Experimental study on premixed hydrogen/air and hydrogen–methane/air mixtures explosion in 90 degree bend pipeline

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A B S T R A C T
Nowadays, hydrogen is being utilized massively in industries as a clean fuel. Displacing of hydrogen due to unique chemical and physical properties has adversely affect on pipeline network, hence increases the potential risk of explosion. This study was carried out to determine the flame propagation of hydrogen/air and hydrogen–methane/air mixtures in pipeline. A 90° pipeline with L/D ratio of 40 was used. Pure hydrogen/air mixture with equivalence ratio, \( \phi = 0.13, 0.17, 0.2, 0.24, 0.27 \) and 0.30 were used in this work. Different composition of hydrogen–methane–air mixtures were tested in this study i.e. 3% \( \text{H}_2 + 97\text{CH}_4 \), 4%\( \text{H}_2 + 96\text{CH}_4 \), 6%\( \text{H}_2 + 94\text{CH}_4 \) and 8%\( \text{H}_2 + 92\text{CH}_4 \). All mixtures were operated at ambient condition. The results show that bending is the critical part of pipeline and higher concentration of hydrogen can affect on maximum overpressure, flame speed and temperature rise of both pure hydrogen/air and methane-hydrogen/air mixtures.

1. Introduction
Hydrogen-enrichment has been recognized as a useful pattern to overcome problems associated to turbulent premixed combustion of natural gas in different systems [1–7] which it would change the fuel-air combustion behavior, namely laminar burning velocity and flame stability dramatically [1,8]. Xiao [9] analyzed the premixed hydrogen/air flame propagation in a horizontal rectangular closed duct. The work resulted that the flame speed decreased rapidly, inducing more turbulent combustion when the flame front develops closer to the side walls. Cammarota et al. [1] studied the explosion behavior of stoichiometric hydrogen-enriched methane/air (with 10% of hydrogen molar content in the fuel) and pure methane/air mixtures in a 5 L closed cylindrical vessel at different initial pressures. In their study, the low hydrogen content has negligible effect on the flame reactivity and the deflagration index as well as the burning velocity on the overpressure. It is also found that the burning velocity decreases with the initial pressure, yet, this effect being less pronounced in the case of the hydrogen-enriched flame.

On the other hand, studies showed that the effect of hydrogen substitution to methane in terms of maximum rate of pressure rise or laminar burning velocity for any initial...
pressure is quite dramatic [10,11]. The addition of hydrogen to methane gives considerably the flame stability, wide flammable regions and relatively higher burning velocity, thus a good replacement for hydrocarbon fuels. In addition, the hydrogen presence affects the flow field in both quantitative and qualitative terms [11,12]. As the value of hydrogen increases in mixture, the velocity of the toroidal vortex increases [12]. However, the safe use of hydrogen—methane as alternative fuel on the pipeline is still unclear.

The transportation of the hydrogen from manufacturing to end users could affect the integrity or durability of the pipeline network therefore the existing gas pipeline network are designed, constructed and operated using natural gas. The hydrogen would also mix with natural gas once introduced into the pipeline. Hence, for the safe use of hydrogen fuels, it is essential to fully characterize and quantify their explosion behavior. The leakage and failure in the gas pipelines carrying a massive volume and tremendous pressure of hydrogen could also become a potential catastrophic incident leading to severe casualty and cost [2]. The effect of obstruction, junctions and bends that normally integrated in piping design would create issues associated with reaction location and the flame stability [3,8].

For authors’ knowledge, there is sparse experimental studies have been carried out in micro scales [9,13], particularly in 90° bend [14–17]; hence, this study was carried out focusing on the flame propagation of hydrogen/air and hydrogen—methane/air mixtures explosion in 90° pipelines in order to investigate the physical and dynamic characteristics (e.g. maximum pressure, rate of pressure rise, temperature changes and flame speed) of these gas/air mixtures explosion.

2. Methodology

A 90° pipeline, with 3 m long in horizontal, 1 m in vertical and 0.1 m diameter, with L/D ratio of 40 was used in this study (Fig. 1). The pipeline is 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. The mixtures were ignited at the center of entrance point of pipeline. The flammable mixture was initiated by an electrical spark, which gives 16 J energies for the gas explosion tests.

