

EXPERIMENTAL STUDY ON THE EFFECT OF CURVED TUBE OF PREMIXED HYDROGEN-AIR EXPLOSION

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Abstract

This paper presents the influence of bending and retonation effect on the overpressure and flame propagation on hydrogen-air and methane-air mixtures at ambient condition, ranges between 13 to 54 % v/v. The curved pipe consists of 5.1 m long, 0.1 m diameter tube, giving a total volume of 0.042 m³. From the results, it was observed that the highest explosion severity occurred at slightly rich concentration ($\Phi=1.2$) or 36% v/v. giving a maximum overpressure of 8 bar. It was also interesting to note that pressure at the pipe downstream exhibits in a circa of 2 times higher overpressure as compared at the bend. The complex interaction between the flame stretch, fast flame and pressure wave (acoustic wave) effect at the end wall or retonation, would be best described on the phenomenon observed.

Keywords: 90° Bend, Closed pipe, Retonation, Hydrogen-air mixture,
Methane-air mixture.

1. Introduction

Flame propagation in tubes is one of the important subjects on fundamental characteristics in gas or dust explosion [1-6]. It has given rise to a large number of studies and numerous significant advances have been made in the understanding of flame dynamics [7-10]. However, most of the studies focus on the flame propagation in straight pipe/tubes. Practically, ducts commonly include non-straight

Nomenclatures

<i>DDT</i>	Deflagration to detonation
dP/dt	Rate of pressure rise, bar.s ⁻¹
ER or Φ	Equivalence ratio
H ₂ O ₂	Hydrogen peroxide
<i>L/D</i>	Ratio of length of pipe to diameter pipe
<i>S_L</i>	Flame speed, ms ⁻¹
<i>V</i>	Volume, m ³

Greek Symbols

ϕ	Equivalence ratio
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sections, e.g., bends and T-junctions. Therefore, there is also requirement for understanding the effects of these sections on flame dynamics.

Phylaktou et al. [11] reported that flame speed and overpressure increase in a circa ~5 times higher in a 90 degree bend tube compared to similar experiment carried out in straight pipes in methane/air explosion. This effect was similar if 20% blockage ratio baffle used at the same position. Zhou et al. [12] investigated the impact of a 90 degree bend on the very later stage of flame propagation in a closed duct. They suggested that the flame tends to avoid contact with the inner and outer walls when it propagates in the bend.

The flame dynamics would be affected by a combined effect of body force, hydrodynamic instability, diffusive-thermal instability and boundary layer effect, etc., which will probably generate an irregular flame front rather than a plane one [2, 3, 6, 7]. Xiao et al. [10] believed that the interactions among the flame front, the flame-induced reverse flow and the vortices directly cause the inversion of the flame front, leading to higher overpressure in particular on baffles and bending region.

Reduction of flame area caused by wall quenching at the bend could make a drastic velocity change in unburned gas. As a consequence, vortices pattern at the flame front (or known as tulip flame) would attenuate the burning rate thus overpressure and flame speeds [2]. In general, the flame propagation in a tube depends on various parameters: initial pressure, equivalence ratio, chamber length, igniters geometry. None of them has rigorously got a leading position while combined effect is more recognizable.

All previous works contributed a general insight into premixed flame in tubes. But still many problems remain baffled, particularly on the fast flame interaction and pressure wave (acoustic wave) effect at the end wall. This phenomenon, known as retonation is not well-explored and the understanding on this phenomenon should be examined thoroughly; recognized as one of the factor contributing to the onset of detonation [13]. Based on work by Liberman et al. [14], retonation wave has a crucial contribution to deflagration to detonation (DDT) if the pipe length is within 3.4 to 6.1 m length. Blanchard et al. [15] supplemented that the pressure developed from the retonation process after the bending is much weaker, when compared to the pressure development at the bending. This observation was contradicted with findings reported by Wang et al. [16]. Their work indicated that the retonation wave is stronger at the bending point. The disagreeable findings could be due to the experimental method and the fuel reactivity used.

Hence, the present work aims to give additional insight on the influence of curved bend on flame acceleration using hydrogen as a fuel, including flame acceleration, overpressure and flame velocity. A series of experiments under wide range of equivalence ratios in a closed tube on both end will be reported.

2. Experiments

A series of tests were conducted to observe the flame behaviour and pressure profile for hydrogen-air mixture concentrations ranging 13-54% v/v. Only stoichiometric concentration of methane-air will be used. The test geometry with L/D ratio of 51 consists of a horizontal steel pipe (length=3 m, diameter=0.1m, volume=0.042m³) with 90 degree bends (1D) and added a further 2.1 m to the length of the pipe based on the centreline length of the segment. The pipe was made up of 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. Figure 1 shows the schematic configuration of the experimental rig.

