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Flame Acceleration of Premixed Natural Gas/Air Explosion in Closed Pipe

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***Abstract*—**An experimental study has been done to investigate the flame acceleration in a closed pipe. A horizontal steel pipe, 2m long and 0.1m in diameter (*L*/*D* of 20), was used in this work. For tests with 90 degree bends, the bend had a radius of 0.1m and thus, the pipe was lengthened 1m (based on the centreline length of the segment). Ignition was affected at one end of the vessel while the other end was closed. Only stoichiometric concentration (Φ, = 1.0) of natural gas/air mixtures will be reported in this paper. It was demonstrated that bend pipe configuration gave three times higher in maximum overpressure (5.5 bars) compared to straight pipe (2.0 bars). From the results, the highest flame speed, of 63ms^{-1}, was observed in a gas explosion with bent pipe; greater by a factor of ~3 as compared with straight pipe (23ms^{-1}). This occurs because bending acts similar to an obstacle, in which this mechanism can induce more turbulence, initiating combustion in an unburned pocket at the corner region and causing a high mass burning rate, which increases the flame speed.

***Keywords*—**Bending, gas explosion, bending, flame acceleration, overpressure.

I. Introduction

THE acceleration of the flame inside a pipe is a complex phenomenon involving several variables spanning from fuel nature and mixture composition to geometrical characteristics of the pipe such as length, diameter, wall roughness or presence of obstacles in the flame path.

During explosions, flame flow through the vessel usually is laminar at its initial propagation. Overpressure is only generated later, due to rapid turbulent combustion in the shear layers and recirculation zones induced by the obstacles created either by blockage or bending [1]. As the turbulence intensity increases, the flame front configuration becomes more complicated. The overall explosion process may accelerate further as the flame front velocity increases, due to deflagration of turbulent burning. Ibrahim and Masri [2] argued that the rise in burning and pressure in vessels is due to the propagation of a flame front that travels to the unburned mixture of a combustible fuel in a premixed combustion system. A method for evaluating the unburned mixture velocity was developed, which converts the observed speed of expanding spherical flames to the speed with respect to the unburned mixture [3].

The influence of bends was also of interest, as they are often perceived as a complicated problem involving the interaction between fluid dynamics, heat transfer and turbulent combustion by promoting flame acceleration and detonation even though little previous published work exists to justify or quantify this perception of increased risk of detonation [4]. Phylaktou et al. [5] showed that with a short tube of a 90 degree bend can enhance the flame speed by a factor of five and was equated to the effect of baffle with a blockage ratio of 20% at the same position. Another investigation using propane-air mixture showed that 24% enhancement of flame acceleration was observed when 90-degree bend placed half way down a tube [6].

Oakley and Thomas [7] 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 about safety standards for flame arresters with regards to the lack of knowledge of where deflagration to denotation will or can occur in a pipe and what factors can contribute to this effect. For the flame arrester, questions on the best location for these devices have been raised along with the contributing factors in this phenomenon. Hence, it is important to be able to predict the mode of flame acceleration and combustion behavior at various points in the pipe in order to install appropriate protective systems. The uncertainty of the flame propagation patterns and the overpressures could pose significant consequences in applying the standard testing of protective measures such as flame arrester [8].

This study aims to provide additional data and to investigate the effect of pipe configuration (i.e., straight and bending) on gas explosion in a pipeline, using stoichiometric natural gas/air mixtures as a fuel.

II. Materials and Method

A horizontal steel pipe, 2m long and 0.1m in diameter (*L*/*D* ratio of 20), was used in this project. Only stoichiometric concentration i.e. equivalence ratio (Φ) = 1.0 will be reported in this paper. The pipe was made up of a number of segments ranging from 0.5 to 1m in length, bolted together with a gasket seal in-between the connections and blind flanges at both ends. Evacuation performed prior to introduction of the gas ensured that no leakage was present in the pipe during the

