NATURAL GAS COMBUSTION INSIDE A CONFINED VOLUME CHAMBER USING GAS-JET IGNITION METHOD

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ABSTRACT: The demand for natural gas is increasing since recent climate change. Natural gas is considered an abundant energy source with low greenhouse-gas emissions. A natural gas engine usually operates in lean-burn mode to gain the advantage of high thermal efficiency and low nitrogen oxides emission. A problem typically associated with natural gas combustion in lean mode is poor ignitability. The objective of this study is to improve ignitability of lean natural gas combustion using gas-jet ignition method. Several experiments were done using a confined volume chamber apparatus. Images of the combustion flame were captured using a high speed camera, and hydrocarbon emissions were measured. The result showed that the gas-jet ignition method is effective in improving ignitability of lean natural gas mixture. An addition of 30% hydrogen gas to the natural gas fuel improves both the ignitability and further flame propagation, thus lowering the hydrocarbon emission.

KEYWORDS: *Natural Gas, Hydrogen, Combustion, Gas-Jet Ignition*

1.0 INTRODUCTION

Recent climate change due to global warming have led us to search for sustainable energy sources with the lowest possible greenhouse-gas emissions. Our main energy, which is sourced from fossil fuel is increasing in demand due to the world development and technology advancement. According to 2013 International Energy Outlook report, we require 56% more energy in 2040 than in 2010 [1]. The report projected that demand on oil and coal will decrease while demand on renewable energies and natural gas will increase. The increase in demand on natural gas not because it is renewable, but because it has abundant reserved capacity and has the lowest average specific carbon dioxide emission among the non-renewable fossil fuel energy resources [2]. As of January 2009, World Proved Reserves of Oil and Natural Gas stated that the world natural gas reserved has the capacity of 6,342 trillion cubic feet, in contrast to oil reserved that has the capacity of 1,342 billion barrels [3, 4].

2.0 PREMIXED VS GAS-JET IGNITION METHODS

A CNG engine usually operates in lean mode where the equivalence ratio is between 0.7 and 1.0, to gain the advantage of high thermal efficiency and low NOx emission [5, 6]. Within those operating range, a premixed ignition method is typically used to combust the air-fuel mixture. Using this method, fuel is injected late in the induction stroke and early in the compression stroke. This type of fuel delivery is most suitable for high load operation, i.e. stoichiometric equivalence ratio or higher. From previous work of [7, 8] it is known that the lean combustion operating limit for this type of fuel delivery is ϕ=0.6 to 0.8.

Another well-known problem in lean-burn CNG engines is poor ignitability [9-11]. The gas-jet direct ignition concept was pioneered by Kamoto et al. [12] and Kidoguchi et al. [13] to overcome the ignitability problem. The basic idea of this concept is to ignite the gaseous fuel when combustible mixture is locally available in the vicinity of ignition position. This normally happens during or slightly after injection. To realize this idea there are many parameters need to be considered such as;

- type of fuel
- injector design
- injection pressure
- injection duration
- ignition position
- ignition timing
- ambient pressure
- ambient temperature
- air motion

The method of combining a gas-jet ignition with an early fuel injection is named the gas-jet ignition with a two-stage injection. At globally lean combustion, the gas-jet direct ignition supplies a stratified fuel-air mixture, where the combustible mixture is locally available in the vicinity of ignition position. The gas-jet ignition setting is usually fixed while the first injection timing and duration are changed to suit the desired mixture equivalence ratio. The timing diagram for this method is shown in Figure 1(a).

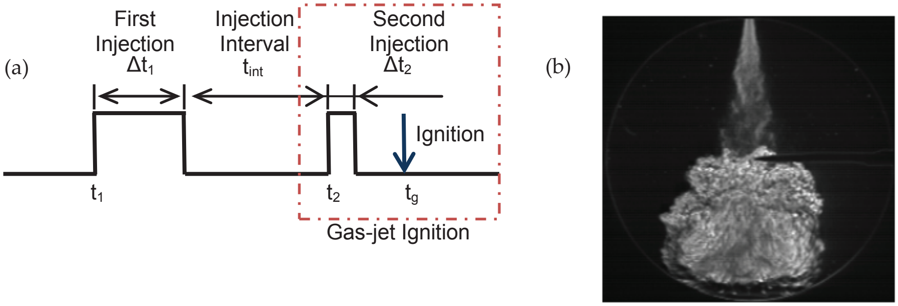

Figure 1: (a) Signal timing diagram of the two-stage injection with gas-jet ignition; (b) Schlieren image of an earlier work of gas-jet ignition experiment [13]

