Flame propagation of highly reactive combustible mixtures in closed pipe with L/D of 51

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Flame propagation in a confined pipe with diameter 0.1 m and 5.1 m long, given a length to diameter ratio (L/D) of 51, was experimentally studied. Hydrogen and acetylene were used as reactive combustible mixture with various concentrations to observe the explosion flame propagation trend in the pipe. Experimental work was operated at ambient condition. Results showed that both gaseous have a consistent trend of flame propagation in one-half of total pipe length in which the acceleration is due to the piston-like effect. Beyond the distance, the effect of oscillating pressure, acoustic pressure wave and a fast flame contributes to the maximum overpressure profiles of both gases. However, the retonation effect was only observed in acetylene/air explosion but not in hydrogen explosion.

1. Introduction

The processing industry has raised a major concern in term of safety due to accidental gas explosions that have frequently happened and caused serious damage. These phenomena can take place in confined area within vessel, pipes, channels or tunnels, and the used of pipeline to convey the reactive material from one vessel to another could possibly lead to the development of an explosion and potentially damaging overpressures. In most engineering applications, explosion is initiated by the ignition,when the premixed gas-air mixture is in contact with hot surface to form flame front. Initially, explosion occurs via deflagration mode classified as subsonic combustion. The chemical reaction occurs at roughly constant pressure and laminar burning velocity around 1 m/s. The flame is formed and propagates in laminar mode. However, due to various flame instabilities mechanism (hydrodynamic instability, thermal diffusion, Darrius-Landau), involved during the propagation, turbulent flame is developed. Numerous experiments also show that turbulent flame can be generated by interactions of flame front with the acoustic waves (Liberman et al (2010), Bradley et al(2008) and Oran and Gamezo(2007)). This interaction lead to the flame perturbation through R-T and K-H instabilities which can increase the flame surface area (wrinkles) as well as flame acceleration. Further acceleration, deflagration to detonation (DDT) has a tendency to initiate before detonation occurred in gas explosion. In detonative mode, supersonic front propagation velocities on the order of a couple of thousand meters per second would be observed and the pressure ratio across the detonation wave is in the range of 15–20 (for stoichiometric fuel air mixtures) (Ciccarelli and Dorofeev, 2008). This is roughly twice the maximum possible pressure produced by a deflagration in the same mixture under adiabatic, constant volume conditions. In this mode of combustion, chemical reactions occur as a result of adiabatic shock heating and therefore the shock wave and the trailing reaction zone are coupled and propagated at a constant velocity. Due to complicated and rapid process for chemical reaction in combustion, deflagration-to-detonation transition (DDT) becomes one of the major challenges in combustion theory where the exact mechanism is still poorly understood and predictive of the locations/points of DDT occurrence is still questionable.

Extensive and comprehensive studies on understanding of the flame propagation and DDT processes have been made (Zipf et al (2014), Wu et al (2007) and Thomas et al (2001)). However, most of the studies focus on the on the flame propagation in obstructed pipe/tube by using premixed NG/air, methane/air, ethylene/oxygen and hydrogen/air mixture. There is no doubt, that

the presence of obstacle in pipe favorable to randomize the flow thus enhance the flame speed and overpressure to 5 time higher as compared to the straight pipe/tube. However, in closed pipe/tube, the end wall is acted as an obstacle, which has a tendency to initiate the flame perturbation and hence, affect the explosion behavior. Liberman et al.(2010) reported that the interaction between flame and shock wave that reflected from the end tube may affect the flame evolution whilst Zhu et al. (2012), believed that the effect of reflected acoustic wave enhanced the pressure evolution by a factor of 1.5. In contrast, Thomas et al.,(2001) supplemented that the interaction between reflected acoustic wave and flame may slower the flame propagation and thus affect the pressure development. The discrepancy on experimental findings could be due to the differences of experimental method and the fuel reactivity. It can be said that, those finding contributed a general insight into premixed flame in tubes. Yet, there are still many problems remain baffled, especially on the hot flame interaction and pressure wave (acoustic wave) effect at the end wall. This phenomenon, known as retonation is not well explored and the understanding of this phenomenon should be examined thoroughly; recognized as one of the factors contributing to the onset of detonation (Thomas et al. (2010)). In practical, there are large quantities of different pipe configuration in the chemical or processing plant. Thus, it is important to understand the mechanism causing the flame perturbation and its potential on the detonations hazard in such that the corrective action can be designed to be safer. Theoretically, hydrogen gas is highly diffusive in air while acetylene is mainly associated to the highly exothermic due to the triple bond structure. This means that both gaseous are highly combustible and has a potential to initiate detonation hazard in industrial pipes and gas mixtures. The main focus in this experimental work is to observe and examine the flame propagation and the potential mechanism of reactive fuels leading the transition deflagration to detonation in closed pipe.

