CHEMICAL ENGINEERING TRANSACTIONS

VOL. 36, 2014

A publication of
AIDIC
The Italian Association
of Chemical Engineering
www.aidic.it/cet

Guest Editors: Valerio Cozzani, Eddy de Rademaeker
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ISBN 978-88-95608-27-3; **ISSN** 2283-9216

DOI: 10.3303/CET1436046

The Influence of 90 Degree Bends in Closed Pipe System on the Explosion Properties Using Hydrogen-Enriched Methane

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This work sought to evaluate the explosion severity on hydrogen enrichment in methane-air mixture explosion. For this purpose, different hydrogen mixture compositions ranges between 4 to 8% v/v were considered. This work was performed using CFD tool FLACS that has been well validated for safety studies on both natural gas/methane and hydrogen system. FLACS is used to validate the maximum pressure and flame speed predicted by the CFD tool for combustion of premixed mixtures of methane and hydrogen against the experimental data. Experimental work was carried out in a closed pipe containing 90-degree bends with a volume of 0.41 m^3, operating at ambient conditions. From the experiment observation, it shown that the coupling effect of bending and thermal diffusivity gave the dramatic influent on explosion severity in hydrogen-methane/air at very lean concentration. However, simulation results showed that FLACs is under-predicting the overpressure at very lean concentration of hydrogen in methane/air mixtures. It can be said that lower hydrogen content in methane/air mixture limits the hydrogen diffusivity, leading to the decrease of the burning rate and flame speeds. It is also demonstrated that the presence of 90-degree bend in closed pipe system increases the simulated flame speeds to the factor of 2-3, as compared to the experimental data. There are significant discrepancies between experimental and simulation, however, the results seem conservative in general.

1. Introduction

The acceleration of the flame inside a pipe is a complex phenomenon involving several variables spanning from fuel nature and mixture composition to geometrical characteristics of the pipe such as length, diameter, wall roughness or presence of obstacles in the flame path. During explosions, flame flow through the pipe is usually laminar at its initial propagation. Overpressure is only generated later, due to rapid turbulent combustion in the shear layers and recirculation zones induced by the obstacles created either by blockage or bending (Fairweather et al., 1999). As the turbulence intensity increases, the flame front configuration becomes more complicated. The overall explosion process may accelerate further as the flame front velocity increases, due to deflagration of turbulent burning. Turbulent velocity is a key parameter governing the process of flame acceleration as the rise in burning and pressure in pipe is due to the interaction of expansion-induced flow of a flame front that travels to the unburned mixture of a combustible fuel in a premixed combustion system, in which amplify the turbulence and flame speed as reported by Kasmani et al (2012, 2013). The influence of bends was also of interest, as they are often perceived as a complicated problem involving the interaction between fluid dynamics, heat transfer and turbulent combustion by promoting flame acceleration and detonation even though little previous published work exists to justify or quantify this perception of increased risk on detonation (Blanchard et al, 2010). Phylaktou at al (1993) showed that with a short tube of a 90 degree bend can enhance the flame speed by

Please cite this article as: Sulaiman S.Z., Kasmani R.M., Mat Kiah M.H., Kidam K., Hassim M.H., Ibrahim N., Ali R.R., 2014, The influence of 90 degree bends in closed pipe system on the explosion properties using hydrogen-enriched methane, Chemical Engineering Transactions, 36, 271-276 DOI: 10.3303/CET1436046

a factor of five and was equated to the effect of baffle with a blockage ratio of 20 % at the same position. Chatrathi et al (1992) work observed that when 90 degree bend placed half way down a tube, there is an increment of 24 % on flame acceleration.

Nevertheless, the effect of the obstruction on the explosion severity related to hydrogen enrichment in methane-air mixtures is still unclear. Yet, hydrogen is commonly used to blend with methane as alternative fuel for extending the flammability limit (Di Sarli and Benedetto, 2008). To be noted that hydrogen behaves 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 (Cammarota et al, 2009). Porowski and Teodorczyk (2013) carried out work on the hydrogen-methane/air mixtures explosions in pipe, however they only focus on straight pipeline with blockage ratio 0.4 to 0.7. For authors' knowledge, there is sparse information on hydrogen-methane/air mixtures explosion in closed pipe or confined vessel, 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. The uncertainty of the flame propagation patterns and the overpressures could pose significant consequences in applying the standard testing of protective measures such as flame arrester (EN12874, 2001).

