Mixture Strength Measurements in the Combustion Chamber of SI Engine via Rayleigh Scattering* (Concentration Fluctuation in a Motored Engine)

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An experimental study was conducted to determine the time histories of fuel vapor concentration and its fluctuation in the combustion chamber of a spark ignition engine. Laser Rayleigh scattering was applied for remote, nonintrusive, point probing of the vapor concentration in the combustion chamber, which was caused by the continuous injection of Freon-12 into an intake port. The conventional engine was modified to make the optical diagnostics accessible. The results showed that the concentration fluctuation consisted of a temporal concentration fluctuation in a specific cycle and a cyclic variation of the temporal mean concentration in this particular cycle, which could be separated and measured accurately by the present experimental apparatus. It was also found that the concentration fluctuation increased and reached a maximum, after which it decreased during the intake and compression strokes. The concentration fluctuation was largely affected by the air fuel ratio and the engine speed.

Key Words: Internal Combustion Engine, SI Engine, Mixture Formation, Rayleigh Scattering, Laser Diagnostics, Vapor Concentration Fluctuation

1. Introduction

It is well known that cyclic combustion variations occur in almost all spark ignition (SI) engines. This is particularly important in dealing with the lean combustion which is desirable because of the prospect of a marked reduction in fuel consumption. It is this cyclic combustion variation that determines the limit of the engine diet for lean combustion. Increasing interest in the lean combustion has resulted in a considerable number of investigations elucidating the causes of the cyclic combustion variations in SI engines. It has been reported that three factors are considered to contribute mainly to this cyclic variation, i.e., the air motion, mixture strength, and the residual gas. However, the relative importance of these parameters is not fully defined. In the last ten years, many studies have repor-

ted on the investigation of fluid motion to clarify its influence on cyclic combustion variations in SI engines, however, few have addressed the mixture strength field. This is likely to be due to its complexity, which is influenced by many time-dependent variables and to the difficulty in developing an effective diagnostic technique for its quantitative detection inside the SI engine combustion chamber. As a consequence, further efforts must be applied for better understanding of the mixture formation process in order to clarify its influence on cyclic combustion variations in SI engines.

Recently, the authors measured the fuel vapor concentration distributions in the combustion chamber of an SI engine via laser Rayleigh scattering for better understanding of the physical state of fuel vapor. The mixture formation process during the intake stroke was simulated by the timed or continuous injection of fuel into the steady flow of dust-free dry air through an intake port^{(1)~(5)}. The measurements of the time history of the fuel vapor concentration were also reported in the combustion chamber of a motored SI engine with timed liquid fuel injection^{(6),(7)}. It was disclosed that the newly devel-

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oped Rayleigh scattering optical system was useful for the time- and space-resolved measurements of vapor concentration in the combustion chamber either in the case of gaseous or liquid fuel injection. It was shown that the fuel vapor concentration increased with the time elapsed from the start of the fuel injection and reached a peak after which it decreased during the intake stroke. It showed a very slight increase during the compression stroke. The vapor concentration field was found to show marked variation with time and space, and to be largely dependent on the fuel injection pressure, the fuel injection duration, the kinds of fuels tested, the intake valve configuration, its temperature and the air flow rate. It was also found that there was a strong correlation between the peak vapor concentration during the intake stroke and the vapor concentration at the end of the compression stroke.

As the engine mixture formation process is quasi-periodic because of the cyclic nature of the engine operation, the physical state of the fuel vapor may change not only temporally in a specific cycle, but also cyclically in a given cylinder. Thus, the diagnostics for the temporally and cyclically fluctuating state of the fuel vapor seems to be more important for understanding the mixture formation process occurring in the combustion chamber and for further clarifying its effect on cyclic combustion variations in SI engines. However, the period of the engine cycle is short so that the conventional averaging techniques used for "stationary" concentration field are not applicable. Hence, it is of great significance to seek a suitable method for describing the instantaneous state of the fuel vapor in the engine combustion chamber.