2. Methodologies

1.1 Explosion test rig

A straight steel pipeline with a diameter of 0.1 m, measuring 5.1 m horizontally (L/D 51), was used for the explosion test, as shown in Figure 1. The pipeline was composed of several segments. Each segment ranged from 0.5 to 1 m in length and they were bolted together with a gasket seal between flanges and blind flanges at both ends.

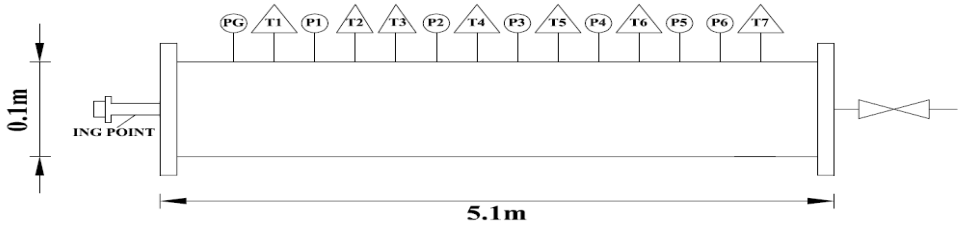

Figure 1 Explosion test rig

1.2 Gas mixtures

Gas mixtures, hydrogen/air and acetylene/air were prepared using partial pressure method to an accuracy of 0.1 mbar (0.01% of composition). Concentrations were varied between 12 % to 54% v/v (equivalence ratio, Φ =0.6 to 1.8) for hydrogen/air mixture and 4.6% to 12.4 v/v%. (Equivalence ratio, Φ =0.6 to 1.6) for acetylene/air mixture. The mixture was ignited at the center of one end of the pipe by means of a spark discharge (ignition energy approximately 16J). The ignition source was placed at the center of one of the blind flanges.

1.3 Sensors and data collection

Pressure measurements were taken at various points along the length of the pipe, using piezoresistive pressure transducers (indicates as P1 to P7 in Figure 1), used to continually measure

the pressure development and rates of pressure rise. The history of flame travel along the pipe was recorded by an axial array of mineral insulated, exposed junction, type K thermocouples (T_1 to T_7). 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. Flame speed was determined by using flame arrival time on the mounted thermocouple and the known distance from the spark plug. A 32-channel with 16-Bit NI CompactDAQ was used to record all the data from the sensor using frequency of sampling at 1 kHz. A number of explosion tests (minimum three) were carried out to ensure reproducibility and accuracy.

3. Results and discussion

3.1 General features of the explosion development

Figure 2 represents the explosion development of stoichiometric hydrogen/air mixtures in closed straight pipe. The maximum overpressure attained at 5.5 barg before the flame accelerated towards the end pipe. It was clearly observed that oscillating pressure dominates the peak overpressure at t = 2.3s. It can be depicted that, the flame is initially in hemispherical flame shape, before elongating towards the end pipe. Based on previous studied on closed pipe (Xiao et al, 2011,2012), it is impossible to sustain a hemispherical flame shape in large pipe diameter due to D-L, R-T and diffusive instability which caused by the flame quenched at the pipe side wall. According to Bychkov and Liberman (2000), flame is distorted by the D-L instability if the length tube is equal or greater than $200L_{f,}$ (L_f is the initial flame thickness). In this study, the initial flame speed is measured at a distance of 0.26 m (or 220 mm) from the ignition point. Using Matalon (2009) assumption that, laminar flame thickness for premixed hydrogen/air mixture is less than 1 mm and if we assumed the length scale at initial position (from the ignition point) in this study was 260 mm (260 mm x 1 mm), this condition was sufficient to support the L-D instability, leading the flame front to distort. At this instance, flame front is no longer in hemispherical shape, the flame will now go through an inversion process with the oscillating pressure (Clanet and Serby, 1996,1998). The oscillation pressure development between 2.23-2.24 s can be related to the backward propagating train of compression waves created by the strongly unsteady flame propagation in the pipe (Sulaiman et al, 2014). Subsequently, the amplitude of occilations was decreasing, followed by lower heat release and hence, causing the flame to quench. It can be said that the interaction between flame and reflected acoustic/shock wave leads to the fluctuation on the dynamic behavior.
Figure 2 also indicates that it took about 2.38 s for flame to travel from the ignition point toward the end pipe at the average flame speed of 191.6 ms^{-1}. When flame travels along the pipe, turbulence may generate due to hydrodynamic instability and interaction with acoustic/shock wave as explained above. This may result in increase of flame surface area and burning rate, hence the flame speeds and overpressure. From Figure 2, flame reached the maximum speed of 371 ms^{-1} before decelerating at near end wall. It may be postulated that the reflected acoustic/shock wave contributes to the fierce flow perturbation and yet the flame speed fluctuation towards the end pipe.

