Quasi 2-D Measurements of Gaseous and Liquid Fuel Concentrations Using Two-Color Laser Beam Scanning Technique

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Abstract: Planer Laser Induced Fluorescence (PLIF) has been employed to measure the spatial liquid and vapor fuel concentration distributions, although it is generally difficult to achieve quantitatively accurate measurement. The authors devised a 2-D fuel spray concentration distribution measurement method which combines three optical principles; absorption, fluorescence, and scatter. NO2 gas was used as a fluorescence dopant while Ar* laser was employed as a light source by scanning across the cylinder in order to measure the spatial fuel concentration distribution. This technique was applied to gaseous jets and swirl sprays. Quantitative measurement was successfully achieved in both tests. Also, the characteristics of liquid and vapor fuel concentration distribution using a swirl type injector were confirmed.

1. Introduction
In order to achieve simultaneous reductions of exhaust gas emissions and fuel consumption rate for internal combustion engines, development of a new combustion system using new energy sources such as natural gas, hydrogen, GTL and DME has been explored. In the development process, it is strongly required to measure the spatial distribution of the air/fuel mixture concentration inside a cylinder. Recent advantages of optical measurement systems allow us to achieve this. 2-D planar laser induced fluorescence (PLIF) is widely used for the measurement of gaseous and liquid jets. Ueda et al. [1] blended iodine as a fluorescent dopant into the injection gas and measured the jet concentration using a laser sheet as a light source. Kido et al. [2] blended iodine into the ambient gas to estimate the jet concentration using a laser sheet as a light source. Kido et al. [2] blended iodine into the ambient gas to estimate the jet concentration by measuring the spatial distribution of ambient gas concentration. These methods, however, cause some difficulty in obtaining quantitative data, as the effect of quenching must be accounted for in addition to keeping iodine, normally in solid state under room temperature, in a gaseous state. Thereby, Fujimoto et al. [3] used NO2 as a fluorescent dopant to measure the stratified charge mixture concentration. NO2 has another feature as a dopant because it is not as sensitive to temperature variation up to 700 K [4]. Senda et al. applied Exciplex LIF to diesel sprays using Naphthalene and TMPD as fluorescence dopants [5]. Suzuki et al. measured spatial distributions of liquid and evaporated fuel concentrations using two-color laser beam [6].

In this study, NO2 was employed as a dopant for the fluorescence measurement, while the absorption measurement was made simultaneously to remove the effect of fluorescence quenching. To measure the absorbance, a laser beam and a photo-multiplier tube were employed. The laser beam,
with its relatively high power density, functions well as the excitation light source and the photomultiplier tube, while relatively inexpensive, has an adequate light sensitivity. In addition, the laser beam was scanned at a relatively fast rate to allow a quasi 2-D measurement on a horizontal plane. This new measurement system was tested to examine its effectiveness in obtaining quantitative data measurements inside a cylindrical constant-volume bomb with a fuel-air mixture formed by gaseous or liquid fuel injections.

2. Principle of the measurement

2.1 Absorption method

\[ E_2 - E_1 = h\nu \]  

(1)

Here, \( E_2, E_1 \) : energy levels, \( h \) : Planck’s constant, \( \nu \) excitation frequency. When the molecules, which have a molecular excitation frequency \( \nu \) (subject to measure) are subjected to light, they absorb the light energy and their energy level ascends correspondingly from the ground level to the excited state. This phenomenon is called absorption. Absorption is proportional to the concentration of the molecules as indicated by the following Eq. 2 called the Lambert-Beer’s law.

\[
\alpha(\nu) = \ln \left( \frac{I_0(\nu)}{I(\nu)} \right) = k(\nu)Cl
\]

(2)

Here, \( I_0(\nu), I(\nu) \): incident and transmitted light intensities, \( \alpha(\nu) \): absorbance, \( k(\nu) \): absorption coefficient [1/m], \( l \): length of light path [m], \( C \): concentration [mol/m^3]. By measuring the absorbance \( \alpha(\nu) \), the concentration \( C \) can be obtained using the known absorption coefficient \( k(\nu) \) and beam length \( l \). Absorption has a high temporal resolution and can be measured without interference from other molecules. The result, however, is an integrated value along the optical path length.

