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EFFECTS OF OBSTACLES ON PREMIXED HYDROGEN-AIR MIXTURES EXPLOSION IN CLOSED PIPE

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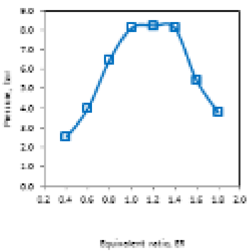
Graphical abstract



Abstract

Results of experiments on explosion premixed hydrogen-air are presented. The data covers a wide range of hydrogen concentration between 13 to 54 % v/v (Φ= 0.4 to 1.8). The experimental work was performed in a closed pipe containing 90 degree bends with a volume of 0.42 m^3operating at ambient conditions. This study was carried out to determine the severity of hydrogen explosion in a closed pipe with length over diameter (L/D) ratio of 51. The results indicate that the worst case accident for hydrogen-air mixture occur at concentration slightly above stoichiometric (Φ 1.2) or 36% v/v. It is also found that pressure downstream the bending region experienced an increase of about 2 times, compared to pressure at the bend. It can be said that a strong backflow or retonation reflecting from the end pipe wall influentthe maximum overpressure downstreamof the bend and this phenomenon was highlighted.

Keywords: Bending, closed pipe, hydrogen concentration, pressure, retonation

Abstrak

Keputusan ujikaji letupan terhadap pracampuran hidrogen-udara dibentangkan. Data ujikaji meliputi pelbagai kepekatan hidrogen antara 13 ke 54% v/v (Φ= 0.4 ke 1.8). Kerja-kerja ujikaji ini dilakukan di dalam paip tertutup yang mengandungi lengkung 90 darjah dengan isipadu 0.43m^3 serta beroperasi pada keadaan bilik. Kajian ini telah dijalankan untuk menentukan keterukan letupan hidrogen dalam paip tertutup pada nisbah panjang dan diameter (L/D) 51. Keputusan menunjukkan bahawa kemalangan kes terburuk bagi pracampuran hidrogen-udara berlaku pada kepekatan Φ 1.2 atau 36%v/v. Ia juga didapati bahawa tekanan selepas lengkok mengalami peningkatan sebanyak 2 kali, berbanding dengan tekanan pada titik lengkok tersebut. Ini disebabkan aliran kebelakang yang kuat atau retonation di hujung paip dinding member kesan positif terhadapa peningkatan tekanan selepas lengkok 90 darjah.

Kata kunci: Lengkok, paip tertutup, kepekatan hidrogen, tekanan, retonation

1.0 INTRODUCTION

The profiles of flame propagation and maximum pressure performed in pipe with of 90 degree bend were broadly studied by Phylaktou et al. [1], Chatrathi et al. [2], Blanchard et al. [3] and Emami et al. [4]using hydrogen-, methane-, propane- and ethylene –air mixture with variable concentration (lean and stoichiometric). Most of the tests were performed at ambient pressure. Phylaktou et al. [1], observed that flame speed and overpressure increase in a factor of 5 in a 90 degree bend tube for methane-air mixtures compared to similar experiment carried out in straight pipes. They reported that condition is similar to the effect using 20% blockage ratio baffle at the same position. To support the experimental observation on effect 90 degree bend pipe on gas explosion, Chatrathi et al. [2] carried out work using lean concentration of propane and ethylene-air mixtures in bending pipe rig. From the work, the highest flame speed and pressure were attained at the bend due to fast burning rate. Emami et al. [4] studied the explosion behavior of hydrogen-enriched methane with lean hydrogen concentration. The observation from the work confirms that at bending, the pressure and flame speed obtained were at the highest value. Most of the researcher observed that flame propagation decay after passes the bend towards the end wall.

Yet, understanding on the interaction between hot flame and pressure wave reflected from the end wall of pipe or so called retonation is still unclear. The retonation phenomenon depends on the length of the pipe; retonation wave is significant if the pipe length is longer enough [5]. Blanchard et al. [6] observed that the pressure developed from the retonation process is weaker as compared to the pressure developed at the bending point. Wang et al. [7] observed the retonation wave is stronger at the bending point. The uncertainty on the onset of retonation wave can be resulted due to the fuel type and experimental rig design. This paper highlights the effect of hydrogen concentration towards explosion characteristics in closed pipe containing 90 degree bend, including the discussion on the retonation phenomenon.

