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Experimental Study of Gas Explosion in Closed Pipe

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Abstract: An experimental study has been carried out to investigate the explosion properties in a pipeline with and without 90 degree bends i.e., flame speeds, overpressure and rate of pressure rise. A horizontal steel pipe, with 2 m long and 0.1 m diameter, giving length to diameter, (L/D) ratio of 20 was used in this project with a range of equivalence ratio, (Φ) from 0.5 to 1.8. For test with 90 degree bends, the bend has a radius of 0.1 m and added a further 1 m to the length of the pipe (based on the centerline length of the segment). Only rear ignition will be reported in this work. Natural gas/oxygen mixture was prepared using partial pressure method and a homogeneous composition was achieved by circulating the mixture using a solid ball which placed in the mixing cell. It was shown that stoichiometric mixtures gave the highest flame speeds measurement, both on straight and bend pipe. Stoichiometric concentration ($\Phi = 1.0$) gave significant maximum overpressure of 5.5 bars for bend pipe, compared 2.0 bars for straight pipe explosion test ~3 times higher. This is due to bending part that act just like obstacles. This mechanism could induce and create more turbulence, initiating the combustion of unburned pocket at the corner region, causing high mass burning rate and hence, increasing the flame speed. It is also shown that the flame speed enhancement is greater by factor of ~3 for explosion in bending pipe compared to straight pipe. The risk assessment and vessel design for this configuration will also be highlighted.

Key words: Gas explosion, bending, flame speeds, ignition position, stoichiometric, equivalence ratio

INTRODUCTION

Obstacles such as bends in pipe and baffle type obstacles are prevalent in many applications and knowledge of effects on explosion properties and phenomena including overpressure, burning rate, flame acceleration and Deflagration to Detonation Transition (DDT) is important for the correct placing of explosion safety devices such as flame arresters and venting devices. Tube bends, for example, are full-bore obstacles used extensively in industrial applications. Chatrathi (1992) found out that a 24% enhancement of the flame speed after a 90 degree bend placed half-way down a tube was observed in propane-air experiments, using 152.4 mm diameter pipe and the pipe was open at the end furthest from the ignition source.

Over past years, explosions in pipes and ducts, flame acceleration and DDT were well researched subject (Ciccarelli and Dorofeev, 2008), however, there were concentrated on the effects of baffle type obstacles or items in the path of the flow (Ibrahim and Masri, 2001). To the author's knowledge, there is sparse study on the explosions through pipe bends used extensively in industrial applications and the effects on flame acceleration, overpressure enhancement and the contribution on DDT severity.

Another investigation was made to study the explosion in 90 degree bend using Constant Temperature Anemometry (CTA) where it showed that a bend induced a significant increase in turbulence effect over the first 30% of the inner diameter of the pipe immediately after the bend (Lohrer *et al*., 2008). Masri *et al.* (2000) stated that the flame will accelerate as it interacts with the obstacles. In their work, it is clear that flame speed is enhanced by increasing the obstruction blockage ahead of the flame. The worse effect occurs when the obstacle was a rectangular cross-section type compared with circular or triangular cross-section type. In the study by Phylaktou *et al.* (1993), they found that there is an increase in flame speed and overpressure of methane/air mixtures in a 90 degree bend tube compared to similar experiment carried out in straight pipes. The flame speeds was enhanced in a factor of 5 and this condition is similar to the effect using baffle of 20% blockage ratio at the same position.

Ignition position also affects the explosion properties especially the shape of flame as discussed in previous study. Sato *et al.* (1996) investigated the effects of

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ignition position on the shape of the flame front and the flame speed for methane-air explosions using an open ended small square channel containing a 90 degree bend. However, only a limited number of experiments were carried out and no comparison was given to an experimental set-up without the bend.

Observations of the flame front when travelling through a rectangular 90 degree bend was done by Zhou *et al*. (2006). They showed that the flame fronts experienced a ‘flame shedding’ where the flame propagates quickly around the inside of the bend. This observation agreed with 3D particle modeling of the flow around the bend. It is found that large vortexes were created just downstream of the inside wall of the bend while flow followed a more streamlines pattern around the outside of the bend.

The objective of this study is to investigate the effect of pipe configuration, i.e. straight and bending on gas explosion in the pipeline. The fuel used is natural gas/oxygen with equivalent ratio, Φ = 0.5 to 1.8. Parameters to be studied are flame speed, overpressure and rate of pressure rise. From the experimental result, it is purposed to install the safety device such as flame arrester as one of the protection measured technique.

