Mixture Strength Measurements in the Combustion Chamber of SI Engine via Rayleigh Scattering*
(Ensemble-Averaged Concentration Fluctuation and Cyclic Variation of Temporal Concentration Fluctuation near the Spark Plug)

Fu-Quan ZHAO**, Toshikazu KADOTA***
and Tooru TAKEMOTO**

Laser Rayleigh scattering was applied for remote, nonintrusive point probing of the vapor concentration and its fluctuation near the spark plug of a motored spark ignition engine, which was caused by the intermittent injection of Freon-12 vapor into an intake port. The theoretical analysis showed that the instantaneous fuel vapor concentration can be split into three components: the ensemble-averaged mean concentration, the cyclic variation of temporal mean concentration and the temporal concentration fluctuation in a specific cycle. This paper concentrates on the measurements of the ensemble-averaged concentration fluctuation and the cyclic variation of temporal concentration fluctuation. The results show that the cyclic variation of temporal concentration fluctuation is too large to be neglected, and both the ensemble-averaged concentration fluctuation and the cyclic variation of temporal concentration fluctuation increase and reach a peak after which they decrease during the intake and compression strokes. They are strongly affected by air fuel-ratio, engine speed, injection duration and injection timing.

Key Words: Internal Combustion Engine, SI Engine, Spark plug, Mixture Formation, Laser Rayleigh Scattering, Concentration Fluctuation, Cyclic Variation

1. Introduction

The cyclic variation of the mixture strength field is an important factor that affects the cyclic engine combustion variation. Especially important are the cyclic fluctuations of the mixture strength field near the spark plug which influence the initial stage of the flame development and its propagation process—the possibility of establishing a stable kernel and developing it into a turbulent flame, which dominates the following combustion process, thereby affects the cyclic combustion variation, engine exhaust and so on.

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** Department of Mechanical Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashi-Hiroshima 724, Japan
*** Department of Mechanical Engineering, University of Osaka Prefecture, 1-1, Gakuen-cho, Sakai 593, Japan

The local air-fuel ratio and turbulence in the vicinity of the spark plug can vary from cycle to cycle; thus, cyclic dispersion is observed. When spark ignition (SI) engines are operated in lean-burning conditions, the cyclic fluctuation of engine combustion near the spark plug becomes more important. Due to the temporal and cyclic variations of the fuel vapor concentration near the spark plug in an inhomogeneous mixture, a spark may ignite a very lean region of the microstructure in one cycle and a fuel-rich one in the next, while the overall air-fuel ratio in the cylinder remains constant. This causes different pressure pulses inside the engine cylinder, and hence cyclic dispersion takes place. This indicates that the power obtained from the combustion of the entire charge depends significantly on the precise mixture distribution at the spark plug. This is because it takes a disproportionately long time for a kernel initiated by a spark to grow into a true flame front that can
propagate at the rate determined by the bulk properties of the engine diet. It is the local structure that largely determines the extent of the delay, and thereby the time at which the peak pressure is reached and the power obtained from the cycle.

From the above statements, it is clear that the mixture strength field at the spark plug plays a dominant role in the cyclic variation of engine combustion. Clarification of its temporally and cyclically fluctuating characteristics is vital for further understanding of the cyclic variation of engine combustion as well as for its reduction. However, previous studies have been limited to gas sampling. Laser-based nonintrusive measurements of the fuel vapor concentration fluctuation with high temporal and spatial resolution at the spark plug are urgently necessary. However, this is hindered by the difficulty of viewing this portion due to the complicated locations of the engine valves.

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.(11)-(17) The measurements of the time histories of the mean concentration and concentration fluctuation in the combustion chamber of a motored SI engine were also reported for a wide range of engine operating conditions.(9)-(12) Previous reports(11)(12) described a method for expressing the temporally and cyclically fluctuating characteristics of the fuel vapor inside the engine combustion chamber. It was disclosed that the temporally and cyclically fluctuating characteristics of the fuel vapor could be expressed clearly 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 the air-fuel ratio and engine speed on the time histories of the above four parameters were investigated in the combustion chamber of a motored SI engine with an elongated engine cylinder.

