

Experimental Study on Premixed Flame Acceleration in Closed Pipe

M. H. Mat Kiah^{a*}, R. M. Kasmani^a

Faculty of Petroleum and Renewable Energy Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

*Corresponding author: misshasimawaty@yahoo.com

Article history

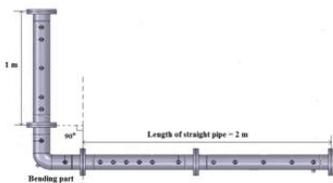
Received : 27 December 2012

Received in revised form :

28 February 2013

Accepted : 15 April 2013

Grahical abstract



Abstract

An experimental study has been carried out to investigate the flame acceleration in closed pipe. 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. 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). Ignition was affected at one end of the vessel while the other end was closed. Natural gas/oxygen mixtures were studied with equivalence ratio, Φ ranges from 0.5 to 1.8. It was demonstrated that bending pipe gave three times higher in overpressure (5.5 bars) compared to 2.0 bars of straight pipe. It is also shown that the flame speed is 63 m s^{-1} , greater by factor of ~ 3 for explosion in bending pipe in comparison with straight pipe (23 m s^{-1}). This is due to bending acting similar to 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.

Keywords: Gas explosion; bending; equivalence ratio; flame acceleration; overpressure

Abstrak

Satu eksperimen telah dijalankan untuk mengkaji pecutan nyalaan dalam paip tertutup. Sebuah paip keluli mendatar, dengan 2 m panjang dan 0.1 m diameter, diberi nisbah panjang kepada diameter (L/D) 20 telah digunakan dalam projek ini. Bagi kajian dengan 90 darjah bengkokan, bengkokan mempunyai jejari 0.1 m dan tambahan 1 m panjang paip (berdasarkan panjang tengah segmen). Pencucuhan dilakukan pada satu hujung salur dan hujung satu lagi ditutup. Campuran gas asli/oksigen dikaji dengan skala nisbah keseimbangan, Φ daripada 0.5 hingga 1.8. Didapati paip bengkokan menunjukkan tiga (3) kali lebih tinggi tekanan lebih (5.5 bar) berbanding 2.0 bar bagi paip lurus. Didapati juga halaju nyalaan adalah 63 m s^{-1} , lebih tinggi dengan faktor ~ 3 bagi paip bengkokan jika dibandingkan dengan paip lurus (23 m s^{-1}). Ini kerana bengkokan bertindak seperti penghalang. Mekanisma ini boleh merangsang dan menghasilkan lebih aliran gelora, memulakan pembakaran campuran tak terbakar di sudut bengkokan, menyebabkan kadar pembakaran tinggi dan kemudian, meningkatkan halaju nyalaan.

Kata kunci: Letupan gas; bengkokan; nisbah keseimbangan; pecutan nyalaan; tekanan lebih

© 2013 Penerbit UTM Press. All rights reserved.

1.0 INTRODUCTION

Environmental and safety concerns relating to volatile organic solvents (VOCs) lead to a vast increase in the amount of piping and number of system handling flammable fuel air mixtures for collection, containment and transport. Control over these mixtures is also required until flammable gases can be safely discharged. Due to the risk and consequence from the above situation, protection system such as venting and placement of flame arresters is needed to reduce the overpressure generated in case of explosion, dependant on the conditions they are likely to encounter. Venting in tubes and pipes has been studied intensively,¹ however there is uncertainty on the determination of ignition position in advance, leading a major difficulty for venting system to apply in large L/D configuration.

Bjerketvedt *et al.*,² found out that the pressure development in closed pipe is similar as in closed vessel. The flame will accelerate rapidly at first before slowing down due to the obstruction of the closed end downstream. A sufficiently large run up distance is necessary for actual development of supersonic combustion regimes, or so called fast flames. The minimum run-up distances depend on mixture properties (such as the laminar burning velocity, laminar flame thickness, and isobaric sound speed in the combustion products), initial conditions, obstacle configuration and duct size.⁶ Geometries, confinement feature and turbulent properties of the gas mixture into which the flame front propagates will influence development of the reaction front.⁷ The uncertainty of the flame propagation patterns and the overpressures could pose significant consequences in applying the standard testing of items such as flame arresters as stated in European Standard EN 12874 (2001).⁸

