EXPERIMENTAL AND SIMULATION STUDY ON GAS EXPLOSION IN CONFINED PIPE

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Abstract

Experimental tests on hydrogen-enriched methane were simulated using numerical CFD tool FLACs. In this work, hydrogen concentration ranges between 4 to 8 % v/v was mixed with methane/air to observe the characteristic of flame speed and maximum pressure profile during the gas explosion. Experimental work was carried out in a closed pipe containing 90 degree bends with a volume of 0.41 m^3 which operates at ambient conditions. From the experiment observation, adding hydrogen into methane-air mixture, the pressure is approximately 2 times higher and flame speed in a factor of 2 to 25 compared with pure methane-air gas explosion. Results also show that FLACs is under-predicted the flame speed and mass burning rate when low hydrogen concentration diffused in methane-air. This is due to low hydrogen content in methane-air mixture which limits the hydrogen diffusivity yet reducing the burning rate. It also observed that the presence of 90 degree bend in closed pipe system influences the explosion severity to the factor of 2-3 using simulation, as compared to the experimental done. There are significant discrepancies between experimental and simulation, however, the results seem conservative in general.

KEYWORDS: 90° Bend, closed pipe, flame speed, maximum pressure, rate of pressure rise, hydrogen enrichment

1. Introduction

The profiles of flame propagation and maximum pressure performed in pipe with of 90 degree bend were broadly studied by Phylaktou [1], Chatrathi [2], and Blanchard [3] using hydrogen-, methane-, propane- and ethylene –air mixture with variable concentration (lean and stochiometric). Most of the tests were performed at ambient pressure. Phylaktou [1], observed that flame speed and overpressure increase in a factor of 5 of methane-air mixtures in a 90 degree bend tube compared to similar experiment carried out in straight pipes and this condition is similar to the effect using 20% blockage ratio baffle at the same position. This would be due to ability of Blanchard [3] suggested that 90 degree bend in pipe to provide an efficient way to create a turbulence yet enhance the flame speed, overpressure and shorten the DDT run-up distance for ethylene- and hydrogen –air mixture with stochiometric concentration. To support the experimental observation on effect 90 degree bend pipe on gas explosion, Chatrathi [2] observed that the highest flame speed and pressure attained at the bend using propane-and ethylene- air mixture with lean concentration due to fast burning rate. It is clearly shows that the presence of bend in pipe configuration plays an important role on creating turbulence as well as increase mass burning rate associated with combustion of normal fuel mixture.

Nevertheless, the effect of the obstruction on the explosion severity related to hythane fuel or so call hydrogen enrichment in methane is still unclear. Yet, hydrogen is commonly used to blend with methane as alternative fuel for extending the flammability limit [4-6]. To be noted that hydrogen behave intrinsically with other hydrocarbon, for instance i.e. hydrogen possess higher specific heat energy, higher diffusivity rate, wide range of flammability limit and such. Thus blended hydrogen with hydrocarbon gas especially methane tends to create issues associated with reaction location and the flame stability [4, 7, 8].

To date, there is lack information on hydrogen-methane/air mixtures explosion in closed pipe, making this investigation as an entrée for other related research investigation on impact of blending hydrogen in methane on explosion severity in pipe, particularly in bending configuration.Current literature on the hydrogen-methane/air mixtures explosions in pipe line has been studied by Porowski and Teodorczyk [9], however, the work focus on straight pipeline with blockage ratio 0.4 to 0.7 [9]. As mentioned earlier the presence of 90 degree bend in pipe configuration can create turbulence and accelerates the flame propagation. Therefore, this paper highlights the effect of adding hydrogen in methane-air mixture towards explosion characteristics in closed pipe containing 90 degree bend. In the following, the numerical computational fluid dynamics (CFD) gas explosion code FLACs will be used to reproduce and validate the experimental results obtained and emphasize is made for the peculiar phenomenon regarding on lean hydrogen concentration gas explosion.

2. Experimental set-up

A series of tests were conducted to observe the flame behavior and pressure profile for different methane-air-hydrogen mixture concentrations. The test geometry consist of a horizontal steel pipe (length,=2.0 m, diameter=0.1m, volume=0.41m^3) with 90 degree bends (radius = 0.1 m) and added a further 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. Refer to Fig. 1 for the overall schematic of the experimental rig.

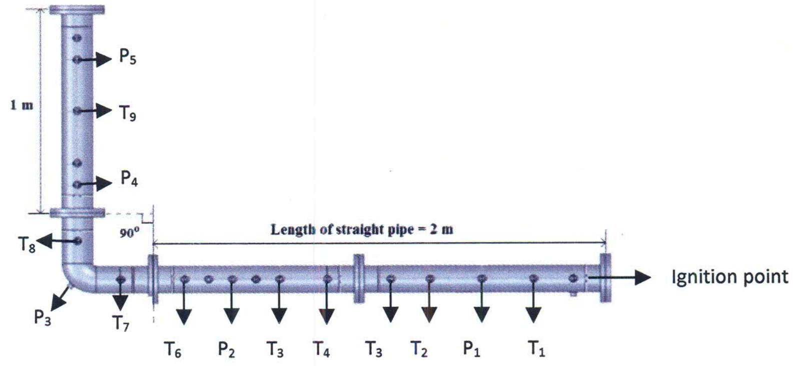


Fig. 1. Schematic configuration of testing pipe, T_1-T_9; Thermocouple, P_1-P_5; Pressure transducer

