Effect of Gas-jet Ignition Technique on the Extension of CNG Lean Combustion Limit

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Abstract. Lean combustion of CNG has the advantage of high thermal efficiency and fewer pollutants than other fossil fuels. However, problems such as ignitability, cyclic variation and high THC emission were common at combustion leaner than equivalence ratio $\phi=0.7$. The application of gas-jet ignition method to lean combustion was able to address such problems. This paper introduces the concept of gas-jet ignition method, which ensures ignitability at lean bulk equivalence ratio. Moreover, this method is applied to a real CNG engine. Results of engine performance experiment shows that two-stage injection method combined with gas-jet ignition has successfully widen the operating range of a CNG engine from low to high load at corresponding $\phi=0.17$ to 1.1.

Introduction

Concern about our energy sources sustainability is growing due to recent drastic climate change. Harnessing renewable energy is an appropriate measure in sustainable development, but fossil-fuel energy still dominates our energy chain sources even in the near future. Natural gas, although not renewable, combusts efficiently and produces far fewer pollutants than other fossil fuels. A compressed natural gas (CNG) engine usually operates at equivalence ratio between 0.7 and 1.0; however lean combustion is required to achieve high thermal efficiency and low nitrogen oxides (NO\textsubscript{x}) emission \cite{1,2}. Lean burn system employs air/gas mixture that has more air than the stoichiometric ratio in the combustion cylinder. Problems such as ignitability, cyclic variation and high total hydrocarbon (THC) emission were common for combustion leaner than equivalence ratio 0.8 \cite{3,4}. The gas-jet direct ignition is one of countermeasures to improve ignitability at lean combustion \cite{5}. The purpose of this study is to extend the stable lean operating range of the CNG engine with less toxic emission by applying the gas-jet ignition method.

Concept of Gas-jet Ignition Method

The basic concept of the gas-jet direct-ignition is to ignite the gaseous fuel during or slightly after injection. Early studies on the gas-jet direct-ignition concept began in 2002 by Kidoguchi \textit{et al.} \cite{5}. The purpose of gas-jet ignition is to ensure ignitability of CNG at lean conditions. The technique is to form combustible mixture locally at spark position in spite of globally lean condition. The initial flame can well propagate by the supply of the following injected fuel.

First, the essential points of gas-jet ignition were fundamentally investigated with a constant volume chamber (CVC) experiment. Fig. 1 shows experimental setup to observe gas-jet injection and flame development using Schlieren photography technique. The CVC has a capacity of 613cc and 70mm in diameter of observation glass windows. The gas fuel injector was installed at the upper part of the chamber, and an ignition point of a spark plug was set at 35mm downstream of outlet of the gas injector. The ambient condition in the CVC was quiescent air with room temperature and pressure of 0.75MPa. A high-speed digital video camera (Kodak, Ektapro HS4540) was used to capture Schlieren.
images of the gas-jet at 9,000 fps. The gas fuel injection period was constant at 10 ms, and ignition was performed at the time $t=0$ i.e. when the gas jet reaches the spark electrodes. Schlieren images of the gas-jet injection are shown in Fig. 2. The gas-jet spray appears in shades of gray in contrast with dark background. The combustion flame appears in distinctly brighter color. At low injection pressure $p_j = 1.0 \text{ MPa}$, the gas-jet is ignited, at $p_j = 1.4 \text{ MPa}$ quenched, and at $p_j = 1.6 \text{ MPa}$ misfired. For low speed gas-jet with $p_j = 1.0 \text{ MPa}$, the flame starts to develop immediately after ignition below the center of the electrodes. The flame continued to develop downstream. However, for gas-jet with $p_j = 1.4 \text{ MPa}$, the initial flame kernel is observed after ignition but it failed to develop. The flame kernel is quenched at the bottom part of the chamber. On the other hand, no visible flame kernel is observed for high speed gas-jet with $p_j = 1.6 \text{ MPa}$. It is considered as misfired. Analysis of gas-jet velocity indicates that the gas-jet stream speed is important factor to achieve stable combustion when applying the gas-jet direct ignition method in a real engine. It is necessary to control the gas-jet stream speed near the ignition position. Next, the effectiveness of multi-stage injection for CNG combustion stabilization is explained. Fig. 3 shows four ignition positions studied in a constant volume combustion chamber; (1) the STD ignition position which is at 35 mm downstream of the injector outlet, (2) US which is 6 mm downstream the gas injector nozzle but has a 5 mm offset from the center of the nozzle axis, (3) UC without bluff body, which is 12 mm downstream the gas injector nozzle, and (4) UC with bluff body, which has one of the electrodes that obstructs the downstream path of the gas-jet. Because of the 5 mm off center, the US ignition position has the lowest gas-jet stream velocity compared with other ignition positions. The fuel injection methods are single injection and multiple injections as shown in Fig. 4. The total injection time was 10 ms for both single injection and multiple injections. For the single injection, the gas-jet was ignited at the time when the fuel jet stream first reaches at the STD or US ignition position. For the multiple injections the fuel was delivered in 3 pulses over the 10 ms total injection period. In the multiple injections, ignition at UC is performed after injecting small amount of fuel by the first pulse injection. The first step is to create flame kernel and the other two-steps making it burn by supplying fuel in a fully grown-up flame.