2.2 Fluorescence method

When molecules that had been excited by the incident light return to the ground state, a quantity of energy equivalent to the difference between the two energy levels will be radiated. Since fluorescence intensity is affected not only by the sample concentration but also by the ambient temperature and pressure, quantitative measurement is difficult to conduct in engine fields.
2.3 Light scattering method

When droplets exist on the light path, incident light will be scattered by droplets. With an assumption that all droplets are spherical and have the same diameter, the scatter light intensity is proportional to the square of diameter and number density as particle parameter is less than 5.

2.4 Combination of the three methods

Measurement principle is schematically shown in Fig.1. In this study, an Ar⁺ laser (488/514.5 nm, 4 W, beam-diameter 6 mm (1/e²)) was used as the light source and NO₂ gas, as a fluorescence dopant that will absorb both 488 and 514.5 nm wavelength light, but its absorbance depends on the wavelength. Meanwhile, laser beam decays due to light scattering from droplets, but the decay characteristics depend on the wavelength. The absorbance of each wavelength can be described as follows.

\[ \alpha_{488} = \alpha_{488Lab} + \alpha_{488Lsc} \]
\[ \alpha_{514.5} = \alpha_{514.5Lab} + \alpha_{514.5Lsc} \]

Here, \( \alpha \): absorbance, \( \alpha_{Lab} \): absorbance due to fluorescence, \( \alpha_{Lsc} \): decay due to scattering. Thereby, subtracting (4) from (3), decay due to fluorescence can be estimated as Eq. 5.

\[ \Delta\alpha = \alpha_{488Lab} - \alpha_{514.5Lab} \]

The experimental apparatus is shown in Fig.2. A stepping motor with a mirror was employed to scan the laser beam in order to ensure that the beam enters the quartz cylinder (bore: 80 mm, thickness: 10 mm) in parallel during the scan. Two cylindrical lenses were adapted to compensate the beam direction due to the refraction in the cylinder. The in-cylinder pressure was measured by using a strain-type pressure transducer. The laser-beam passing through the cylinder was initially focused by a concave mirror into a liquid light guide and was then divided into two photo-multiplier tubes attached with a 488 and a 514.5 nm narrow band-pass-filters. In order to measure the fluorescence intensity, a quartz window was employed under the cylinder. The fluorescence image was detected using a 550 nm long-pass-filter and captured with an image-intensified high-speed video camera (Photron Fastcam ultima, 4500 fps, 8-bit 256x256 resolution) with an attached image booster. The gated exposure time of intensified camera was set at 100 μs. Meanwhile, scattered light image was also detected using a 514.5 nm narrow band-pass-filter and captured with a high-speed video camera.

3. Experimental Results

3.1 Calibration Results

The ambient pressure was varied from atmospheric to 0.4 MPa in every 0.1 MPa. The NO₂ concentration was varied from 0.18 to 0.89 mol/m³. The temperature was set at around 295 K. A required time for a single scanning inside the cylinder was 9 ms at standard condition (stepping motor speed of 120 r/min). The following results are the average of five sequential scans.

Figure 3 shows the relationship between absorbances (488, 514.5 and the difference) and NO₂ concentration when the ambient gas pressure is varied from 0.1 to 0.4 MPa. The temporal variation of absorbance corresponding to the spatial variation of absorbance due to beam scanning can be estimated using Eq. 5. The absorbance increases almost linearly with the NO₂ concentration regardless of the ambient pressure as Lambert-Beer’s law shows. The shot-to-shot variation was less than 5 % of the averaged value.

Figure 4 shows the averaged spatial distribution of the absorption coefficient \( k(\nu) \) on the cylinder centre-line of \( Y=0 \) mm. The values indicate an almost independent relation between the absorption coefficient and the NO₂ concentration. Similar results were obtained when the ambient pressure was varied. From this figure, the measurement accuracy can be estimated less than ±10 % if the ambient NO₂ concentration is diluted by a factor of five (NO₂ concentration varies from 0.89 to 0.18 mol/m³).
Figure 5 shows the relation between the fluorescence intensity averaged for five runs and NO$_2$ concentration. The fluorescence intensity value is the line-average on the cylinder center at Y=0 mm. The vertical bars indicate data scatter among five runs. The intensity increases linearly with NO$_2$ concentration at an ambient atmospheric pressure. Meanwhile, some shift from the linear correlation line can be found in higher ambient pressure conditions. This non-linearity originates from the non-radiative transition increase due to the collision of molecules under high pressure. The measurement accuracy can be estimated less than ±14% if the ambient NO$_2$ concentration is diluted by a factor of three (NO$_2$ concentration varies from 0.89 to 0.36 mol/m$^3$).