Hence, this paper highlights the effect of adding very lean hydrogen in methane-air mixture towards explosion characteristics in closed pipe, focusing on bending configuration by using CFD code FLACS. Part of the work is reported elsewhere (see Emani et al (2013) and Kiah and Kasmani (2013)),

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2. Experimental set-up

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

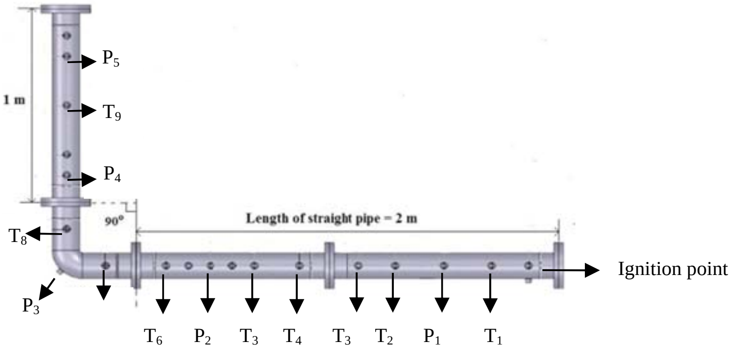

Figure 1 Schematic configuration of pipe, thermocouples denote as T_1-T_9 and P_1-P_5 indicates the pressure transducer

All tested mixture methane-air-hydrogen were prepared using partial pressure method with different hydrogen and methane concentration initially at atmospheric condition. . Different hydrogen concentration (i.e. 3, 4, 6 and 8% v/v) added into methane-air mixtures (i.e. 97, 96, 94 and 98%v/v) was used and only end ignition will be considered in this paper. The flammable mixture was initiated by an electrical spark, which gives 16 J energies for the gas explosion tests. Maximum pressure, P_{max} was measured at the P_1 pressure transducer (Keller Series 11) close to the upstream end of the explosion pipe and P3 will represent best the pressure at bending. Flame speeds were measured from the time of arrival of the flame at an array of thermocouples on the pipe centerline. The average flame speed between two thermocouples was determined and ascribed to the mid-point of the distance between the thermocouples. Thermocouples used in this work are mineral insulated, exposed junction, type K thermocouples. The response time for this type of thermocouple is about < 2 m/s. 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. The CFD-FLACS simulation

The simulation reported in this paper has been carried out using CFD tool FLACS, version 9.1 (GexCon, 2010). The FLACS code is primarily aimed at simulating the dispersion of flammable gas in process areas and subsequent explosions of gas-air mixtures. The conservation equations for mass, momentum, enthalpy, turbulence and species, closed by the ideal gas law are included. The CFD model solves the 3D Reynolds-averaged Navier-Stokes equations on a Cartesian grid. The conservation equations for mass, momentum, enthalpy and chemical species are solved using a finite-volume method. Turbulence is modelled using the two-equation k-ε model. The interaction between the reactive fluid flow and the surrounding geometry is taken into consideration through a distributed porosity concept. The k-ε model is modified to capture the effect of turbulence production from subgrid geometry. FLACS is based on flame model, giving a flame thickness of 3-5 grid cells and ensures that the flame propagates into the reactant with the specified velocity that accounts, among others, for the flame wrinkling due to the instabilities and turbulence level.

3.1 Model setup

In this work, the geometry model that best replicates the actual experimental rig is shown in Figure 2. The domain in which the grid was defined ranged between -1 to 3 m in the x and y directions while 0 to 0.m in z direction, equivalent to 0.05 m grid size. It is worth noting that 0.05 m grid cell size indicates reasonable prediction on explosion properties in 90 degree closed pipe using hydrogen-methane-air mixture. The boundary conditions used in the model were adiabatic wall and outer part of the boundary is assumed to be at atmospheric pressure. The ignition point is set at close at the upstream of the pipe end and six monitor point is assigned at different coordinates, represents as M1, M2, M3, M4, and M5 to measure the pressure-time and flame velocity-time data, as shown in Figure 2.. The initial pressure and temperature is set to be at atmospheric condition.

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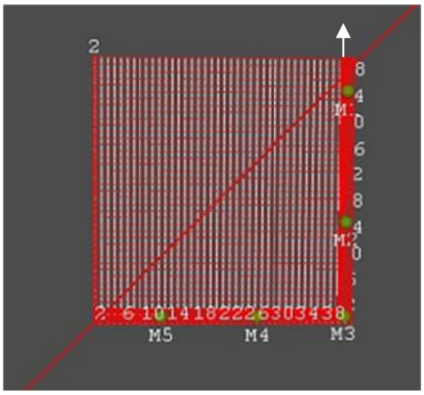

Figure 2 The geometry of computational domain in FLACs numerical simulation

4. Results and discussion

4.1 Pressure generation in bend pipe.

The pressure-time profile is illustrated in Figure 3a-d for the case with and without hydrogen addition on methane/air mixtures. It can be observed that time taken to reach maximum peak of 6 bars is 100 times faster for methane/air mixtures in FLACs, in comparison with experimental result as shown in Figure 3a. This would suggest that, adiabatic wall assumption 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 (Middha and Hansen, 2009), thus rapidly increases the enhancement of mass burning rate.