During explosions, flame flow through the vessel usually was a laminar at its initial propagation. Overpressure only being generated later, due to rapid turbulent combustion in the shear layers and recirculation zones induced by the obstacles created.⁹ As the turbulence intensity increases, the flame front configuration becomes more complicated. In Furukawa *et al.* work,¹¹ they observed that the radius of flame front curvature convex toward unburned mixture is larger than those convex toward burned gas. The average radius of the flame front curvature of lean mixture is larger than those of the near stoichiometric and the rich mixture flames. As the turbulence intensity increases, the flame front configuration becomes more complicated. When the turbulence intensities are low, wrinkles cannot be observed at the base part of the flame. The lower the turbulence intensity, the longer the nonwrinkled part becomes.

The overall explosion process may accelerate further as the flame front velocity increases, due to deflagration of turbulent burning. Ibrahim and Masri,¹² argued that the rise in burning and pressure in vessels is due to the propagation of flame front that travel to the unburned mixture of combustible fuel in premixed combustion system. A method for evaluating the unburned mixture velocity was developed which is desired to convert the observed speed of expanding spherical flames to the speed with respect to unburned mixture.¹⁵

Oakley and Thomas,¹⁷ highlighted that in many situations, in order to aid ATEX compliance, correctly placed and specified flame arresters are needed, dependent on the conditions they are likely to encounter. However, there is still some uncertainty over where best to locate these devices and concerns have been raised with safety standards for flame arrestors in regards to the lack of knowledge of where deflagration to detonation will or can occur in a pipe and what factors can contribute to this effect. For the flame arrester, questions on the best location of these devices and particular attention have been raised with safety standard for flame arresters in regards to the lack of knowledge of where deflagration to detonation will/can occur in a pipe and the contributing factors on this phenomenon.¹⁷ Hence, it is important to be able to predict the mode of flame acceleration and combustion behaviour at various points in pipe in order to install appropriate protective systems such as flame arrester or venting at the correct location. This research is vital in ensuring safety operation of the industrial process involving medium scale piping especially the transmission and distribution of gases from one equipment to another equipments.

This study aims to provide additional data and to investigate the effect of pipe configuration, i.e. straight and bending on gas explosion in the pipeline. The fuel used was natural gas/oxygen with equivalent ratio, Φ ranges between 0.5 to 1.8.

2.0 EXPERIMENTAL AND METHOD

A horizontal steel pipe, with 2 m long and 0.1 m diameter, giving L/D ratio of 20 was used in this project with a range of equivalence ratio (Φ) from 0.5 to 1.8. The pipe was made up of a number of segments ranging from 0.5 to 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 Figure 1 for the overall schematic of the experimental rig.

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. Natural gas at calculated pressure is then injected into the mixing vessel for both natural gas/oxygen compositions with the desired equivalent ratio before transferred into main testing pipe. Sample of natural gas/oxygen mixtures has been tested using Gas Chromatography to check its concentration. 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 is in near limit mixtures. The history of flame travel along the pipe was recorded by an axial array of mineral insulated, exposed junction, type K thermocouples. The time of flame arrival is 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. Flame speed was determined from the experiment by using flame arrival time on the mounted thermocouple with known distance from the spark plug. Data on flame propagation was acquired using data logger by National Instrument. 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.

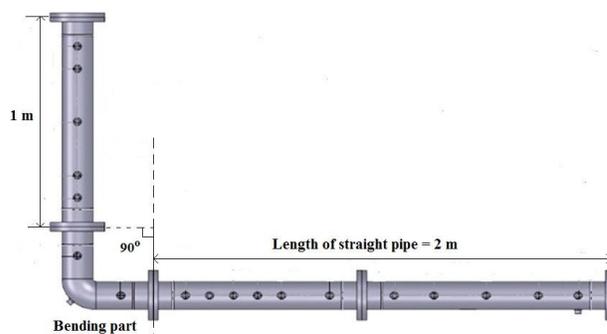


Figure 1 Overall schematic of the experimental rig

3.0 RESULTS AND DISCUSSION

3.1 Explosion in Straight Pipe

3.1.1 Pressure Development/Profile on Straight Pipe

Pressure profile against time, t for lean, stoichiometric and rich concentrations were shown in Figure 2. From Figure 2, it is illustrated that $P = 2.0$ bars was attained at stoichiometric concentration compared to $P = 1.0$ bar ($\Phi = 1.6$) and $P = 0.8$ bar at $\Phi = 0.6$. The similar result was obtained by previous study by Blanchard *et al.* (2010).³ 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. For $\Phi = 1.6$ (rich mixtures), two pressure peaks are observed from the plotted graph. First peak shows that at shorter time, $t = 0.25$ s, the pressure is ~ 1.0 bar. Another one peak is observed for rich concentration at $t = 0.75$ s, giving the pressure of 1.3 bars. High gases mixture content for rich concentration possibly could create more turbulence, further increasing burning

rate and enhancing flame speed and hence, increase in overpressure.