This paper describes an experimental investigation which provides detailed information of the temporal and cyclic fluctuation of the fuel vapor concentration in the combustion chamber of an SI engine. A method is presented for describing the temporally and cyclically fluctuating state of the fuel vapor inside the engine combustion chamber. The effects of the air fuel ratio and the engine speed on the time histories of the mean concentration and the concentration fluctuation are also investigated.

2. Theoretical Analysis and Definition

Irradiation of laser light on gaseous molecules causes Rayleigh scattering whose intensity is characteristic of chemical species. The intensity of Rayleigh scattered light from a multi-component mixture of gases I_r is given by

$$I_r = C I_0 N \sum_i X_i \sigma_{ri}, \quad (1)$$

where

C : constant relevant to the optical system

I_0 : intensity of incident laser light

N : number density of molecules

X_i : mole fraction of species i

σ_{ri} : Rayleigh scattering cross section of species i

For a binary mixture of fuel vapor (f) and air (a), Eq. (1) reduces to

$$X_f = \frac{I_r}{C I_0 N} \frac{\sigma_{ra}}{\sigma_{rf} - \sigma_{ra}}. \quad (2)$$

If we assume

$$\begin{aligned} N &= N_s \\ I_r &= I_{rsa} : X_f = 0 \\ I_r &= I_{rs} : X_f = X_{fs}, \end{aligned} \quad (3)$$

the following equation is derived.

$$\frac{X_f}{X_{fs}} = \frac{I_r \frac{N_s}{N} - I_{rsa}}{I_{rs} - I_{rsa}} \quad (4)$$

The subscript s , denotes the standard condition at which the Rayleigh scattered light intensity is calibrated vs the fuel vapor mole fraction. If the fuel-air mixture is assumed to be an ideal gas, the fuel vapor concentration during the intake stroke can be derived from Eq. (4) as follows

$$\frac{X_f}{X_{fs}} = \frac{I_r \left(\frac{P_s}{P} \right) \left(\frac{T}{T_s} \right) - I_{rsa}}{I_{rs} - I_{rsa}}, \quad (5)$$

where P and T are the in-cylinder pressure and temperature. With the transformation of Eq. (4), the fuel vapor concentration during the compression stroke can be expressed as

$$\begin{aligned} X_f/X_{fs} &= \left[I_r \left(\frac{P_s}{P_c} \right) \left(\frac{T_c}{T_s} \right) \left(\frac{V}{V_c} \right) (1 - X'_{fj} + X'_{jc}) - I_{rsa} \right] \\ &\quad / (I_{rs} - I_{rsa}). \end{aligned} \quad (6)$$

Here, the subscript c denotes the start of the compression, X'_{fj} is a hypothetical mean fuel vapor concentration during the compression stroke provided that the fuel vapor existing inside the engine combustion chamber mixes uniformly with the ambient air, and X'_{jc} is a hypothetical mean fuel vapor concentration with the same meaning as X'_{fj} but at the beginning of the compression stroke. If liquid fuel is charged into the combustion chamber, X'_{fj} may be different from X'_{jc} due to the evaporation of the liquid fuel during the compression stroke. As gaseous fuel is supplied in the present work, X'_{fj} is known to be equal to X'_{jc} . When the Rayleigh scattered light intensity in standard conditions is obtained beforehand, the fuel vapor mole fraction can be determined from the Rayleigh scattered light intensity measured at the point of interest and the measured results of the pressure, the temperature and the volume of the combustion chamber. Since the temperature fluctuation is slight during

the intake stroke of a motored SI engine, $T = T_c = T_s$ was assumed in solving these equations, which will not bring about any serious errors in estimating the fuel vapor mole fraction or its fluctuation.

