LIF Visualization of In-Cylinder Mixture Formation in a Direct-Injection SI Engine

Akihiko Kakuhou, Tomonori Urushihara, Teruyuki Itoh, Yasuo Takagi

Nissan Motor Co., Ltd.
1, Natsushima-Chuo, Yokosuka-City
Japan

ABSTRACT

Flow measurement using a LDV and in-cylinder fuel vapor visualization by laser induced fluorescence (LIF) were performed on a direct injection gasoline engine in which swirl flow was used to achieve charge stratification. The measured results indicate that swirl works to transport the fuel spray to the piston bowl and then to guide the fuel vapor in the piston bowl to the spark plug.

Performance tests were also carried out to determine the area of the fuel injection timing and spark ignition timing for stable combustion. The factors limiting the region of stable combustion were also made clear.

INTRODUCTION

Charge stratification is one way of accomplishing lean combustion which is a principal means of improving the combustion characteristics of SI engines. Researchers attempted early on to develop direct-injection gasoline engines in which the charge would be stratified by injecting fuel directly into the cylinders. In recent years, mixture stratification systems have been devised and adopted in which evaporation of liquid fuel droplets is promoted by initially trapping the fuel spray in a bowl provided in the piston surface and then in-cylinder gas flow is used to transport a well-mixed air-fuel mixture to the vicinity of the spark plug. With these mixture stratification systems, however, the intake port geometry must be modified from that of existing engines in order to generate in-cylinder gas flow suitable for mixture transport.

In a previous report, the authors presented a direct-injection gasoline engine capable of accomplishing charge stratification with minimal modifications made to the intake system of existing engines. As the first step in the present research, a laser doppler velocimeter (LDV) was used to measure the in-cylinder gas flow obtained with the charge stratification system of this engine, and laser induced fluorescence (LIF) was employed to visualize fuel vapor behavior in the combustion chamber. The results revealed the behavior of the fuel in the process from direct injection into the cylinder, to evaporation in the piston bowl, formation of a combustible mixture and transport to the spark plug. In this process, the role played by the in-cylinder gas flow in transporting the mixture in the combustion chamber was made clear. As the next step, performance tests were conducted to determine the range of fuel injection timing and spark ignition timing that would allow stable combustion. A comparison of the factors limiting that range and the mixture visualization results showed quantitatively the conditions needed for achieving good in-cylinder mixture formation.

TEST ENGINE AND MEASUREMENT METHODS

Test Engine

The test engine was a four-valve-per-cylinder unit having a pentroof combustion chamber. Table 1 shows the main specifications of the engine. As illustrated in Fig. 1, a high-pressure fuel injector was installed at the bottom of the intake port and oriented so that the fuel was sprayed toward the cylinder central...
axis. This swirl injector formed a hollow cone spray having a cone angle of approximately 60 deg. The fuel injection pressure was set at 7 MPa. Also as seen in Fig. 1, a nearly round bowl was provided in the piston crown. A swirl control valve was installed at the inlet of the intake port, as shown in the figure. Three types of valves were used to generate different patterns of strong swirl flow.

**Flow and Mixture Distribution Measurement Methods**

In-cylinder gas flow measurement by LDV. A backscattering LDV with a rotary diffraction grating was used to measure in-cylinder gas flow under motoring operation. The state of the in-cylinder gas flow was determined on the basis of average flow velocity patterns obtained by calculating a moving average for 10 crank angle (CA) degrees. As shown in Fig. 2, an optical access engine with quartz observation windows at both ends of the combustion chamber was used in this research to facilitate in-cylinder gas flow measurement and fuel vapor visualization.

**Measurement of steady-state flow characteristics.** An impulse swirl flow meter and an impulse tumble flow meter were fabricated and used to measure the swirl and tumble ratios. A detailed description of the devices is given in a previous report.

LIF visualization of in-cylinder mixture formation. A Kr-F excimer laser operating at a wavelength of 248 nm (400mJ/pulse) was used as the light source to visualize the fuel vapor and droplets. The fuel used was isoctane containing 0.2% dimethylanthraquinone (DMA) as a fluorescent tracer. The fluorescence emitted by DMA under laser light exposure was photographed through a 280-400 nm band-pass filter using a high-speed shutter camera fitted with an image intensifier. In LIF visualization of in-cylinder phenomena, it is not always easy to introduce ultraviolet light over the entire observation range desired because of the limited size of the quartz observation window. In the present work, therefore, a coaxial LIF system was adopted whereby DMA fluorescence was photographed from the incident direction of the ultraviolet light so as to eliminate dead angles. The LIF system configuration is shown schematically in Fig. 3. The phenomena that were visualized with this LIF system from each end of the combustion chamber are indicated in Table 2.