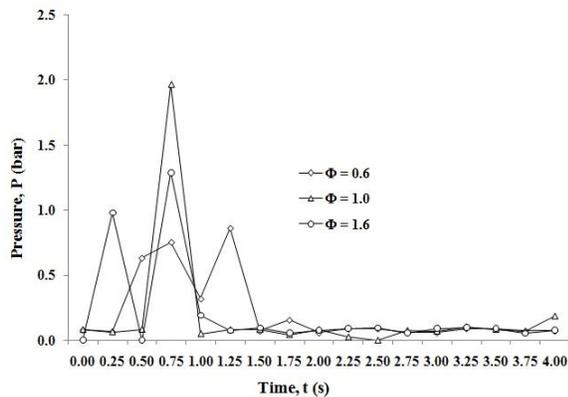


Figure 2 Pressure against time at lean ($\Phi = 0.6$), stoichiometric ($\Phi = 1.0$) and rich ($\Phi = 1.6$) concentration on straight pipe

3.1.2 Effect of Equivalence Ratio on Explosion Pressure in Straight Pipe

Pressure profile against distance from ignition, x is shown in Figure 3. 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. 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).¹⁸ 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 is 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.

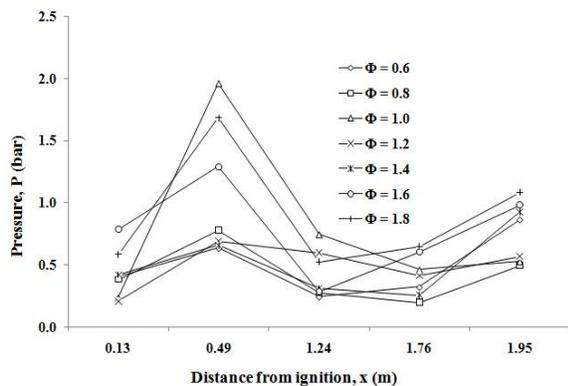


Figure 3 Pressure profile against distance from ignition at different mixture concentration on straight pipe

3.1.3 Rate of Pressure Rise, dP/dt on Straight Pipe

Rate of pressure rise, dP/dt profile against distance from ignition, x is shown in Figure 4. Stoichiometric concentration ($\Phi = 1.0$) gave the highest dP/dt of 8 bar s^{-1} . This would explain the highest flame speed obtained as shown in Figure 5. The increasing flame speed will enhance the pressure and this will increase the rate of pressure rise. Blanchard *et al.*,³ found out that the maximum rate of pressure rise for methane is 4.2 bar s^{-1} for $L/D = 112.0$ lower than the present study. This could be explained by the effect of pipe length. The longer the pipe, rate of pressure rise will decrease due to flame having longer travelling distance to reach the end of pipe. The severity of the explosion is depended on the rate of pressure rise and in this case it could pose to pipe destruction.²¹

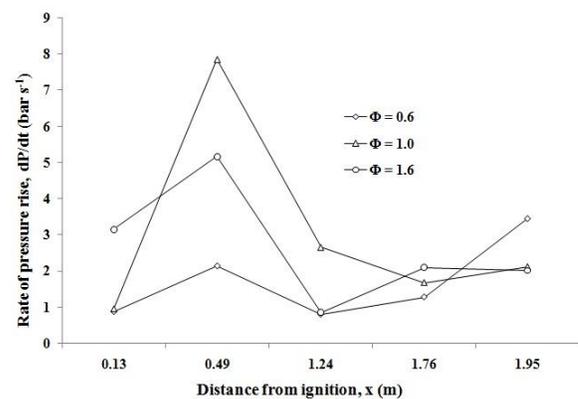


Figure 4 Rate of pressure rise against distance from ignition at lean ($\Phi = 0.6$), stoichiometric ($\Phi = 1.0$) and rich ($\Phi = 1.6$) concentration on straight pipe

3.1.4 Flame Speeds on Straight Pipe

Figure 5 shows the flame speed, S as a function of distance from ignition, x with different equivalence ratio. The flame speeds increased from laminar burning of 3 m s^{-1} to 23 m s^{-1} , obtained at $\Phi = 1.0$. The lean mixtures gave the lowest maximum flame speed of 8 m s^{-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 Chuanjie *et al.* (2010).⁴ Their study shows that the decrease of gas concentration results 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 or 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.