MATERIALS AND METHODS

Initial preparation of equipment and fuel/air mixture: A horizontal steel pipe, with 2 m long and 0.1 m diameter, giving L/D ratio of 20 was used in this project. The pipe was made up of a number of segments ranging from 0.5-1 m in length, bolted together with a gasket seal in-between the connections and blind flanges at both ends. Evacuation prior to introduction of the gas test was done to ensure no leakage presented in the pipe during the tests. For test with 90 degree bends, the bend had a radius of 0.1 m and added a further 1 m to the length of the pipe (based on the centerline length of the segment). Refer to Fig. 1 for the schematic configuration of the main testing pipe.

The natural gas/oxygen mixture was formed by partial pressures and a homogeneous composition was achieved by circulating the mixture using a solid ball which placed in a mixing cell. Pressurized air (pure oxygen) was injected into the mixing cell, followed by natural gas (methane). Both gases were injected into the mixing cell at certain amount of pressure as calculated initially to reach the desired equivalent ratio. The mixing cell was used to get the correct volume of natural gas/oxygen mixture and to obtain the initial homogeneity of the mixture. Mixing cell was also functioned to let natural gas/oxygen mixture achieved the homogenous mixture at certain time. A few sample of natural gas/oxygen mixture that transferred to the main testing pipe had been collected and tested its concentration using Gas Chromatography to make sure it reached the desired equivalent ratio.

The mixture was ignited at the center of one end of the pipe by means of a spark discharge. A 16 J ignition energy was used in all tests to ensure ignition in near limit mixtures. The history of flame travel along the pipe was

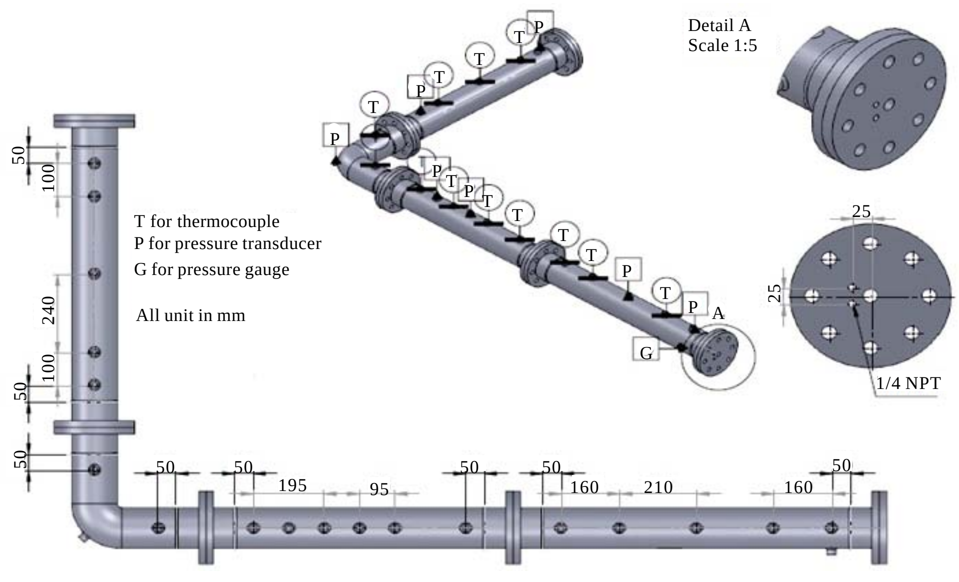

Fig. 1: Schematic configuration of main testing pipe

recorded by an axial array of mineral insulated, exposed junction, type K thermocouples. The time of flame arrival was detected as a distinct change in the gradient of the analogue output of the thermocouple and in this way, the average flame speed between any two thermocouples could be calculated. The pressure at various points along the length of the pipe was recorded using piezoelectric pressure transducers (Keller Series 11). A 16 channel transient data recorder was used to record and process all the data. Each explosion was repeated at least three times for accuracy and reproducibility.