All tested mixture methane-air-hydrogen were prepared using partial pressure method with different hydrogen and methane 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. A 16 J ignition energy was used in all tests to ensure ignition is in near limit mixtures. 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 thermocouple 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. FLACs simulation

3.1 Solver details

FLame ACceleration Simulator (FLACs) was established by Christian Michelsen Research Institute in Norway and distributed as a commercial software package by CMR-GexCon [10]. The numerical code FLACs is a structured 3D Cartesan grid, used second order scheme (Kappa schemes with weighting between 2nd order upwind and 2nd order difference with delimiters to resolve the compressible equation using finite volume method [10, 11]. The conservation equations for mass, momentum, enthalpy, mass fraction of chemical species, turbulent kinetic energy and dissipation of rate turbulent kinetic energy given by [12, 13]

$$\frac{\partial}{\partial t}(\rho\varphi)+\frac{\partial}{\partial xj}(\rho u_i\varphi)-\frac{\partial}{\partial xj}\left(\rho\Gamma\varphi\frac{\partial\varphi}{\partial xj}\right)=S\varphi \tag{1}$$

Where ρ is density (kg/m3), xj is the length coordinates (m), ui is the mean velocity (m/s) and φ is the transport property. The turbulent flow is described by standard k-ε model with some modification on generation of turbulence behind the subgrid obstacle and turbulent wall function. The element which contribute to the production of turbulent kinetic energy (P_k) such as flow shear stresses (G_s), wall shear stresses (G_w), buoyancy (G_b) and subgrid object (G_o) are described in the transport equation as follows

$$P_k=G_s+G_w+G_b+G_o \tag{2}$$

The combustion model is considering one-step reaction kinetic model. A chemical equilibrium model is used to estimate the composition of the combustion product. The flame model gives the flame a constant thickness equal to 3-5 grid cells and ensure that the flame propagates with the specified burning velocity [14]. The burning velocity model is consisting of the following three sub-models:

(1) Laminar burning velocity model, S_L (m/s). The model is restricted for region close to the ignition source where flame front is assumed to be smooth. At this region laminar flame velocity is described as:

$$S_L=S_L^0\left(\frac{P}{P_0}\right)^{\gamma P} \tag{3}$$

where P is pressure (bar) and γP fuel dependent parameter

(2) Quasi-laminar regime. The model applicable when flame start wrinkles due to the effect of flame instabilities which resulting by the increase of burning velocity. The velocity is given by:

$$S_{QL}=S_L(1+aR)^{0.5} \tag{4}$$

where *R* is the flame radius and *a* is a constant, typically between 2 and 8, depending on factors related to the gas mixture and the number of walls located by the ignition point.

(3) Turbulent burning velocity, S_T (m/s). This model describes the turbulent burning velocity as a function of turbulent flow, u′ (m/s) and length scale, l_T (m). In FLACS, this model is simplified by Bray [15] based on experimental data obtained by Abdul Gayed[16] and represented as following empirical expression:

$$S_T = 15 S_L^{0.784} u'^{0.412} l_T^{0.196} \tag{5}$$

The geometry of computational domain, grid meshing and boundary condition are defined and constructed in CASD drawing package (Computer Aided Scenario Design) before enter into FLACs while Flowvis, a graphical presentation program developed by CMR is used for post processing. The CFD code FLACs is permissible for explosion study since it has been properly validated against critical experiment [17-19].

3.2 Model geometry, grid meshing and boundary condition

In this work, two cylinders (length= 2m and 1 m, diameter =0.1m) joined at the edges with 90 degree angle were considered to replicate the actual experimental rig as shown in Fig. 2. The domain in which the grid was defined used in the simulation ranged from -1 to 3m in the x and y directions while 0 to 0.1m in z direction. This range indicated the grid cell size equivalent to 0.05 m. No attempt has been made to study the sensitivity of grid size since in FLACs; flame has a fixed thickness 0.03-0.05m grid cell and below than 0.01m the grid dependency become insignificant. It is worth to note that 0.05m grid cell size indicated reasonable prediction on explosion properties in closed pipe containing 90 degree bends using methane-air- hydrogen mixture. The boundary conditions used in the model were adiabatic wall and outer part of the boundary is assumed to be atmospheric pressure. The ignition point is set at one end of the pipe and monitor point is set at 6 different coordinates (M1, M2, M3, M4, and M5) to measure the pressure-time and flame velocity-time data. The initial pressure and temperature is set to be 1 atm and 20°C respectively.