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tests. For tests with 90-degree bend, the bend had a radius of 0.1m and added a further 1m to the length of the pipe (based on the centreline length of the segment). Refer to Fig. 1 for the overall schematic of the experimental rig. For maximum reduced pressure, P_{max}, this was taken from P_1 pressure transducer as it located at the centre of the vessel for both test vessels. Flame speeds in the primary vessel were calculated from the time of flame arrival at an array of thermocouples on the vessel centerline (symbols as T) in Fig. 1). The ignitor was a 16 J spark. Fuel-air mixtures were prepared using the partial pressure method, to an accuracy of 0.1 mbar (0.01% of composition). A sample of each gas mixture was tested using gas chromatography for fuel's concentration validity. Data on flame propagation was acquired using National Instrument data logger. A 16-channel transient data recorder was used to record and process all the data. As part of the experimental program, three repeat tests were performed at each condition and these demonstrated good consistency and reproducibility, with peak pressures varying by less than ± 5 % in magnitude.

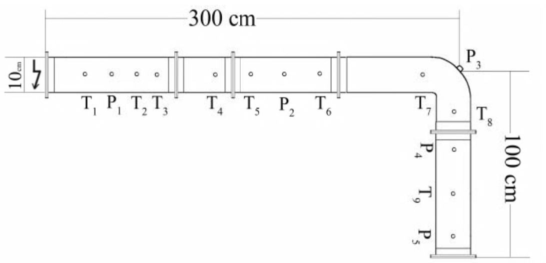

Fig. 1 Schematic configuration of pipe, thermocouples denote as T_1-T_9 and P_1-P_5 indicates the pressure transducer

III. Results and Discussions

A. Pressure Development and Flame Speed on Pipe

The pressure generation is illustrated in Fig. 2 for the case of straight and bend pipe explosion. The first observation is the significant increase in overpressure for bending pipe as compared to straight pipe. The increase in maximum overpressure was approximately three times, from 1.9 to 5.3 bars. The maximum overpressures for bend configuration was found at around 70% of the pipe length, occurring at the bending part as shown as Fig. 3. The inductive effects of the duct bend bring the flame front expand and tension, then make it curve, fold and make the area of flame front sharply increase, which results that the contact of gas and oxygen is much fuller and the diffuseness is more homogeneous. So the combustion velocity, heat release rate and flame propagation velocity increase.

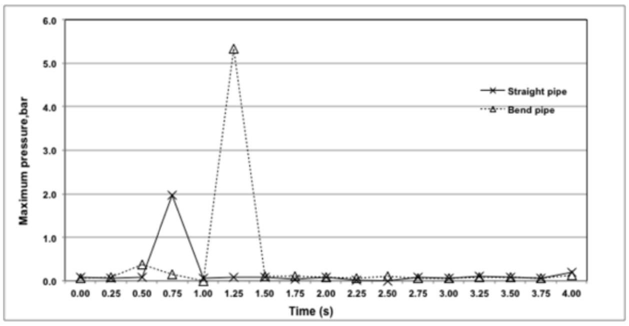

Fig. 2 Pressure vs. time at for straight and bend pipe at stoichiometric ($\Phi = 1.0$)

The rapid combustion makes combustion production rapidly expand and accelerate and brings the larger overpressure. At the same time, the disturbance resulting from un-burn mixed gas heated and compressed by leading shock wave, makes the flow gradient further increase and the flame front further curve and fold, which brings the turbulence kinetic energy further increase and the combustion rate much larger. So the positive feedback is brought between the gas flow and combustion process. Meanwhile, the reflection and diffraction of shock wave brought by obstacles make the propagation more complex. Lots of reflection wave and diffraction wave entering into the reaction zone results in sharp increase of the reaction velocity and heat release rate, which offers the energy for the shock wave propagation and makes shock wave intensity increase. The increase of shock wave intensity further heats and compresses the un-disturbed gas, so the positive feedback effect between the gas, shock wave and flame front is formed [9], [10]. It is confirmed that the change of gas explosion propagation characteristics in bend duct is the combined result of turbulence flow, expansion wave, total resistance and surface thermal effect.