RESULTS AND DISCUSSION

Effect of equivalence ratio on explosion pressure in straight pipe: Pressure profile against distance from ignition, x is shown in Fig. 2. It is clearly seen that for almost all of mixture concentrations from $\Phi = 0.6$ to 1.8, higher pressure obtained at shorter x before decreasing after that point. Equivalent ratio, Φ of 1.0 (stoichiometric concentration) gave the highest pressure of ~2.0 bars compared to the lean and rich concentration. The result obtained is similar with Blanchard *et al*. (2010). They found out that the highest explosion pressure for straight pipe was in a range from 1.3 to 1.8 bars. During the explosion, the flame will propagate along the pipeline. The increasing flame speed will create pressure waves and influence the flame front to expand. The net effect is for the mass-burning rate of the flame to increase due to the larger flame area of the spherical flame. This would create more turbulence and hence higher overpressures due to the faster flame speeds in the pipe. Pressure develops in the pipe to reach the maximum value and then will keep decreasing until reach the end of closed pipe. The pressure observed to increase slightly when reaching the end length of pipe which is obviously can be seen on rich concentration ($\Phi = 1.2$ to 1.8). The closed end can act as an obstacle to the flame propagation and this will enhance the pressure development at that regime.

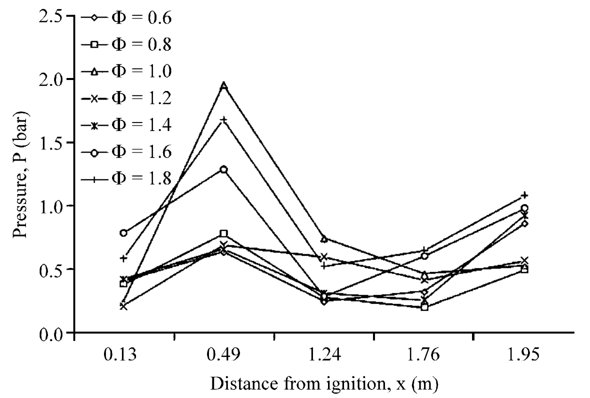

Fig. 2: Pressure profile against x at different mixture concentration

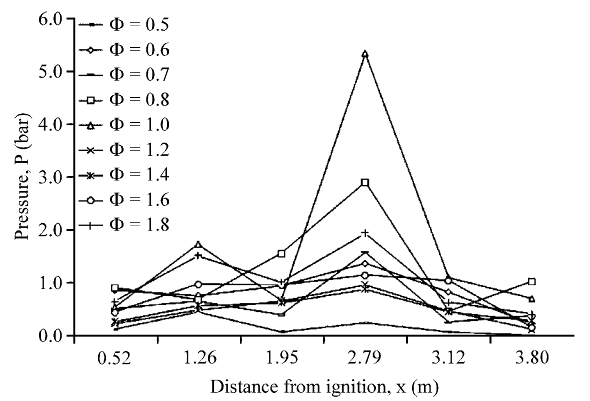

Fig. 3: Pressure rise versus x with different mixture concentration

Effect of equivalence ratio on explosion pressure in 90 degree bend pipe: Figure 3 shows the pressure development in closed pipe with 90 degree bends at different equivalent ratio from $\Phi = 0.5$ to 1.8. At initial, the pressure keeps increase and then decrease slightly before the bending. The highest pressure, ~5.5 bars obtained at stoichiometric concentration ($\Phi = 1.0$) compared to lean and rich concentration. This result increase in the factor of 3 compared to the maximum pressure of the straight pipe, ~2.0 bars at the same mixture concentration. Blanchard *et al*. (2010) found out that the maximum pressure for explosion with 90 degree bend pipe is ~1.3 bars for L/D = 112 compared to straight pipe, p = 0.9 bars. Kindracki *et al*. (2007) found out that the maximum explosion pressure for methane/air mixtures is ~5.5 bars at $\Phi = 1.0$ (stoichiometric concentration) which is similar to the present study. A conclusion can be made here which is different pipe size can affect the maximum explosion pressure.

At the bend, flame have longer travel distance to accelerate and hence, will create a greater amount of turbulence downstream of the system. This will increase the pressure and create overpressure in that area. Turbulent flow effect the enhancement of the flame speed and overpressure in closed pipe during the explosion. From Fig. 3, we clearly can see that higher pressure obtained for almost all equivalent ratio for the distance from ignition, x = 2.79 m where the bending starts. 90 degree bend pipe configuration produces more turbulent area at angle of bend which acting as