3.2 Compensate of intensity distributions of fluorescence and scattering light

Fluorescence intensity is proportional to the mole concentration of dopant and also the incident light intensity. Here, as the incident light decays due to absorption by dopant on the path, compensation of this is necessary [1,2]. In addition, compensation due to scattering is also required in spray measurements. The authors have examined the method of compensation in only gaseous phase field [7]. Thereby, compensation due to the decay by scattering from droplets is described as follows.

Figure 6 shows the schematic of compensations. As indicated, consider N cells on the path. Each cell has the same size as a pixel of CCD camera. At first, compensation for fluorescence image is as follows. In each cell, decay of light due to scattering is analyzed by transmitted light extinction method which means that extinction by scattering can be expressed Eq. (6) when incident light with intensity of $I_0$ passes through a layer with particles whose number density is $N(D)$ and diameter is $D$.

$$
-\ln\left(\frac{I}{I_0}\right) = RQ_{ext} \frac{\pi}{4} \int_0^l \int_0^{D_p} N(D)D^2dDdl \quad (6)
$$

Here, $I_0$ and $I$ are light intensity before and after the layer, respectively. $l$ is a path length. $R$ is an optical constant ($R=0.075$ in this study) while $Q_{ext}$ is an extinction coefficient which is 2.0 at large particle parameter. Because the droplet diameter distribution is necessary to estimate $N(D)$, it was measured using ILIDS method [8]. The result is indicated in Fig. 7.

Results in Fig. 7 are measured at 4.5 ms after start of injection with n-heptane as a fuel. Measured region is 45 and 60 mm in Z direction and 10, 20 and 30 mm in r direction with an area of $Z \times r = 10 \times 10$ with a thickness of 0.5 mm.

Finally, the compensation for fluorescence can be read as Eq. 7.

$$
\ln\left(\frac{I_{n-1}}{I_n}\right) = kC_n dL + RQ_{ext} \frac{\pi}{4} \int_0^{D_p} N(D)D^2dDdl \quad (7)
$$
Here, $\text{d}L$ is the length of one cell. By calculating this recurrence formula, compensation can be done.

Next, the compensation for scattered image is as follows. Assuming that the droplet diameter is constant in each cell, the scattered light intensity $E_n$ can be expressed as Eq. 8.

$$E_n = A_n \tau_n I_0 S_{\text{scat}} N_n = A_n \tau_n I_0 \frac{\pi}{4} D_{\text{ave}} (x, y)^2 N_n$$

(8)

Here, $A_n$ is a detecting sensitivity constant, $\tau_n$ is an extinction rate of incident light, $S_{\text{scat}}$ is a scattering cross section and $D_{\text{ave}}$ is a mean droplet diameter. $\tau_n$ can be expressed as Eq. 9.

$$\tau_n = \exp(-S_{\text{scat}} \sum_{i=0}^{n-1} N_i)$$

(9)

Combining Eqs. 8 and 9, Eq. 10 can be deduced. Using this Eq., the compensation for scattered image can be done.

$$\tau_n = \exp\left(-\frac{1}{A_n} \sum_{i=0}^{n-1} \frac{E_i}{\tau_i}\right)$$

(10)
4. Results and discussion
4.1 Gaseous fuel injection

N₂ and H₂ gases were injected into a chamber using a hole-type injector (φ 1.6 mm x 1) under atmospheric condition. Table 1 summarizes experimental conditions. The gas properties are listed in Table 2. It was verified that the difference of coexistent gas does not affect the fluorescence intensity. The injection pressure was set at 0.05, 0.1, and 0.2 MPa (gauge) and the injection duration was fixed at 9 ms. Initiation of the laser beam scanning was synchronized with the start of fuel injection. The time duration for a single scan of 35 mm inside the cylinder took 9.0 ms. The following results are the averaged values of 5 runs and include error bars.

