Quantitative 2-D Fuel Distribution Measurements in a Direct-Injection Gasoline Engine Using Laser-Induced Fluorescence Technique

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ABSTRACT

To improve the accuracy of fuel concentration measurements in a direct-injection gasoline engine by LIF (laser-induced fluorescence) technique, two approaches have been conducted. The combination of acetone as the fluorescence tracer of fuel and 266nm as the excitation wavelength was used for the first approach in order to minimize the error caused by the temperature dependence of LIF intensity. The second approach was the correction of the equivalence ratio obtained from raw LIF image for the severe temperature distribution caused by evaporation and superheating of injected fuel. The temperature distribution in the mixture was calculated, then the equivalence ratio was corrected for the effects of air density variation and remaining LIF temperature dependence. This improved technique was applied to the quantitative analysis of mixture formation process in a visualized direct-injection gasoline engine both in early and late injection conditions.

INTRODUCTION

New type of spark-ignition (SI) engines which have gasoline direct-injection (DI) system have been developed and begun to use in practice [1,2]. The outstanding features of the engines are the great improvement of fuel economy as well as high output power compared with conventional port-fueled SI engines. These advantages are realized by the stratified combustion at partial loads and homogeneous combustion at higher loads. In this way, the mixture preparation and the combustion characteristics in the cylinder are significantly changed according to the engine operating conditions. Therefore, optimizing the in-cylinder mixture formation process is the key technology, because it dominates engine performances such as fuel consumption, output power and exhaust emissions. Consequently, the development of measurement technique which enables precise investigation of mixture formation process is strongly required for the further development of DI gasoline engines.

PLIF (Planar Laser-Induced Fluorescence) technique is a powerful tool for this purpose, because it allows the instantaneous 2-D fuel distribution measurements [3-6]. In general, however, LIF intensity is affected not only by the fuel concentration but also by both the ambient temperature and pressure. This property of LIF causes a serious problem on the accuracy of the quantitative fuel concentration measurements in engines. The authors have reported the optimum combination of fluorescence tracer and excitation wavelength which features very low temperature and pressure effects on LIF intensity [7]. This technique facilitates the quantitative analysis of mixture formation process in a port-fueled SI engine [8]. In the case of DI engines, the minimization of the temperature dependence of LIF intensity is still important. However, even by the use of such small temperature dependence combination, it can not be neglected the temperature effect because of the existence of severe temperature distribution in the mixture, which is caused by the evaporation and superheating of the fuel injected into the cylinder. Furthermore, when the fuel concentration is expressed in the form of air/fuel ratio or equivalence ratio, the results must be corrected for the increase of air density originates from the air temperature drop.

The objective of this study is to develop the method which can greatly improve the accuracy of fuel concentration measurements in a direct-injection gasoline engine by LIF technique. Firstly, the combination of fluorescence tracer and excitation wavelength we have reported [7,8] was used in order to minimize the error caused by the temperature effect on LIF intensity. Secondly, the effects of the air density variation and remaining temperature dependence of LIF intensity was corrected for the equivalence ratio obtained from the LIF images. For the second purpose, temperature distribution caused by evaporation and superheating of the fuel injected into the cylinder was calculated. This improved technique was applied to the quantitative analysis of mixture formation process in a visualized direct-injection gasoline engine both in early and late injection conditions.

IMPROVEMENT OF MEASUREMENT ACCURACY

Fluorescence Tracer and Excitation Wavelength

The selection of the fluorescence tracer and excitation
wavelength is very important because it characterizes the temperature and pressure effects on LIF intensity. Figure 1 shows the temperature and pressure dependence on LIF intensity measured for some fluorescence tracers excited at 248nm or 266nm with a heated and pressurized constant volume vessel [7,8]. It can be understood that the LIF intensity of acetone excited at 266nm shows the lowest temperature dependence compared with any other combinations. The second candidate is 3-pentanone with 266nm excitation. However, it has been revealed that 3-pentanone suffers more serious temperature effect on the LIF intensity than acetone at the high temperature region [8]. The pressure dependence of LIF intensity is also quite low with these combinations. On the other hand, even with the use of acetone, LIF intensity is strongly affected by the temperature and pressure variations when excited at 248nm.

From these results, the quantitative fuel distribution measurements were made by LIF of acetone excited at 266nm. In this study, acetone was doped in iso-octane fuel at a concentration of 10% by weight.