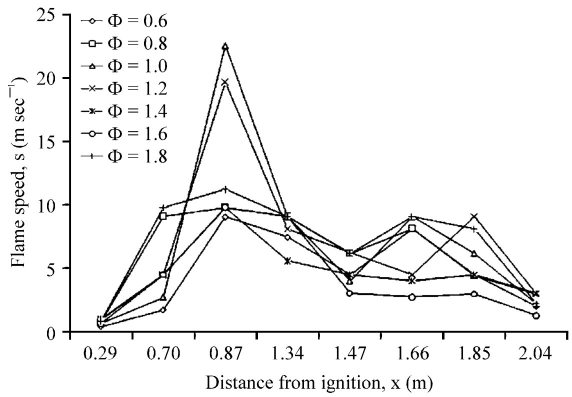

Fig. 4: Flame speed profile against x at various concentrations

Table 1: Turbulent enhancement factor for various equivalent ratios

Equivalence ratio, Φ	Turbulent enhancement factor
0.6	2.0
0.8	3.6
1.0	2.7
1.2	1.4
1.4	1.1
1.6	1.0
1.8	1.2

obstruction for the flame to travel to reach the end of pipe. Table 1 shows the calculated of turbulent enhancement factor generated by dividing the maximum explosion pressure of bending to the straight pipe maximum pressure obtained during the tests. From this study, it is found that the enhancement factor is the highest at $\Phi = 0.8$ of 3.6.

Flame speeds on straight pipe: Figure 4 shows the flame speed, S as a function of distance from ignition, x with different equivalence ratio ($\Phi = 0.6$ to 1.8). The flame speeds increased from laminar burning of 3-23 m sec^{-1}, obtained at $\Phi = 1.0$. The lean mixtures gave the lowest maximum flame speed, ~8 m sec^{-1} compared to the stoichiometric and rich mixtures. Different fuel concentration causes the significant different in rate of flame acceleration along the centerline of the pipe as reported by Zhu *et al.* (2010). They found out that the decrease of gas concentration resulted in a decrease in the heat released by the reaction that is important for the speed-up of the flame. Meanwhile, the more heat had been released during the process through the system due to fast propagation of the flame along the distance of the tubes/pipes. This phenomenon will enhance the flame speeds because the time duration for the flame had reached the end point of the system when travelling is shortened.

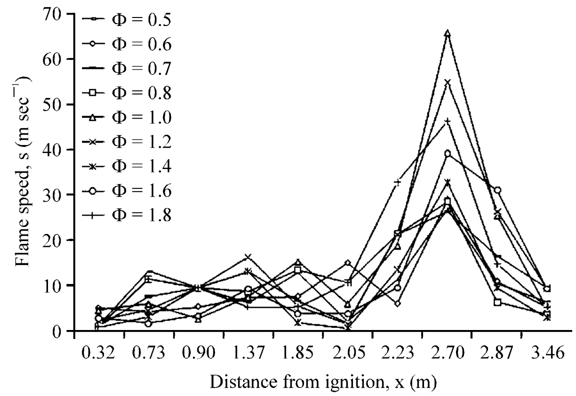

Fig. 5: Flame speed on 90 degree bend pipe

At rich concentration, the highest value of flame speed is ~20 m sec^{-1}, not much different with the flame speed of stoichiometric concentration. Rich mixtures ($\Phi = 1.2$) are known to be more susceptible to developing surface instabilities (flame cellularity) which would lead to higher burning rate and hence, higher flame speeds (Ferrara *et al.*, 2005). The faster flame speeds with end ignition can be explained based on the flame propagation mode. The burnt gases are only allowed to expand in one direction from end ignition site, resulting in an elongated hemispherical flame with larger surface area and hence, faster expansion compared to centrally ignited flames. Flame speed at lean and very rich mixture showed lower flame speed due to the slower reaction rate and lower heat diffusion to facilitate flame propagation.

From this observation, stoichiometric mixtures ($\Phi = 1.0$) gave the highest flame speed measurement. This result supported the observation done by Pekalski *et al.* (2005). Their work indicated that the methane concentration in air corresponding to the highest explosion parameters was larger at stoichiometric concentration of 9.5% v/v. At stoichiometric concentration, the mass burning rates is at the highest rate due to complete combustion of fuel which cause temperature to be the hottest among any other equivalent ratio. At this condition, the mixture reactivity is at maximum and more heat released. Rapid flame acceleration causes the pressure waves that lead the flame front to expand bigger thus generating further mass burning rate before decelerating towards the end pipe.