![Diagram of equipment setup for gas-jet Schlieren imaging](image)

**Fig. 1** Equipment setup for gas-jet Schlieren imaging

![Schlieren images of gas-jet fuel injection](image)

**Fig. 2** Schlieren images of gas-jet fuel injection
Fig. 5 shows the ignition probability IP of changing the injection method and an ignition position relative to the injection pressure \( p_i \). From the figure, if the injection pressure becomes high and the gas-jet stream speed increases, ignition probability will decrease. However, 100% ignition probability is obtained at higher injection pressure by multiple injections compared with single injection. When especially the gas-jet stream decreases in speed using the electrode in the case of UC with Bluff body, the ignition probability of 100% can be maintained up to \( p_i=3.0 \text{MPa} \). Stable gas-jet combustion is obtained as shown in the real image by performing the three-step-pulse injections. For the gas-jet ignition, fuel supply after ignition is important to control initial flame propagation.

![Fig. 3 Layout of gas injector and ignition position](image)

![Fig. 4 Fuel delivery and ignition methods](image)

![Fig. 5 Effect of multiple-injection and ignition position on ignitability of gas-jet ignition method](image)

Application of Gas-jet Ignition Method on CNG Engine

The test engine used in this study is a prototype 2-cylinder Z-crankshaft engine [6] with specifications shown in Table 1. During the experiment, the engine speed and the injection pressure were kept at 900rpm and 3MPa respectively. Data from the encoder signals and pressure transducer were recorded via an A/D converter. An exhaust gas analyzer (Horiba, MEXA-1500D) was used to measure the exhaust gas emission in real time. CO and CO\(_2\) concentrations were measured by Non-dispersive Infrared Absorption method. The THC emissions were measured by Flame Ionizer Detector method using a gas chromatograph (J-Science Lab, GC7000TF). The combustion chamber layout in Fig. 6 shows the gas injector, which is inclined at 25\(^\circ\) from the lower face of cylinder head. The gas injector, the piston cavity and the spark-ignition position are coplanar. The piston cavity guides the gas-jet toward the spark position and also has an effect of decreasing jet velocity. The combustion chamber has a 7mm-height upper volume that serves as a clearance for the intake and exhaust valves displacement. The piston clearance height at top dead center (TDC) is 2.5mm. Fig. 7 shows the gas-jet spray images captured using Schlieren photography technique by a high-speed camera in a CVC experiment. The CNG spray injected from the injector was guided by the piston cavity towards the spark position. The fuel just arrived at the spark position at \( t=1.11 \text{ms} \) after start of injection and at \( t=1.54 \text{ms} \) the fuel continued to be supplied towards the spark position while some part of it had spread away from the spark position.
At present there are three types of fuel delivery and ignition method for CNG direct injection engines [7]: (a) premixed-type ignition, (b) gas-jet ignition, and (c) gas-jet ignition with two-stage injection. Their timing diagrams are shown in Fig. 8. For this study, the ignition timing was fixed, \( \theta_g = \text{TDC} \). Using the premixed-type ignition, fuel is injected early at -170\(^\circ\)ATDC. Using the gas-jet ignition, fuel is injected at -6\(^\circ\)ATDC near the ignition timing, which forms combustible mixture around spark position at time of ignition \( \theta_g = \text{TDC} \) with keeping gas-jet velocity low. Using the two-stage injection, the first injection timing, \( \theta_1 \) and its duration, \( \Delta \theta_1 \) are varied depending on the bulk equivalence ratio, \( \phi \). The gas-jet part with second injection cannot have long injection duration because increasing fuel delivery by second injection tends to blow out the initial flame. The second injection timing and duration are same as the gas-jet ignition, namely \( \theta_j = -6\(^\circ\)ATDC \) and \( \Delta \theta_2 = 2\(^\circ\)CA \).