When an operating engine is taken into consideration, the application of conventional concentration fluctuation concepts is complicated by the fact that the mixture state in the combustion chamber changes not only temporally at a specific cycle but also cyclically. Although the overall features of the mixture concentration profiles may repeat each cycle, the details do not because the mean concentration can vary significantly from one engine cycle to the next. There are both cyclic variations in the mean at any point in the cycle, as well as the concentration fluctuations about that specific cycle's mean concentration. This transient fuel vapor concentration in the engine combustion chamber as described above can be expressed as follows:

$$X_f(\theta, i, j) = X_{fT}(\theta, j) + x_{f1}(\theta, i, j) \quad (7)$$

$$X_f(\theta, i, j) = X_{fE}(\theta, i) + x_{f2}(\theta, i, j), \quad (8)$$

where

θ : crank angle

i : the i th number of digitized points within the crank angle window $\Delta\theta$ centered at the nominal crank angle θ

j : cycle number.

In Eq. (7), it is shown that the instantaneous vapor concentration at a specific crank angle position in a particular cycle can be divided into two components, i.e., the time-averaged mean concentration within a specific crank angle window in a specific cycle as well as the fluctuating component at this particular crank angle and specific cycle. Equation (8) shows that the instantaneous fuel vapor concentration inside the engine combustion chamber can be expressed as the sum of the ensemble-averaged mean concentration and the fluctuation at that instant. From the above explanation, $X_{fT}(\theta, j)$ can be defined as

$$X_{fT}(\theta, j) = \frac{1}{N_d} \sum_{i=1}^{N_d} X_f(\theta, i, j), \quad (9)$$

where N_d is the dividing number of the small crank angle window $\Delta\theta$. The ensemble-averaged mean concentration $X_{fE}(\theta, i)$ can be written as

$$X_{fE}(\theta, i) = \frac{1}{N_c} \sum_{j=1}^{N_c} X_f(\theta, i, j), \quad (10)$$

where N_c is the total sampling cycle number. When Eq. (8) is averaged temporally within the small crank angle window, the following equation can be derived:

$$X_{fT}(\theta, j) = X_{fET}(\theta) + x_{f2T}(\theta, j). \quad (11)$$

The two components on the right side of this equation can be defined as

$$X_{fET}(\theta) = \frac{1}{N_c N_d} \sum_{j=1}^{N_c} \sum_{i=1}^{N_d} X_f(\theta, i, j) \quad (12)$$

$$x_{f2T}(\theta, j) = \frac{1}{N_d} \sum_{i=1}^{N_d} x_{f2}(\theta, i, j). \quad (13)$$

From Eq. (12), it is noted that the ensemble-averaged mean concentration is a function only of the crank angle since the cyclic variation has been averaged out. The difference between the mean concentration in a particular cycle and the ensemble-averaged mean concentration over many cycles is the cyclic variation of the temporal mean concentration, as shown in Eq. (11). With the substitution of Eq. (11) into Eq. (7), the following equation can be derived:

$$X_f(\theta, i, j) = X_{fET}(\theta) + x_{f2T}(\theta, j) + x_{f1}(\theta, i, j). \quad (14)$$

From Eq. (14), it is found that the instantaneous fuel vapor concentration can be split into three components, which are the ensemble-averaged mean concentration, the cyclic variation of the temporal mean concentration, and the temporally fluctuating concentration in this specific cycle. Figure 1 illustrates the breakdown of the instantaneous concentration into an ensemble-averaged component, an individual-cycle mean component, and a component which randomly fluctuates in time at a particular point in space in a single cycle. The last component is the concentration fluctuation defined by the conventional concentration fluctuation concept. Whether this differs significantly from the variation of the temporal mean concentration depends on whether the cyclic variations are small or large. Figure 1 also shows the definitions of some other physical parameters appearing in the above statements.

