). The obstacles were mounted between the section flanges. The first obstacle was positioned 1 m downstream of the spark.
(for all tests) while the second obstacle’s position was varied from 0.5 m to 2.75 m downstream of the first obstacle.

A pneumatically actuated gate valve isolated the test vessel prior to mixture preparation. A vacuum pump was used to evacuate the test vessel before a 1 atm, 10% methane/air mixture was formed by partial pressures. The dump vessel was filled with air to a pressure of 1 atm. After mixture circulation (allowing for at least 4 volume changes), the gate valve was opened and a 16 Joule spark plug ignition was effected at the centre of the test vessel ignition-end flange. The test vessel had an overall length-to-diameter ratio, L/D of 27.7. The set-up is shown in Fig.2.

An array of 24 type-K mineral insulated exposed junction thermocouples positioned along the axial centre line of the test vessel was used to record the time of flame arrival.

The test vessel and dump vessel pressure histories were recorded using an array of 8 Keller-type pressure transducers - 7 gauge pressure transducers (PT1to PT7) and 1 differential (DPT), as shown in Fig.2. Wall static pressure tapping measured by a differential pressure transducer (DPT) were located at 0.5D upstream and 1D downstream of the first obstacle. Pressure transducers, PT4 and PT5 were positioned 0.5D upstream and 1D downstream of the second obstacle and they were used to obtain the pressure differential across this obstacle. These measured pressure drops enabled the calculation of the explosion induced gas velocity through each obstacle by treating the obstacle as an orifice flow meter.

A 32-channel (maximum 200 KHz each channel) transient data recorder (Data Logger and FAMOS) was used to record and process the explosion data. Each test was conducted three times in order to ensure good repeatability and the average of the repeat tests was used for the analysis of the flame speed and overpressure. Where the clarity of the plots can be maintained the repeat test data are shown.

3. RESULTS AND DISCUSSION

3.1. Pressure Development, Flame Position and Flame Speeds

The pressure generation and variation with time is illustrated in Figs. 3 and 4 for the case of no obstacle and a double obstacle configuration respectively. Also shown on these plots are the flame arrival times at the thermocouples along the tube axis.

The first observation is the significant increase overpressure in the two obstacle configuration compared to the no obstacle situation. The increase in maximum overpressure was ten-fold, from approximately 0.25 bar to 2.5 bar.

This was associated with an overall reduction in the tube travel time from 75ms to 65 ms. However it should be noted that up to the point of flame interaction with the first obstacle (at around 50ms) the pressure and flame development was very similar in the two cases. This means that the post-first-obstacle flame travel to the tube exit was
completed in less than 15ms compared to the 25 ms in the case of no obstacle at all. This would require an almost doubling of the flame speed in this section of the tube.

Fig.3. Example of pressure trace (transducer PT1), and flame position with time for the empty tube (no obstacles)

Fig.4. Example of pressure trace (transducer PT1), and flame position with time, for a double obstacle case (obstacle separation distance of 1.75m)
Figure 4 shows that the maximum pressure was recorded after the flame exited the tube. This is simply an artefact of the distance between the flame front and the recording pressure transducer (in this case PT1 which is located on the ignition flange). Pressure changes associated with the leading flame front take a finite time to before they register on the various pressure transducers along the tube which depends on the separation distance between the “event” location and the recording device and the speed of sound in the intervening medium.

A direct comparison of the two pressure traces is given in Fig.5, which additionally includes the case of a single obstacle at 6.2 tube diameters from the spark. Again this plot demonstrates the pre-first obstacle similarity of pressure development in the tube, giving confidence in the repeatability of the tests. Post first-obstacle, good similarity is observed for the effect of first obstacle for both the single and double obstacles cases. The maximum overpressure due to the first obstacle was just over 1 bar in both cases.

