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# Biogas flame propagation in the interconnected pipe: The effect of biogas/air mixture concentration

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**Abstract.** Flame propagation in the interconnected pipe with various size has a potential to initiate an explosion hazard. Thus in this study, the biogas/air flame propagation was investigated in the interconnected pipe. The experiment was conducted in pipe interconnected with three different diameters which are 5 cm, 10 cm and 46 cm respectively. The biogas is mixed with the ratio of 60:40 of methane and carbon dioxide. The concentration of biogas/air was varied at ER: 0.8 - 1.4 respectively. The mixtures were ignited using a spark plug. The pressure and flame speed were measured using thermocouples K type and pressure transducers located along the rig. Pure methane was also tested to examine the effect of $CO_2$ on the biogas flame propagation. From the experimental analysis, the highest maximum overpressure (2.5 bar) and flame speed (41.9 m/s) were recorded at the smallest pipe diameter (0.5 cm) at rich concentration, ER= 1.2 and 1.4 respectively. The results show that the thermal diffusive effect is one of the factors contributed to the flame propagation that resulted to the increase of the maximum overpressure and flame speed. However, the presence of $CO_2$ in biogas makes the biogas explosion is less severe as compared to the methane.

***Keywords***: *biogas, gas explosion, flame propagation, overpressure, diffusive-thermal instability*

## 1. Introduction

Biogas is mainly composed of 50-75% methane ($CH_4$) and 25-50% carbon dioxide ($CO_2$). One of the biogas advantages as compared to other fuels such as liquefied petroleum gas and natural gas, biogas deflagration speed is lower. Furthermore, other fuels have lower auto-ignition temperature and broader in flammability interval than biogas (Cacua et al., 2011).

Gas explosions in pipelines are among the thermal dynamics disasters that create a serious threat associated with safety issues in the transportation of gases or reactive material in the process industries. Thus, a comprehensive investigation of the flame propagation mechanism is required for effective prevention and mitigation in relation to the gas explosion disasters. One of the major factors affecting

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flame propagation mechanism and pressure development that contributes to the strong explosion is a pipe or duct size (Lautkaski, 2012). Sulaiman et al., (2017) have observed the flame propagation and pressure development in a smaller pipe size (diameter: 5 cm and length: 25 cm). They reported that fast flame or self-flame accelerations by the elaborate interaction between the quenching effect and re-ignition process will lead to a violent explosion. Other researches supported the above proposition by using somewhat narrow pipe or duct (diameter: 5 cm and length: 10-20 cm) with a sharp vessel-duct area (Veracruz, 2002). It was shown that the turbulent flame brings about the stronger explosion (i.e. with higher pressure amplitudes) during re-ignition (Gwak & Yoh, 2013), (Liu & Liu, 2013). Moreover, a comprehensive experiment on the influence of the pipe or duct size on the flame propagation are reported in the literature (Makarov et al., 2007), (Gwak & Yoh, 2013), (Veracruz, 2002). These experiments demonstrate that the pipe or duct diameter ranging 6-10 cm (Makarov et al., 2007), (Veracruz, 2002), (Gwak & Yoh, 2013), (Liu & Liu, 2013) and duct length ranging 20-80 cm (Kyung et al., 2014) have a denoting effect on the dynamic of flame propagation and also pressure characteristic during the explosion process. They also reported that the explosion occurred due to the reversal flow where the flame will travel backwards from duct to the main vessel, enhancing the burning rate by means of rapid pressure rise in the vessel and leads to the extensive damage (Makarov et al., 2007), (Kyung et al., 2014), (Gwak & Yoh, 2013).

Besides pipe or duct size, fuel concentration (or equivalence ratio of the fuel and air) and the turbulent flame are among the factors influencing the flame propagation mechanism which lead to the explosion. From the above research, it shows that the gas explosion inside the pipe or duct that has been studied, most of the works are limited to a smaller size with the length and diameter ranging from, 10-80 cm and 5-10 cm respectively. Furthermore, their works are focused on the flame propagation in the pipe with the same size and without interconnected, which does not represent the actual pipe configuration in the industry. It should be noted that, beyond the limit, the flame propagation mechanism and pressure development in the pipe, will be different (Liu & Liu, 2013). For instance, by changing the pipe size (diameter and length) and fuel concentrations may change the laminar burning velocity of the flame and hence, increasing the mass burning rate of spherical flames (Veracruz, 2002). This would significantly affect the flame and pressure development in the pipe or duct. Therefore, the influence of interconnected pipe with different pipe size and fuel concentration should be examined thoroughly, as it has been recognized as factors contributing to the rigorousness of the explosion. Thus, this research is focused on the flame propagation mechanism in the interconnected pipe with different biogas/air concentration. The effect of $CO_2$ on the flame speed also was examined in order to analyse the severity of the biogas/air flame as compared to the methane/air flame.