All tested fuel-air mixtures were prepared using partial pressure method at ambient condition. The mixture was ignited at the centres of one end of the pipe. The flammable mixture was initiated by an electrical spark, which gives 16 J energies for the gas explosion tests. The history of flame travel along the pipe was recorded by an axial array of mineral insulated, exposed junction, type K thermocouples. Flame speeds in the pipe were measured from the time of arrival of the flame at an array of thermocouples on the vessel centreline. The average flame speed between two thermocouples was determined and ascribed to the mid-point of the distance between thermocouples. The pressure at various points along the length of the pipe was recorded using piezoelectric pressure transducer (Keller Series, PA-11). A 16-channel transient data recorder from National Instrument was used to record a high speed waveform with a sampling frequency 1000 kHz per channel. Each explosion was repeated at least three times for accuracy and reproducibility.

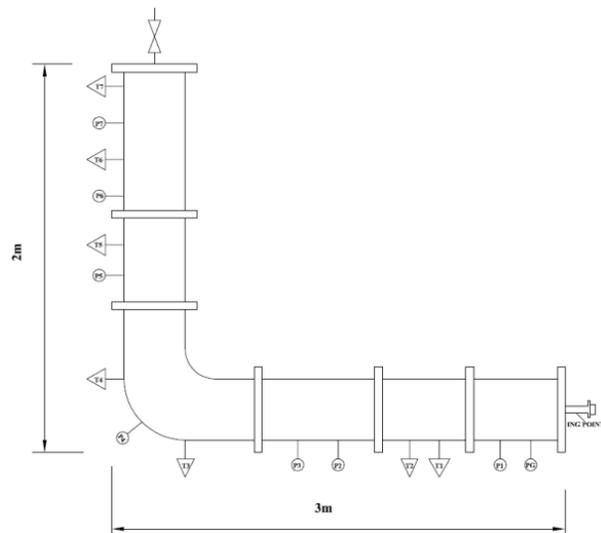


Fig. 1. Schematic Configuration of Test Pipe. T1-T7 Denotes as Thermocouple, and P1-P7 are Pressure Transducer.

3. Results and Discussions

3.1. Overpressure development in the pipe

Figure 2 shows the pressure-time histories (taking P1 as the basis) along the pipe with different equivalence ratio, Φ of 0.6 to 1.4. The pressure varies between 3.5 to 6.5 barg as hydrogen concentration increases and this result was in good agreement with Dahoe and Goey work [17]. The effect of hydrogen concentration on laminar burning velocity would give drastic changes on pressure development. In theory, increasing hydrogen concentration will cause the laminar burning velocity to increase, favourable to enhance the overall mass-burning rate.

At this instant, the local heat release follows a substantial increase in both temperature and pressure. As shown in Fig. 2, the highest pressure of 6.5 bar lies at $\Phi=1.4$, slightly higher compared to the stoichiometric concentration ($P = 6$ bar). It can be postulated that the effect of flame stretch (due to flame instability) is profound, giving additional flame distortion at the flame front of unburned gas, thus increase the burning rate and enhance the laminar burning velocity and subsequently, increase the pressure development [18].

Figure 2 also illustrates the pressure development on lean concentration, $\Phi=0.6-0.8$. From the graph, it is apparent that bigger time lapse ~ 1.1 to 1.3 s was observed, in comparison to the stoichiometric concentration, giving about maximum overpressure of 3.5 barg at $\Phi = 0.6$. It can be said that, at lean concentration, flame instability gave less influent on the stretch intensity and flame shape to form wrinkled structure [19]. It causes the laminar burning velocity become lower, thus limits the overall mass burning rate and yet the pressure increase gradually [20].

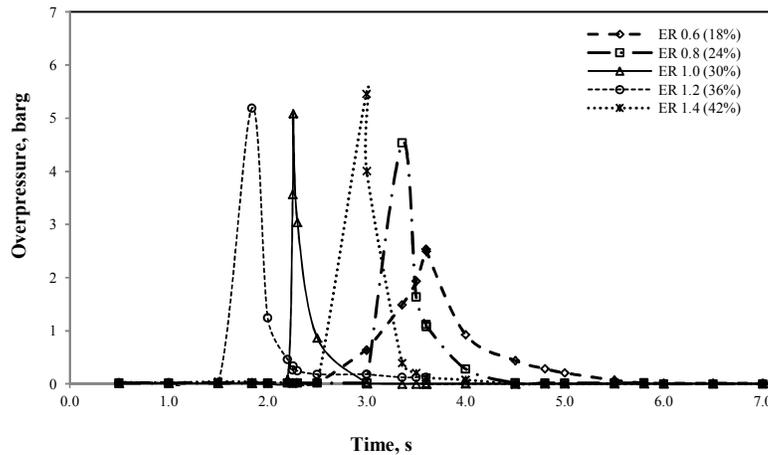


Fig. 2. Pressure Time Histories. P1 is Used as a Basis.