Figure 3 shown the pressure time histories of ethyelene-air mixtures with flame arrival plot. Even though they exhibit the similar peak overpressure as hydrogen of ~ 5.8 barg, but longer period is taken(almost double) for ethylene –air explosion to attain overpressure compared to hydrogen-air mixtures. From the observation, as shown in Figure 3 (right), a pressure ‘spike’ is suddenly appeared at t~ 4.87s, suggesting that the transition to detonation is developed, approaching towards the end pipe.

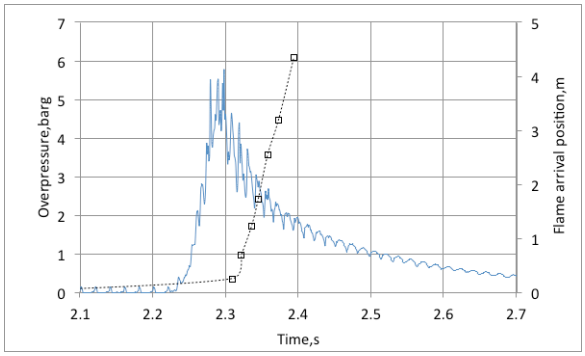

Figure 2: Presssure-time history (P1 based) and flame arrival time for stoichiometric premixed H_2/air in straight pipe.

Using pressure head loss formula as a basis, the unburned gas velocity is 186 m/s, which closed to sonic velocity and it can be depicted as a fast flame. It can be depicted that the effect of retonation wave (compression reflected shock wave) and fast turbulent mixing caused the unburned gas is highly compressible and thus, amplified the overpressure followed by the transition to detonation triggering at near end wall (refer to Figure 4).

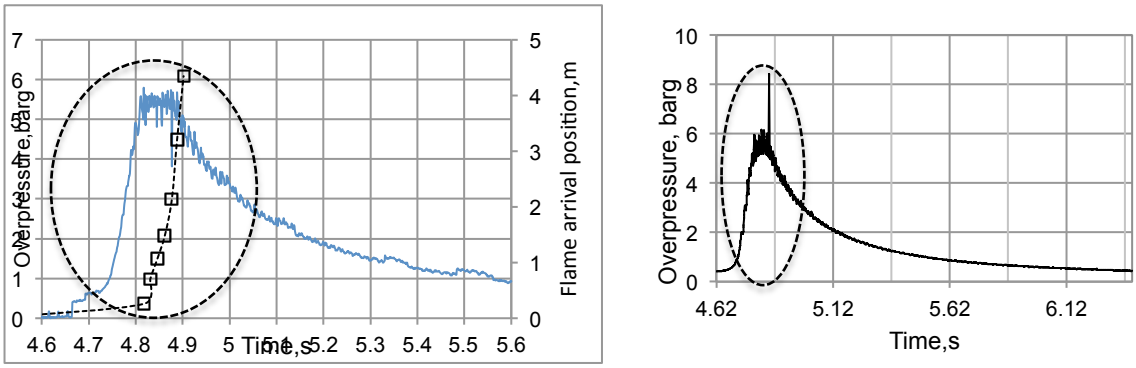

Figure 3 : Smoothing presssure-time histories (based on P1, 0.32 m from igntion point) and flame arrival time for stoichiometric premixed C_2H_2/air in straight pipe (left). Right is the actual graph.