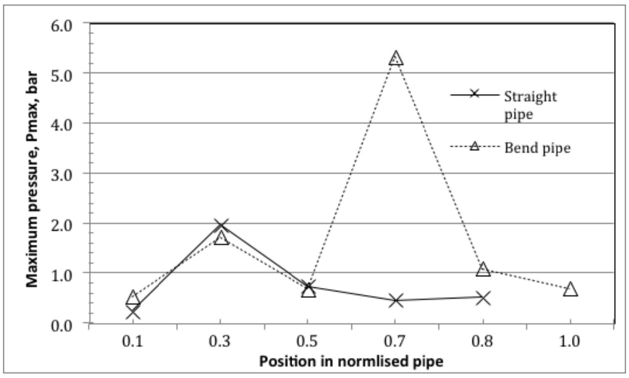

Fig. 3 Maximum pressure for natural gas/air explosion in straight and bend pipe configuration ($\Phi = 1.0$)

Bending could result higher downstream flame speed as illustrated in Fig. 4. It can be said that bending acts as an full bore obstacle that could increase the turbulence effect at the regime, influences the enhancement of flame speed and pressure. It is acknowledged that the form of flame front will be different as it approaches and passes the bending, and does cause an initial acceleration of the flame. The increasing flame speed creates pressure waves and influences the flame front to expand. The net effect is that the mass-burning rate of the flame increases 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. The flame has a longer travel distance at the bend's curvature, which can enhance the time to reach maximum explosion pressure. Blanchard et al. [4] depicted that for straight pipe, flame took a shorter time to reach the maximum explosion pressure due to the laminar effect. Further downstream, maybe due to the quenching on the walls of the pipe or changes n flame geometry, the flame speed decelerated rapidly to speed recorded for explosion in straight pipe (~ 3 m/s).

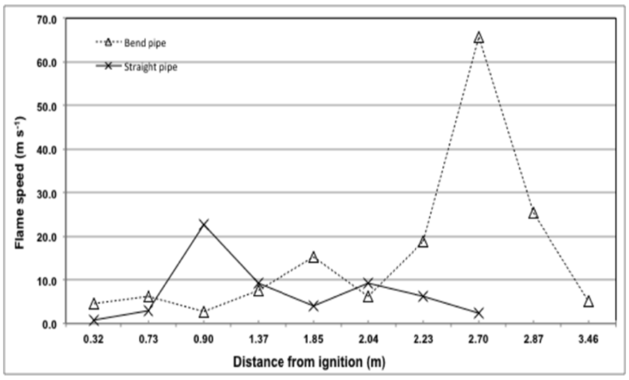

Fig. 4 Flame speed as a function of distance from ignition. Dashed line indicates the bending part

B. Rate of Pressure Rise (dP/dt) on Straight and Bend Pipe Configuration

The rate of pressure rise, d*P*/d*t*, as a function of distance from ignition is shown in Fig. 5. For straight pipe, the highest d*P*/d*t* was obtained at ~8 bar s^{-1}comparing to 23 bar s^{-1} for bend pipe configuration, which about 3 times higher compared to straight pipe. This would explain the highest flame speed obtained as shown in Fig. 4. The increasing flame speed enhances the pressure, and this increases the rate of pressure rise. The same experiment done by Blanchard et al. [4] found that the maximum rate of pressure rise for methane is 4.2 bar s^{-1} for straight pipe, lower than the present study. This could be explained by the effect of pipe length. The longer the pipe, the lower is the rate of pressure rise because the flame has a longer travelling distance to reach the end of the pipe. The severity of the explosion is dependent on the rate of pressure rise, and in this case it could cause pipe destruction [11].

For bend pipe configuration, it can be said that bending poses a significant hazard on explosion severity. This proven that the bend acted as an obstacle and, thus, can enhance the pressure and rate of pressure rise. At the bend area, flame has a longer travel distance to accelerate and, hence, will create a greater amount of turbulence downstream of the system. This increases the pressure and creates overpressure in that area. Dahoe et al. [12] in their determination of laminar burning velocity found that the range of rate of pressure rise for methane is 20 to 300 bar s^{-1}. This range is higher compared to the present study, which used natural gas. Razus et al. [11] found that the maximum rate of pressure rise for propane is about 1400 bar s^{-1}. The more reactive fuels can enhance the value of overpressure and rate of pressure rise due to the increased flame speeds.