At rich concentration, the highest value of flame speed is 20 m s^{-1} , not much different with the flame speed of stoichiometric concentration. Rich mixtures are known to be more susceptible to developing surface instabilities (flame cellularity) which would lead to higher burning rate and hence higher flame speeds.¹⁰ 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.

The flame speed shows higher value at initial of its propagation through the straight pipe before experiencing the retardation, causing low speed towards the few centimeter of the end pipe. When flame reached the end of pipe, it was obstructed by the closed pipe condition. The heat release will be higher and automatically will reduce the speed of the flame.

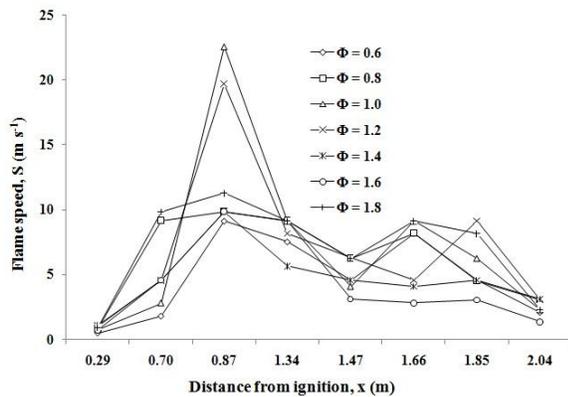


Figure 5 Flame speed profile against distance from ignition at various mixture concentrations on straight pipe

3.2 Explosion in 90 Degree Bend Pipe

3.2.1 Pressure Development of Gas Explosion in 90 Degree Bend Pipe

Pressure profile against time, t is shown in Figure 6. For equivalent ratio, $\Phi = 1.0$, the highest pressure of 5.5 bars observed at $t = 1.25$ s. Similar time is found out for $\Phi = 0.6$ (lean concentration) to reach the peak pressure of 1.3 bars. However, the rich mixture gave longer time, $t = 1.75$ s to reach the maximum pressure.

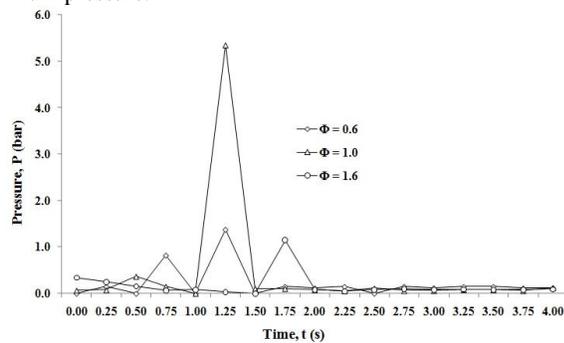


Figure 6 Pressure developments against time at lean ($\Phi = 0.6$), stoichiometric ($\Phi = 1.0$) and rich ($\Phi = 1.6$) concentration on 90 degree bend pipe

As discussed earlier, the flame will take longer travel distance at the curved of bend, this can enhance the time to reach maximum explosion pressure. Bending acts as an obstacle or obstruction which increases the turbulent effect at the regime and influence in enhancement of the flame speed and pressure. Blanchard *et al.* clarified that for straight pipe, flame took shorter time to reach the maximum explosion pressure due to laminar effect.³

3.2.2 Effect of Equivalence Ratio on Explosion Pressure in 90 Degree Bend Pipe

Figure 7 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. Higher pressure obtained for almost all equivalent ratios at distance from ignition, $x = 2.79$ m where the bending is placed. The highest pressure, P of 5.5 bars obtained at $\Phi = 1.0$. This result is increased by the factor of 3 in a comparison of the maximum pressure obtained for the straight pipe. The effect of 90 degree bend almost similar with the baffle effect as studied and highlighted by Blanchard *et al.* (2010).³ They found out that the maximum pressure for 30% baffle was 2.1 bars which is not much different to the maximum pressure for 90 degree bend pipe, 1.8 bars. 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. 90 degree bend pipe configuration produces more turbulent area at angle of bend which acting as obstruction for the flame to travel to reach the end of pipe. Kindracki *et al.*,¹³ found out that the maximum explosion pressure for methane/air mixtures is ~ 5.5 bars at $\Phi = 1.0$ which is similar to the present study.