![Fig.5. Comparison of pressure traces (transducer PT1) for the no obstacle, single obstacle and a double obstacle configuration (separation distance of 1.75m)](image)

In the double obstacle configuration the overpressure oscillated stronger in the region downstream of the first obstacle (compared to the single obstacle case) and after interacting with the second obstacle the overpressure surged to a maximum of over 2.5 bar before the flame vented out of the tube.

Figure 6 shows the flame speeds corresponding to tests in Fig. 5, as derived from the thermocouple flame arrival times, as a function of the axial position along the tube. A smoothing algorithm was applied to the flame arrival data, as described by Gardner (1998), to avoid negative flame speeds where the flame brush appears to arrive at
downstream centreline locations earlier than upstream ones, particularly in the regions of strong acceleration downstream of the obstacles.

![Comparison of flame speeds for the no obstacle, single obstacle and a double obstacle configuration (separation distance of 1.75m) as a function of the dimensionless flame position](image)

The flame speeds, in correspondence to the patterns shown by pressure traces, demonstrated similar flame development upstream of the first obstacle location in all 3 tests. In the case of the single and double obstacle cases the flame speeds were similar up to the point of interaction with second obstacle. The maximum flame speeds in the empty tube reached just over 100 m/s, while with the single this more than doubled to over 250 m/s, and doubled again to over 500 m/s with the introduction of the second obstacle.

### 3.2. Mechanism of Pressure Generation

In vapour cloud explosions it’s common to assume that the overpressure is proportional to the square of the flame speed (Taylor and Hirst 1989; Harris and Wickens 1986). A more detailed expression was given by Harrison and Eyre (1986) from Shell Research Ltd. The assumption was based on simplified acoustic theory given by Taylor (1946) in terms of flame speed and Mach number, M. If the ambient pressure is atmospheric, then the overpressure is given by Eq. (1) as:
Using an ambient speed of sound of 340 m/s, specific heat constant, $\gamma$ of 1.4 and the average experimental flame speed measurements for the double obstacle in Fig.6 and (1.75 m apart) an overpressure trace was calculated using equation (1). This was then compared with the pressure-trace from transducer PT3 from one of the tests as a function of time, as shown in Fig. 7.

\[ P = \frac{2\gamma M^2}{1+M} \]  

Fig. 7. Comparison of the flame speed based pressure trace and that from transducer PT3 for a double obstacle configuration.

As shown in Fig. 7 there is good agreement between the flame-speed based pressure and that measured by transducer PT3 particularly on the profile and timing of the maximum pressure peak. This flame acceleration and pressure peak occur in the region of PT3 and it therefore immediately recorded. The apparent mismatch between the timings of the effect of the first obstacle is again due to the fact that PT3 is some
distance away from the region of effects of the first obstacle and there is there some
time delay in these effects being picked up by PT3.

The implication of this good agreement was that the mechanism of pressure generation
in the present tests is the same as that of vapour-cloud explosions, i.e. the pressure rise
was due mainly to the inertia of the gas immediately ahead of the flame, and that it
was not significantly influenced by the confinement offered by the tubular geometry.
It would however be expected that in a largely-confined system such as the present
arrangement (a tube with an open far-end), the maximum pressure would be a function
of the net volume increase in the system. This is the balance between volume
generation by the combustion process and volume reduction by venting, and therefore
the pressure would not simply be a function of the flame speed as in a vapour cloud
explosion. However, as discussed earlier the pressure records of PT3 (end of tube) and
PT7 (dump-vessel) indicated little pressure difference between the two vessels and
therefore limited venting was taking place at the time of maximum flame acceleration.

Therefore the overpressures measured in this system are due to the high flame which
are caused by the obstacle induced turbulence which itself on the flame speeds
associated flow velocities upstream of the obstacle.

3.3. Optimum Obstacle Separation Distance and Comparison to the
Obstacle Induced Turbulence Profile

With the first obstacle position fixed the second obstacle position was methodically
changed in order to determine the obstacle separation distance which would give the
maximum overall flame acceleration and overpressure.