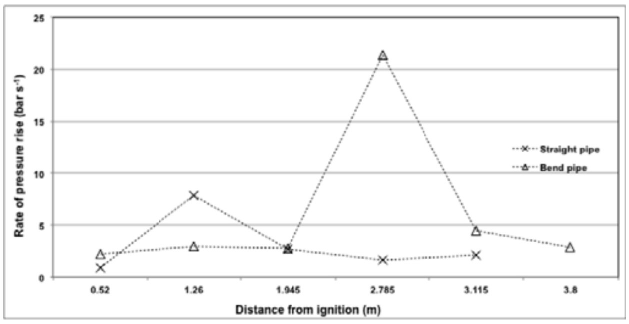

Fig. 5 Rate of pressure rise (dP/dt) as a function of distance of ignition

C. Comparison with Previous Published Data

Table I shows the data on pressure and flame speed in the present work and previously published papers [4], [13], [14] at stoichiometric concentration in closed straight pipe with different *L*/*D* (small, medium and large sized pipe). The highest explosion pressure, 5.3 bars, was obtained at *L*/*D* ~ 10.3 as studied by Kindracki et al. [13]. They used a methane/air mixture with end ignition. The lower explosion pressure was obtained when *L*/*D*< 10.3. For the present study with *L*/*D* ~ 20, as discussed earlier, the maximum explosion pressure for straight pipe is ~2.0 bars. It can be said that with *L*/*D*> 10.3, the maximum explosion pressure is expected to be decreased. Table I shows that the pressure generated during the explosion that affected by length of pipe, *L*and diameter of pipe, *D*.

TABLE I
PRESSURE AND FLAME SPEED OF METHANE/AIR EXPLOSION AT STOICHIOMETRIC CONCENTRATION

Reference	*L*/*D*	Straight pipe		90 degree bent pipe	
		P_{max} (bar)	*S* (m s^{-1})	P_{max} (bar)	*S* (m s^{-1})
Zhang et al. [14]	5.4	0.7	3.5		
Kindracki et al. [13]	10.3	5.3			
Present study	20.0	2.0	23.0	5.5	63.0
Blanchard et al.[4]	112.0	0.9	45.0	1.3	68.0

Fig. 6 shows pressure development in different *L*/*D*'s of straight pipe. According to Munday [15], the vessel shape and size affects the deflagration velocity. The graph illustrates that *L*/*D* gave a profound contribution in determining the overpressure. The maximum pressure is expected to be the highest when *L*/*D* is about 11 and higher *L*/*D* gave lower overpressure. Larger *L*/*D* can increase the flame travel distance due to increase in axial propagation because of the larger pipe diameter. Furthermore, during flame propagation, a longer pipe length can decrease the flame speed due to the increase of heat loss to the pipe wall. For future research, maximum pressure up to 6.0 bars could be predicted for *L*/*D* ranges from 5.4 to 10.3 in determining appropriate explosion protection and mitigation measures.

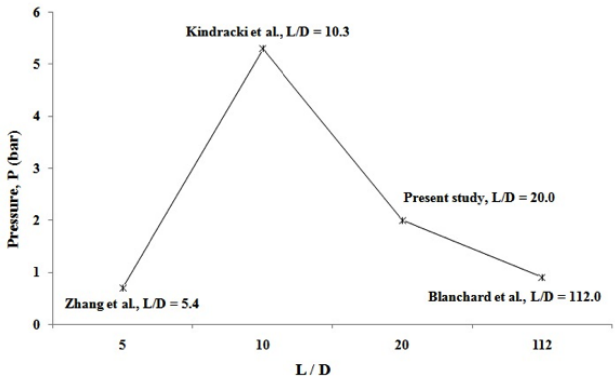

Fig. 6 Explosion pressure for methane/air at stoichiometric conditions for different values of *L*/*D*

IV. Conclusions

The present work has shown that equivalence ratio and pipe configuration played important roles in determining the development of explosion properties. Stoichiometric concentration gave a maximum overpressure of 5.5 bars for bending pipe, compared to 2.0 bars for natural gas/oxygen mixtures in straight pipe gas explosion. Moreover, flame speed enhancement was higher by a factor of 3 for explosions in bent pipe configuration in comparison to straight pipe. This occurred because bending produces an effect similar to an obstacle. Flame speed at both lean and rich mixtures was lower due to the slower reaction rate and lower heat diffusion to facilitate flame propagation. Further, pipe size and configuration were shown to affect explosion propagation and severity.