The magnitude of the cyclic variation of the temporal mean concentration can be determined from the following equation:

$$X_{fR}(\theta) = \left[\frac{1}{N_c} \sum_{j=1}^{N_c} \{x_{f2T}(\theta, j)\}^2 \right]^{1/2}. \quad (15)$$

Fig. 1 Definition of fuel vapor concentration fluctuation

The temporal concentration fluctuation within the crank angle window at a particular cycle is given as

$$x_{f1T}(\theta, j) = \left[\frac{1}{N_d} \sum_{i=1}^{N_d} \{x_{f1}(\theta, i, j)\}^2 \right]^{1/2} \quad (16)$$

Thus, the ensemble-averaged concentration fluctuation can be defined as follows:

$$x_{fET}(\theta) = \frac{1}{N_c} \sum_{j=1}^{N_c} x_{f1T}(\theta, j). \quad (17)$$

The cyclic variation of the temporal concentration fluctuation can be given as

$$x_{fR}(\theta) = \left[\frac{1}{N_c} \sum_{j=1}^{N_c} \{x_{f1T}(\theta, j) - x_{fET}(\theta)\}^2 \right]^{1/2} \quad (18)$$

This shows the cyclically varying intensity of the temporal concentration fluctuation.

To obtain the temporal mean concentration and the temporal concentration fluctuation at a particular position in a specific cycle by Eqs. (9) and (16), the small crank angle window $\Delta\theta$ should be selected suitably. From the preliminary experiment, it is found that neither the ensemble-averaged mean concentration nor the ensemble-averaged concentration fluctuation showed any appreciable dependence on the small crank angle window in the range of one degree to five degrees. On the basis of this result and the waveform of the fuel vapor concentration, the crank angle window was determined as one degree, and the total sampling cycle number was set to be $N_c=30$.

3. Experimental Apparatus and Procedures

A schematic diagram of the experimental apparatus is given in Fig. 2. Used in this study was an air-cooled, four-stroke-cycle, single-cylinder SI engine whose specifications are shown in Table 1. In order to make the optical diagnostics possible, the original engine was fabricated to permit the installation of an extended combustion cylinder with three pyrex glass windows on its side wall. An extended piston was also mounted on the original piston. The engine was driven by a variable-speed electric motor. A timing disk was installed on the extended crank shaft for detecting the engine crank angle. Fresh air was allowed to pass through a laminar air flowmeter, a desiccator containing silica gel for trapping the water mist, an air filter with a pore size of 300 nm and an intake port, and to flow into the combustion chamber. A HEPA (high-efficiency particulate arrest) filter was used as the air filter to trap the dust contained in the intake air. The cylinder pressure was measured with the use of a pressure transducer.

Freon-12 (R 12, $T_b=243.5$ K) was selected to simulate the fuel vapor due to its similarity of density to gasoline vapor, its noninflammability and its comparatively large Rayleigh scattering cross section ($130.18 \times 10^{-27} \text{ cm}^2$ at a wavelength of 488 nm)⁽⁶⁾ which

allowed a more accurate measurement of the mean concentration and the concentration fluctuation by the laser Rayleigh scattering technique. Freon-12 in a high-pressure tank was allowed to pass through a flowmeter and a filter, and to discharge continuously from a stainless steel pipe with an inner diameter of 2 mm into the intake port.

As shown in Eqs. (5) and (6), to determine the fuel vapor concentration, it is necessary to first determine the Rayleigh scattered light intensity I_{rsa} , I_{rs} and the fuel vapor concentration X_{fs} at the standard condition. The relationship between I_{rs} and X_{fs} was determined by supplying the pure Freon-12 to the

Table 1 Engine specifications

Type of Engine	Four-stroke-cycle spark ignition engine
Cooling System	Air-cooled
Number of Cylinders	1
Displacement Volume	589cc
Bore	94mm
Stroke	85mm
Compression Ratio	8.5(3.1)
Intake Valve Timing	O:32° BTDC C:68° ABDC
Exhaust Valve Timing	O:70° BBDC C:30° ATDC
Ignition Timing	0° BTDC below 2200rpm 30° BTDC above 4300rpm

1. Argon laser 2. amplifier 3. light chopper 4. photointerrupter 5. pulse generator 6. injection pipe 7. filter 8. flowmeter 9. pressure regulator 10. fuel tank 11. photomultiplier 12. light stop 13. amplifier 14. low pass filter 15. lens 16. lens 17. pinhole 18. pressure transducer 19. extended combustion cylinder 20. glass windows 21. pinhole 22. beam trap 23. air filter 24. desiccator 25. laminar air flowmeter 26. photointerrupter 27. timing disk 28. engine 29. motor 30. data recorder 31. oscilloscope 32. signal processor 33. XY recorder