2.0 EXPERIMENTAL

A series of tests were carried out to observe the flame behavior and explosion pressure development for different hydrogen-air mixture concentrations ranging from 13 to 54% v/v (Φ= 0.4 to 1.8). The test geometry with L/D ratio of 51 consists of a horizontal steel pipe (length=3 m, diameter=0.1m, volume=0.042m^3) with 90 degree bends (radius = 0.1 m) and added a further 2.1 m to the length of the pipe based on the centerline length of the segment. 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. Fig. 1 shows the schematic of the experimental rig.

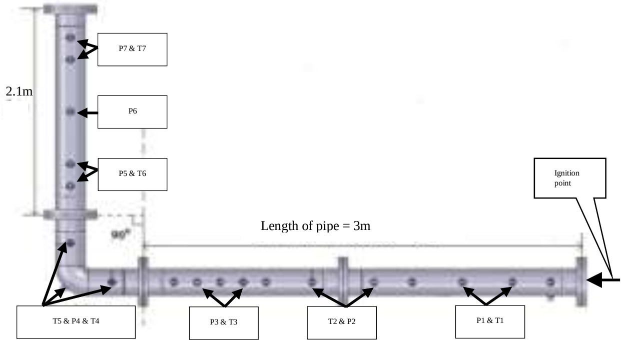
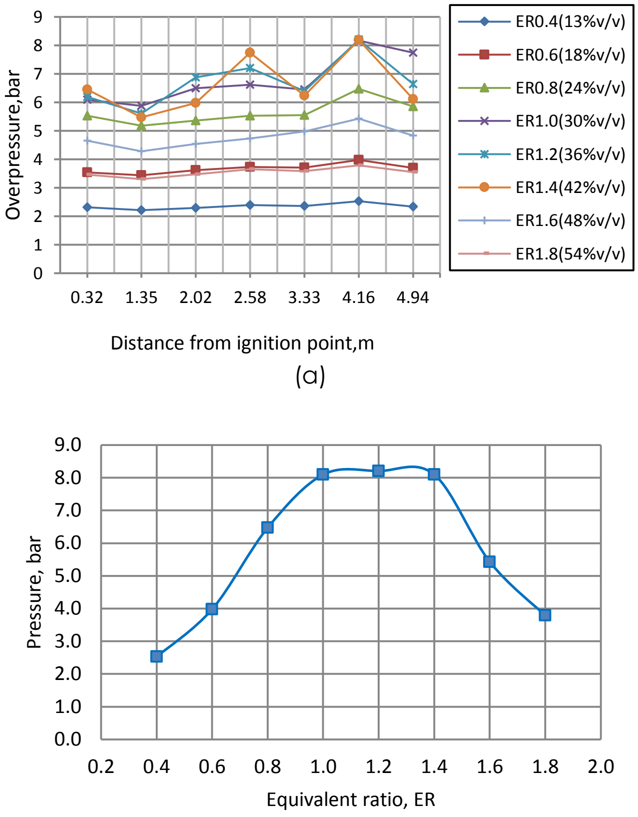


Figure 1 Schematic configuration of testing pipe, T_1-T_7 denotes as thermocouples, P_1-P_7 represents Pressure transducers

All tested mixtures were prepared using partial pressure method with different hydrogen concentration, initially at ambient condition 1 bar and 20 °C respectively. The mixture was ignited at the center of one end of the pipe by means of a spark discharge. 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 centerline. 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 11). A 16-channel transient data recorder from National Instrument was used to record and process all the data. Each explosion was repeated at least three times for accuracy and reproducibility.

3.0 RESULTS AND DISCUSSION

The severity of the explosion on hydrogen-air mixture has been observed in different equivalence ratio, Φ. Equivalence ratio is the actual fuel/oxidant ratio normalized by the stoichiometric fuel/oxidant ratio. Fig 2a-b shows the pressure profile along the pipe as a function of distance from ignition and equivalence ratio, respectively. The vertical dotted line on the graph indicates the bending position, which is 2.58 m from the ignition point. From the graph, it shows that by increasing the hydrogen concentration in explosion mixtures will increase the pressure along the pipe. For instance, at lean concentration, H_2=18% v/v (Φ = 0.6), the pressure is slightly increased to lesser than 5 bar along the pipe. Maximum overpressure is observed at higher concentration, H_2=30%v/v (Φ = 1.0), up to 8 bar. It can be depicted that the explosion pressure development is influenced by the concentration of hydrogen-air mixtures, associating to the heat release rate. For a lean concentration, only small fraction of hydrogen-air mixture is reacted and caused the flame temperature to rise about 2 to 3 times from the initial reactant[8]giving only small heat release. The amount of heat release is insufficient to increase the pressure significantly. However, for a stoichiometric and slightly above stoichiometric concentration, 30% v/v $\leq H_2 \leq$ 42%v/v (1.0≤Φ≤1.4),substantial fraction of hydrogen-air mixtures will be reacted and caused the flame temperature increase to a factor of 6 to 8 from the initial reactant; subsequently contribute to the highest heat release rate and pressure build-up abruptly[8].