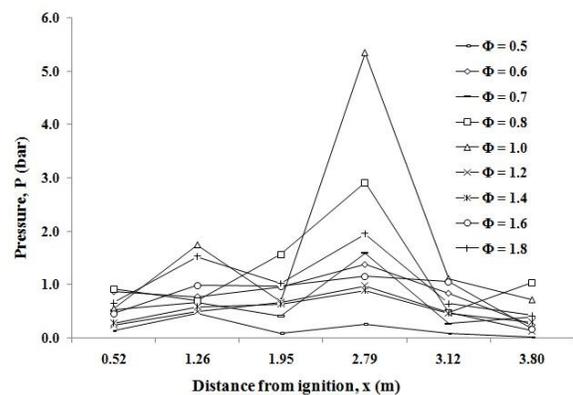


Figure 7 Pressure developments against distance from ignition at various mixture concentrations on 90 degree bend pipe

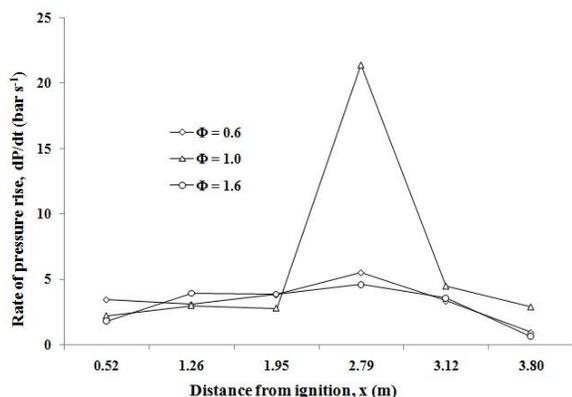
Table 1 shows the data summary for content/concentration checking of mixtures using gas chromatography for equivalence ratio, Φ of 0.6 (lean), 1.0 (stoichiometric) and 1.6 (rich). The average of partial pressure obtained from GC Test given similar value with the initial calculated fill up partial pressure of the gas mixtures.

Table 1 Data summary for content/concentration checking of mixtures using gas chromatography

GC Test	Φ	Gases	Partial Pressure For Mixtures	Area (%)	GC Test Partial Pressure
1	0.6	Natural gas	1.10	0.77954	1.0986
		Oxygen	3.65	2.59107	3.6514
			4.75	3.37061	
2	1.0	Natural gas	1.58	0.84063	1.4040
		Oxygen	3.17	2.00337	3.3460
			4.75	2.84400	
3	1.6	Natural gas	2.11	0.83705	1.9914
		Oxygen	2.64	1.15951	2.7586
			4.75	1.99656	

3.2.3 Rate of Pressure Rise, dp/dt on 90 Degree Bend Pipe

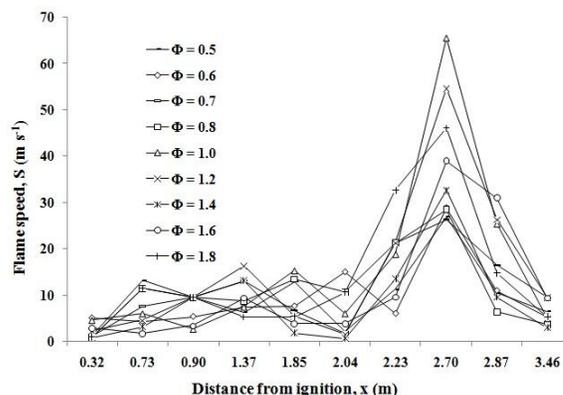
As discussed earlier in section 3.1.1, flame took shorter time to reach the maximum explosion pressure due to laminar effect. For bending and existing of baffle, flame took longer time to reach the maximum explosion pressure due to the turbulence effect caused by the obstruction regime. Figure 8 gave rate of pressure rise against distance from ignition, x for explosions of 90 degree bend pipe. The graph showed that stoichiometric mixtures gave the highest the rate of pressure rise, 23 bar s^{-1} which about 3 times higher compared to the straight pipe.