Figure 3 shows the effect of bending on the pressure development for stoichiometric hydrogen/air concentration. The bend point (indicated as P4) is positioned at 2.6 m from the ignition point, in which the maximum overpressure of 6.6 barg was observed. As mentioned earlier, the initial pressure development is due to the contribution of laminar burning velocity associated with larger surface area;

tulip flame formation due to hydrodynamic instability and thermo-diffusively unstable and the flame front, therefore considerably more distorted [21]. However, the laminar burning velocity is only significant at a short distance from spark ignition [22].

It can be depicted that maximum pressure attained at bend is substantially associated to the high turbulence burning velocity inside the pipe. The presence of bend, as an obstacle, would promote the flame stretch around it, inducing vortices pattern at the flame front, thus intensifying the turbulence vortex and hence, increase the flame surface area by the strong mixing of burned and unburned gas. Interestingly, there is no difference in overpressure attained at P4 and P5 as shown in Fig. 3. It can be said that at the bend, continuous interactions between the fast flame and the flame front would rigorously generate a series of rarefaction and flame-induced reverse flow. This would easily distort the flame surface, thereby increasing the surface area leading to a high energy-release rate.

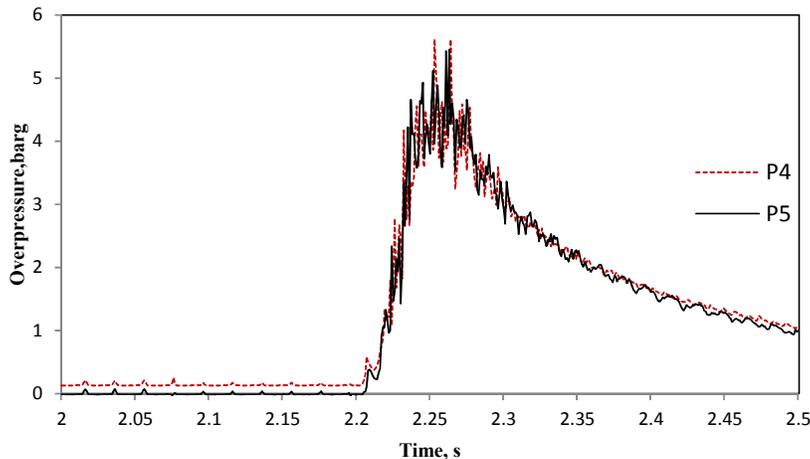


Fig. 3. Pressure Time Histories at P4(at Bend) and P5 (After Bend) for Stoichiometric Hydrogen-Air Concentration.

3.2. Effect of bending on pressure development

Figure 4 shows the effect of bending as a function of equivalent ratio, Φ of hydrogen-air mixture. From Fig. 4, it is clearly seen that two points gave highest pressure i.e. at the bend and 0.8 m before end wall (or 4.16 m from the ignition point). As mentioned earlier, the first pressure rise is due to the bending influence. The presence of 90 degree bend would induce the unburned gas motion to the opposite direction of flame propagation, creating a very strong mixing between hot flames and unburned gas mixture, thus results to more turbulence. At the same time, the presence of unstable species such as hydrogen peroxide (regarding to the excess hydrogen atom) in the preheat zone further promotes the turbulence intensity contributing to the higher pressure experienced when hydrogen concentration increases. Figure 4 clearly illustrated that higher pressure is observed at $\Phi = 1.4$, due to the effect of hydrogen peroxide presence in rich concentration as explained earlier. In contrast, the influence of bending is

insignificant at lean concentration, $\Phi=0.6-0.8$. It can be said that, at lean concentration, flame propagates in a quiescent mixture and limits the mass burning rates. In other words, the magnitude of heat release is insufficient to counter back flame instability causes the flame propagates at constant velocity and pressure along the pipeline.