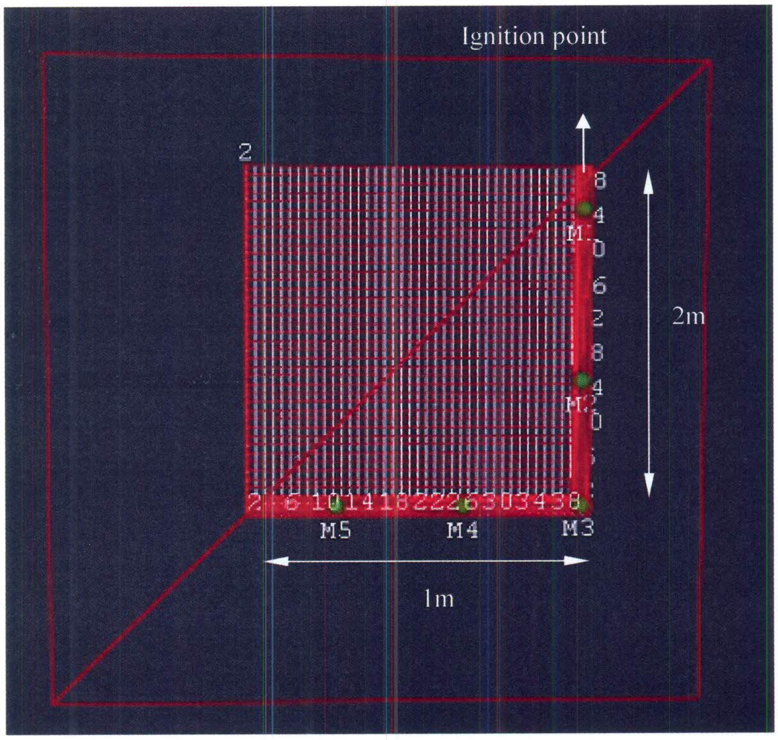
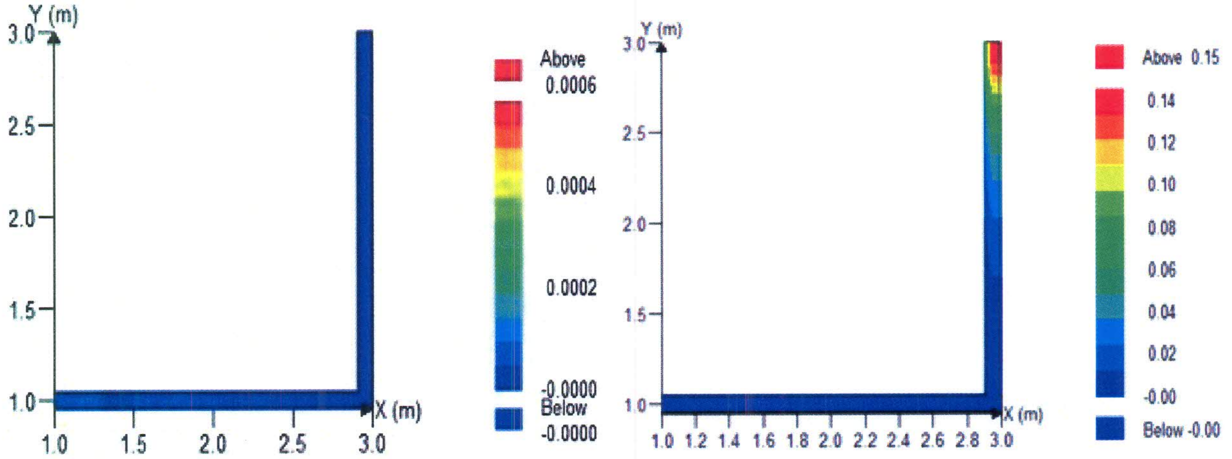


Fig. 2. The geometry of computational domain in FLACs numerical simulation

4. Results and discussion

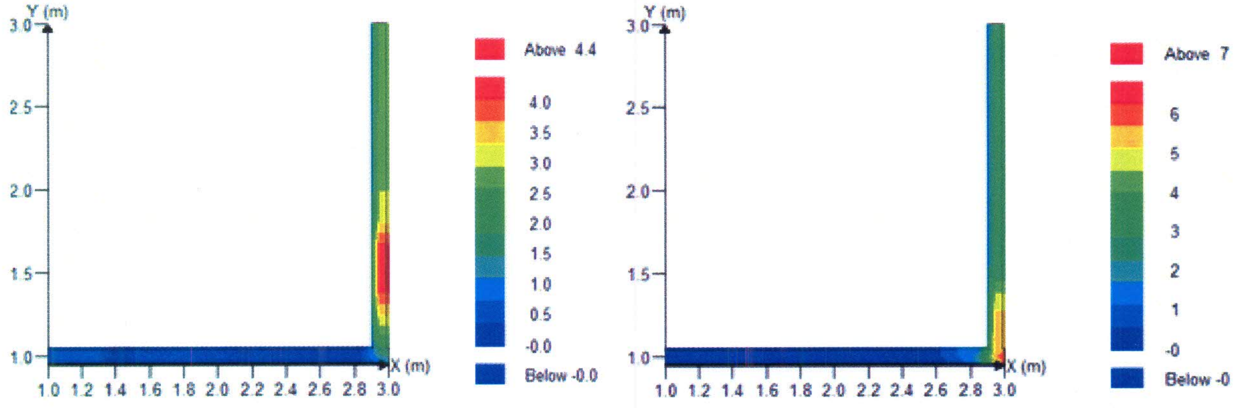
4.1 Effect of hydrogen addition on the pressure time history.