It is postulated that ignition position also had a significant effect on explosion development in pipe. The flame enhancement is greater when the ignition position is placed further down the pipe because the flame has a longer travel distance over which to accelerate.

Acknowledgments

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Nomenclature

dP/dt : rate of pressure rise, bar s^{-1}
D : pipe diameter, m
L/D : ratio of pipe length over pipe diameter, dimensionless
L : pipe length, m
P : pressure, bar
P_{max} : maximum pressure, bar
S : flame speed, m s^{-1}
t : time, s
x : distance from ignition, m
x/D : ratio of distance from ignition over pipe diameter, dimensionless
Φ : equivalence ratio, dimensionless

References

[1] M. Fairweather, Hargrave, G. K., Ibrahim, S. S. and Walker, D. G., Studies of Premixed Flame Propagation in Explosion Tubes. *Combust Flame,* 116 (4), 1999, pp. 504-518.
[2] S.S. Ibrahim and Masri, A. R., The effects of obstructions on overpressure resulting from premixed flame deflagration. *J Loss Prevent Proc,* 14(3), 2001, pp. 213-221.
[3] A. Lipatnikov and Chomiak, J., Turbulent burning velocity and speed of developing, curved, and strained flames. *P Combust Inst,*29(2), 2002, pp. 2113-2121.
[4] R. Blanchard, Arndt, D., Grätz, R., Poli, M. and Scheider, S., Explosions in closed pipes containing baffles and 90 degree bends,*J Loss Prevent Proc,*23(2),2010, pp. 253-259
[5] H.N. Phylaktou, Andrews, G. E. and Herath, P., Fast flame speeds and rates of pressure rise in the initial period of gas explosions in large L/D cylindrical enclosures, *J Loss Prevent Proc,* 3,1990,pp. 355-364
[6] K. Chatrathi K, Going J E, and Grandestaff B. Flame propagation in industrial scale piping, *Process Saf. Prog,* 20, 2001, pp. 286-294
[7] G.I. Oakley and Thomas, G.O., Investigations into concerns about BS EN 12874:2001 flame arresters, Performance requirements, test methods and limits for use, *HSE Research Report 281*, 2004.
[8] EN 12874, European Standard, Flame arresters-Performance requirements, test methods and limits for use, 2001.
[9] M.A. Nettleton, Shock attenuation in a gradual area explosion, *J Fluid Mech*, 60, 1973, pp. 209-223.
[10] R.M. Kasmani, Andrews, G.E. and Phylaktou, H.N., Experimental study on vented gas explosion in a cylindrical vessel with a vent duct, *Process Saf Environ,* 91 (4), 2013, pp. 245-332
[11] D. Razus, Movileanu, C., Brinzea, V. and Oancea, D., Explosion pressures of hydrocarbon-air mixtures in closed vessels. *J Hazard Mater,* 135(1-3), 2006, pp. 58-65.
[12] A.E. Dahoe and Goey, L. P. H., On the determination of the laminar burning velocity from closed vessel gas explosions. *J Loss Prevent Proc,* 16(6), 2003, pp. 457-478.
[13] J. Kindracki, Kobiera, A., Rarata, G. and Wolanski, P. (2007). Influence of ignition position and obstacles on explosion development in methane-air mixture in closed vessels. *J Loss Prevent Proc,* 20(4-6), 2007, pp. 551-561.
[14] Q. Zhang, Li, W., Lin, D. C., Duan, Y. and Liang, H. M., Experimental study of gas deflagration temperature distribution and its measurement. *Exp Therm Fluid Sci,* 35, 2011, pp.503-508.
[15] G. Munday, Detonations in vessels and pipelines, *The Chemical Engineer*, 1971, pp.135-144.