It is interesting to note that, the second pressure increase was observed at the downstream of the bend (or 0.8 m before end wall) for $\Phi=1.0-1.4$ as shown in Fig. 4. This pressure mainly caused by the interaction of hot flames with a intense pressure wave reflected from the end wall (retonation) which subsequently enhance the burning rate [23]. The strong interaction causes the pressure to increase by a factor of 8 from the initial pressure or 1-2 times higher if compared with pressure rises at the bending. Furthermore, the retonation wave speed also contributes to the effect of pressure development [13], giving pressure at end wall higher than at bending for stoichiometric concentration. The similar phenomenon was observed at $\Phi=1.2$ and 1.4, only the pressure at end wall is slightly decreased to 6 barg. The possible explanation can be offered as; the shock wave that is transmitted through the flame front reflects off the channel end wall and then traverses the combustion region, amplifying the flame perturbations generated by the shock wave. This second flame interaction, with the reflected shock wave, produces an accelerating shock wave, thus increases the burning rate and overpressure, and this phenomenon is known as retonation mechanism as shown in Fig. 3 [24]. It can be said that, pressure generated by the retonation process is more distinct as compared at the bend and further study on this phenomenon should be carried out.

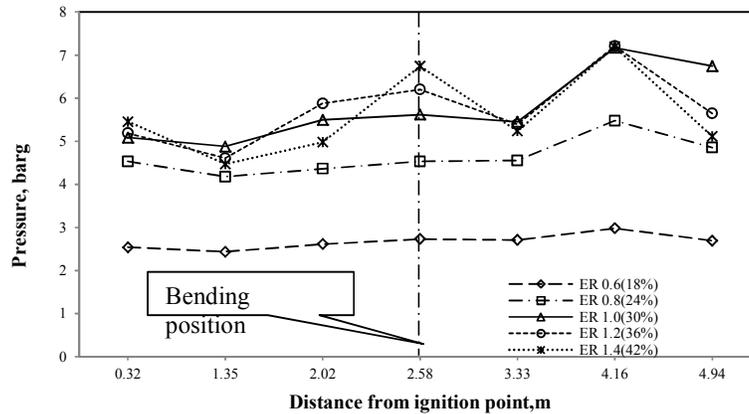


Fig. 4. Pressure Profile Function of Distance from the Ignition Point.

3.3. Rate of pressure rise and factor contributing to the explosion severity

As shown in Fig.5, the rate of pressure rise, dP/dt is independent at the bending, yet gave dramatic increase two times for all concentrations after bending. This phenomenon is associated with the reflected pressure wave described above. Lee [25] pointed out that vorticity is generated in the turbulent flame zone (at bending) by the interaction of the pressure waves with density gradients,

commonly referred as the baroclinic mechanism. The intense combustion associated with very fast flames produces compression waves that interact with pockets of unburned gas in the turbulent flame brush. Furthermore, the interaction of shock waves in the reaction zone directly produce shear layers and turbulence, leading to enhanced burning [24].

By taking the rate of pressure rise at bending as a basis, it was observed that the burning rate is increased almost double at the end pipe due to the interactions between hot flame and reflected pressure wave. It can be postulated that the severity caused by the retonation (downstream of the bend) is more pronounced at higher hydrogen concentration. Furthermore, slightly above stoichiometric concentration of $\Phi = 1.2$ indicates the highest rate of pressure rise (by a factor of ~ 2) as compared with stoichiometric, suggesting that the presence of excess H atom at rich concentration tend to form unstable species, defined as hydrogen peroxide (H_2O_2) through fast intermediate chain branching reaction which initiate the auto-ignition process [26]. This would possibly contribute to the increasing of burning rate and the rate of pressure rise. Nevertheless, lower rate of pressure rise of $83.12 \text{ bar}\cdot\text{s}^{-1}$ at richer concentration of $\Phi = 1.4$ was observed. The presence of additional hydrogen peroxide most probably weaken the retonation wave speed, as mentioned by Thomas et al. [24] and as a consequence, the interaction between hot flame and reflected wave is less pronounced as compared to at $\Phi = 1.0$ and 1.2 , respectively.

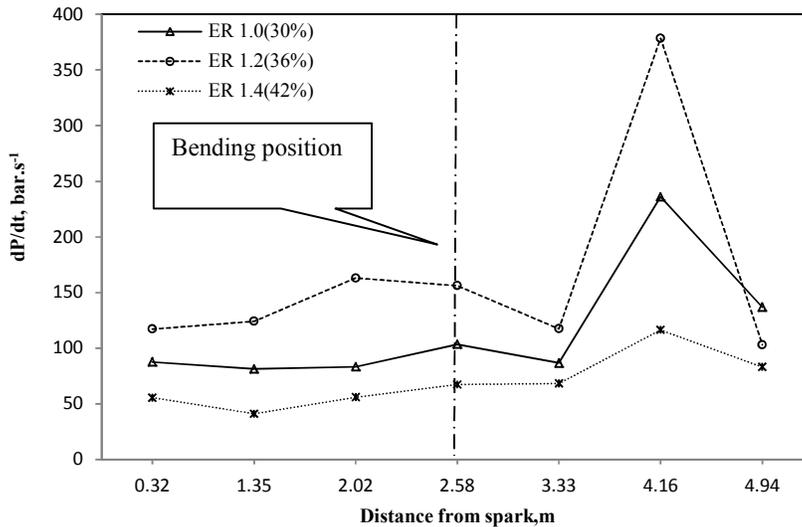


Fig. 5. Rate of Pressure Rise, dP/dt as Function of Distance from the Ignition Point.