Fig. 2 Experimental apparatus

measurement location through a stainless steel pipe with an inner diameter of 4 mm installed inside the engine combustion chamber. The determination of the background light intensity was based on the Rayleigh signal from helium gas discharged from a stainless steel pipe being subjected to irradiation of the focused laser light⁽⁹⁾. All the calibration experiments were performed at atmospheric pressure and room temperature with optical glass windows installed on the extended cylinder to keep the background light equal to that of the actual measurements.

A 2 W linearly polarized cw argon laser emitting monochromatic radiation at a wavelength of 488 nm was used as a light source for Rayleigh scattering diagnostics. A convex lens with focal length of 300 mm was available to focus the incident laser light on the optical center in the combustion chamber where the measurements of fuel vapor concentration were to be obtained. Thus, only a small volume of the gaseous mixture was irradiated. To suppress the spuriously scattered incident laser light, two pinholes and a beam trap were provided. The optical detection system consisted of a convex lens with a focal length of 200 mm, a light stop and a photomultiplier (Hamamatsu R 928), and was placed at a right angle to the incident laser light in the same horizontal plane. This system collected the scattered light from the gaseous mixture contained in a minute volume of the waist diameter of the focused laser light (0.13 mm) divided by a circle with a diameter of 0.25 mm. All the equipments comprising the optical detection system was enclosed in a dark box, and the measurements were performed in subdued light environments to reduce the spurious background light. The output electrical signal from the photomultiplier was transmitted through an amplifier and a low pass filter, and was analyzed with a signal processor.

Figure 3 shows the details of the combustion chamber. The injection pipe was fixed at the top portion of the intake port and the injection was toward the bifurcated point between the two intake valves on the bottom wall of the intake port in the plane passing through the central axis of the engine cylinder. Three glass windows with a thickness of 10 mm and diameter of 35 mm were installed on the side wall of the extended combustion cylinder with a length of 87 mm which was mounted between the cylinder head and the original engine cylinder. Two of the glass windows were available for transmitting the incident laser light into and out of the combustion chamber and the other was for collecting the scattered light. The measurements of fuel vapor concentration were made below the central spark plug. The extended piston was flat at its tip and the compression

ratio was set to be 3.1 in order to avoid any influence on the optical diagnostics.

4. Results and Discussion

Figure 4 shows the time histories of the ensemble-averaged mean concentration with different air fuel ratios at an engine speed of 750 rpm. It is found that the ensemble-averaged mean concentration $X_{JET}(\theta)$ increased with the lapse of time, and reached a peak at a crank angle of 60° after which it decreased during the intake and compression strokes. As the intake valve is opened, the rich mixture formed inside the intake port is presumed to rush into the combustion chamber, which would also descend inside the combustion chamber with the piston movement and be diluted due to turbulent mixing with the surrounding air. It is probable that the above mixture formation process may cause the results shown in Fig. 4. It is also found that the fuel vapor concentration at the end of the compression stroke is almost the same as that corre-

Fig. 3 Details of combustion chamber

sponding to the supplied air fuel ratio. This shows that at this time the Freon-12 vapor has mixed with the ambient air uniformly. From Fig. 4, it is noted that the time history of the ensemble-averaged mean concentration during the intake stroke is similar to the results derived from the liquid fuel injection^{(6),(7)}. The fuel vapor concentration of the liquid fuel injection showed no change or a slight increase during the compression stroke. This is different from the results presented in Fig. 4. It is likely that the evaporation of liquid fuel and the dilution of the generated fuel vapor due to turbulent mixing and molecular diffusion proceed simultaneously, which leads to no change or a slight increase in the fuel vapor concentration during the compression stroke when liquid fuel is supplied.