<table>
<thead>
<tr>
<th>Table 1 Test Engine Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Type</td>
</tr>
<tr>
<td>Bore×Stroke</td>
</tr>
<tr>
<td>Displacement</td>
</tr>
<tr>
<td>Compression Ratio</td>
</tr>
<tr>
<td>Combustion Chamber</td>
</tr>
</tbody>
</table>

**EXPERIMENTAL RESULTS AND DISCUSSION**

Swirl and Tumble Ratios of Tested Intake Systems

The three types of swirl control valves used in the tests had the same opening area. They were designated as swirl control valves A, B and C, in the order of the largest to the smallest swirl ratio. Tests were also conducted without a swirl control valve, in which case the swirl ratio was zero. Figure 4 presents the steady-state flow characteristics of the flow fields produced by these four types of intake systems. The results indicate that pure tumble flow was formed in the cylinder when a swirl control valve was not used. On the other hand, all three types of swirl control valves formed so-called inclined swirl characterized by the simultaneous presence of both swirl and tumble motions.

![Fig. 2 Optical Access Engine](image)

![Fig. 3 Coaxial LIF System for Fuel Liquid Visualization](image)

<table>
<thead>
<tr>
<th>Table 2 Applicable Objectives of Each LIF Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera Direction</td>
</tr>
<tr>
<td>Front View</td>
</tr>
<tr>
<td>Bottom View</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
Relation Between Steady-state Flow Characteristics and Mean Gas Flow Fields

Gas flow in the combustion chamber was measured with the above-mentioned LDV system under motoring operation for the four types of intake systems used in the steady-state flow tests. Figure 5 shows the points where the LDV measurements were made. In order to measure swirl flow in the piston bowl, velocity measurements were made in two directions in a horizontal plane at the 13 points indicated in the bowl. Moreover, to measure swirl flow outside the piston bowl, flow velocity measurements were made in the swirl direction and in the cylinder axial direction at seven points along a straight line parallel to the crankshaft.

Figure 6 shows typical mean flow velocity patterns in the piston bowl when swirl control valve A was used, and Fig. 7 shows the swirl flow patterns in the combustion chamber. It is

Table 3 Conditions for Flow Measurement, Fuel Vapor Visualization and Performance Tests

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LDV Measurement (motoring)</th>
<th>LIF Fuel Vapor Visualization</th>
<th>Performance Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Speed</td>
<td>1400rpm</td>
<td>1400rpm</td>
<td>1400rpm</td>
</tr>
<tr>
<td>Volumetric Eff.</td>
<td>WOT</td>
<td>75%</td>
<td>—</td>
</tr>
<tr>
<td>Pmi</td>
<td>—</td>
<td>—</td>
<td>314kPa</td>
</tr>
<tr>
<td>A/F</td>
<td>—</td>
<td>40 : 1</td>
<td>40 : 1</td>
</tr>
<tr>
<td>Ignition Timing</td>
<td>—</td>
<td>TDC</td>
<td>—</td>
</tr>
</tbody>
</table>

Fig. 4 Steady Flow Characteristics of Tested Intake Systems

Fig. 5 Measurement Points for LDV

Fig. 6 Mean Air Flow Field in Piston Bowl with Swirl Control Valve A

Fig. 7 Mean Air Flow Field in Combustion Chamber with Swirl Control Valve A
seen that the swirl center in the piston bowl nearly coincided with the center of the bowl and diverged from the center of the cylinder. On the other hand, it is thought that swirl flow in the combustion chamber revolved almost around the cylinder central axis. Since the swirl center was an area of negative pressure in relation to the peripheral portion of the swirl, it is presumed that upward flow occurred from the periphery of the piston bowl toward the center of the combustion chamber. Figure 8 shows the axial velocity measured at one point on the cylinder central axis, among the measurement points shown in Fig. 5, for swirl control valves A, B and C and the case without a swirl control valve. It should be noted that the laser light was shaded by the piston from a crank angle of 20 deg.BTDC to 20 deg.ATDC, preventing any measurement. It is seen that the swirl control valve with the largest swirl ratio produced the strongest upward flow from a crank angle of around 40 deg.BTDC of the compression stroke, verifying that swirl worked to generate upward flow as mentioned above.