The 2D of the pressure profile throughout the pipe length is shown in Fig. 5. It can be seen that for 11 ms, the pressure increased from 0.006 to 6.04 bar. A strong mixing between hot flames and unburnt mixture was observed and caused the pressure to increase drastically. It is also shown that pressure increase to 6.04 bar at the bend at 11ms. The shear layers developed at the upper part of the wall (bending) create large vortexes (due to density and pressure gradient) and subsequently induce the turbulence levels at the highest. This could be the reason on the pressure enhancement. The pressure was constant at 6.04 bar before decaying to 0.3 bar , explicitly indicates that the influence of bending is insignificant after the bend.



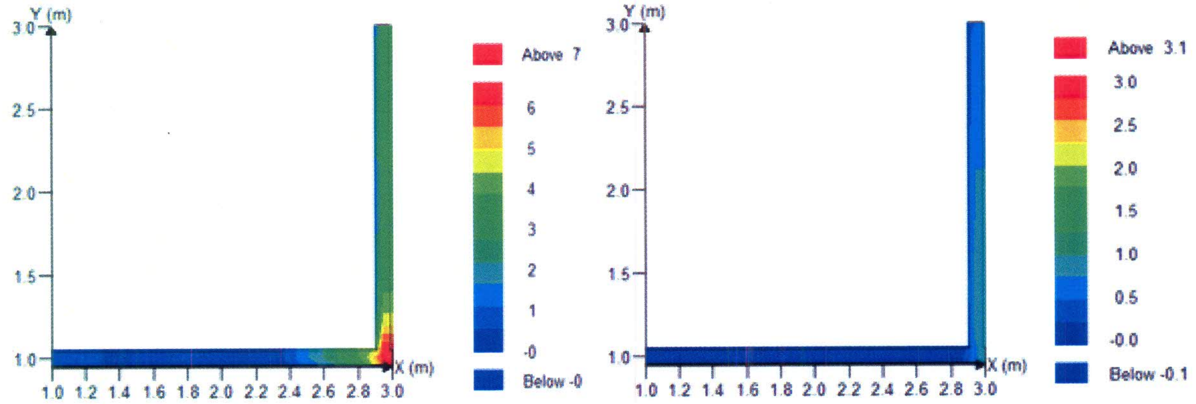
(a) Initial condition (before ignite)

(b) 5 msec; Pressure:0.06 bar



(c) 10 msec, Pressure 3.5 bar

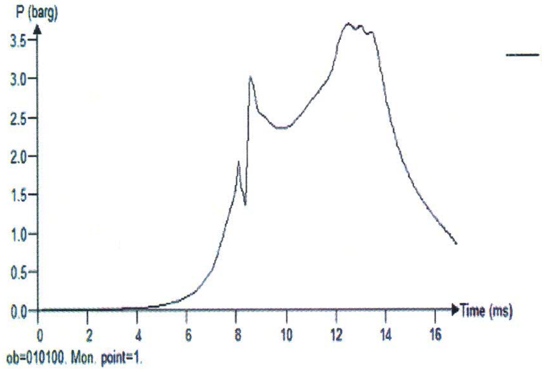
(d)10.5 msec; Pressure:4.2 bar



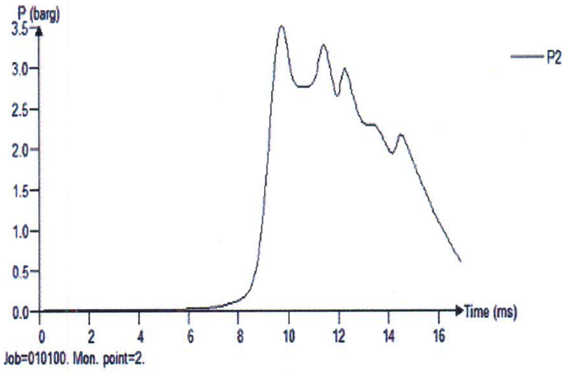
(e) 11 msec, Pressure: 6.4 bar

(f) 12msec, Pressure: 0.3 bar

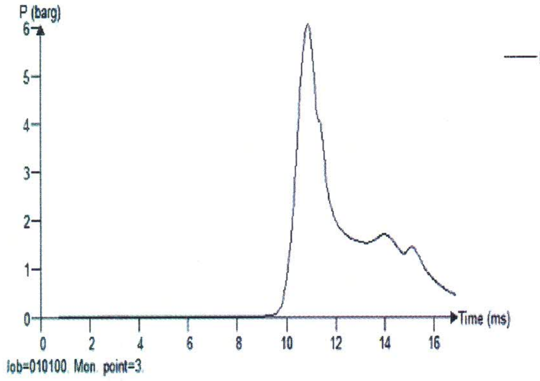
Fig.3 2D snapshots of simulation pressure profile (time step) by the FLACs analysis