Example pressure records from pressure transducer PT3 are shown in Fig. 8, for
different obstacle separation distances. The data clearly demonstrate a very strong
effect of the obstacle separation distance not only in terms of the maximum pressure
achieved but also in terms of the profile of the pressure development. For obstacles in
close proximity to each other (e.g. 0.5 and 1.0m separation distances) the effect of the
obstacles is amalgamated into one pressure rise whilst on the cases where the
separation distances are too large (e.g. 2.75 m separation distance) the effects of the
individual obstacles become distinct with no significant influence of the first obstacle
on the flame behaviour after the second.

The maximum synergistic effect of the two obstacles was obtained at a separation
distance of 1.75 m where evidently the flame accelerated to its maximum value after
the first obstacle before reaching the second. Therefore the highest possible flows
were induced by the accelerating flame through the second obstacle and this would
have resulted in the highest turbulence levels after the second and hence to highest
overpressures, as shown when the flame reached this region. This concept and
behaviour is fully congruent with the turbulence profile downstream of an obstruction
presented by Baines Peterson (1951), and discussed earlier (Fig. 1).
Fig. 8. Example pressure records from pressure transducer PT3, for different obstacle separation distances.

The effect of the separation distance on the maximum overpressure and the maximum flame speed is more clearly illustrated Fig. 9. The obstacle separation distance is presented in terms of a dimensionless distance by dividing the actual distance with the obstacle characteristic scale (as defined earlier). It is shown that the maximum effect of the combined obstacles occurred when the separation distance was approximately 53 obstacle scales (or 1.75 m).

In Fig. 10 the effect of the obstacle separation distance on the maximum overpressure is compared with the Baines and Peterson data on the turbulence profile downstream of an obstruction in non-reacting flows. There was no turbulence data for the same blockage ratio as in the present tests (30%) so the comparison is made to a lower (22%) and a higher (44%) blockage ratio. It is shown that the present tests followed a similar profile to that of turbulence growth and decay, with the maximum however
occurring at a further distance from the obstacle than suggested by the Baines and Peterson data for cold flows.

Fig.9. The effect of dimensionless separation distance on the maximum overpressure and the maximum flame speed.

A possible explanation for the non correspondence between the cold flow position of maximum turbulence and the worst case obstacle separation distance is that once the flame moves through the obstacle the whole of the generated turbulence profile is detached from the obstruction it is in fact conveyed forward (whilst at the same time being consumed) by the advancing flame front.

This work has important implications on the effects of of repeated obstacles on explosions and the design of appropriate experiments that are indeed worst case scenarios.

4. CONCLUSIONS

The present experiments clearly demonstrated the importance of the obstacle separation distance in a double obstacle configuration study. They showed that there is a defined separation distance which gave the most severe explosions in terms of both maximum flame speed and overpressure. The worst case separation distance for a low blockage double obstacle was 1.75 m which produced close to 3 bar overpressure
and a flame speed of over 500 m/s. These values were of the order of twice the overpressure and flame speed with a double obstacle separated 2.75 m apart.

The profile of effects with separation distance was shown to agree with the cold flow turbulence profile determined in cold flows by other researchers. However, the present results showed that the maximum effect in explosions is experienced further downstream than the position of maximum turbulence determined in the cold flow studies. It is suggested that this may be due to the convection of the turbulence profile by the propagating flame. Further work is needed to determine the parameters that influence the worst case separation distance.

In practical applications the worst case separation distance needs to be avoided and in designing suitable experiments the worst case has to be incorporated. The present results would suggest that in many previous studies of repeated obstacles the separation distance investigated might not have included the worst case set up, and therefore existing explosion protection guidelines may not correspond to worst case scenarios.

![Graph](image-url)

Fig. 10. Comparison of the present data to the Baines and Peterson (1951) data for a lower and a higher blockage ratio.
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