A problem is arisen that the boiling point of acetone (56.5°C) is lower than that of iso-octane (99°C). However, this effect may not make a serious problem when the engine operating condition is hot and steady state, because of the following reasons.
(a) In the mixed solution, the evaporating temperature of each substance becomes closer than solo substance [8].
(b) The piston surface temperature is higher than the boiling point of each substance.
(c) In the case of late injection, in-cylinder gas temperature is assumed to be above 500K, much higher than the boiling point of each substance.

Calculation of Temporal Equivalence Ratio Distribution

The temporal equivalence ratio distribution was calculated from LIF images taken with a visualization engine, as the first step. The raw LIF images were averaged over consecutive 16 cycles to reduce the effects of shot-noise of intensified CCD camera, fluctuations of the laser sheet pattern and cycle to cycle variations of the engine. Then the temporal distribution of equivalence ratio \([\phi_{ip}]\) was calculated based on the LIF image of the uniform mixture of predetermined equivalence ratio, \([\phi_{uni}]\), using EQ.(1).

\[
[\phi_{ip}] = C \cdot [\phi_{uni}] \cdot \frac{[\text{LIF}_{adm}] - [\text{Back}]}{[\text{LIF}_{uni}] - [\text{Back}]} \quad (1)
\]

where

- \([\phi_{ip}]\): temporal equivalence ratio distribution image,
- \([\text{LIF}_{adm}]\): LIF image in DI operation,
- \([\text{LIF}_{uni}]\): LIF image in uniform mixture operation,
- [Back]: background image without fuel injection,
- \([\phi_{uni}]\): equivalence ratio in uniform mixture operation,
- \(C\): correction factor for laser power fluctuation and windows blur.

In EQ.(1), it is assumed that the equivalence ratio and the LIF intensity are in linear relation. With the combination of acetone tracer and 266nm excitation, this relation has been confirmed in our previous work by the use of a port-fueled visualization engine [8], where the temperature distribution is not so severe. EQ.(1) was applied to the images which were taken at the same crank angle for each engine operation. From this procedure, the pressure effect on the LIF intensity, which is essentially very low with this combination, is

![Fig. 2 Temperature change of ambient gas caused by fuel evaporation and superheating.](image-url)
almost completely compensated because the in-cylinder pressure trace during the compression stroke shows no large difference in both operations.

**Calculation of Temperature Distribution in Mixture**

As the second step, temperature distribution in the mixture, which is caused by the fuel injected into the cylinder, was calculated in order to make corrections for the temporal equivalence ratio. The procedure is basically the same which was carried out for the spray injected into a constant volume vessel [9] or a rapid compression machine [10], with the assumption that the sensitive heat and the latent heat for the evaporation and the heat for the superheating of vapor is given from the ambient gas, and both are reached to equilibrium temperature $T_{eq}$, namely;

$$m_f \left( \int_{T_0}^{T_a} C_p dT + H_{fg} \right) + m_a \int_{T_a}^{T_{eq}} C_p dT = -m_a \int_{T_a}^{T_{eq}} C_p dT$$

(2)

where

- $m_f$: mass of fuel (kg),
- $m_a$: mass of ambient gas (kg),
- $T_0$: initial temperature of liquid fuel (K),
- $T_a$: initial temperature of ambient gas (K),
- $T_d$: boiling point of liquid fuel (K),
- $T_{eq}$: equilibrium temperature of fuel and ambient gas (K),
- $C_p$: specific heat of liquid fuel at constant pressure (kJ/kg·K),
- $C_p$: specific heat of vapor fuel at constant pressure (kJ/kg·K),
- $H_{fg}$: latent heat of fuel vaporization at $T_d$ (kJ/kg).

From Eq.(2), the $T_{eq}$ can be calculated for air fuel ratio $(m_f/m_a)$, namely for equivalence ratio $\phi$, when $T_a$ and $T_0$ is given. Figure 2 shows calculated results for the mixed fuel used in this experiment. Here, $T_0$ is assumed to be 323K. For example, the temperature drop becomes about 160K at the condition of $T_a=700K$ and $\phi=3.0$. This temperature drop changes gas density as well as LIF intensity. Consequently, the correction for this effect must be required to improve the measurement accuracy.