To understand the temporally and cyclically fluctuating state of the fuel vapor, an experimental program was designed to enable extensive measurement of the fuel vapor concentration and its fluctuation around the spark plug in the combustion chamber of a motored SI engine with a timed injection of fuel, simulated by Freon-12, into dust-free dry air through an intake port under the application of laser Rayleigh scattering. The effects of several engine operating parameters, for example, the air-fuel ratio, the engine speed, the fuel injection duration and the fuel injection timing, were also investigated thoroughly. The results for the ensemble-averaged mean concentration and the cyclic variation of temporal mean concentration derived from this investigation have been reported in a previous paper(13). The present paper describes the results for the ensemble-averaged concentration fluctuation, the cyclic variation of temporal concentration fluctuation, and the effects of various engine parameters on them.

2. Experimental Methods and Procedures

Many laser-based nonintrusive diagnostic techniques, for example, Rayleigh scattering, Raman scattering, Mie scattering, laser-induced fluorescence (LIF), absorption and schlieren method, can be employed to measure the fuel vapor concentration. The selection of diagnostic techniques should be dependent on the characteristics of the flow field to be detected and the behavior of the diagnostic technique to be employed. Due to the smaller scattering cross section of Raman scattering, the insufficiency of the quenching data for LIF, the seeding difficulty for Mie scattering, the integrated measurements of the concentration field for absorption and the schlieren method, and other related problems, Rayleigh scattering seems to be the best candidate for the determination of fuel vapor concentration in the combustion chamber of SI engines due to its comparatively large scattering cross section and its simplicity and ease of implementation relative to other techniques. Thus, Rayleigh scattering is employed in this study. Irradiation by laser light of gaseous molecules causes Rayleigh scattering, whose intensity varies depending on the chemical species. This measured scattered light intensity is used to determine the fuel vapor concentration.(11)-(12)

Generally, the flow phenomena in the engine combustion chamber are quasi-periodic because of the cyclic nature of the engine operation. Thus, 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 in a specific cycle but also cyclically. Although the overall features of the mixture concentration profiles may be repeated in each cycle, the details are not because the mean concentration can vary significantly from one engine cycle to the next. There are cyclic variations in the mean at any point in the cycle, as well as concentration fluctuations around that specific cycle's mean concentration. This transient fuel vapor concentration in the engine combustion chamber above can be expressed as follows:

$$X_\ast(\theta, i, j) = X_{\ast \theta}(\theta, j) + x_{\ast i}(\theta, i, j) \quad (1)$$
\[ X(\theta, i, j) = X_{rt}(\theta, i) + x_{fl}(\theta, i, j), \]  
\[ \text{where} \]  
\[ \theta: \text{crank angle}, \]  
\[ i: \text{the} \ i^{th} \text{number of digitized points within the crank angle window} \Delta \theta \text{centered at the nominal crank angle} \theta, \]  
\[ j: \text{cycle number}. \]  

In Eq. (1), it is shown that the instantaneous vapor concentration at a specific crank angle position in a particular cycle can be divided into two components: the time-averaged mean concentration within a specific crank angle window in a specific cycle, and the fluctuating component at this particular crank angle and specific cycle. Equation (2) 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, \( X_{rt}(\theta, i) \) can be defined as

\[ X_{rt}(\theta, i) = \frac{1}{N_d} \sum_{j=1}^{N_c} X(\theta, i, j), \]  
\[ \text{where} \ N_d \text{is the dividing number of the small crank angle window} \Delta \theta. \]  

The ensemble-averaged mean concentration \( X_{rt}(\theta, i) \) can be written as

\[ X_{rt}(\theta, i) = x_{rt}(\theta, i), \]  
\[ \text{where} \ N_c \text{is the total sampling cycle number. When} \]  