**Figure 8** Rate of pressure rise against distance from ignition at lean ($\Phi = 0.6$), stoichiometric ($\Phi = 1.0$) and rich ($\Phi = 1.6$) concentration on 90 degree bend pipe

The highest value of dp/dt was obtained at $x = 2.8 \text{ m}$ which at the curved of bending. It proven that the bend acted as obstacle and thus, can enhance the pressure and rate of pressure rise. At bend regime, 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. Dahoe *et al.*,⁵ in their determination of laminar burning velocity found out that the range of rate of pressure rise for methane is 20 to 300 bar s^{-1} . This range higher compared to the present study which used natural gas. Razus *et al.*,²¹ observed that maximum rate of pressure rise for propane is about 1400 bar s^{-1} . The more reactive fuel used can enhance the value of overpressure and rate of pressure rise due to the increased in flame speeds.

3.2.4 Flame Speeds on 90 Degree Bend Pipe

Figure 8 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 bending part start at $x = 2.0 \text{ m}$ and end at $x = 2.8 \text{ m}$. For the present study, it is shown that the highest flame speed, of 63 m s^{-1} obtained at stoichiometric concentration at $x = 2.7 \text{ m}$ from ignition, giving good agreement with results obtained by Blanchard *et al.* (2010).³ According to their work, flame will propagate along the pipe length freely without attended of baffles or obstacles. Obstacles will increase the flame speed due to enhancement of travel distance of the flow which caused by the turbulent effect occurred.

**Figure 9** Flame speed against distance from ignition at various mixture concentrations on 90 degree bend pipe

It is also shown that the flame speed is 63 m s^{-1} , greater by factor of ~ 3 for explosion in bending pipe in comparison with straight pipe (23 m s^{-1}). This is due to bending acting similar to 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.

3.3 Comparison with Published Experimental Data

Table 2 shows the data of pressure and flame speed for present work and previous published papers (Blanchard *et al.*,³ Kindracki *et al.*,¹³ Zhang *et al.*,²²) at stoichiometric concentration in closed straight pipe with different L/D (smaller, medium and bigger size of pipe). The highest explosion pressure, 5.3 bars obtained at $L/D \sim 10.3$ as studied by Kindracki *et al.* (2007).¹³ They used methane/air mixture with end ignition. The lower explosion pressure obtained when $L/D < 10.3$. For the present study with $L/D \sim 20$, as discussed earlier, the maximum explosion pressure for straight pipe is $\sim 2.0 \text{ bars}$. It can be said that with $L/D > 10.3$, the maximum explosion pressure expected to be decreased. This comparison table shows that the pressure generated during the explosion effected by the length of pipe, L and diameter of pipe, D .

Table 2 Pressure and flame speed of methane-air explosion at stoichiometric concentration

Reference(s)	L/D	Straight		90 degree	
		P _{max} (bars)	S (m/s)	P _{max} (bars)	S (m/s)
Zhang <i>et al.</i> , (2011)	5.4	0.7	3.5		
Kindracki <i>et al.</i> , (2007)	10.3	5.3			
Present study	20.0	2.0	23.0	5.5	63.0
Blanchard <i>et al.</i> , (2010)	112.0	0.9	45.0	1.3	68.0

Figure 10 shows the pressure development in different L/D of straight pipe. According to Munday,¹⁶ the vessel shape and size will affect the deflagration velocity. Detonation limit will increase with increasing of vessel size.²⁰ Piping system with L/D ~ 5.4 gave the lowest explosion pressure, ~ 0.7 bar.²² The pressure kept increased until reached the maximum pressure at L/D ~ 10.3. The pressure decreased when L/D more than 10.3. Larger L/D can increase the flame travel distance due to increase in axial propagation because of the larger pipe diameter. Besides that, during 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, maximum pressure up to 6.0 bars could be predicted for L/D ranges from 5.4 to 10.31 in determining the appropriate explosion protection and mitigation measures.