**Correction for Equivalence Ratio**

As the final step, the correction for the temperature is carried out for the temporal equivalence ratio. In practice, the initial value of $\phi$ is given by $\phi_{tp}$ and then corrected value $\phi_{c}$ is calculated by the convergence method as shown in Figure 3. Figure 4 shows the calculated results at $T_a=700K$. For example, in the case of $\phi_{tp}=3.0$, the corrected value $\phi_{c}$ becomes 2.2 at 266nm excitation and 1.7 at 248nm excitation, respectively. Figure 5 shows correction rate for $\phi_{c}$, which consists of the contributions of air density change (A in Fig.5) and temperature dependence of LIF intensity (B in Fig.5). In the case of 248nm excitation, the total correction rate $(A+B)$ itself is quite large and the major correction is originated from the temperature dependence of LIF intensity $(B=\phi)$. In the case of 266nm excitation, on the other hand, the total correction rate becomes smaller and the major correction is originated from the air density change (A), which value is the same in the case of 248nm excitation. Namely, in the case of 266nm excitation, the correction for the temperature dependence of LIF intensity $(B=\phi)$ is very low. However, about 50% of measurement error is estimated at $\phi_{c}=3.0$ even in the case of 266nm excitation, if there is no correction. This fact shows the importance of the correction described here.

**Application to Engine Experimental Results**

The temporal equivalence ratio value for each pixel of the image [$\phi_{tp}$] which was derived from Eq.(1) was corrected using the relation between $\phi_{tp}$ and $\phi_{c}$ as shown in figure 4. At this time, it became necessary to know the in-cylinder gas temperature $T_a$. It was calculated using the ideal gas equation from the in-cylinder pressure trace which was measured during the LIF imaging. The composition and the

![Fig. 3 Flow chart of correction for equivalence ratio.](image)

![Fig. 4 Calculated results of Equivalence Ratio Correction.](image)
mass amounts of in-cylinder gases, which were required in the above calculation, were derived from the measured value of the charging efficiency, injection amounts, and the residual gas ratio.

**ENGINE EXPERIMENTS AND RESULTS**

The technique described in the previous section was applied to the quantitative analysis of mixture formation process in a direct-injection gasoline engine [1], using a visualization engine.

**Experimental Apparatus**

**Visualization engine.** A schematic of the visualization engine apparatus is shown in Figure 6. The specifications of the engine are listed in Table 1. The engine is a 4-valve, pent-roof cylinder head, direct-injection, single cylinder, spark ignition engine. In-cylinder swirl flow is generated by the use of shrouded inlet valves. A swirl type high pressure injector is mounted between two inlet ports. Fuel is injected into the narrow zone of the piston cavity. This zone is called "mixture formation area". Another injector, which is an air-assist injector, is also used to make a pre-vaporized uniform mixture injecting toward a porous electric heater which are placed in the inlet line 0.8 m upstream from the inlet ports.

The cylinder head has two quartz windows to permit the laser sheet passing through the combustion chamber. The inner surface of these windows are cylindrical shape, while the shape of outer surface has been specially designed to make light rays parallel either inside and outside of the cylinder head [11]. Engine performance test can be possible when these windows are replaced by metal dummies. An electromagnetic gas sampling valve can be attached to these dummy windows to measure the residual gas portion in the cylinder. A quartz piston is mounted at the top of elongated piston for observation from piston bottom direction. This quartz piston has a unique involute shaped cavity which is the same as the production engine.

**Optical arrangement for LIF measurements.** An schematic of LIF measurements apparatus for the visualization engine is shown in Figure 7. The fourth harmonic of a Nd:YAG laser (Spectra Physics GCR-3) was used for excitation light source. The mean laser power was 60 mJ/pulse. The laser light was split into two beams, both were formed into the horizontal laser sheets and then introduced into the combustion chamber from the opposite side. Although the laser light is gradually absorbed by the tracer when it passes through the combustion chamber, the influence of laser intensity distribution caused by this absorption can be greatly reduced by this counter incidence method. In this experiment, such influence was below 1% at the severest condition. The location of each laser sheet

![Fig. 6 Construction of Visualization engine.](image_url)