The gas-jet ignition method employs late injection timing which is very near to the ignition timing. The ignitability of the first flame core relies on local fuel-air mixture concentration near the ignition position. Too rich or too lean local mixture will cause the first flame core to quench before it begins to propagate to other parts of the combustion chamber[14, 15]. Due to this, the lean burn gas-jet ignition method sometimes unstable and produces misfires. The purpose of this study is to investigate the cause of cyclic variations of the gas-jet ignition, and whether the addition of hydrogen can improve the combustion stability.

3.0 EXPERIMENTAL METHOD

Without proper equipments, it is difficult to observe flame development in a real engine. In this study, the combustion flames were recorded using a confined volume chamber (CVC) apparatus. Figure 2(a) shows an experiment setup for observing flame development inside the CVC. The CVC was inserted with several parts so that the volume cavity inside the chamber is similar to the test engine at top dead center (TDC), which has a clearance height of 2.5mm. A transparent Pyrex glass was installed on only one side of the chamber to allow visibility for flame observation.

Section A-A in Figure 2(b) shows the layout of the gas injector and spark plug with respect to the CVC volume cavity. The gas injector was installed at the top of the CVC. Two types of fuel, CNG and CNG with hydrogen addition, were supplied via a fuel accumulator. The fuel was regulated at 3.0MPa.

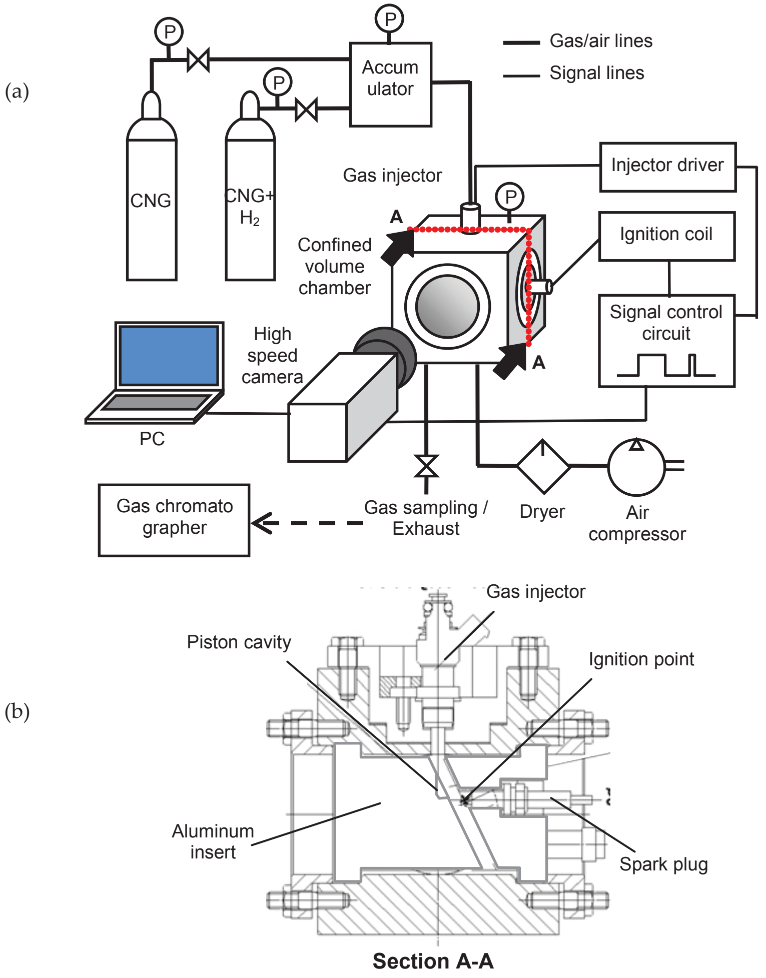

Figure 2: (a) Experiment setup for combustion flame imaging; (b) cross-section of the confined volume chamber [16]

A high-speed camera (NAC, Memrecam GX-1) was used to capture images of flame development as seen through the transparent glass window. All the images were shot in the dark to prevent ambient light interference to the flame observations. The camera was attached with 50mm f/1.4 manual-focus lens. The optimum recording setting for this experiment was at 10,000fps and shutter speed of 97μs.