## 2. Experimental Procedure

The explosion experiment was carried out in a lab scale explosion test rig. The test rig has three parts; mixing chamber, duct and dumping vessel. Shown in Figure 1 is the experimental set-up. Pressure transducers are denoted as P1-P5 meanwhile thermocouples are denoted as T1-T10. Pressure transducers were used to measure the overpressure while thermocouples were used to measure the flame speed along the rig. Biogas was simulated by mixing methane with carbon dioxide. In this study, biogas with 60% vol/vol $CH_4$ and 40% vol/vol $CO_2$ was used as a basis. Both gases of $CH_4$ and $CO_2$ with purity 99.9% were purchased from a local company.

The tested mixture, biogas-air was applied at different concentration with equivalent ratios, ER (ER= 0.8, 1.0, 1.2, 1.4). The biogas/air mixture was mixed directly in the test rig using the partial pressure method. The partial pressure method of mixture preparation adds the flammable gas to a vacuum and then adds air to approx. 1.013 bar. The biogas/air mixture was ignited at the centre of one end of the pipe by means of a spark discharge (ignition energy approximately 16J). The ignition source was placed at the centre of one of the blind flanges. Three experiments were performed for each condition to ensure good reproducibility.

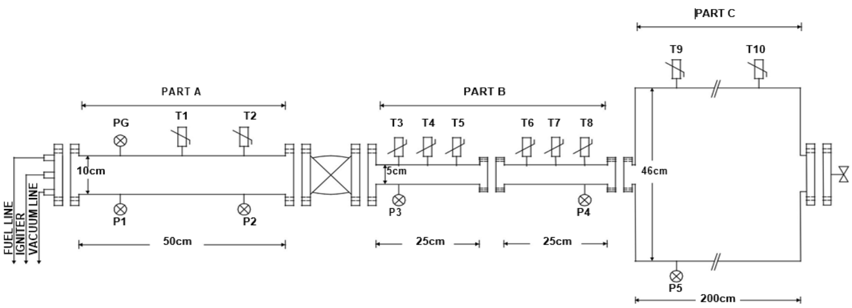


Figure 1: Experimental Set-up

## 3. Results and discussions

### *3.1 Maximum overpressure along the pipe*

Figure 2 shows the effect of equivalence ratio, ER on the maximum overpressure pressure in the pipe interconnected with three different sizes. It is clearly shown that the maximum overpressure was increased when entering the smaller pipe (5 cm) before decrease as soon as reaches at the bigger pipe (46 cm) for all fuel concentration. The decreasing overpressure was suspected due to the reverse flow. The negative pressure difference occurred once the flame travel from the bigger pipe to the smaller pipe. This phenomenon leads to the reversal flow and subsequently creates turbulence. At this instance, the flame surface area increase resulted to the increase of the mass burning rate as well the maximum over pressure. This would be the reason for the increase of the maximum overpressure to about 32% when the flame entering the small duct (5 cm). Apart from that, the decreasing of the overpressure once flame travel to the bigger pipe (46 cm) was due to the quenching effect. Once the flame touches the pipe wall, it will quench and cause the turbulent flame to become more stable. This condition gives a negative effect towards mass burning rate and resulted to the decrease of maximum overpressure once the flame enters the bigger pipe.

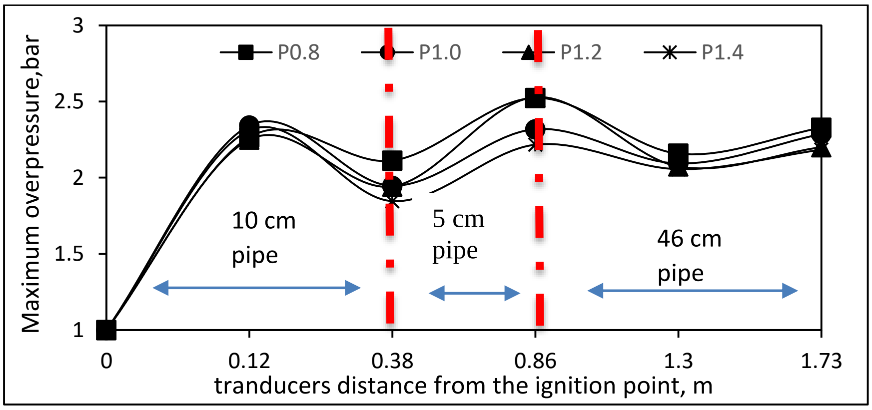


Figure 2: Maximum overpressure trend along the pipe

Furthermore, Figure 2 shows that the highest maximum overpressure pressure was attained at ER=1.2 (rich concentration) and not at stoichiometric concentration. The pressure was recorded at 2.5 bar. The peculiar trend was due to the diffusive-thermal instability (Im & Chen (2002). At rich concentration (ER=1.2) thermal diffusive dominates the flame curvature and increasing the flame surface area. At this instance, the mass burning rate increase which leads to the increase of the maximum overpressure.

*3.2 Flame speed along the pipe*

The flame speed trend for all biogas/air concentration (ER) is illustrated in Figure 3. It is clearly shown that the flame speed trend is consistent for all concentrations. The flame speed increased to about 8% when the flame entered the smaller pipe (5 cm). When flame propagates in smaller pipe diameter, the flame curvature tends to decrease leading to the rapid propagation. This resulted to the fast combustion and hence increasing the flame speed. However, due to the quenching effect and continually combustion, the flame propagates at a constant velocity. This phenomenon describes the fluctuated flame speed trend along the smaller pipe diameter. Figure 3 also shows that; the second acceleration was recorded when the flame enters the 46 cm pipe diameter before decreased as soon approach to the end of a pipe. In larger pipe diameter, the unburned gas amount reacted with the flame is more as compared to the smaller pipe diameter. This interaction makes the flame re-accelerates until reach to the highest speed.