Flame speed on 90 degree bend pipe: Figure 5 shows the flame speed against the distance from ignition, x for lean, stoichiometric and rich mixtures concentration on 90 degree bend pipe. The horizontal line in the graph represents the position of the thermocouples. The

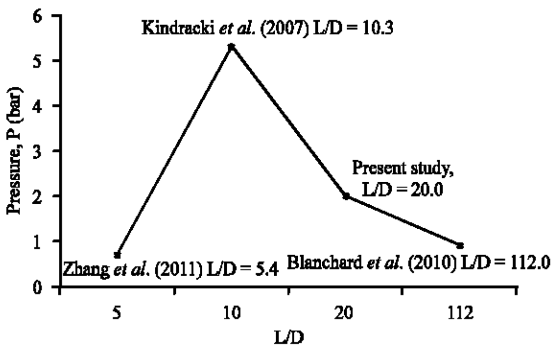

Fig. 6: Explosion pressure for methane-air at stoichiometric condition for different L/D

Table 2: Pressure and flame speed of methane explosion at stoichiometric

		Straight		90 degree	
References	L/D	P_{max} (bar)	S (m sec^{-1})	P_{max} (bar)	S (m sec^{-1})
Zhang *et al.* (2011)	5.4	0.7	3.5		
Kindracki *et al.* (2007)	10.3	5.5			
Present study	20.0	2.0	23.0	5.5	63.0
Blanchard *et al.* (2010)	112.0	0.9	45.0	1.3	68.0

bending part start at x = 2.0 m and end at x = 2.75 m. For the present study, it is found that the highest flame speed, ~63 m sec^{-1} obtained at stoichiometric concentration which is x = 2.7 m. Blanchard *et al.* (2010) found out that the maximum flame speed for methane/air explosion with 90 degree bend pipe was 67 m sec^{-1}. This value is almost similar with the present study. According to them, flame will propagate along the pipe length freely without attended of baffles/obstacles. Obstacles will increase the flame speed due to enhancement of travel distance of the flow which caused by the turbulent effect occurred. Flame speed value obtained ~3 times higher compared to the straight pipe.

Comparison with the previous published data

Explosion pressure on straight pipe: Table 2 shows the data of pressure and flame speed for present study and previous published papers (Blanchard *et al*., 2010; Kindracki *et al*., 2007; Zhang *et al*., 2011) at stoichiometric concentration in closed straight pipe with different L/D (smaller, medium and bigger size of pipe). The highest explosion pressure, 5.5 bars obtained at L/D ~10.3 as studied by Kindracki *et al.* (2007). They used methane/air mixture with end ignition. For the present study with L/D~20, as discussed earlier, the maximum explosion pressure for straight pipe is ~2.0 bars. For L/D>10.3, it is clearly seen that maximum overpressure is increased but larger L/D, maximum overpressure is decreasing.

Figure 6 shows the pressure development in different L/D of straight pipe. According to Munday (1971), the vessel shape and size will affect the deflagration velocity. Detonation limit will increase with increasing of vessel size (Tieszen, 1985). Piping system with L/D ~ 5.4 gave the lower explosion pressure, ~0.7 bars (Zhang *et al*., 2011). The pressure decreased when L/D more than 10.3. Larger L/D can increase the flame travel distance due to increase in axial flame propagation because of larger pipe diameter. Besides that, during the flame propagation, longer pipe length can decrease the flame speed due to the increase of heat loss to the pipe wall. For the future research, here we can predict the maximum explosion pressure will be obtained for the range of L/D from 5.4 to 112.0. The study on explosion properties with the different L/D is important as L/D would be one of the significant parameters affecting the maximum pressure in fuel/air explosion and further investigation should be explored in future.

CONCLUSION

From the present study, stoichiometric mixtures (Φ = 1.0) gave the highest pressures and flame speeds measurement, both on straight and bend pipe. The stoichiometric concentration gave significant maximum overpressure of 5.5 bars for bend pipe, compared 2.0 bars for straight pipe explosion test ~3 times higher. This is due to bending part that act just like obstacles. This mechanism could induce and create more turbulence, initiating the combustion of unburned pocket at the corner region, causing high mass burning rate and hence, increasing the flame speed. It is also shown that the flame speed enhancement is greater by factor of ~3 for explosion in bending pipe compared to straight pipe. Flame speed at lean and rich mixture showed lower speed due to the slower reaction rate and lower heat diffusion to facilitate flame propagation. It is also expected that the flame speed enhancement will be greater when the ignition position is placed further downside of the pipe due to the flame having longer travel distance to accelerate. From the present and previous results, it can be said that different pipe size and configuration affects the explosion propagation and its properties. It is crucial to install the safety devices (flame arrestor, venting, etc.) at certain point that shown overpressure to know the applicability of this safety devices in preventing the explosion phenomena.

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