The engine performance using all combination of fuel delivery method against equivalence ratio is shown in Fig. 9. In the diagram, \( \eta \) indicates thermal efficiency, IMEP is mean effective pressure, \( p_{\text{max}} \) is peak cylinder pressure, and COV means coefficient of variance. Typical for premixed-type ignition method, relatively high THC, low CO and NOx emission are obtained in lean condition where \( \phi < 1.0 \). At \( \phi = 0.7 \), combustion becomes unstable showing high cyclic variations as indicated by high COV of IMEP. Thus, the \( \phi = 0.7 \) for premixed-type ignition is treated as lean combustion limit for this engine.

### Table 1 Test engine specifications

<table>
<thead>
<tr>
<th>Engine mechanism</th>
<th>Z-crankshaft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>324cc (2 cylinders)</td>
</tr>
<tr>
<td>Bore × Stroke</td>
<td>68.0mm × 44.6mm</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>7.4</td>
</tr>
<tr>
<td>Injection system</td>
<td>Direct Injection (3MPa)</td>
</tr>
<tr>
<td>Ignition type</td>
<td>Spark Ignition at TDC</td>
</tr>
<tr>
<td>Fuel type</td>
<td>CNG (Type13A)</td>
</tr>
<tr>
<td>Engine speed</td>
<td>900rpm</td>
</tr>
</tbody>
</table>

![Fig. 6 Combustion chamber layout](image6.png)

![Fig. 7 Schlieren images of gas-jet injection](image7.png)

![Fig. 8 Engine fuel delivery and ignition timing diagrams](image8.png)

![Fig. 9 Engine performance using three types of fuel delivery and ignition methods](image9.png)
Applying the gas-jet ignition extends operating range less than $\phi=0.7$. At $\phi<0.3$, reducing equivalence ratio, that is reduction of gas-jet duration, increases COV of IMEP drastically despite little change observed in THC, CO and NOx emissions. Over-lean mixture may produce cyclic variation. Addition of first injection prior to gas-jet ignition can control equivalence ratio from $\phi=0.3$ to $0.7$. As shown in the same figure, the gas-jet ignition with two stage injection method enables the engine to be operated between $\phi=0.35$ and $\phi=0.8$. Fixed gas-jet part by second injection supports ignitability at lean condition less than $\phi=0.7$. However, increasing equivalence ratio (first injection duration) deteriorates CO emission. It is believed over rich mixture tends to be formed near spark plug by the increase of fuel delivery by first injection. The rich mixture may inhibit the initial flame propagation and sometimes cause incomplete combustion. Mixture distribution caused by first injection affects initial flame development. Injection timing of the first injection as well as fuel delivery will be also important factor to form mixture distribution. Engine performance in Fig. 9 shows that the three fuel delivery and ignition methods, i.e. premixed-type ignition, the gas-jet ignition, and the gas-jet with two-stage injection successfully widen the operating range of the test engine from low to high load at corresponding equivalence ratio of $\phi=0.17$ to 1.1.

Conclusions

From this study, the following conclusions were made; Gas-jet ignition method ensures good ignitability of CNG at lean condition. The concept of gas-jet ignition has been accomplished by controlling the velocity of gas-jet near spark position. The application of the gas-jet ignition and two-stage injection to a CNG engine successfully extends the lean combustion limit from $\phi=0.7$ to 0.17. It enables the CNG engine to work in a wider range of operating loads.

References