Eq. (2) is averaged temporally within the small crank angle window, the following equation can be derived:

\[ X_{rt}(\theta, i) = x_{rt}(\theta, i) + x_{fl}(\theta, i, j). \]  

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

\[ x_{rt}(\theta, i) = \frac{1}{N_d \cdot N_r} \sum_{j=1}^{N_c} x(\theta, i, j), \]  
\[ x_{fl}(\theta, i, j) = \frac{1}{N_d} \sum_{x=1}^{N_c} x(\theta, i, j). \]  

From Eq. (6), it is noted that the ensemble-averaged mean concentration is a function of only 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. (5). With the substitution of Eq. (5) into Eq. (1), the following equation can be derived:

\[ X(\theta, i, j) = X_{rt}(\theta) + x_{fl}(\theta, i, j) + x_{rt}(\theta, i, j). \]  

From Eq. (8), it is found that the instantaneous fuel vapor concentration can be split into three components: the ensemble-averaged mean concentration, the cyclic variation of 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. This last component is the concentration fluctuation, defined by the conventional concentration fluctuation concept. Whether this differs significantly from the variation of temporal mean concentration depends on whether the cyclic variations are small or large. Figure 1 also shows the definitions of the other physical parameters appearing in the above statements.

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

\[ x_{fl}(\theta, i, j) = \left[ \frac{1}{N_d \cdot N_r} \sum_{x=1}^{N_c} x_{fl}(\theta, i, j) \right]^{1/2}. \]  

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

\[ x_{fl}(\theta, i, j) = \left[ \frac{1}{N_d \cdot N_r} \sum_{x=1}^{N_c} (x(\theta, i, j))^2 \right]^{1/2}. \]  

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

\[ x_{fl}(\theta, i) = \left[ \frac{1}{N_d \cdot N_r} \sum_{x=1}^{N_c} x_{fl}(\theta, i, j) \right]. \]  

The cyclic variation of temporal concentration fluctuation can be given as

\[ x_{fl}(\theta, i, j) = \left[ \frac{1}{N_d \cdot N_r} \sum_{x=1}^{N_c} (x(\theta, i, j) - x_{rt}(\theta))^2 \right]^{1/2}. \]  

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. (3) and (10), appropriate small crank angle window \( \Delta \theta \) should be selected. From the preliminary experiment, it was 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

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**Fig. 1** Definition of fuel vapor concentration fluctuation

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angle window was determined as three degrees, and the total sampling cycle number was set to be \( N_s = 30 \).

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 were given in previous reports\(^{(8)-(12)}\). In order to make the optical diagnostics accessible, the original engine head was fabricated to permit the installation of three Pyrex glass windows. 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 made to pass through a laminar air flowmeter, a desiccator containing silica gel for trapping moisture, an air filter with a pore size of 300 nm and an intake port, and was then allowed to flow into the combustion chamber. A HEPA (high-efficiency particulate arrest) filter was used to trap the dust contained in the inflowing air. The cylinder pressure was monitored with a pressure transducer.

Freon-12 (R12, \( T_e = 243.5 \) K) was selected to simulate the fuel vapor due to its density similar to that of multicomponent gasoline vapor, its nonflammability and its comparatively large Rayleigh scattering cross section \( (130.18^{-27} \text{ cm}^2 \) at a wavelength of 488 nm\(^{(14)}\), which allows a more accurate measurement of the mean concentration and the concentration fluctuation by means of the laser Rayleigh scattering technique. Freon-12 in a high-pressure tank was allowed to pass through a filter, and then to discharge intermittently into the intake port. An electromagnetic valve with an exit diameter of 2 mm was actuated by an electrical signal from a pulse generator. To operate the pulse generator, a photointerrupter was installed near a light chopper fixed on the extended cam shaft. Fuel injection duration and the injection timing could be changed by adjusting the pulse generator and the setting position of the chopper on the extended cam shaft. Fuel injection was suspended once every ten cycles so as to prevent fuel accumulation inside the engine combustion chamber.