Table 1. Experimental conditions

| Injection gas | N₂, H₂ |
|---------------|--------|
| Injection pressure (gage) [MPa] | 0.05, 0.1, 0.2 |
| Ambient pressure [MPa] | 0.101 |
| Initial NO₂ concentration [mol/m³] | 0.90 |
| Injection duration [ms] | 9.0 |

Table 2. Gaseous properties @293K

|          | H₂      | N₂      |
|----------|---------|---------|
| Sound speed [m/s] | 1300    | 350     |
| Molecular weight     | 2       | 28      |
| Density [kg/m³]     | 0.082   | 1.138   |

Figure 8 shows the corrected spatial distributions of NO₂ on three cross sections of Z=10, 25, and 45 mm with N₂ and H₂ injection pressure of 0.2 MPa. Decay of NO₂ concentration is remarkably steep near the center of injection, especially for H₂ injection case. The jet area increases as the measurement cross-section decreases. Although a hole-type injector was employed, the jet profile distorts from a circular shape. This is probably attributed to the machining accuracy of the tested injector. As the injection pressure surpasses the critical pressure ratio, the initial jet velocity reaches transonic speed. The sonic speed ratio between H₂ and N₂ is 3.7 : 1, while the density ratio is 1 : 14. Thus, the momentum ratio becomes 13.7 : 14, a nearly equivalent ratio. The jet volume, V, estimated by the one dimensional quasi-steady theory can be given by Eq. 11.

\[ V = \frac{\pi \gamma^\frac{3}{2}}{\tan\left(\frac{\theta}{2}\right)} \left(\frac{u_0 d_s t}{\gamma} \right)^\frac{3}{2} \]  

(11)

where, \( \gamma \) is density ratio between the jet and ambient gas, \( u_0 \) is jet speed at the nozzle exit, \( d_s \) is the nozzle diameter, and \( t \) is time. This equation indicates that the jet volume ratio H₂ and N₂ is 0.99 : 1, a nearly equal ratio. That is why the jet cross-section areas are almost equal in Fig. 8.

Furthermore, spatial distributions of NO₂ concentration at injection pressures of H₂ gas varying from 0.05 to 0.2 MPa are shown in Fig. 9. As previously predicted, the jet momentum increases with injection pressure due to a higher jet density and volume. Also, injection velocity reaches sonic speed under the critical pressure ratio causing an increase in jet momentum.

4.2 Liquid fuel injection

The ambient pressure and temperature were set at atmospheric and room temperature, respectively. Two kinds of fuels of n-heptane and n-pentane were injected to measure liquid and evaporated phases. Injection pressure was fixed at 0.5 MPa, allowing ILIDS measurement with high data-rate. Measurements were made at two horizontal sections of Z = 45 and 60 mm. Due to a restriction of
temporal resolution, measurement was made at nearly steady state. The start of injection was set 3 ms before start of scanning. The experimental conditions and physical properties of fuel are listed in Tables 3 and 4, respectively.

**Fig. 9** NO$_2$ concentration distribution on horizontal plane with H$_2$ jet in different injection pressures

**Fig. 10** Vapor and liquid droplets distribution

**Table 3** Experimental conditions

| Condition | Value |
|-----------|-------|
| ...       | ...   |

**Table 4** Fuel properties @293K, 101.3kPa

| Property | Value |
|----------|-------|
| ...      | ...   |

| Fuel       | heptane, pentane | Saturated vapor pressure [kPa] | heptane, pentane |
|------------|------------------|--------------------------------|------------------|
| Injection pressure (gauge) [MPa] | 0.5              | 6.1                            | 68.3             |
| Ambient pressure [MPa]         | 0.101            | 98.4                           | 36.1             |
| Initial NO₂ concentration [mol/m³] | 0.90             | Molecular weight | 100.2           |
| Injection duration [ms]        | 9.0              |                                | 72.15            |

Figure 10 shows mean concentrations of liquid and vapor phases for 5 runs. Upper result is the mole fraction of fuel vapor while lower one is the droplet number density. A profile of hollow-cone that is a feature of swirl-type injector is observed. The vapor concentration is higher in n-pentane as its boiling-point is lower than of n-heptane.

5. Conclusions
A new system to measure the quasi 2-D gaseous and liquid concentrations was developed using a combination of fluorescence, absorption and scattering methods while utilizing the laser beam scanning technique. This system was tested and applied to gaseous jet and liquid spray fields inside a cylindrical bomb. The following results were obtained.

(1) The quasi 2-D concentration measurements of gaseous jets injected at transonic speeds into a cylindrical bomb were carried out at various injection pressures and types of injection gases. As a result, quantitative measurements of the gas jet concentration were successfully obtained and the assumption that the gaseous jet volume depends on the jet momentum was verified.

(2) A hollow-cone spray which is a feature of a swirl-type injector was confirmed by this measuring system when n-heptane or n-pentane was injected with a pressure of 0.5 MPa inside a cylinder. Some differences due to the volatility of fuel were found in both liquid and vapor concentrations.

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