However, different pressure generation profile was illustrated for hydrogen enrichment in methane-air mixture (Figure 3b-d), in which the experimental results gave higher overpressures compared to simulated FLACs. It is interesting to note that, there is slight or no change in pressure generation for FLACS for 4, 6 and 8% v/v of H_2 in 96%, 94% and 92% v/v methane/air mixture explosion as shown in Figure 3b – d. Kinetically, methane is strongly depended on the H and OH radical to initiate the reactivity (Cammarota et al, 2009). FLACS simulation gave under predicting results ~30 -70% limit of discrepancy compared to experimental data for a very low concentration of hydrogen diffuses in methane/air mixtures. Discrepancies between experimental and numerical results shown in Fig. 3b-d could be partly explained by uncertainties on very low H2 concentrations. 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 (Dagaut and Nicolle, 2005). This phenomenon may possibly delay the hot flame expansion and yet reducing the mass-burning rate. Reynolds Averaged Navier–Stokes (RANS) equations and a k–**ε** model for turbulence used in FLACS to resolve diffusive fluxes is not correctly modelled in this case. Even though the modelled maximum pressure profile is reproduced, but it was lower than the one obtained in the experiments with H2 gradients.

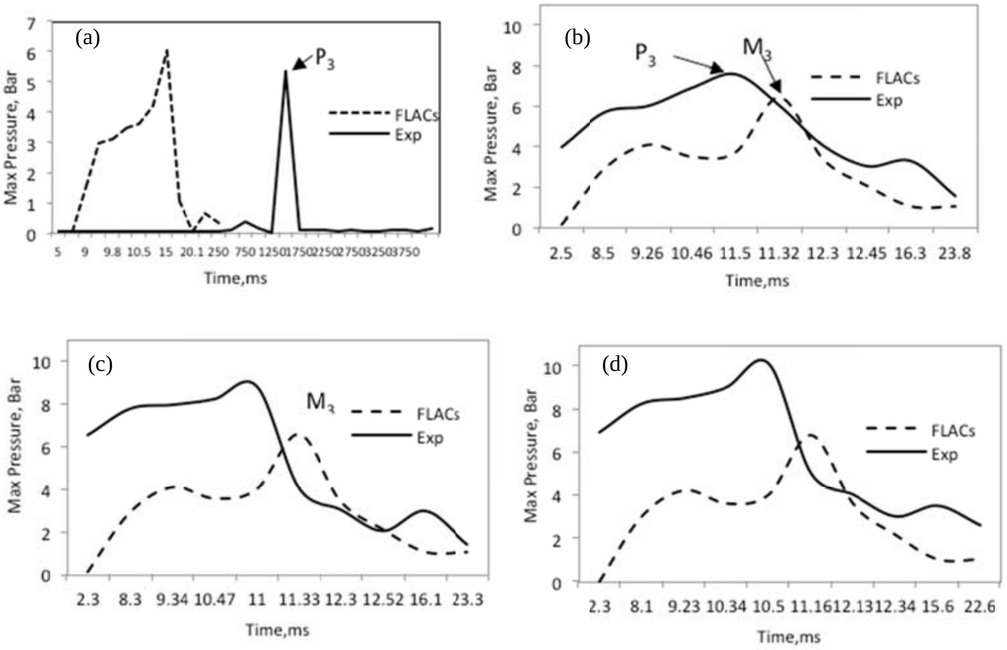

Figure 3 Pressure generation as a function of time at reference point of M3(FLACS) and P3(experimental rig) (a) 100 % methane-air mixture (b) 4 % of hydrogen in 96% methane-air mixture (c) 6 % of hydrogen in 94 % methane-air mixture (d) 8 % of hydrogen in 92 %methane-air mixture

In contrast, experimental data shown in Figure 4 was consistent with Sankaran and Im work (2006), in which, pressure increase significantly with addition of very lean H2 concentration in the methane-air mixture. It stipulated that, the presence of 4 to 8 % v/v hydrogen in the 96 – 98% v/v methane-air mixture able to significantly increase the mass-burning rate. Lower hydrogen content in methane-air mixture, indicates smaller Lewis number which means the diffusivity would affect the flame stability by reducing the flame stretch rate as stated by Shoshin and Goey (2010). This would make the flame flows slowly through the reaction zone and the interaction between the available flame areas would greatly influence the burning rate as well as the pressure development. It is worth noting that, since low hydrogen content in methane-air mixture, the numerical diffusion in FLACs code limit the hydrogen diffusivity yet reduces the burning rate, as mentioned earlier. This would directly influence the mass burning rate as well as pressure development in the system.