A 2 W linearly polarized cw argon laser emitting monochromatic radiation at a wavelength of 488 nm was used as the light source for Rayleigh scattering diagnostics. A convex lens with focal length of 300 mm focused the incident laser light on the optical center in the combustion chamber. Thus, only a small volume of the gaseous mixture was irradiated. To suppress 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 stopper and a photomultiplier (Hamamatsu R928). This system collected scattered light from the gaseous mixture, which was contained in a minute volume of the waist diameter of the focused laser light \( (0.13 \text{ mm}) \) and divided by a circle with a diameter of about 0.25 mm. All of the equipment comprising the optical detection system were enclosed in a dark box, and measurements were performed in a subdued light environment to reduce spurious background light. The output electrical signal from the photomultiplier was transmitted through an amplifier and a low-pass filter (cut-off frequency : 5 kHz), and was analyzed with a signal processor.

As stated in previous reports\(^{(8)-(12)}\), to determine the fuel vapor concentration, it is necessary to first determine the Rayleigh scattered light intensities from pure air and the standard fuel/air mixture with a known concentration under standard conditions. The scattered light intensity from the standard fuel/air mixture with a known concentration was determined by supplying pure Freon-12 to the 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 which was subjected to irradiation by the focused laser light\(^{(15)}\). 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.

Figure 3 shows the details of the combustion

![Fig. 2 Experimental apparatus](https://example.com/fig2.png)

**Fig. 2** Experimental apparatus
chamber. The injection pipe was fixed at the upper stream of the intake port and the fuel was injected toward the bifurcated point between the two intake values on the bottom wall of the intake port in the plane passing through the central axis of the engine cylinder. Two glass windows with thickness of 8 mm and diameter of 16 mm were installed on the sidewall of the cylinder head for transmitting the incident laser light into and out of the combustion chamber. There were holes in this engine head for installing the spark plugs. The hole for the central plug was fabricated allowing installation of a piece-glass window with diameter of 20 mm and thickness of 8 mm for collecting the laser-induced scattered light. The other plug hole was employed to fix the pressure transducer. To reduce spuriously scattered light from the solid surfaces, the cylinder wall and the piston surface were painted black. With the above-stated modifications of the engine, the concentration measurement was possible just below the central spark plug hole; the engine compression ratio was 3.1.

3. Results and Discussion

Figure 4 shows a schematic diagram of the time histories of the fuel vapor concentration in terms of percentage mole fraction $X_t$ and the electrical signal $V_t$ for actuating the fuel injector. The abscissa is the crank angle with the origin at the top dead center (TDC) prior to the intake stroke. The curve was used to define typical factors expressing the characteristics of the fuel vapor concentration, which are the fuel vapor concentration at the end of the compression stroke $X_t(T_{GE}, x_{in})$, the peak vapor concentration during the intake stroke $X_t(T_{GE}, x_{in})$, and the period of time between the initiation of the fuel injection and the appearance of the peak vapor concentration $\theta_{kip}(T_{GE}, x_{in})$. The crank angle at the initiation of fuel injection and the fuel injection duration are denoted as $\theta_i$ and $\theta_i$, respectively.

Figure 5 shows the time histories of the ensemble-averaged concentration fluctuation $x_{kip}(\theta)$ with different air-fuel ratios (A/F) at the engine speed of 650 rpm. The air-fuel ratio was changed by adjusting the injection pressure while the injection duration was kept constant. It was found that the ensemble-
The averaged concentration fluctuation increased with the lapse of crank angle, and reached a peak at the crank angle of about 90 degrees, after which it decreased monotonously during the intake and compression strokes. In comparison of this result with those of the previous report, under the same experimental conditions, it is noted that the crank angle at the appearance of the maximum for the ensemble-averaged concentration fluctuation is almost the same as that of the ensemble-averaged mean concentration, which indicates that, with the timed fuel injection, the concentration fluctuation is large when the mean concentration is high. It is also found that $x_{J_{TDP}}(\theta)$ increased in the full crank angle range with decrease in the air-fuel ratio.