For every experiment, the chamber was filled with fresh air from a compressor until the pressure was 1.2MPa. The test started soon after the air inside the chamber reached a quiescent state, which took about 3 seconds. The quiescent state of air inside the chamber was verified prior to this study using a Schlieren imaging technique. The combustion products were collected using several gas sampling bags. The gas samples were analyzed for hydrocarbon composition by Flame Ionization Detector (FID) method using a gas chromatography equipment (J-Science Lab, GC7000TF).

The gas-jet combustion timing diagram of this test is shown in Figure 1(a). The first injection was delivered early and separated from the gas-jet ignition with an injection interval, t_{int}. The duration of the first injection, Δt_1 was varied depending on the bulk equivalence ratio, ϕ which corresponds to the engine operation load. The gas-jet ignition combines second gas injection with ignition. The second injection timing t_2 was carried out at 1.11ms before the spark ignition timing tg with fixed injection duration Δt_2 of 0.36ms simulating the engine test. Timing, $t_g – t_2$ and duration, Δt_2 were optimized similar as in engine test to support ignitability. Fuel quantity of the second injection corresponded to bulk equivalence ratio of $\phi=0.02$.

4.0 RESULTS AND DISCUSSION

In the previous studies by the authors, it is suggested that flame development of the first flame kernel of the gas-jet ignition is the key factor causing unstable combustion, misfires and high THC emission. In this study, flame development of the gas-jet ignition with two-stage injection was observed in a CVC. As mentioned earlier, the CVC has a volume cavity similar to the test engine at TDC. A visible zone of this optical system represents the clearance space of 2.5mm as illustrated in Figure 3. Following the gas-jet ignition process, the initial flame ignited by the spark grows in the upper volume, and then develops into the visible zone of the clearance volume.

Figure 3 also contains samples of images obtained using CNG fuel at $\phi=0.2$ with injection interval of $t_{int}=15$ms. These images are arranged from top to bottom in a sequential manner at 0.5ms interval from 0.5ms after the spark until 6ms after the spark. These are the raw images obtained directly from the high-speed camera. On the left column are images of pure CNG combustion flame, and on the right column are images of CNG combustion with an additional of 30% hydrogen gas.

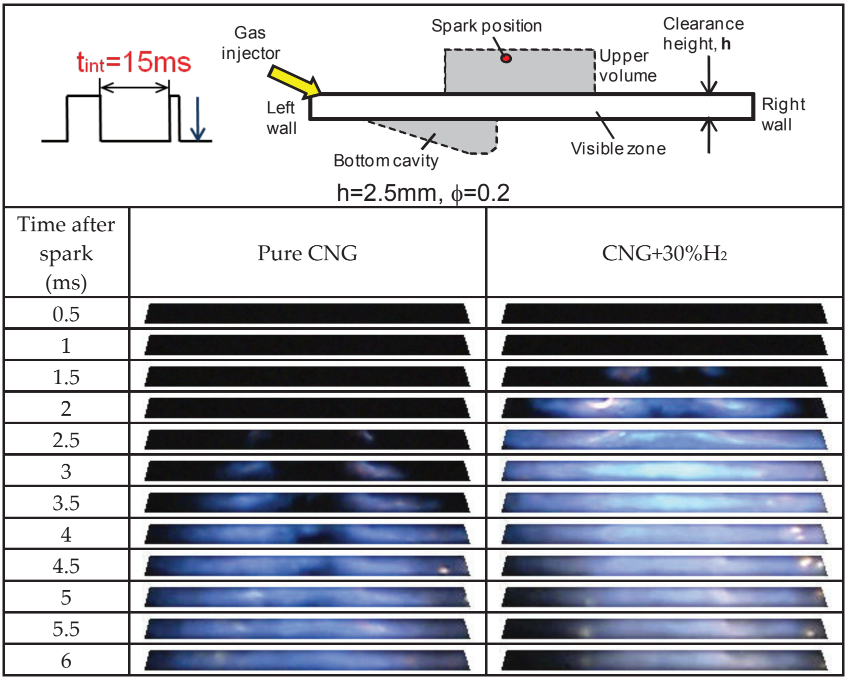

Figure 3: Flame visualization captured using a high speed camera

Through observing the images, the first visible flame indicates that the flame begins to propagate from the upper volume before moving towards the clearance space. Time elapsed between the ignition and the first flame observation tells about the average speed of flame kernel formation and growth in the upper volume region. Whereas, time elapsed between the first flame observation and the flame tip reaches the right wall gives information about the rate of flame development into the narrow clearance space.