The history of flame propagation along the pipeline was recorded by an axial array of mineral insulated, exposed thermocouples. The average flame speed between two thermocouples was determined and ascribed to the mid-point of the distance between the thermocouples.

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The pressure at various points along the length of the pipe was recorded using piezoelectric pressure transducers (Keller Series 11). A 14 channels transient data recorder was used to record and process all the data via LabView (Software National Instrument Company). Each explosion was repeated at least 3 times for accuracy and reproducibility.

Only low concentrations of hydrogen and hydrogen—methane mixtures were utilized in this study. For pure hydrogen-air mixture, equivalence ratio of 0.13, 0.17, 0.2, 0.24, 0.27 and 0.3 were used. Different concentration of hydrogen—methane—air mixtures were prepared in this experiment i.e. 3%H2 + 97CH4, 4%H2 + 96CH4, 6%H2 + 94CH4 and 8% H2 + 92CH4. Moreover, methane, hydrogen and oxygen initially stored at different storage tank and kept at higher pressure than mixer vessel to facilitate gas flow from tank into the mixer vessel. Mixing cell was used for forming the methane-hydrogen/air and hydrogen/air mixtures by considering partial pressure method so a homogeneous composition was achieved.

3. Result and discussion

Fig. 2 shows the pressure profiles against the distance from ignition in 90° bend pipe. The vertical dotted line on the graph indicates the bending position. It can be seen that the pressure increased gradually while approaching the bending before sharply decreased after the bend due to the flame propagation obstructed by the closed end as well as heat losses [14]. It was observed that with enhancement of 8% H2 v/v into methane—air mixture, the maximum pressure obtained was 10 bars, about 1.2 bars higher than maximum overpressure of pure H2—air mixture, as illustrated in Fig. 2. It can be depicted that the mass-burning rate of the flame has clear effect on pressure rising due to the larger flame area of the spherical flame for both mixtures. This would create more turbulence as well as higher overpressures regarding to the faster flame speeds in the pipe. On the basis of maximum overpressure of pure H2/air mixtures, it can be said that the enhancement of H2 concentration into methane-hydrogen/air leads to the dramatic increasing of maximum overpressure. The closed end pipelines also increase the pressure development at the regimes of flame propagation because it acts same as same as obstacles.

The reactivity of explosion on methane-hydrogen/air mixture has been studied in different vessels [1,10,11,19–22]. It was observed that by increasing the percentage of hydrogen in mixtures, the overpressure values increased slightly. It can be said that the additional of hydrogen content in methane—air mixtures could increase the burning velocity and thus, giving higher overpressure, especially at the bend area. Even though the result obtained in this study has a good agreement with previous works, yet, the value of overpressure increased dramatically in 90° bend [14].

Furthermore, it seems that the addition of hydrogen into the methane/air mixtures would speed up the reaching time of the flame to the bending section about 5 ms, as compared
with pure hydrogen. However, it is interesting to note that the time variance to reach the end pipe on either pure hydrogen or methane-hydrogen is negligible (Fig. 3).

Fig. 4 illustrated the rate of pressure rise as a function of distance from the ignition, with the reference point at the bend. The significant profile of $\frac{dP}{dt}$ was observed on 6% $H_2 + 94%CH_4$, 8%$H_2 + 92%CH_4$, 8%$H_2$ and 9%$H_2$. This phenomenon is in good agreement with previous study [14] due to the release of energy and chaotic combination of reactivity mixtures by adding more hydrogen to methane–air mixtures. On
the other hand, rate of pressure rise is experienced a sudden decrease after the bend. This is due to flame propagation is obstructed by the closed end, leading to the overpressure to drop significantly. Furthermore, the explosion severity based on pressure rise is shown in Table 1. However, it can be depicted that the $K_G$ (deflagration index for gas explosion severity) values obtained was increasing with the increase of hydrogen percentage in the mixtures; although it can be considered as weak severity. Moreover, since $K_G$ value depends on initial condition, mixture concentration and properties, it is lower than pure methane in Sphere Apparatus System [23].