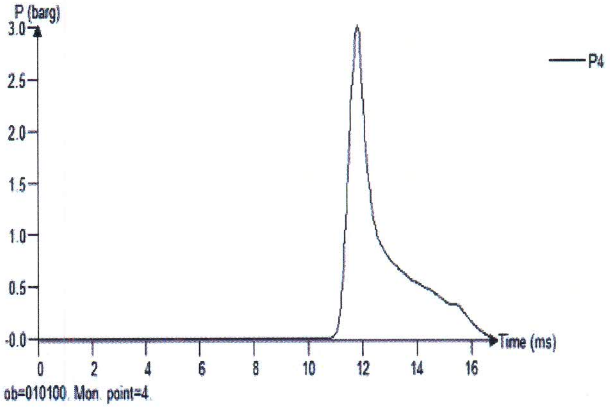
(a) M1: Pressure 3.7 bar



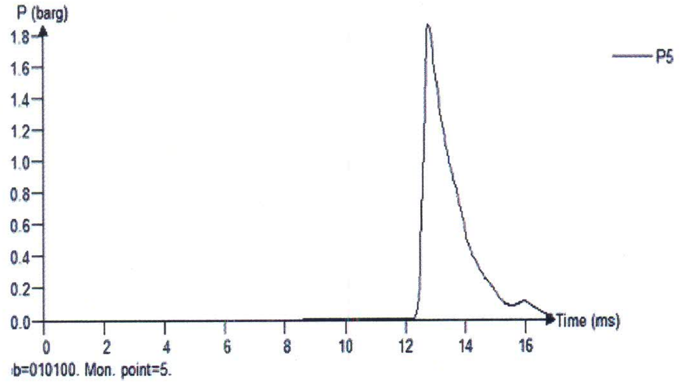
(b) M2:Pressure 3.5 bar



(c) M3 (Bending): Pressure 6.04 bar



(d) M4 : Pressure 3 bar



(d) M5 : Pressure 1.86 bar

Fig. 4 Pressure development at 5 monitors point for methane explosion (FLACs)

Fig.5a-d shows the comparison between FLACs and experimental result on pressure-time profile. The simulated pressure profile indicates based on M_1, occasionally M_3 is used to indicate at the bending point. The results shown in Fig. 4a, it clearly indicates that, the simulated pressure increases faster and reaches the maximum level pressure of 6 bars, after ignited in 0.011 s. This is relatively 100 times earlier faster from the experimental data for pure methane-air mixture. The results suggest that, adiabatic wall assumption which represents in FLACs tend to limit the quenching rate dramatically leading to the continuous reaction (when hot flame is in contact with unreacted mixture) in rapid manner [18, 20], thus increases and causes the enhancement of mass burning rate. However, different profile regime was obtained for hydrogen enrichment in methane-air mixture (Fig.4b-d), the development is quite different. The simulated pressure increase to the maximum level pressure with a slightly delay about 0.0018 to 0.0112 s respectively. It can be stipulated that, the adiabatic wall represents in FLACs is insignificant for hydrogen-methane-air mixture, due to reduction of global reactivity[21]. Kinetically, methane is strongly depended on the H and OH radical to initiate the reactivity [7]. In this study, it can be said that low hydrogen content in the methane-air mixture is insufficient to produce relevant effect in methane reactivity since the presence of H radical tends to consume methane molecule rather to be involved in the reaction[21]. This phenomenon may possibly delay the hot flame expansion and yet reducing the mass burning rate. It should be noted that, in the simulation finding, there is no significant effect on varying the hydrogen concentration (4 to 8% v/v) in methane-air mixture for simulation observation as shown in Fig. 5b-d. The simulated pressure increase moderately as the hydrogen concentration increased in the methane-air mixture. It shows that, FLACs is under-predict to portray the flame speed and mass burning rate profile during gas explosion when low concentration of hydrogen diffuses in methane-air. In contrast, experimental results as shown in Fig, 6 was consistent with Sankaran [22] findings, in which, pressure increase significantly when adding hydrogen in the methane-air mixture. It indicates that, the presence of 4 to 8% v/v hydrogen in the methane-air mixture able to improve the mass burning rate.