![Fig. 5 Details of equivalence ratio correction.](image_url)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cylinders</td>
<td>1</td>
</tr>
<tr>
<td>Displacement volume</td>
<td>500 cm³</td>
</tr>
<tr>
<td>Bore</td>
<td>86 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>86 mm</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>7.3</td>
</tr>
<tr>
<td>Number of valves</td>
<td>Inlet: 2, Exhaust: 2</td>
</tr>
<tr>
<td>Steady swirl ratio</td>
<td>2.4</td>
</tr>
<tr>
<td>Fuel Supply System</td>
<td>High Pressure Swirl Injector &amp; Air-assist Injector</td>
</tr>
<tr>
<td>Fuel Pressure</td>
<td>12 MPa (Direct Injection), 0.3 MPa (Port Injection)</td>
</tr>
</tbody>
</table>
images [Back] were taken without fuel injection but with laser radiation. All LIF images were taken after the exhaust emissions became stable when the operating mode was changed. The engine operating conditions are listed in Table 2.

Results and Discussion

The measured LIF images were processed according to the procedure explained in the previous section, then the corrected equivalence ratio distribution were obtained.

Examination for correction. Figure 8 shows the image processed results taken in late (compression stroke) injection condition. Observation view field is the laser sheet portion inside the circle except for the blind region between the bottom and the side wall of the cavity by the small curvature of it. The lower part in Figure 8 shows the distribution of corrected equivalence ratio, while the upper part shows the temporal images (before correction) derived from Eq.(1). The qualitative behavior of the mixture is not so different in both cases. However, it is obvious that the value of the temporal equivalence ratio is expressed much higher than the corrected value even with the acetone and 266nm excitation combination. Therefore, in the case of other combination of fluorescence tracer and excitation wavelength, more serious error is involved in the measurement results, if there is no correction.

In the following section, mixture formation process is discussed based on the corrected equivalence ratio images.

Mixture formation in late injection. In Figure 8, fuel is injected in the mixture formation area (see Fig. 6) so as not to wet the spark plug by fuel spray. Fuel evaporates in this area and then arrived at the laser sheet plane along the cavity surface around -50 ATDC. The equivalence ratio of the richest region in the mixture exceeds 2.5. After that, the mixture is diffused and moved toward the spark plug by air swirl motion (-50° to -30°). At the same time, the richest portion comes back slightly toward the injector by the effect of curved side wall of the cavity. Spark plug fouling is further reduced as the richest mixture does not reach the spark position. Finally (-30°), the equivalence ratio around the spark plug becomes 1.0-1.5, suit for ignition. The main portion of the mixture has moved to the combustion space in the cavity.

Mixture formation in early injection. Figure 9 shows the results taken in early (intake stroke) injection condition. In this case, remarkable fuel stratification can not be observed even at -90°. And almost homogeneous mixture whose equivalence ratio is close to the overall equivalence ratio (φ = 0.85) has been prepared until the end of the compression stroke (-30°).

From these measurements, the mixture formation concepts of this DI gasoline engine have been confirmed, quantitatively.
Fig. 8 Image processed results of quantitative fuel distribution measurements in late injection case, and the comparisons between before and after correction.

Fig. 9 Image processed results of quantitative fuel distribution measurements in early injection case.

CONCLUSION

(1) The method which improves the accuracy of quantitative fuel concentration measurements in a direct-injection gasoline engine by LIF (laser-induced fluorescence) technique was developed. The combination of acetone as the fluorescence tracer of fuel and 266nm as the excitation wavelength was used in order to minimize the error caused by the temperature dependence of LIF intensity. Then, the correction of the equivalence ratio obtained from raw LIF image was carried out for the severe temperature distribution caused by evaporation and superheating of injected fuel. From these examinations, it was revealed that the considerable error is involved in the equivalence ratio which is directly calculated from the LIF intensity, even by the use of acetone with 266nm excitation combination. More serious error is inevitable with the use of other combination of fluorescence tracer and excitation wavelength, if there is no correction.

(2) This technique was applied to the analysis of mixture formation process in a DI gasoline engine. In the case of late (compression stroke) injection, fuel evaporates in the mixture formation area and forms a rich mixture (\( \phi > 2.5 \)). Then, the mixture is moved toward the spark plug, changing its concentration to suitable for ignition (\( \phi = 1.0-1.5 \)) around the spark plug at ignition timing. In contrast to this, remarkable fuel stratification can not be observed even at -90° in the case of early (intake stroke) injection. Almost homogeneous mixture whose equivalence ratio is close to the overall value has been prepared until the end of the compression stroke.

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