Moreover, Figure 3 also shows that the highest flame speed; 41.9 m/s was achieved at rich biogas/air concentration (ER=1.4). To be noted methane is the main reactive component in biogas. According to Anggono, 2017, methane is prone to fast diffusion and promotes more intense mixing between unburned and burned gases. This condition may increase the flame stretch effect, leading to a higher mass burning rate and hence increase the flame speeds (Anggono et al., 2012). It is suspected that at ER 1.4, the stretch effect makes the methane flame curvature increase and resulted to the highest flame speed as compared to the other concentration.

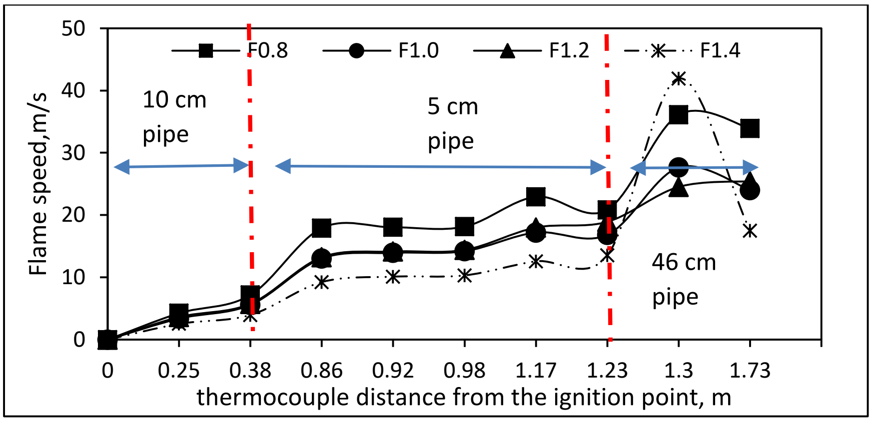


Figure 3: Flame speed propagation in pipe

*3.3 Effect of presence of carbon dioxide*

Figure 4 illustrates the flame speed trend for both biogas/air and methane/air mixtures at different concentration. The flame speed was recorded at T1. From the figure, it is clearly shown that the flame speed methane/air flame is higher to about 15-28% for all concentration as compared to the biogas/air flame. The presence of the $CO_2$ in biogas makes the biogas/air flame propagates slower the methane/air flame. According to Ayache (2017), $CO_2$ has a better suppression effect. $CO_2$ tends to absorbed the heat during the combustion process and reduced the adiabatic flame temperature as well as burning velocity. This condition resulted to the decrease of the biogas/air flame speed and makes the methane/air flame is severe as compared to the biogas/air flame.

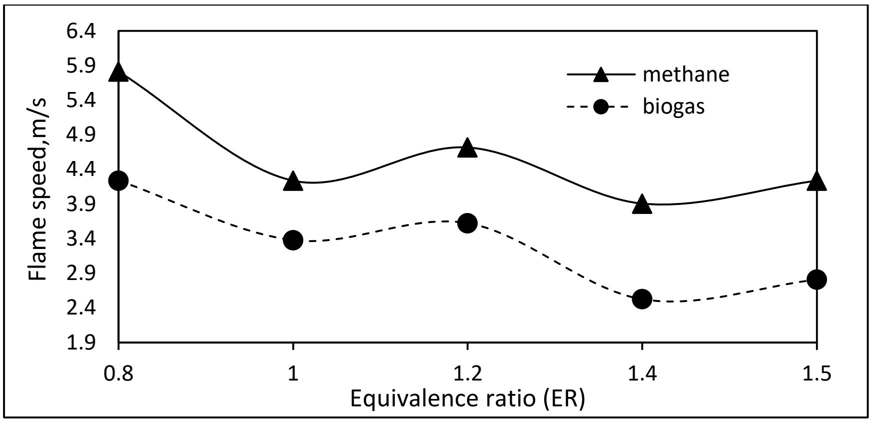


Figure 4: Biogas and methane flame propagation in pipe

## 4. Conclusion

i. The highest maximum overpressure (2.5 bar), was reached at ER=1.2) while the highest flame speed (41.9 m/s) was attained at ER=1.4. Both explosion characteristic (maximum overpressure and flame speed) was attained at rich concentration instead of stoichiometry concentration.
ii. At rich concentration (ER=1.2 & 1.4), biogas flame the flame was instable due to thermal diffusive effect. At this instance biogas flame tend to stretch resulted to the higher mass burning rate and therefore, increase the flame speeds and maximum overpressure.
iii. The presence of $CO_2$ in biogas has suppressed the biogas/air flame to propagate. This makes the biogas is less severe as compared to the methane/air flame.

## 5. Acknowledgement
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