Image processing and data analysis were done by converting the raw images into binary images. The right-end and left-end of the binary domain were used as the flame tip, and movement speed was computed from time of position change. Figure 4 shows the results of the visible flame analysis for pure CNG fuel and CNG with 30% hydrogen addition in chamber height of h=2.5mm. In this figure, only two injection interval cases were selected, t_{int}=5ms and t_{int}=15ms. Time that the flame was first observed is expressed with symbols □ and ▷, while symbols ■ and ▶ represent the time that the flame front reaches the right-end of the wall. The flames were observed between these two symbols.

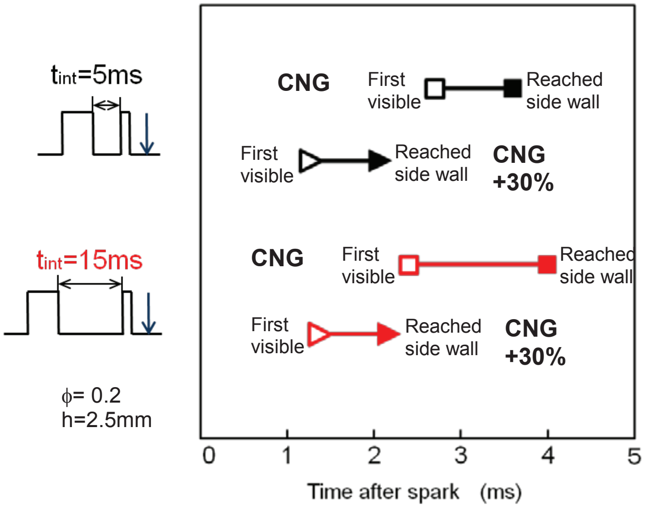

Figure 4: Flame propagation analysis

In the combustion of pure CNG, short injection interval t_{int}=5ms showed a longer delay of the first visible flame compared with long t_{int}=15ms. The cause of this delay is short t_{int} creates relatively rich mixture in the upper volume. It slows initial flame development, causing significant delay in flame exiting from the upper volume. In contrast, long t_{int}=15ms showed a relatively slower time in reaching the right-end of the wall than short t_{int}=5ms. With a lean bulk equivalence ratio of ϕ=0.2, long t_{int} creates a high percentage of over-lean mixture in the clearance space thus slows the flame propagation towards the cylinder wall.

The addition of 30% hydrogen into the CNG fuel produced almost two times faster first visible flame for both short and long injection interval, as compared to pure CNG combustion. The time taken for the flame to reach the right-end wall was also shortened for both injection intervals. From these results it is confirmed that the hydrogen addition improves both initial flame development and further flame propagation.

Next, samples of the combustion products from the CVC were collected and their THC levels were measured using a gas chromatography equipment. Figure 5 shows THC index of the combustion of pure CNG at an equivalence ratio of ϕ=0.2 to 0.5 and within the maximum interval time of 15ms. The THC index values shown in the figure were calculated as follows:

$$\text{THC Index} = \frac{\text{THC}_{\text{out}} \times \text{Combustibility\%} + \text{THC}_{\text{in}}(1 - \text{Combustibility\%})}{\text{THC}_{\text{in}}}$$

The term combustibility found in the THC Index formula is defined as the percentage of successful number of tests that the chamber pressure raises over 1.5MPa from maximum cylinder compression pressure, to the total number of tests performed. Please take note that the maximum cylinder compression pressure is 1.2MPa without ignition and combustion. The combustibility is calculated as follows:

$$\text{Combustibility} = \frac{\text{No. of tests with p>1.5MPa}}{\text{No. of tests}}$$