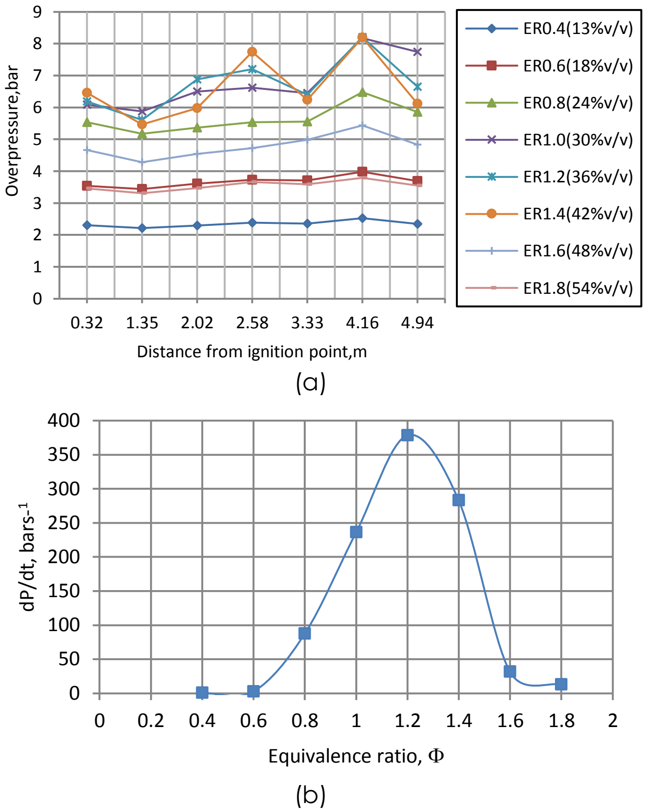


(a)

(b)

Figure 2 Pressure profile function of (a) distance from the ignition point and (b) equivalent ratio (P6 based)

The effect of bending presence in the closed pipeline system also been studied as shown in Fig 2a. It shows that, the pressure peaks occurred at two different locations i.e. at the bend and 0.8 m before end wall (or 4.16 m from the ignition point). The first pressure rise observed at the bend. The presence of obstacle such as 90 degree bends causes strong mixing between hot flames and fresh unburned hydrogen-air mixtures, which induces more turbulence. The higher heat release rate from hydrogen-oxygen reactions attenuates the turbulence mixing and enhances the pressure rise about 6-7 times from the initial pressure. Right after the flame passing the bend (or 0.8 m before end wall), the second pressure started to build-up. This pressure mainly caused by the interaction of hot flames with reflective pressure wave from the end wall (retonation). The intense interaction of burned and unburned gases downstream the pipe causes the pressure build-up ~ 1-2 times higher as compared to pressure observed at the bending point. Yet, this retonation effect is only pronounced between concentration 30% v/v to 42%v/v (Φ = 1.0 to 1.4). It can be said that the pressure generated by the retonation phenomenon is more severe than at the bend.



(a)

(b)

Figure 3 Rate of pressure rise, dP/dt as function of (a) distance from the ignition point and (b) equivalent ratio (P6 based)

Fig.3 a illustrates the rate of pressure rise, dP/dt as a function of distance from the ignition point whereas Fig 3b shows the influence of Φ to the rate of pressure rise. The significant profile of dP/dt is shown at 30%$\leq H_2 \leq$ 42% (1.0 ≤ Φ ≤ 1.4). At these fuel concentrations, the fraction of hydrogen-air mixtures is at the highest mixing ratio to completely burn-out, increasing the flame temperature and releasing the maximum amount of heat to drastically increase the pressure development. The more pronounced retonation effect of hydrogen-air explosion in pipe with L/D 50 is also illustrated in Fig 3a. The comparison of dP/dt is given with variable equivalence ratio. The rich concentration of hydrogen-air mixture, Φ =1.2 which content 36%v/v H_2 denotes the maximum rate of pressure rise 380 bar/s close to the end wall pipe. By taking the rate of pressure rise at the bending as a basis, the increment is more or less 2.4 times. Similar trend also indicates by stoichiometric (Φ =1.0) and near stoichiometric (Φ =0.8) concentration which content 30%v/v and 24%v/v H_2,postulates that the severity causes by the retonation is more significant as compared to the effect of bending.