Figure 5 shows the cyclic variation of the temporal mean concentration at different air fuel ratios in the same experimental conditions as Fig. 4. It is shown that the cyclic variation of the temporal mean concen-

Fig. 4 Effect of air fuel ratio on ensemble-averaged mean concentration

Fig. 5 Effect of air fuel ratio on cyclic variation of the temporal mean concentration

tration $X_{RT}(\theta)$ changed along with the crank angle, and reached a maximum at the crank angle of 60° during the intake stroke. This is almost equal to the crank angle when the maximum of the ensemble-averaged mean concentration appeared. It is also evident that the cyclic variation of the temporal mean concentration increased with the decrease in the air fuel ratio. Figure 6 demonstrates the time histories of the ensemble-averaged concentration fluctuation at different air fuel ratios. It is found that $x_{fET}(\theta)$ also showed a maximum during the intake stroke. However, its appearance was slightly earlier than those of $X_{fET}(\theta)$ and $X_{RT}(\theta)$. It is also found that the ensemble-averaged concentration fluctuation increased with the decrease in air fuel ratio. In a comparison of the maxima shown in Figs. 4, 5 and 6, it is clear that the cyclic variation in the temporal mean concentration is about 7 % of the ensemble-averaged mean concentration, and nearly 1/3 of the ensemble-averaged concentration fluctuation. Therefore, it is determined that the concentration fluctuation consists of a temporal concentration fluctuation in a specific cycle and a cyclic variation in the temporal mean concentration at this particular cycle. The cyclic variation in the temporal concentration fluctuation at different air fuel ratios is presented in Fig. 7. It is found that, when the temporal concentration fluctuation is taken into consideration, its cyclic variation is also too large to be neglected.

Figures 8, 9, 10 and 11 show the effect of engine speed on $X_{fET}(\theta)$, $X_{RT}(\theta)$, $x_{fET}(\theta)$ and $x_{RT}(\theta)$. The experimental results showed that the time histories of the above four parameters were similar to each other and their maxima increased slightly with the increase in the engine speed, but the crank angles at their appearances were delayed.

Fig. 6 Effect of air fuel ratio on ensemble-averaged concentration fluctuation

The experimental results indicated that the fuel vapor concentration shows a marked temporal and cyclic fluctuation in the engine combustion chamber. Minor fluctuations in the following factors are assumed to cause these temporal and cyclic fluctuations:

1. the amount of fuel entering the engine combustion chamber,
2. the amount of air entering the engine combustion chamber,
3. the air flow pattern and the spatial distributions of the mixture within the engine cylinder,
4. the amount of wall wetting,
5. residual gas,
6. recycled exhaust gas.

The first three are thought to be the dominant factors

Fig. 7 Effect of air fuel ratio on cyclic variation of the temporal concentration fluctuation

Fig. 8 Effect of engine speed on ensemble-averaged mean concentration

Fig. 9 Effect of engine speed on cyclic variation of the temporal mean concentration

Fig. 10 Effect of engine speed on ensemble-averaged concentration fluctuation

Fig. 11 Effect of engine speed on cyclic variation of the temporal concentration fluctuation

in the cyclic fluctuations of vapor concentration in this study. As the fuel vapor remaining in the previous cycle is also present in the combustion chamber, its fluctuation in the amount and spatial distribution are also responsible for the cyclic fluctuations of fuel vapor concentration as derived in this investigation. In the commercial engine, the liquid fuel of gasoline is mainly charged into the engine combustion chamber. The wall wetting may also become a serious problem which influences the cyclic concentration fluctuation and thus, the cyclic fluctuations of the combustion process due to the fluctuations of the wall temperature. The fluctuations in the residual gas and recycled exhaust gas will also contribute substantially to the cyclic variations in the mixture strength. Thus, to reduce the influence of mixture strength on the cyclic variations of engine combustion, all the above factors should be taken into consideration and optimized.