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

The flame propagation profile along the pipe is shown in Figure 5. It can be seen that the influence of bending is more pronounce for hydrogen-methane-air mixture explosion, about 2 times higher at the bend configuration. It can be said that the instability of thermal diffusivity in hydrogen-methane air mixtures is the main factor leading to increase of flame stretch, and this subsequently would increase the flame surface area sharply. The distortion of flame surface area makes the interaction of fuel and oxygen more fully, and the diffusion will be more uniform, which leads to the increase of heat release rate and the acceleration of the flame propagation velocity. The increasing flame speed creates pressure waves and influences the flame front to expand. It is worth to acknowledge that the form of flame front will be different as it approaches and passes the bending, and does cause an initial acceleration of the flame.

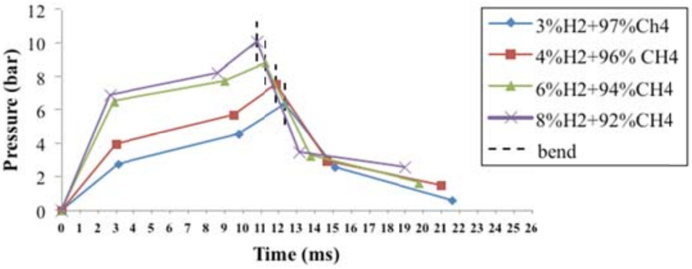

Figure 4: Pressure -Time profile of hydrogen-methane/air mixtures in 90-degree pipeline. Dashed line indicates the bending position(Emani et. al., 2013)

This coupling effect of bend and thermal diffusivity would suggest that the hydrogen enrichment to methane/air mixture gave the dramatic increasing in the mass-burning rate of the flame and turbulent intensification, leads to maximum overpressure and flame speed. However, the maximum flame speed was obtained after bending for FLACs simulation, opposite of experimental result (Refer to Figure 5). It can be speculated that the turbulent flow associated with the flame interaction at the bending will lead to higher burning rate and magnification of the pressure amplitude downstream of the pipe (Pedersen and Middha, 2012), giving flame speed at the highest of 614 m/s at 8 % hydrogen-methane/air mixtures for FLACs simulation. However, the flame acceleration profile is well reproduced.

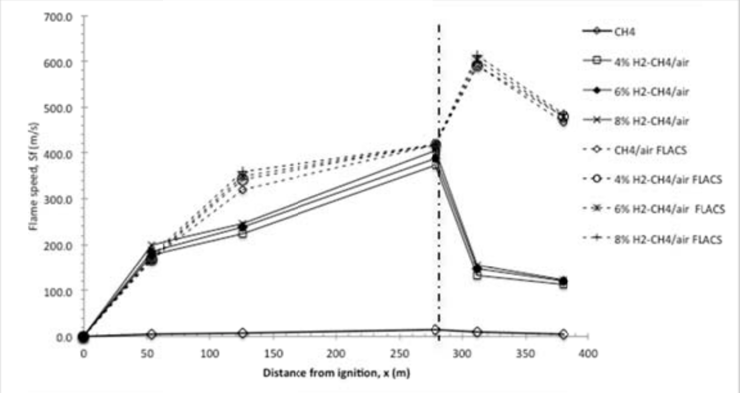

Figure 5: Experimental measurements and FLACs simulation on flame speed as a function of distance from ignition. Dashed line indicates the bending position.

5. Final remarks

CFD code FLACSs simulation have been performed and analysed on the effect of bend pipe configuration. The numerical modeling are under predicted the experimental result on predicting the overpressure of hydrogen-methane/air explosion, about 30 – 70 % limit of discrepancy. However, the simulation seems to reasonably agree well with experiment on flame speed, suggesting that flame model k- ε may be used to estimate the flame propagation in different pipe configuration. Some future improvements could be implemented into the code to overcome the diffusivity constraint, for example more sophisticated turbulence models like RNG or Realizable versions of the k– ε model currently implemented, in order to reproduce flame acceleration observed experimentally in a better way in the obstacles region. From the study, it shown that the coupling effect of bending and thermal diffusivity gave the dramatic influent of explosion severity in hydrogen-methane/air at lean concentration. In practical application, bends in pipework system should be taken into account as part of safety analysis and considered when placing explosion protection devices such as flame arresters or venting devices.

Acknowledgements

This research study was supported by the Universiti Teknologi Malaysia for funding this research under GUP vote no Q.J130000.2642.06J66 and The Gas Technology Centre (GASTEG)-UTM, Malaysia.

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