Besides rate of pressure rise, deflagration index, K_G is one of the important indicators to characterize the explosion severity based on the mixture reactivity. K_G is part of the element in designing the basis explosion protection and mitigation such as explosion relief venting or etc. In this case, the value of K_G is calculated to determine the explosion severity in this obstruction pipe by varies the hydrogen concentration. In Table 1, it shows that the deflagration index increases with increasing the hydrogen concentration and yet under certain conditions the deflagration index decreased accordingly. The maximum KG is observed at concentration 36% v/v (Φ= 1.2) which slightly above stoichiometric concentration. This results indicate that the worst case accident for hydrogen-air mixture occurred at a concentration slightly above stoichiometric and this observation is in a good agreement with Young-Do and Daniel work[9].

Table 1 Deflagration Index for gas explosion due to retonation effect

Hydrogen-air mixture, Φ (%v/v)	dP/dt_{max}, $bar.s^{-1}$	$V^{(1/3)}$, m	K_G $(dP/dt)maxV^{(1/3)}$, $bar.m.s^{-1}$
0.4 (13%)	57.12	0.04	19.86
0.6 (18%)	91.62	0.04	31.86
0.8(24%)	87.65	0.04	30.48
1.0(30%)	236.10	0.04	82.09
1.2(36%)	378.55	0.04	131.62
1.4(42%)	83.12	0.04	28.90
1.6(48%)	31.78	0.04	11.05
1.8(54%)	12.89	0.04	4.48

The flame speed profile as a function of equivalent ratio is shown in Fig. 4. The highest flame speed was530 m/s, observed at H_2=36% v/v (Φ=1.2). The rate changes almost 3 times higher as compared to a lean concentration, H_2=13% v/v (Φ=0.4) at 164 m/s. It can be said that, increasing the hydrogen concentration may enhance the amount of heat release, thus subsequently increase the flame speed. As shown in Fig 4a, the flame starts to decrease at rich concentration, $H_2 \geq 36\%$ v/v ($\Phi \geq 1.2$). It can be said that, at low $H_2 \leq 24\%$ v/v ($\Phi \leq 0.8$) and high $H_2 \geq 36\%$ v/v ($\Phi \geq 1.2$) 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 [10, 11].

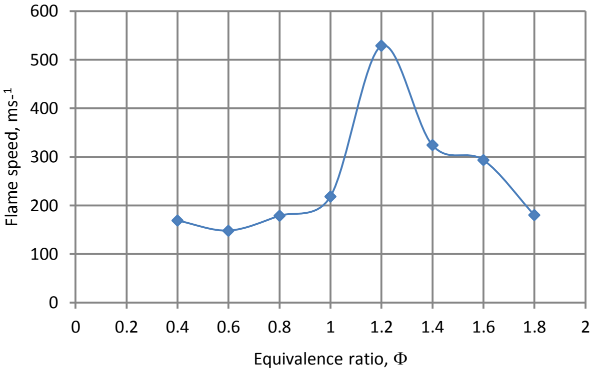


Figure 4 Flame speed as function of equivalent ratio

The flame speed as a function of distance of ignition is shown in Fig 5. The vertical dotted line on the graph indicates the bending position. It shows that the flame speed increases drastically when approaching the bending region. Yet, second peak of flame speed occurred downstream of the bend, causing the very fast flame reaching the pipe end wall. The possible explanation on this peculiar phenomenon is due to high unburned gas velocities induced at the bend by the most reactive explosion, creating very high turbulence levels after the bend which gave rise to very fast flames and very high back pressures. It is noted that the interaction of hot flame with pressure waves which reflected from the end wall play an important role contributes to the second acceleration. However, the flame speed profile in this study is contradicted with previous studies for pure hydrogen in 90° bend [3, 4]. The difference is mainly due to the different experimental rig design.