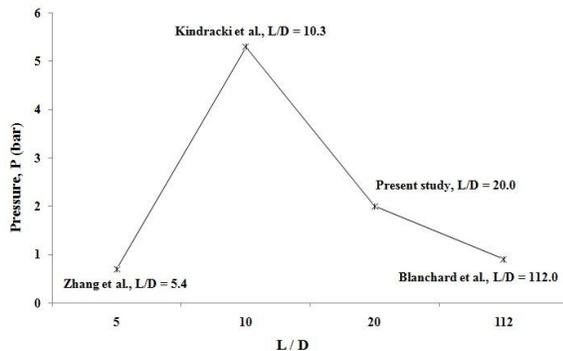
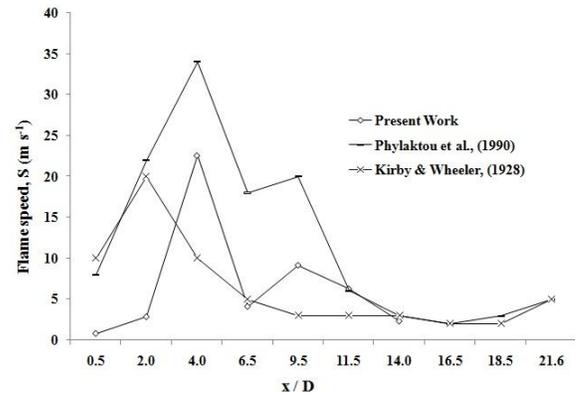
**Figure 10** Explosion pressure for methane-air at stoichiometric condition for different value of L/D

Figure 11 shows the flame speed against x/D for present work and previous published study (Kirby and Wheeler,¹⁴ Phylaktou *et al.*,¹⁹) for natural gas/oxygen mixture in both closed end pipe with the L/D of 20 at stoichiometric concentration. It can be depicted that result from the present study gave similar maximum flame speed value as obtained by Kirby & Wheeler (1928).¹⁴ However, the flame pattern observed agreed with the theory (refer to Figure 11). Phylaktou *et al.*,¹⁹ found out that the maximum flame speed was ~ 35 m s⁻¹, higher than result obtained from the present study, ~ 23 m s⁻¹. In this case, this is probable of larger L/D of 21.6 used in Phylaktou *et al.*,¹⁹ gave higher flame speed compared to present study. Pipe configuration such as pipe roughness and its length also play the important role on the flame speed value. The roughness of the pipe will act as obstruction, which will reduce the speed of flame during its propagation.

**Figure 11** Flame speed against x/D for present work and previous study at stoichiometric condition

4.0 CONCLUSIONS

From the present work, it can be said that equivalence ratio and pipe configuration play important roles in determining the development of explosion properties. Stoichiometric concentration gave maximum overpressure of 5.5 bars for bend pipe, compared to P = 2.0 bars for straight pipe. It is also shown that the flame speed enhancement is higher by the factor of 3 for explosion in bending pipe in comparison to straight pipe. This is due to that bending giving similar effect as obstacles. 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 postulated that ignition position also gave significant effect on explosion development in pipe. The flame 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. Further, it can be said that different pipe size and configuration affects the explosion propagation and severity.

Acknowledgement

M. H. Mat Kiah would like to thank the Universiti Teknologi Malaysia, Universiti Malaysia Pahang and the Ministry of Higher Education, Malaysia for funding of this research under GUP vote no Q.J130000.2642.06J66.

Nomenclature

Base quantity	Name	Abbreviation
Rate of pressure rise, dP/dt	Bar per second	bar s ⁻¹
Diameter, D	Meter	m
Length, L	Meter	m
Pressure, P	Bar	bar
Maximum pressure, P _{max}	Bar	bar
Flame speed, S	Meter per second	m s ⁻¹
Distance from ignition, x	Meter	m
Equivalence ratio, Φ	Equivalence ratio	Φ