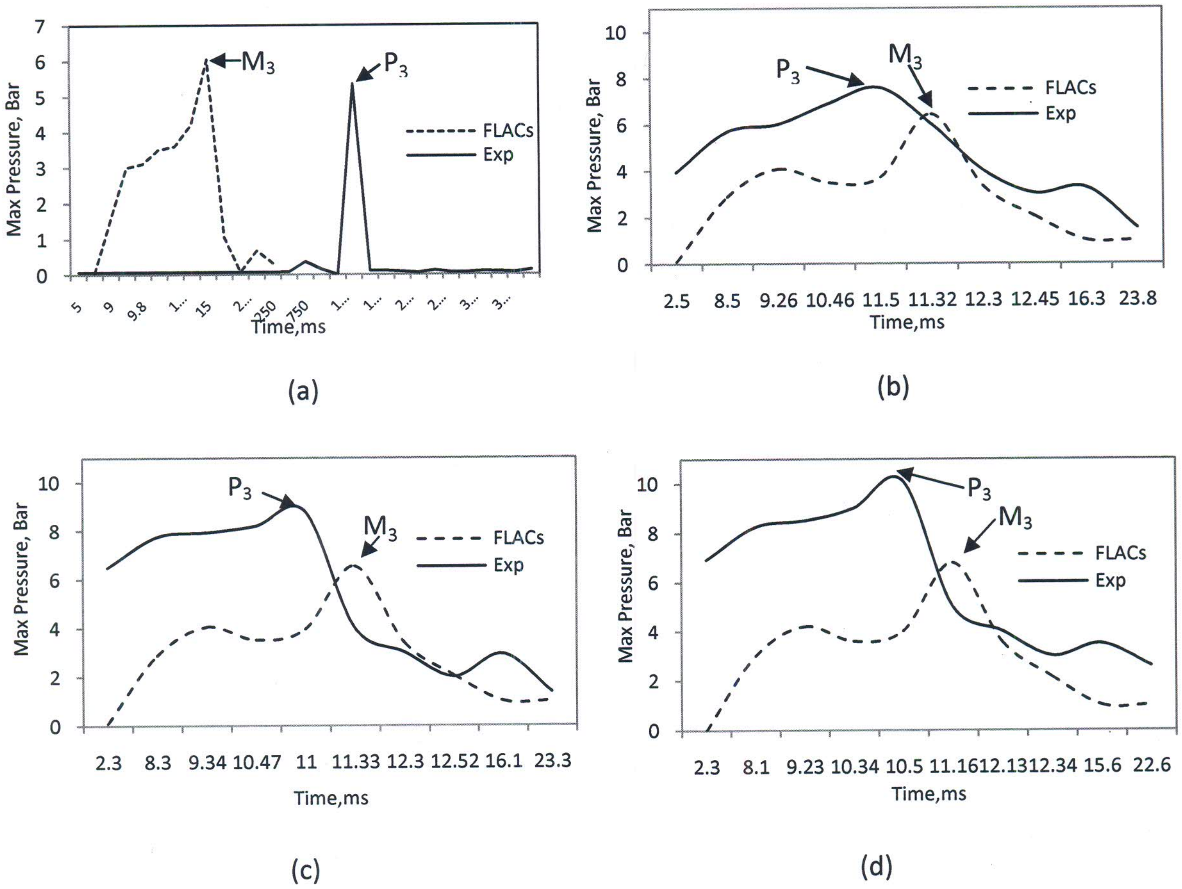


Fig.5. Pressure profile function of time (a) 100% methane-air mixture (b) 4% of hydrogen in 96% methane-air mixture (c) 6% of hydrogen in 94% methane-air mixture (d) 8% of hydrogen in 92%methane-air mixture

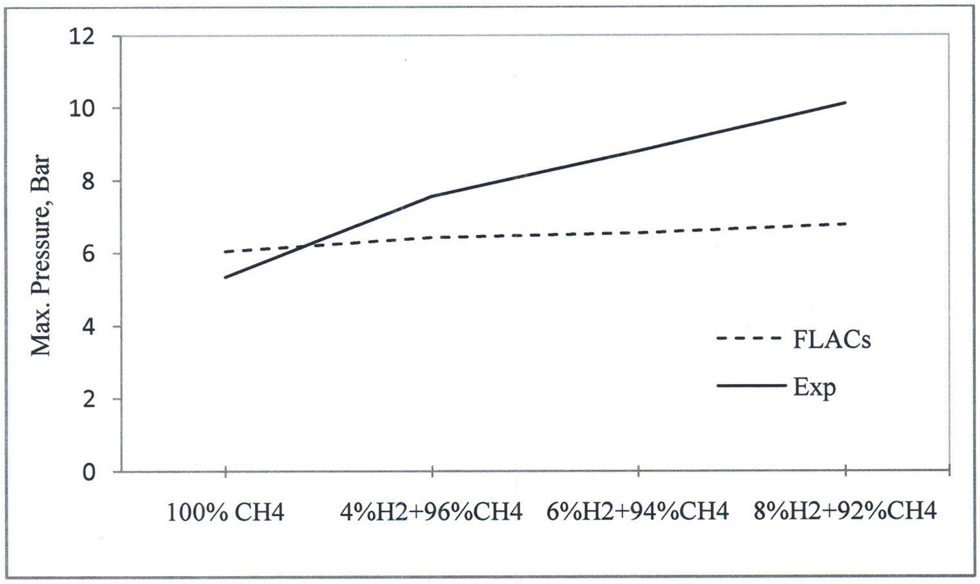
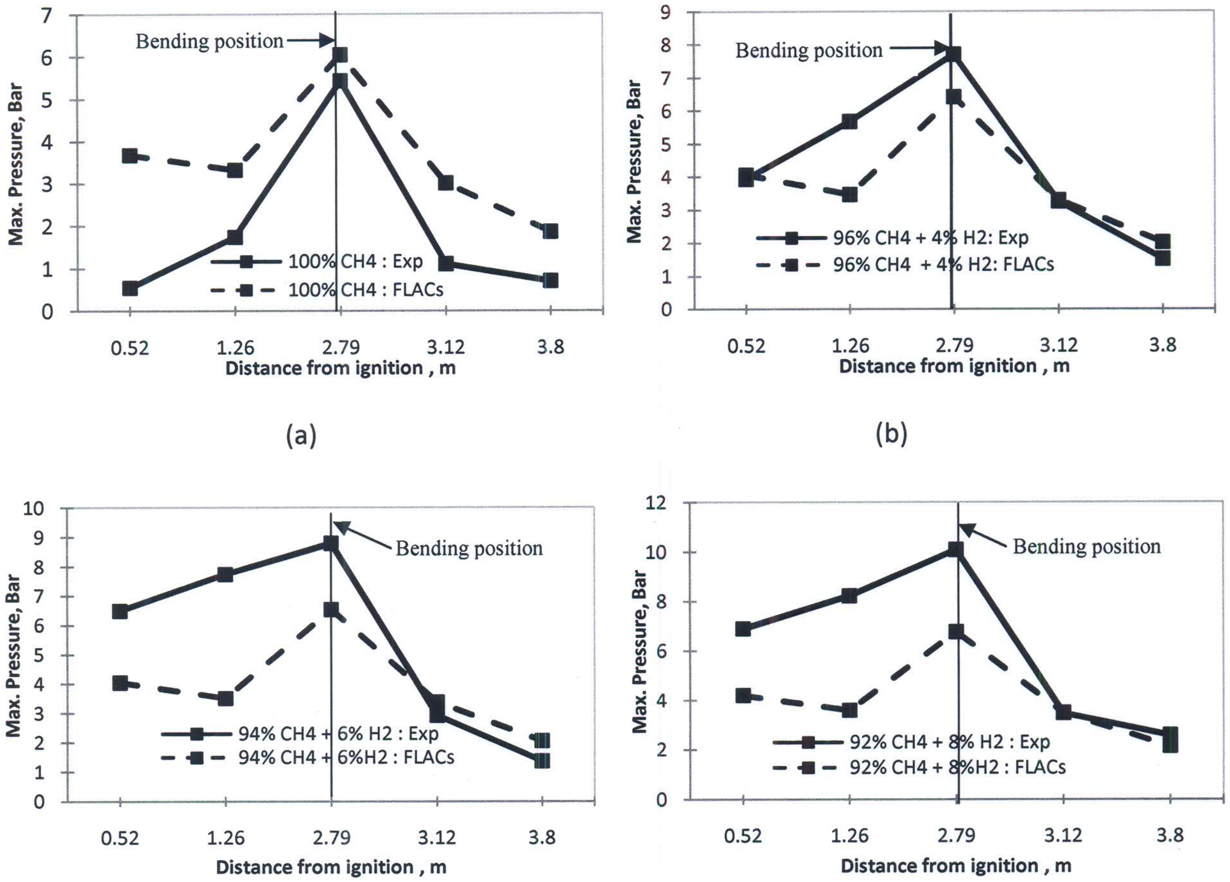