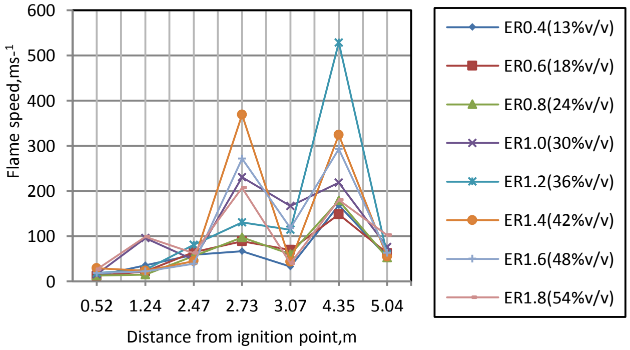


Figure 5 Flame speed as function of distance from the ignition point and

Table 2 Maximum pressure: Comparison with published data

Reference	Fuel	L/D	P max
Phylaktou et al.,[1]	CH_4/air	18.7	4.69
Mat Kiah [13]	CH_4/air	20	5.5
Blanchard et al., [3]	CH_4/air	112	1.3
Chatrathi et al.,[2]	C_3H_8/air	98	1.4
Chatrathi et al.,[2]	C_2H_4/air	98	9
Current study	H_2/air	51	8.2

Table 2 indicates the comparison data between current works result and published data with different L/D, ratio of length to diameter (small, medium and large pipe size) and fuel type. It shows that the highest overpressure, 9 bar was obtained at L/D 98 as studied by Chatrathi et al., [2]. They used ethylene/air mixture. The lower explosion pressure was indicated by Blanchard et al., [3] using methane/air mixture at L/D of 112. No solid conclusion can be made from the scattered data, as increased the L/D is not necessary to increase or decrease the overpressure or increased the fuel reactivity is not increased the overpressure. According to Munday [14] vessel configuration and size is a major factor contributing to the deflagration speed. Thus it is suspected that the difference of experimental test rig design used by the researcher resulted on variable outcome leading to non-linear relationships. Furthermore, it also suspected that the difference obstacle distance in this case (90 degree bend) from the ignition point caused a variation overpressure development which due to the effect of heat losses to the pipe. The longer the obstacle distance from the ignition point, the more heat losses to the pipe wall, yet flame-wave interaction become weaker and vice versa. This is affected the burning rate as well as overpressure development.

4.0 CONCLUSION

A wide range of hydrogen-air concentration was used experimentally to observe the flame speed and pressure development on the closed pipe system containing of 90 degree bend. The results shown that the retonation effect is dramatically influent the explosion severity ~ 2 times higher than at the bending. The peculiar trend suggested that the strong retonation is a main factor caused the pressure and flame speed to rise significantly. It worth to note that, the maximum KG of 132 bar.m.s^{-1}occurred at H_2=36%v/v ($\Phi = 1.2$) which is higher than at stoichiometric. However, the results are conservative in general.

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References

[1] H. Phylaktou, M.Foley, and G. E.Andrews. 1993. *Journal of Loss Prevention in the Process Industries*. 6: 21-29

[2] K. Chatrathi, J. E.Going, and B,Grandestaff. 2001. *Process Safety Progress*. 20: 286-294

[3] R. Blanchard, D. Arndt, R. Grätz, M. Poli, and S. Scheider. 2010. *Journal of Loss Prevention in the Process Industries*. 23: 253-259

[4] S. D. Emami, M. Rajabi, C. R. Che Hassan, M. D. A. Hamid, R. M. Kasmani, and M. Mazangi. 2013. *International Journal of Hydrogen Energy*. 38: 14115-14120

[5] M. A. Liberman, M. F. Ivanov, A. D. Kiverin, M. S. Kuznetsov, A. A. Chukalovsky, and T. V. Rakhimova. 2010. *Acta Astronautica*. 67: 688-701

[6] R. Blanchard, D.Arndt, R.Grätz, and S.Scheider. 2011. *Journal of Loss Prevention in the Process Industries*. 24: 194-199

[7] C. Wang, W.Han, J.Ning, and Y.Yang. 2012. *Safety Science*. 50: 709-717

[8] K. S. Raman, 1998. *Graduate aeronautical laboratories,California Institute of Technology*. Pasadena

[9] Y-D. Jo, and D. A.Crowl. 2010. *Process Safety Progress*. 29: 216-223

[10] S. H. Kang, S. W. Baek, and H. G. Im. 2006. *Combustion Theory and Modelling*.10: 659-681

[11] R. Sankaran, and H. G.Im. 2006. *Combustion Science and Technology*. 178: 1585-1611

[12] H. Phylaktou, and G. E.Andrews. 1991. *Combustion and Flame*. 85: 363-37

[13] M.H. Mat Kiah, 2013. *Master Thesis*. Universiti Teknologi Malaysia

[14] G.Munday, 1970, *The Chemical Engineer*. 248:135-