From Figure 5, the THC Indexes at equivalence ratio ϕ=0.4 and 0.5 were equal to unity due to misfires and 0% combustibility. The THC Index at ϕ=0.2 was higher than ϕ=0.3 although we obtained 100% combustibility with injection intervals t_{int}=8 to 13ms during experiment. In contrast, the THC Index at ϕ=0.2 was lower than ϕ=0.3 with t_{int} shorter than 7ms. It indicated that bulk lean mixtures have performed better with short injection interval where locally rich mixture accumulated near the ignition position and favored the flame kernel development. In contrast, with long injection intervals, the fuel from the first gas injection dispersed throughout the chamber, creating a relatively homogeneous mixture that is leaner than the lean limit of CNG fuel.

Next, the THC Indexes of mixed fuel CNG+30%H2 were measured and the results are shown in Figure 6. The combustions at ϕ=0.2 were improved with both short and long injection interval. However the reduction of THC was more obvious with short injection interval than long injection intervals. Hydrogen addition supports the combustion of a local rich mixture better than "leaner than lean limit" mixture.

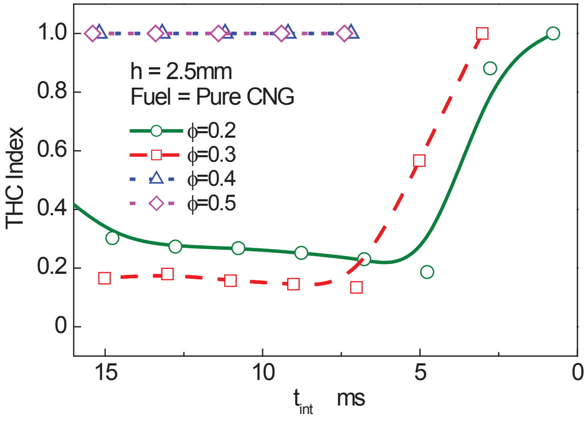

Figure 5: THC Index of pure CNG (h=2.5mm)

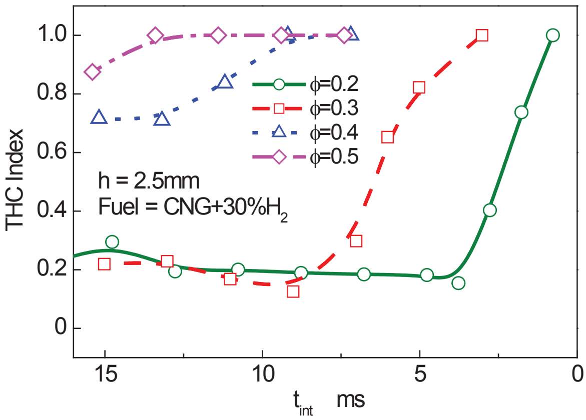

Figure 6: The THC Index of CNG with 30% H2 addition (h=2.5mm)

At ϕ=0.3, with hydrogen addition was not able to improve the THC emission. The THC emitted from the pure CNG combustion (Figure 5) is slightly lower than CNG with hydrogen addition, with both short and long injection intervals. However, using the mixed fuel, we obtained a single injection interval that showed the best THC Index. It suggested that in narrow space combustion, at certain equivalence ratio, the addition of hydrogen may increase the sensitivity effect of the injection interval on the THC emission.

Overall, the addition of hydrogen to the CNG fuel improved the combustion at any equivalence ratio, thus producing relatively lower THC Indexes. Lower THC Indexes were obtained in a wider range of injection intervals t_{int}. Hydrogen addition lowers the THC Index even at relatively shorter t_{int} than pure CNG. It suggested that the addition of hydrogen helps the combustion of CNG fuel and able to reduce the effect of injection interval duration.

5.0 CONCLUSION

This paper presented the experiment of CNG combustion using the two-stage injection with gas-jet ignition method. The experiment was done using a confined volume chamber to mimic an actual gas engine at TDC. It was found that long injection interval, helps faster initial flame development, but slows flame propagation towards the side wall. The addition of hydrogen to the CNG fuel improves initial flame development and flame propagation. The addition of hydrogen also improved the combustion at any equivalence ratio, thus producing relatively lower THC Indexes. Lower THC Indexes were obtained in a wider range of injection intervals.

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