Fig. 6. Experimental measurements and FLACs simulation on effect of hydrogen enrichment on maximum pressure

4.2 Influence of 90 degree bends on the maximum pressure, P_{max} in methane-air enriched hydrogen mixtures

The variations of maximum pressure, P max by FLACs and experimental data are shown in Fig. 7a for pure methane-air and Fig. 7b-d for methane-air enrichment hydrogen. The graph is plotted against distance from the ignition location (represent M1-M6). It is well understood that flame propagate through bending creates a complicated problem which subsequent changed the velocity and created turbulence. This hypothesis is well described by Fig.76a-d, in which simulated and experiment profile indicates pressure rise significantly at the bend by a factor of 2 to 3 respectively. This is due to a strong mixing between hot flames and unburnt mixture when flame enters the bend, subsequently induce more turbulence and hence, the pressure is increased. However, the pressure drops by a factor of 2 to 3 after passing the bend, indicates that the influence of bending is insignificant after the bend. This is due to insufficient energy to reignite the remaining unburnt mixture. Fig. 7b-d also shown that low hydrogen content (4-8% v/v) in methane-air mixture, slightly increase the maximum pressure by a factor of 1. This is in contrast with simulation prediction, where there is no significant effect on pressure development by adding 4-8% v/v in methane-air mixture. Lower hydrogen content in methane-air mixture, indicates smaller Lewis number [22, 23]. A small Lewis number show that diffusion affects the flame stability by reducing the flame stretch rate [23-25]. This would make the flame flows slowly through the reaction zone and the interaction between the flame area available would greatly influence the burning rate as well as the pressure development. Also noted, since low hydrogen content in methane-air mixture, the numerical diffusion in FLACs code limit the hydrogen diffusivity yet reduces the burning rate [14]. This would directly influence the mass burning rate as well as pressure development in the system. To overcome this difficulty, numerical scheme with higher resolution in space and time is required to avoid the numerical diffusion.