Flame speed profile against the distance from ignition was shown in Fig. 5. A significant rate changes can be seen in flame acceleration along the centerline of the pipe due to different fuel concentration [24]. The highest flame speed is 406 m/s on 8%H$_2$ + 92%CH$_4$ mixtures which is observed at the bend, almost two times higher, as compared to the flame speed of a very lean concentration of 3%H$_2$ + 97%CH$_4$ i.e. 178 m/s. By taking maximum flame speed for pure hydrogen as a basis, it can be seen that it is about 1.33 times increment of flame speed in additional of hydrogen into the mixtures. This confirms the previous results of Phylaktou et al. [12] and Zhu et al. [24]. They indicated that higher gas concentration increase the heat released by the reaction which increase flame speed.

In other words, adding more hydrogen to mixtures resulted in significantly earlier times of flame arrival to 90° pipeline (Fig. 3), same as rig enclosure [8] and plenum chamber [25], giving higher flame speeds for both pure hydrogen/air and methane-hydrogen/air mixture as concluded by Hu et al. [26]. The acquiesced data showed that while the flame speed reached to the maximum value at the bend, it declined dramatically after the bend. The flame speed losses suffered

<table>
<thead>
<tr>
<th>Mixture</th>
<th>$dP/dt_{max}$ (bar/s)</th>
<th>$V^{(1/3)}$ (m)</th>
<th>$K_G = (dP/dt)_{max}V^{(1/3)}$ (bar.m.s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3%H$_2$ + 97%CH$_4$</td>
<td>51.25</td>
<td>0.09</td>
<td>4.6125</td>
</tr>
<tr>
<td>4%H$_2$ + 96%CH$_4$</td>
<td>63.55</td>
<td>0.09</td>
<td>5.7195</td>
</tr>
<tr>
<td>6%H$_2$ + 94%CH$_4$</td>
<td>77.85</td>
<td>0.09</td>
<td>7.0065</td>
</tr>
<tr>
<td>8%H$_2$ + 92%CH$_4$</td>
<td>93.16</td>
<td>0.09</td>
<td>8.3844</td>
</tr>
<tr>
<td>3.9% H$_2$</td>
<td>40.54</td>
<td>0.09</td>
<td>3.6486</td>
</tr>
<tr>
<td>5.1% H$_2$</td>
<td>52.34</td>
<td>0.09</td>
<td>4.7106</td>
</tr>
<tr>
<td>6.0% H$_2$</td>
<td>64.53</td>
<td>0.09</td>
<td>5.8077</td>
</tr>
<tr>
<td>7.2% H$_2$</td>
<td>76.34</td>
<td>0.09</td>
<td>6.8706</td>
</tr>
<tr>
<td>8.1% H$_2$</td>
<td>87.74</td>
<td>0.09</td>
<td>7.8966</td>
</tr>
</tbody>
</table>
at the bend are caused by both friction and momentum exchanges resulting from a change in the direction of flow. Interestingly, the recorded maximum flame speeds in this study are different in comparison with previous studies for pure hydrogen in 90° bend [17,27]. This difference can be result of different experimental rig design.

4. Conclusion

Regarding to importance of hydrogen and hydrogen–methane mixtures as a fuel carriers, this study was conducted to determine the maximum pressure, rate of pressure rise, flame speed and temperature changes of hydrogen/air and methane-hydrogen/air mixtures in 90° bend pipeline in ambient pressure and temperature. The findings showed that:

1. due to intense fluctuation of flame speed and pressure, it is observed that bending is the critical part in the pipeline. Accordingly, the potential risk of failure in pipeline becomes more probable at this part,
2. higher concentration of hydrogen in both pure hydrogen/air and methane-hydrogen/air mixtures can affect dramatically on maximum overpressure and flame speed,
3. higher explosion reactivity can be seen in methane-hydrogen/air mixture regarding to changes of explosion mechanism properties of methane/air mixture.
4. the explosion severity based on pressure rise has low significant effect on lower concentration of both hydrogen/air and methane-hydrogen/air mixtures in 90° pipeline.

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References