3.4. Flame propagation in bend pipe

The flame speed profile as a function of distance from ignition is shown in Fig. 6, which shows that, the highest flame speed of 530 m/s is observed at $\Phi = 1.2$, which almost 2.4 times higher as compared to stoichiometric concentration, $\Phi = 1.0$ ($S_f = 218 \text{ m/s}$). It can be said that, increasing the hydrogen concentration to the certain

level may increase the amount of heat release, in which subsequently increase the flame speed. Meanwhile, flame starts to decrease at 300 m/s at $\Phi=1.4$. This is because of the hydrogen content in the mixture is insufficient to imbalance the diffusive-thermal stability thus reduce the flame stretch rate as well as mass burning rate which later, affecting the flame acceleration [27, 28].

As expected, the presence of 90-degree bend causes the flame speed to increase when approaching the bending position. However, it is surprising to observe for the second peak flame speeds at 4.35 m from the ignition, causing the flame to speed tremendously before reaching the end wall. The peculiar flame speed profile is relatively similar to all concentration hydrogen but not at stoichiometric ($\Phi = 1.0$) and rich concentration ($\Phi = 1.4$). This is possibly caused by the complicated interactions between flame acceleration, quenching effect and flame shape, in which as a consequences, affect the mass-burning rate [11, 29]. Worth to note that the interaction of fast flame with reflective pressure waves at the end wall plays an important role contributing to the second acceleration. However, the flame speed profile in this study is contradicted with previous studies [30, 31] due to the different pipe configuration (L/D), fuel concentration and ignition position which play an important role on the flame propagation development.

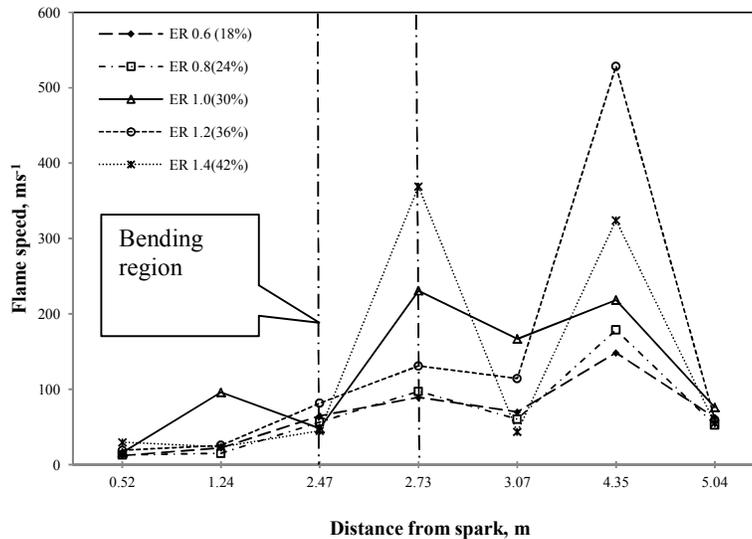


Fig. 6. Flame Speed as a Function of Distance from the Ignition Point.

4. Conclusions

A wide range of hydrogen-air mixtures concentration was used experimentally to observe the explosion characteristics i.e. flame speed, overpressure, and rate of pressure rise in the closed pipe with 90-degree bend. The results show that the increase of over pressure and flame speed is mainly due to the effect of flame stretch (due to flame instability), which contributes to the increase of burning rate and overpressure. It worth noting that the retonation effect due to the interaction between hot flame and reflected wave from end wall would intensify the burning rate and rate of pressure rise, giving overall overpressure to be increased ~ 1.2

compared to the overpressure at bending position. The most important feature of these results is that for hydrogen, the worst-case gas explosion was at $\Phi = 1.2$ and not at $\Phi = 1.0$, with maximum overpressure of 8 bars. This finding could be misleading as stoichiometric concentration ($\Phi = 1.0$) is considered a worst-case scenario in closed vessel explosion in most published data and this information should be included for design procedures for protection and mitigation measures, particularly on venting design.

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