Jurnal Teknologi

Full Paper

EXPERIMENTAL STUDY ON FLAME PROPAGATION IN A STRAIGHT PIPE

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Article history
Received
19 May 2015
Received in revised form
24 March 2016
Accepted
1 May 2016

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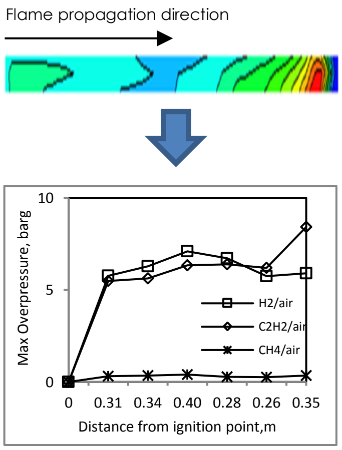
Graphical abstract



Abstract

Flame propagation in a closed pipe with diameter 0.1 m and 5.1 m long, as well as length to diameter ratio (L/D) of 51, was studied experimentally. Hydrogen/air, acetylene/air and methane/air with stoichiometric concentration were used to observe the trend of flame propagation throughout the pipe. Experimental work was carried out at operating condition: pressure 1 atm and temperature 273 K. Results showed that all fuels are having a consistent trend of flame propagation in one-half of the total pipe length in which the acceleration is due to the piston-like effect. Beyond the point, fuel reactivity and tulip phenomenon were considered to lead the flame being quenched and decrease the overpressures drastically. The maximum overpressure for all fuels are approximately 1.5, 7, 8.5 barg for methane, hydrogen, and acetylene indicating that acetylene explosion is more severe.

Keywords: Overpressure,fast flame,reflection wave, closed straight pipe, end pipe

Abstrak

Perambatan nyalaan api telah dijalankan di dalam paip tertutup dengan diameter 0.1 m dan 5.1 m panjang, serta nisbah panjang kepada diameter (L/D) 51 melaui kajian ujikaji . Hidrogen/udara, asetilena/udara dan metana/air pada kepekatan stoikiometri telah digunakan untuk melihat trend penyebaran nyalaan api di sepanjang paip. Ujikaji telah dijalankan pada keadaa operasi: tekanan 1 atm dan suhu 274 K. Keputusan menunjukkan bahawa semua bahan api menunjukkan trend perambatan nyalaan api yang stabil pada pertengahan paip di mana pecutan adalah disebabkan oleh kesan omboh. Di luar jangkauan titik, kereaktifan bahan api serta kesan fenomena tulip menyebabkan nyalaan api dipadamkan dan tekanan berlebihan berkurangan secara mendadak. Tekanan berlebihan pada tahap maksimum bagi semua bahan api adalah 1.5, 7, 8.5 barg untuk metana, hidrogen, dan asetilena dan ini membuktikan bahawa letupan asetilena adalah lebih teruk.

Kata kunci: Tekanan berlebihan, nyalaan cepat, gelombang pantulan, paip lurus tertutup, penghujung paip

1.0 INTRODUCTION

The chemical 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 a confined area like vessels, pipes, channels or tunnels. Worst, the used of pipeline to convey the reactive material from one vessel to another could lead to the explosion with damaging overpressures. On the engineering applications, explosion is initiated when the premixed gas-air mixture is in contact with a hot surface to form flame front, in the presence of the ignition sources. Initially, explosion occurred via deflagration mode and classified as subsonic combustion. The chemical reaction occurs at roughly constant pressure and the laminar burning velocity around 1 m/s. However, due to various flame instabilities mechanism such as hydrodynamic instabilities, thermal diffusion and Darrius-Landau phenomenon involved in the propagation, turbulent flame is developed. Numerous experiments also show that an intense interaction of the flame front and the acoustic waves [1-4]. This interaction leads to the flame perturbation through Rayleigh-Taylor(R-T) and K-H instabilities in which increasing the wrinkling flame surface areas. The net result is the rise in mass burning rate, rapidly speeding the flame and thus, increasing the overpressure. Extensive and comprehensive studies have been carried out by many researchers to understand the flame propagation in pipes or tubes [5-9] . However, most of the studies focus on the flame propagation in obstructed pipe/tube using premixed natural gas (NG)/air, methane/air, ethylene/oxygen and hydrogen/air mixture. The presence of an obstacle in pipes will promote a flow randomization and subsequently, enhance the flame speed and overpressure up to 5 times higher as compared to the straight pipe/tube [10]. However, in a closed pipe/tube, the end wall is acted as an obstacle which has a strong tendency to initiate the flame perturbation and give a significant effect to the explosion development. Liberman et al.,[1], reported that the interaction between flame and shock wave that reflected from the end tube may affect the flame evolution. Zhu et al., [8] suggested that the effect of reflected acoustic wave enhances the pressure evolution by a factor of 1.5. However, different observation was reported by Thomas et al[11]. In their work, they found that the interaction between reflected acoustic wave and flame may slow down the flame propagation and thus, affect the overall explosion severity. The discrepancies are due to the non-standard experimental methods and the fuel reactivities. It can be said that those findings contribute to a general insight on the physical and dynamic premixed flames during explosion in tubes. Nevertheless, there are still many problems remain baffled, particularly on the fast flame interactions and acoustic wave effect at the end wall. This phenomenon is not thoroughly explored and the understanding of this phenomenon is vital; recognized as one of the factors contributing to the onset of detonation[12].