Figure 6 demonstrates $x_{J_{TDP}}$, $x_{J_{TH}}$, and $\theta_{J_{TDP}}$ derived from the results of Fig. 5 as defined in Fig. 4. As seen from this figure, with the decrease in the air-fuel ratio, $x_{J_{TDP}}$ and $x_{J_{TH}}$ increased but $\theta_{J_{TDP}}$ decreased. The decrease in the air-fuel ratio brings about an increase in the injected fuel quantities and an increase in the fuel jet speed due to the increase in the injection pressure, which is likely to cause an increase in the ensemble-averaged concentration fluctuation and a decrease in the arrival time of the peak vapor concentration.

In comparison of the maximum of the ensemble-averaged concentration fluctuation with the results of previous reports under the same experimental conditions, it is found that the ensemble-averaged concentration fluctuation is about 30% of the ensemble-averaged mean concentration, and nearly twice the cyclic variation of temporal mean concentration. This shows that the concentration fluctuation is composed of a temporal concentration fluctuation in a specific cycle and a cyclic variation of temporal mean concentration in that particular cycle. The latter also accounts for a large portion of the concentration fluctuation.

Figures 7 and 8 provide the cyclic variation of temporal concentration fluctuation under the same experimental conditions as in Fig. 5. The cyclic variation of temporal concentration fluctuation also showed a peak during the intake stroke, after which it decreased monotonously through the intake and compression strokes. It is also noted that with the decrease in the air-fuel ratio, the cyclic variation of temporal concentration fluctuation increased in the full range of the crank angle. The cyclic variation of temporal concentration fluctuation reached maximum slightly later than the ensemble-averaged concentration fluctuation. As demonstrated clearly in Fig. 8, $x_{J_{TH}}$, $x_{J_{TH}}$, and $\theta_{J_{TH}}$ decreased with the increase of the air-fuel ratio. From all the above statements, it is evident that the cyclic variation of temporal concentration fluctuation is too large to be neglected.

Figures 9-12 show the effect of engine speed on the ensemble-averaged concentration fluctuation and the cyclic variation of temporal concentration fluctuation.
fluctuation. For varying engine speed, the air-fuel ratio and the injection duration were kept constant by adjusting the injection pressure. It was found that with increase in the engine speed, the maxima of the ensemble-averaged concentration fluctuation and the cyclic variation of temporal concentration fluctuation increased and the crank angles at their appearances were greater. Moreover, the cyclic variation of temporal concentration fluctuation increased in the full range of the crank angle with increase in the engine speed.

Fig. 9 Effect of engine speed on the time history of ensemble-averaged concentration fluctuation

Fig. 10 Effect of engine speed on $x_{JETP}, x_{INT}, \theta_{JETP}$

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

Fig. 12 Effect of engine speed on $x_{JETP}, x_{INT}, \theta_{JETP}$

Fig. 13 Effect of injection angle on the time history of ensemble-averaged concentration fluctuation

Fig. 14 Effect of injection duration on $x_{JETP}, x_{INT}, \theta_{JETP}$
speed. The increase in engine speed may enhance the mixing of fuel and air and also decrease the mixing time. This is likely to lead to a mixture formation process as shown in these figures.