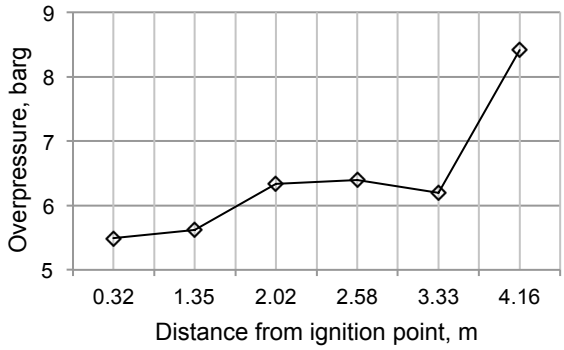

Figure 4: Acetylene/air explosion at for stoichiometric concentration

Figure 5 shows the maximum pressure profile as a function of equivalence ratio. For hydrogen/air mixture, the maximum overpressure was obtained at stoichiometric concentration, Φ = 1.0 however, it was not the case for acetylene. For acetylene/air explosion, it shows that a peak overpressure of ~12 barg occured at the rich side stoichiometric i.e. Φ =1.2. The possible explanation can be offered as; at rich concentration the excess acetylene is reacted further with air at preheated zone (Bakič et al, 2006) and cause the flame temperature increase yet support the

pressure development at rich concentration. The different kinetic mechanism of hydrogen and acetylene is shown in Table 1. It illustrated that it takes three step reaction for ethylene to complete the chemical reaction during explsoion comapred to hydrogen which was only two. Furthermore, the dynamic detonation properties need to be considered as acetylene-air posses a smallest detonation cell size (9.8 mm) compared to hydrogen-air (15 mm) and other fuel-air mixture (Lee,1984). This indicates that acetylene-air mixture poses a quick-chemistry control with rapid exothermic reaction, increasing the radical production, which is proportional to the pressure development (Varatharajan and Williams, 2001). Yet, lower burning velocity of acetylene would be the significant factor for longer period taken to complete the explosion development in pipe as shown in Figure 2 and 3 as acetylene/air mixture took 4.85 s to attain the highest overpressure while hydrogen/air mixture reached the peak overpressure within 2.32 s.

Table 1: Hydrogen and acetylene steps reaction.

Hydrogen/air chain reactions (Shanshan et al., 2012)	Acetylene/air chain reactions (Matei et al., 2002)
$H + O_2 \leftrightarrow O + OH$ (I) $O + H_2 \leftrightarrow H + OH$ (II)	$C_2H_2 + O_2 \rightarrow CH_2O + CO$ (I) $CH_2O \rightarrow CO + 2H$ (II) $C_2H_2 + OH \rightarrow CH_2CO + H2$ (III) $C_2\,H_2 + 2O_2 \rightarrow 2OH$ (IV)

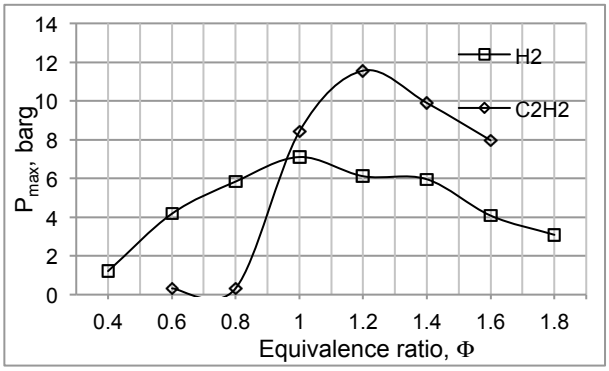

Figure 5: Maximum pressure at various equivalence ratio of hydrogen/air and acetylene/air mixture

4. Conclusion

A wide range of hydrogen-air and acetylene-air mixtures concentration was used experimentally to observe the flame propagation in a straight closed pipe. The results showed that acetylene/air mixture gives the highest maximum overpressure approximately ≈ 8.2 barg, as compared with hydrogen/air mixture, of 7.1 barg. It took shorter time to attain maximum overpressure of hydrogen (t = 2.3s) compared to ecetylene-air mixtures explosion of 4.8 s. Aquiring more steps in kinetic reaction mechanism during acetylene combustion coupled with the excess acetylene is reacted further with air at preheated zone at rich concentration for a quick-chemistry control with rapid exothermic reaction would be the possible explanation of this phenomenon on why it took longer time for acetylene explosion. A sudden ‘spike’ near the end pipe on acetylene-air explosion is due to the acoustic/shock wave traveling back to the combustion zone hence, amplifies the combustion inside the pipe. However , DDT is not triggered at the hydrogen/air mixture.

Acknowledgments

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