In practical, there is a large quantity of straight pipes in the chemicals or processing plant. Thus, it is important to understand the mechanism causing the flame perturbation and its potential for the detonations hazard so that the corrective action can be inherently safer design. Theoretically, hydrogen fuel is highly diffusive in air while acetylene associated with highly exothermic characteristic due to the triple bond structure. It implies that both gaseous are highly combustible and has a potential to initiate detonation hazard in industrial pipes and gas mixtures. Thus, the main focus of this work is to examine the flame propagation and the potential mechanism that lead to the explosion in a straight closed pipe

2.0 EXPERIMENTAL

2.1 Test Rig

Figure 1 shows the explosion test rig with L/D ratio of 51 consists of a horizontal steel pipe (length=5 m, diameter=0.1 m, volume=0.042 m3) used in this study. 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.

2.2 Fuel Mixtures Preparation

A stoichiometric concentration of fuel mixtures, hydrogen/air, acetylene/air and methane/air were prepared using partial pressure method. 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, denoted as ING POINT in Figure 1.

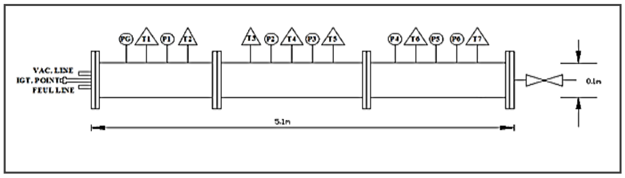


Figure 1 Schematic configuration of testing pipe, T1-T7; Thermocouple, P1-P7; Pressure transducer

2.3 Sensors And Data Collection

Pressure measurements were taken at multiple points along the length of the pipe, using piezoresistive pressure transducers (indicates as P1 to P6 in Figure 1). The history of flame travel along the pipe was recorded by an axial array of type K thermocouples (T1 to T7). 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 were carried out to ensure reproducibility and accuracy.

2.4 Flame Surface Area Equation

The flame surface area, A_f is calculated using equation (1) [13] for all flame speeds measured at T1

$$A_f = \frac{F_s . A_c}{S_L . \left(\frac{\rho u}{\rho b}\right)} \qquad (1)$$

where F_s is a measured flame speed (at T1), A_c is a tube cross-sectional area, ρu/ρb is an expansion ratio due to density difference between unburned and burnt gas and S_L is a laminar burning velocity.

3.0 RESULTS AND DISCUSSION

3.1 General Explosion Development In Closed Pipe

Figure 2-4 show that flame is initially propagating slowly, with lower pressure and flame speeds before reaching at the end pipe wall. The flame speed was 13.8, 10.9, 7.4 m/s for hydrogen/air, acetylene/air and methane/air, respectively at 0.26 m from the ignition point or at T1. Harris [14] reported that burning velocity for hydrogen, acetylene, and methane at stoichiometric concentration is 3.5, 1.58, 0.45 m/s, respectively. Thus, it can be said that, even though the flame propagates slower, the speeds are greater than the laminar flame speed. Figure 2-4 also show that flame is increased as the pressure increases. A consistent trend was observed in all figures; the peak overpressure occurred before the flame reaching the end wall pipe. It is suspected that the flame wrinkling phenomenon responsible to the rapid pressure development and fast flame propagation in the pipe. As the flame front moves forward through the unburned gas mixture, the flame is no longer stable due to the thermo-diffusion instabilities and flame stretch. This leads to flame wrinkling with a greater total flame surface area [15].

To support the justification, flame surface area, A_f is calculated using Eq. 1 [13]. It showed that the estimated flame area at early flame propagation for all fuels is about 49 - 76 % of the total pipe surface area. From the calculation, acetylene experiences the bigger flame i.e. 76% from the total area. The flame area represents the ormation of cellular flame structure and the subsequent self-accelerating (turbulization) of the flame.