(a)

(b)

(c)

(d)

Fig. 7. Experimental measurements and FLACs simulation on effect of bending on maximum pressure (a) 100% methane-air mixture (b) 4% of hydrogen in 96% methane-air mixture (c) 6% of hydrogen in 94% methane-air mixture (d) 8% of hydrogen in 92%methane-air mixture

4.3 Influence of 90 degree bends on the flame speed in methane-air enriched hydrogen mixtures

The flame propagation profile throughout the pipe length is shown in Fig. 8. It can be seen that the influence of bending is more pronounce for methane-air mixture from the experimental data, in a good agreement with Blanchard's work [3]. The results show that, flame acceleration gave a 3 times higher at the bends, suggesting that, when flame enters the bend, normal reflection occurs where most of the unburnt mixture does not transmit downward and causes strong mixing between hot flames and unburnt mixture. Hence it could increase the turbulence intensity as well as flame speed. However, the hypothesis is not best described for hydrogen enrichment in methane-air mixture. The presence of 4 -8% hydrogen in methane-air mixture indicate that flame propagate as slow deflagration throughout the system. The unusual features in the results confirmed that the extremely low 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 [22, 26]. In contrast, the simulated flame speed increase almost 2 times after the bending. In FLACs simulation, the shear layers developed at the upper part of the wall (after bending) create large vortexes (due to density and pressure gradient) and subsequently induce the turbulence levels at the highest. This could be the reason for the flame accelerations at velocity of 584 to 614m/s respectively.

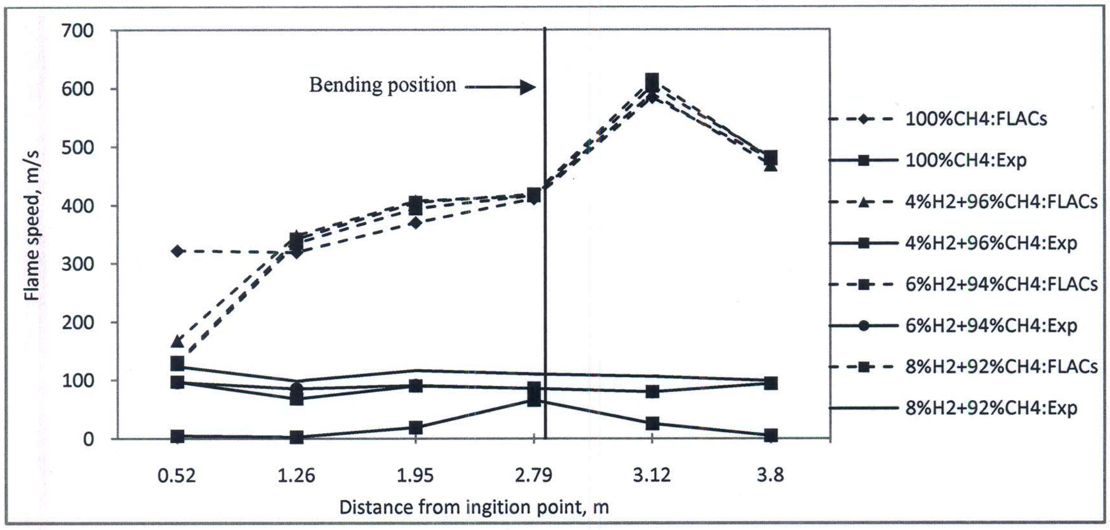


Fig.8. Experimental measurements and FLACs simulation on Effect of bending on flame speed

4.4 Rate of pressure rise, dp/dt profile throughout the closed system

Instead of flame speed, Rate of pressure rise, dP/dt is one of the important indicators to characterize the explosion severity [1] since the rate of pressure rise is proportionally to the mass burning rate [27]. Phylaktou [1] and Blanchard [28] reported that the rate of pressure rise increase with the presence of 90 degree bend for methane-air mixture by a factor of 2 to 7 as compared to straight pipe. Likewise, the increase of rate of pressure rise is dependent with the presence of bend as shown in Table 1. FLACs prediction confirm that the influence of bend on the explosion severity, by showing the increment of pressure rise significantly. Noted that the presence of obstruction (90 degree bend) enhances the combustion rate which subsequently increase the rate of pressure rise by a factor of 2 to 8 respectively. After the bend, it shows that the rate of pressure rise decreases more or less 2 to 5 times lesser which comparable with Phylaktou [1] and Blanchard [28] finding work. It is worth to note that the presence of bend in piping system may affect the venting requirement. However, the detailed discussion on influence of bending towards explosion severity characteristic is required, but this is not the focal point of this paper. However the discussion will be explored in the next paper.

Table 1. Influence of 90 degree bend on rate of pressure rise

Concentration, %	FLACs- dP/dt, bar s^{-1}			Exp. dP/dt, bar s^{-1}		
	Before bend	At bend	After bend	Before bend	At bend	After bend
100% CH_4/air	4344	9152	5713	2.8	21.4	4.4
4% H_2 96% CH_4	5708	9719	7432	60	63.55	150
6% H_2 94% CH_4	5416	10332	7267	65	77.85	200
8% H_2 92% CH_4	5733	10891	8131	80	93.16	250

5. Conclusion

The Numerical CFD explosion code FLACSs was used to validate against experimental data on the effect of 90 degree bend presence in the closed pipe system. The simulation results are compared well to the experimental data and shown that the presence of 90 degree bends in closed pipe system is dramatically influent the explosion severity significantly by the factor of 2 to 5. The results were considerably acceptable when the highest peak maximum pressure is observed at the bending point, which in good agreement with the experiment data. There are also discrepancies trend between observation and prediction, but the results are conservative in general. In addition, the presence of for 4-8% hydrogen enrichment in methane-air mixture may retard the flame propagation by imbalance the diffusive-thermal stability.

Acknowledgements

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