References

- (1) A. Alexiou, G. E. Andrews, H. Phylaktou. 1996. Side-vented Gas Explosions in a Long Vessel: The Effect of Vent Position. *Journal of Loss Prevention in the Process Industries*. 9(5): 351–356.
- (2) D. Bjerketvedt, J. R. Bakke, K. van Wingerden. 1997. Gas Explosion Handbook. *Journal of Hazardous Materials*. 52(1): 1–150.
- (3) R. Blanchard, D. Arndt, R. Gratz, M. Poli, S. Scheider. 2010. Explosion in Closed Pipes Containing Baffles and 90 Degree Bends. *Journal of Loss Prevention in the Process Industries*. 23(2): 253–259.
- (4) Z. Chuanjie, L. Zhenguang, L. Baiquan, J. Bingyou. 2010. Effect of Variation in Gas Distribution on Explosion Propagation Characteristics In Coal Mines. *Mining Science and Technology*. 20(4): 516–519.
- (5) A. E. Dahoe, L. P. H. Goey. 2003. On the Determination of the Laminar Burning Velocity from Closed Vessel Gas Explosions. *Journal of Loss Prevention in the Process Industries*. 16(6): 457–478.
- (6) S. B. Dorofeev. 2011. Flame Acceleration and Explosion Safety Applications. *Proceedings of the Combustion Institute*. 33(2): 2161–2175.
- (7) H. Eickhoff. 2002. *Analysis of the Turbulent Burning Velocity*. *Combustion and Flame*. 129(4): 347–350.
- (8) EN 12874, European Standard. 2001. Flame Arresters-performance Requirements, Test Methods And Limits For Use.
- (9) M. Fairweather, G. K. Hargrave, S. S. Ibrahim, D. G. Walker. 1999. Studies of Premixed Flame Propagation in Explosion Tubes. *Combustion and Flame*. 116(4): 504–518.
- (10) G. Ferrara, S. K. Willacy, H. N. Phylaktou, G. E. Andrews, A. D. Benedetto, M. C. Mkpadi. 2005. Duct Vented Propane-air Explosions with Central and Rear Ignition. *Fire Safety Science, IAFSS*. 8: 1341–1352.
- (11) J. Furukawa, K. Maruta, T. Hirano. 1998. Flame Front Configuration of Turbulent Premixed Flames. *Combustion and Flame*. 112(3): 293–301.
- (12) S. S. Ibrahim, A. R. Masri. 2001. The Effects of Obstructions on Overpressure Resulting from Premixed Flame Deflagration. *Journal of Loss Prevention in the Process Industries*. 14(3): 213–221.
- (13) J. Kindracki, A. Kobiera, G. Rarata, P. Wolanski. 2007. Influence of Ignition Position and Obstacles on Explosion Development in Methane-Air Mixture in Closed Vessels. *Journal of Loss Prevention in the Process Industries*. 20(4–6): 551–561.
- (14) W. A. Kirkby, R. V. J. Wheeler. 1928. *Chem Soc*. 3203.
- (15) A. Lipatnikov, J. Chomiak. 2002. Turbulent Burning Velocity and Speed of Developing, Curved, and Strained Flames. *Proceedings of the Combustion Institute*. 29(2): 2113–2121.
- (16) G. Munday. 1971. Detonations in Vessels and Pipelines. *The Chemical Engineer*. 135–144.
- (17) G. I. Oakley, G. O. Thomas. 2004. *Investigations into Concerns About BS EN 12874: 2001 Flame Arresters. Performance Requirements, Test Methods And Limits For Use*. HSE Research Report 281.
- (18) A. A. Pekalski, H. P. Schildberg, P. S. D. Smallegance, S. M. Lemkowitz, J. F. Zevenbergen, M. Braithwaite, H. J. Pasman. 2005. Determination of the Explosion Behaviour of Methane and Propene in Air or Oxygen at Standard and Elevated Conditions. *Process Safety and Environmental Protection*. 83(5): 421–429.
- (19) H. Phylaktou, M. Foley, G. E. Andrews. 1993. Explosion Enhancement Through A 90-Degrees Curved Bend. *Journal of Loss Prevention in the Process Industries*. 6(1): 21–29.
- (20) S. R. Tieszen. 1985. Detonation Cell Size Measurements in Hydrogen-Air-steam Mixtures. *Progress in Astronautics and Aeronautics*. 106: 205–219.
- (21) D. Razus, C. Movileanu, V. Brinzea, D. Oancea. 2006. Explosion Pressures of Hydrocarbon-air Mixtures in Closed Vessels. *Journal of Hazardous Materials*. 135(1–3): 58–65.
- (22) Q. Zhang, W. Li, D. C. Lin, Y. Duan, H. M. Liang. 2011. Experimental Study of Gas Deflagration Temperature Distribution and Its Measurement. *Experimental Thermal and Fluid Science*. 35: 503–508.