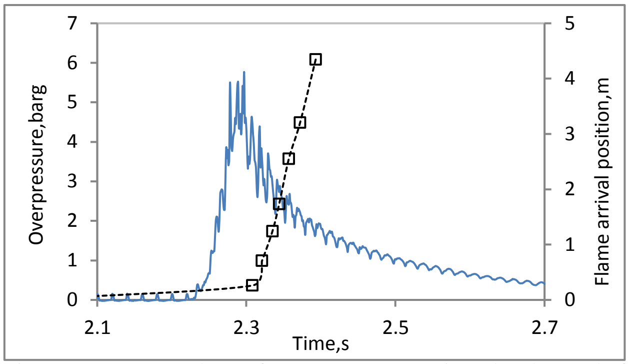


Figure 2 Presssure history (P1 based, 0.32 m from igntion point) and superimposed flame arrival time for stoichiometric premixed H_2/air in straight pipe

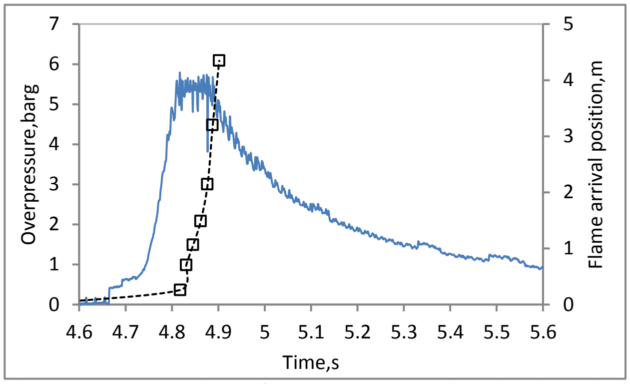


Figure 3 Presssure history (P1 based, 0.32 m from igntionpoint) and superimposed flame arrival time for stoichiometric premixed C_2H_2/air in straight pipe

Furthermore, in closed pipe system, the end pipe wall is considered as an obstacle, which both flames or waves will reflect back when reaching the end pipe due to the water hammer effect [16]. Moreover, Jiang et al., [17] reported that initial flame propagation is governed by a sonic compression and rarefaction wave. The explanation can be further supported on the apparent oscillatory pressure showed in Figures 2-4. From the figures, it was suggested that the oscillation was strong enough to result in flow reversal. This could enhance the acoustic/shock wave created ahead of the flame front to propagate back as soon the flame reaching the end pipe wall. The reversal flame further amplifies the burning rate in a long interval and gave a positive feedback to the flame speed and hence, the overpressure development.

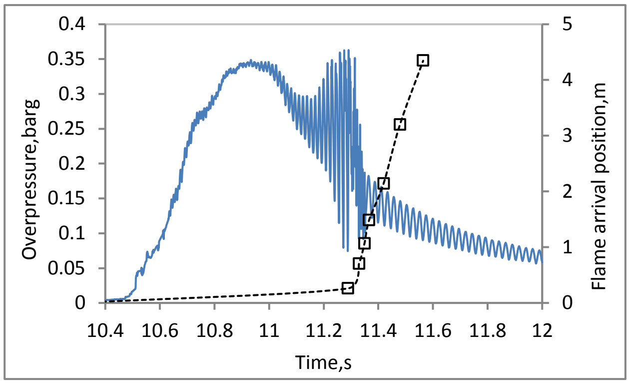


Figure 4 Presssure history (P1 based, 0.32 m from igntionpoint) and superimposed flame arrival time for stoichiometric premixed CH_4/air in straight pipe

3.2 Pressure Development Along The Closed Pipe

Figure 5 showed the overpressure as a function of distance from the ignition position. The overpressure reading was taken at the maximum value on each pressure transducer. All graphs presented in this section are taken from each fuel/air mixture at stoichiometric concentration (Φ = 1.0).