Demonstrated in Figs. 13 - 16 is the effect of injection duration on the two concentration parameters: the ensemble-averaged concentration fluctuation and the cyclic variation of temporal concentration fluctuation. The injection duration was changed by adjusting the injection pressure while the air-fuel ratio was kept constant. As shown in Figs. 13 and 15, both the ensemble-averaged concentration fluctuation and the cyclic variation of temporal concentration fluctuation showed a peak during the intake stroke, after which they decreased monotonously through the intake and compression strokes. Furthermore, they increased in the fuel crank angle range with decrease in the injection duration. As shown in Figs. 14 and 16, \( x_{\text{GETP}} \), \( x_{\text{GETT}} \), \( x_{\text{ETP}} \), and \( x_{\text{ETT}} \) increased with decrease in the injection duration, but \( \theta_{\text{GETP}} \) and \( \theta_{\text{GETT}} \) decreased. The decrease in injection duration results in an increase in injection rate per unit time and an increase in fuel jet velocity. This may cause the results shown in these figures.

Figures 17 - 20 show the effect of injection timing on the ensemble-averaged concentration fluctuation and the cyclic variation of temporal concentration fluctuation. From Figs. 17 and 19, it was found that the time histories of the two concentration parameters are not dependent on the fuel injection timing and show similar tendencies; namely, after fuel injection they increase along the crank angle and reach a peak, after which they decrease monotonously. As shown in Fig. 18, \( x_{\text{GETP}} \) and \( x_{\text{GETT}} \) showed a maximum as a function of the injection timing, but \( x_{\text{GET}} \) increased with the delay of the injection timing. The delay of the injection timing causes reduction in mixing time, which may prolong the fuel air mixing process until the later stages of the compression stroke. From Fig. 20, it is found that \( x_{\text{GET}} \) and \( x_{\text{GETT}} \) show a maximum as a function of the injection timing, but \( x_{\text{ETT}} \) increase with the delay in injection timing.

From previous report\(^{(13)}\) and this report, it has
been clarified clear that with the present experimental system, it is possible for the concentration fluctuation to be measured near the spark plug; the effects of several engine operating parameters on the mean concentration and the concentration fluctuation have been investigated in detail. Further detailed research work is needed to increase the number of measurement locations and broaden the range of experimental conditions in order to clarify the relationship between the fluctuation of the mixture strength field and the cyclic variation of the engine combustion, and finally to reduce cyclic engine combustion.

4. Conclusions

An experimental study was carried out to perform highly space- and time-resolved measurements with laser Rayleigh scattering of the ensemble-averaged concentration fluctuation and the cyclic variation of temporal concentration fluctuation near the spark plug in the combustion chamber of a motored SI engine with timed injection of Freon-12 into the dust-free dry air through an intake port.

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 temporal mean concentration in this particular cycle. The present experimental apparatus is effective for separating and measuring these fluctuations. Under the present experimental conditions, the latter is smaller than the former.

(2) The cyclic variation of temporal concentration fluctuation is too large to be neglected.

(3) Both the ensemble-averaged concentration fluctuation and the cyclic variation of temporal concentration fluctuation show a maximum during the intake stroke, after which they decrease monotonously through intake and compression strokes.

(4) With the decrease in the air-fuel ratio, the ensemble-averaged concentration fluctuation and the cyclic variation of temporal concentration fluctuation increase in the full range of the crank angle, and the maximum of the former appears a little earlier than the maximum of the latter.

(5) With increase in engine speed, the crank angles for which the maxima of the ensemble-averaged concentration fluctuation and the cyclic variation of temporal concentration fluctuation appear are delayed, and the cyclic variation of temporal concentration fluctuation increases in the full range of the crank angle.

(6) With the decrease in the injection duration, the ensemble-averaged concentration fluctuation and the cyclic variation of temporal concentration fluctuation increase in the full range of the crank angle, and their maxima appear a little earlier.

(7) The time histories of the ensemble-averaged concentration fluctuation and the cyclic variation of temporal concentration fluctuation are similar for different injection timings, and their values at the end of the compression stroke increase with the delay in injection timing. Their maxima, appearing during the intake stroke, and the crank angles of their appearances show a maximum as a function of the injection timing.

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References