5. Conclusions

An experimental study was conducted to perform highly space- and time-resolved measurements of the fuel vapor concentration fluctuation in the combustion chamber of a motored SI engine with continuous injection of Freon-12 into the dust-free dry air through an intake port. The fuel vapor concentration and its fluctuation were determined by laser Rayleigh scattering. The temporally and cyclically fluctuating characteristics of the fuel vapor were analyzed theoretically in detail and expressed in terms of the ensemble-averaged mean concentration, the cyclic variation of temporal mean concentration, the ensemble-averaged concentration fluctuation, and the cyclic variation of temporal concentration fluctuation. The effects of air fuel ratio and engine speed on the time histories of the above four parameters were also investigated.

The fundamental conclusions drawn from this study are summarized as follows:

- (1) The concentration fluctuation consists of a temporal concentration fluctuation in a specific cycle and a cyclic variation of the temporal mean concentration in this particular cycle. The present experimental apparatus is effective for separating and determining these fluctuations. Under the present experimental condition, the former is larger than the latter.
- (2) The ensemble-averaged mean concentration and the ensemble-averaged concentration fluctuation show a maximum during the intake stroke after which they decrease simply. The appearance of the maximum of the latter occurs earlier than that of the former.
- (3) The mean concentration and the concentration fluctuation increase with the decrease in the air fuel ratio in the full range of the crank angle.
- (4) With the increase in the engine speed, the maxima of the mean concentration and the concentration fluctuation increase, and the crank angles of their appearances are delayed.

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References

- (1) Kadota, T., The Application of Laser Rayleigh Scattering to the Local Mixture Strength Measurements in SI Engine during Intake Stroke, SAE Trans., Vol. 96, Sec.-7, Paper No. 872151 (1987).
- (2) Kadota, T., Satoh, T., Memon, M. A. and Sumida, O., Mixture Strength Measurements in the Combustion Chamber of SI Engine via Rayleigh Scattering, Trans. Japan Soc. Mech. Eng. (in Japanese), Vol. 54, No. 498, Series B (1988), p.492.
- (3) Kadota, T., Zhao, F.-Q. and Satoh, T., Effect of Intake Valve Configuration on the Mixture Strength Field in the Combustion Chamber of an SI Engine, Trans. Japan Soc. Mech. Eng. (in Japanese), Vol. 54, No. 502, Series B (1988), p. 1535.
- (4) Kadota, T., Zhao, F.-Q. and Tsuzaki, H., Mixture Strength Measurements in the Combustion Chamber of SI Engine via Rayleigh Scattering (2nd Report, Results at Liquid Fuel Injection), Trans. Jpn. Soc. Mech. Eng. (in Japanese), Vol. 55, No. 519, Series B (1989), p. 3558.
- (5) Kadota, T., Zhao, F.-Q. and Tsuzaki, H., Laser Rayleigh Scattering Measurements of the Fuel Vapor Concentration in the Combustion Chamber of SI Engine, Proc. of IPC-5, Vol. 1, Paper No. 891196 (1989), p. 196.
- (6) Kadota, T., Zhao, F.-Q. and Miyoshi, K., Mixture Strength Measurements in the Combustion Chamber of SI Engine via Rayleigh Scattering (3rd Report, Results in the Motored Engine), Trans. Jpn. Soc. Mech. Eng. (in Japanese), Vol. 56, No. 532, Series B (1990), p. 837.
- (7) Kadota, T., Zhao, F.-Q. and Miyoshi, K., Rayleigh Scattering Measurements of Sparked Fuel Vapor Concentration in a Motored Spark Ignition Engine, SAE Trans., J. of Engines, Vol. 99, Sec.-3, Paper No. 900481 (1990), p. 1101.
- (8) Shardanand and Rao, A.D.P., Absolute Rayleigh Scattering Cross Sections of Gases and Freons of Stratospheric Interest in the Visible and Ultraviolet Regions, NASA Tech. Note, NASA TN D-8442 (1977).
- (9) Fourquette, D. C., Zurn, R. M. and Long, M. B., Two-Dimensional Thermometry in a Turbulent Nonpremixed Methane Hydrogen Flame, Combust. Sci. Technol., Vol. 44 (1986), p. 307.