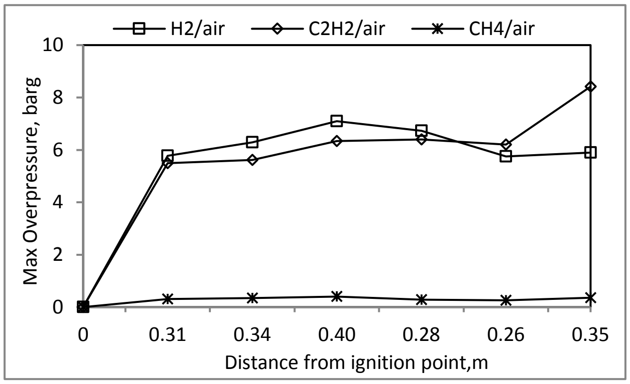


Figure 5 Pressure development along the pipe for all fuels

It is clearly showed that the trend for all fuels are consistent which, all maximum overpressure occurred at the distance, x = 2.02 m from the ignition position. The maximum overpressure results from the highest burning rate due to the flame surface distortion [18] giving a rise to mass burning rate and flame speeds. During this condition, the tulip formation is formed, promoting an intense turbulence due to the vortex creation [19]. Further, the reflective wave from the end pipe gives a strong interaction between the fast flame and turbulence to increase the flame speeds and hence, the pressure rises. However, at the distance, x > 2.02 m, the trend was inconsistent for reactive fuels. Hydrogen/air and acetylene/air gave a gradual pressure development yet, and methane/air showed a pressure drop to about 2-5 times lower than overpressure at x = 2.02 m. The inconsistent trend can be related to the expansion ratio. The expansion ratio is defined as the flame propagation due to the ratio of the density of burnt (ρu) and unburned gas (ρb). Acetylene poses higher expansion ratio, E, (E~9), as compared to, hydrogen (E~8) and methane (E~7.4). It shows that all fuels have a different mass burning rate that reflects to the inconsistet pressure development as illustrated in Figure 5. It is also showed that the overpressure of acetylene/air mixture was increased rapidly at the distance, x > 4.16 m. This can be related to the higher expansion ratio.

Acetylene fuel is different from most hydrocarbon fuels. It has a highly exothermic behavior and the magnitude of heat release during the reaction is higher [20]. Thus, it can be said that, during the rapid interaction between the flame and reflective acoustic waves, the magnitude of heat release is susceptible to intensify the flame burning in a longer period. This condition has a tendency to surpass the quenching rate to the surrounding wall. As shown in Figure 6, a rapid increase of pressure was observed at x = 4.94 m, near to the end pipe. It can be elucidated that, the unusual pressure trend was affected by the longer burning interval, giving sufficient time for the unburned gas ahead of the flame front to be highly compressed. This will give a stronger interaction between the flame and reflected wave, hence, amplifies the burning rate. The justification can be supported by the overpressure data recorded at 4.94 m from the ignition position as presented in Figure 6. Even though a pressure spike formed at 4.84 s as seen in Figure 6, there is no apparent of detonation phenomenon as flame speeds measured was at 281.2 m/s, below a sonic velocity (340 m/s).

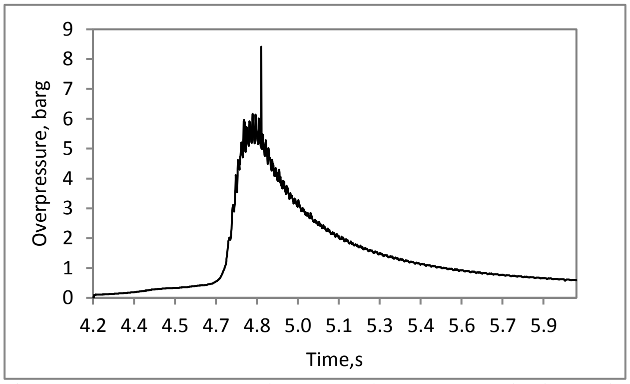


Figure 6 Acetylene/air explosion at stoichiometric concentration (x=4.16 m from ignition point)

4.0 CONCLUSION

Different fuel reactivity (hydrogen, acetylene and methane) was used experimentally to examine the explosion characteristic i.e. flame speed and overpressure in closed pipe system. The finding shows that

Fuel reactivity contributes to a different response on the flame propagation, and this have a direct relationship to the flame speed and overpressure. The most reactive fuel, acetylene gives higher flame propagation and thus, higher total pressure during explosion development.

All fuels are having a consistent trend of flame propagation in one-half of the total pipe length due to the piston-like effect. Beyond that, the effect of fuel reactivity and tulip phenomenon was considered to the inconsistent trend towards the end of pipe.

Highly exothermicity behaviour of acetylene causes the burning rate to extremely faster and hence, makes the acetylene fuel is highly explosive as compared to hydrogen and methane.

Acknowledgement

The authors would like to thank the Universiti Teknologi Malaysia for the research grant (No; QJ130000 2542 03H41) that have developed the explosion test facility. They would also like to thank the Malaysian Ministry of Higher Education (MOHE) for supporting S.Z.Sulaiman's Ph.D. studies.

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