**Effect of Swirl on In-cylinder Fuel Behavior**

The LIF system was used to visualize the behavior of the fuel spray and fuel droplets when fuel was injected into the cylinder in the compression stroke. Visualizations were obtained for two cases, one with swirl control valve A, which produced the largest swirl ratio of the three swirl control valves mentioned earlier, and the other without any swirl control valve. Figure 9 shows the area of the combustion chamber in which the fuel behavior was visualized, and the visualized results obtained are compared in Fig. 10. A swirl injector was used which formed a hollow cone spray having a cone angle of approximately 60 deg. ATDC, indicating that any sudden upflow of the fuel spray due to tumble motion was avoided. As a result, it is thought that this prevented fuel droplets from wetting the spark plug and that it also reduced the amount of fuel overflowing the piston bowl. In the interval from 30 deg to 20 deg.BTDC, it is observed that fuel vapor rose from the piston bowl toward the spark plug. This transport of the fuel following initial injection into the piston bowl is thought to be attributable to swirl-induced upward flow near the cylinder central axis which was seen in the LDV

![Injection End Timing = 50 deg BTDC](image)

**Fig. 8** Time History of Axial Velocity at The Center of Combustion Chamber

**Fig. 9** Fuel Vapor Visualization Area (Front View)

**Fig. 10** Fuel Vapor Motion in Cylinder

---

**Without Swirl Control Valve A**

**Swirl Control Valve**
measured results.

**Relation between Engine Performance and Visualized Mixture Behavior**

Performance tests were conducted using swirl control valve A to investigate the range of fuel injection timing and spark ignition timing that would allow stable stratified combustion. The results obtained are shown in Fig. 11.

It is seen that a stable combustion region exists between 50 deg to 40 deg.BTDC in relation to the fuel injection end timing; however, such a region of stable combustion does not exist at a fuel injection end timing of 60 deg.BTDC. Figure 12 shows the fuel vapor behavior that was visualized by LIF at each fuel injection end timing. With a fuel injection end timing of 60 deg.BTDC, fuel was injected before the piston ascended to a position near the fuel injector. The fuel spray was not trapped in the piston bowl and traveled as far as the exhaust side of the combustion chamber. As a result, the fuel vapor was not concentrated near the spark plug around a crank angle of 20 deg.BTDC when ignition occurred. By contrast, the fuel vapor was concentrated near with spark plug with a fuel injection end timing of 40 deg. BTDC and 50 deg.BTDC. The visualized results showed good agreement with the performance test data.

The LIF system was then used to visualize the liquid fuel film in the piston bowl from the bottom of the combustion chamber. The visualization area is shown in Fig. 13, and the visualized results for the fuel spray and liquid fuel film are shown in Fig. 14. The large cloud shape seen in a crank angle interval of around 10 deg after the end of fuel injection is the fuel spray. Subsequently, the white trace remaining at the bottom of the piston bowl is the fuel film. With a fuel injection end timing of 60 deg.BTDC, it is observed that the fuel film disappeared before the piston reached TDC of the compression stroke. However, with a fuel injection end timing of 40 deg.BTDC, the fuel film was still present at TDC of the compression stroke. It is thought that this fuel film does not contribute to combustion, so an earlier fuel injection end timing is desirable with respect to improving combustion efficiency. It should be noted that these visualization experiments were conducted using DMA (boiling point of 193 deg.C) as the fluorescent tracer and that the piston surface temperature of the optical access engine is presumably lower than that of the piston surface in an actual engine. Therefore, it should be understood that the visualized results do not necessarily reproduce the exact fuel film state in an actual engine.

**CONCLUSIONS**

This paper has presented the results of in-cylinder gas flow
measurements by LDV and in-cylinder fuel vapor visualization by LIF for a direct-injection gasoline engine in which the mixture was stratified. The test engine was fitted with an intake system which was virtually identical to that of existing gasoline engines with four valves per cylinder. The experimental results made the following points clear.

(1) The synergistic effect of a round piston bowl positioned eccentrically to the cylinder central axis and swirl motion generated by a swirl control valve forms upward flow near the center of the cylinder from the piston surface toward the cylinder head in the latter half of the compression stroke.

(2) When fuel was injected directly into the cylinder, it was seen that the fuel initially injected into the piston bowl was transported by this upward flow toward the spark plug to accomplish mixture stratification.

Performance tests were conducted to determine the range of fuel injection timing and ignition timing that would allow stable stratified combustion. A comparison of the results with LIF visualizations of the mixture behavior revealed the following points.

(3) When the fuel injection timing is too early, the fuel spray is not trapped in the piston bowl and travels as far as the exhaust port side of the combustion chamber, which precludes mixture stratification.

(4) With the visualization system used in this work, it was observed that the fuel film forming on the bottom of the piston bowl increased as the fuel injection timing was retarded. This observation suggests that an earlier fuel injection timing is desirable with respect to improving combustion efficiency.

As a result, the best injection timing is determined from balance between fuel trapping by piston crown and fuel film in the piston bowl.

REFERENCE


