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Research Report

Laser Diagnosis Using Optically Accessible Single Cylinder Engine

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ABSTRACT A technique for measurement of temperature and internal exhaust gas recirculation (EGR), i.e., residual gas, distributions in an internal combustion engine cylinder was developed using laser induced fluorescence (LIF) with an optically accessible single cylinder engine. A two-line excitation LIF method was adopted for temperature measurements. The combination of 248 and 266 nm excitation wavelengths with a toluene tracer was selected due to the high LIF quantum efficiency and high intensity ratio for two-line excitation. The stratified temperature field generated by heated air supplied using one of two intake ports was clearly observed in the cylinder. A novel diagnostic technique termed the tracer-producing LIF technique, which enables 2-dimensional measurement of the internal EGR in an engine cylinder, was developed. The distinguishing feature of this technique is the utilization of a fuel additive that does not itself emit an LIF signal under irradiation with UV-light, but whose combustion products produce strong LIF emissions. This technique was applied to a newly developed optically accessible gasoline engine, in which the entire pent-roof area can be observed from the side of the engine. The internal EGR behavior and the gas exchange process between burned gas and fresh air were measured. An inhomogeneous internal EGR distribution was also confirmed to exist at the time of ignition.

KEYWORDS Laser Diagnosis, Optically Accessible Engine, LIF, Measurement, Combustion, SI Engine

1. Introduction

To realize internal combustion engines with high thermal efficiency, high output power and low exhaust emissions, it is important to confirm whether combustion progresses as intended in the cylinder. A laser induced fluorescence (LIF) based technique and an optically accessible single cylinder engine are described for the measurement of:
(1) Unburned gas temperature distribution.
(2) Internal exhaust gas recirculation (EGR).
Here, internal EGR indicates combustion gas from the previous cycle that remains in the cylinder, as well as the gas exhausted from the cylinder once and drawn back into the cylinder during valve overlap.

The first topic under investigation is temperature measurement. The temperature distribution in an engine cylinder before ignition is one of the most important factors influencing fuel evaporation and auto-ignition in the fuel-air mixture. Many thermometry techniques have been studied in the past few decades.[1-8] Recently, such work has been focused on two types of laser-based measurements; infrared (IR) laser absorption[9,10] and LIF techniques.[11,12] The IR absorption method requires a relatively simple diagnostic system and highly precise measurement is possible. However, this method is limited to line-of-sight data, so that neither the local temperature nor its distribution can be obtained. In contrast, the LIF technique allows two-dimensional measurements with high spatial resolution using a laser-light sheet. LIF thermometry utilizes the characteristic that the LIF intensity from a fluorescent tracer is affected by temperature. This thermometry is mainly classified into two techniques: two fluorescent tracers with one excitation line[11] or one tracer with two lines.[12] In the former case, it is difficult to guarantee that two types of fluorescent tracer have identical evaporation characteristics for all engine operating conditions. The latter technique is an alternative approach to solve this problem using one tracer and two excitation lines. The wavelength dependency of LIF intensity with temperature enables thermometry by taking the ratio of the LIF intensity of the two excitation lines.

In previous work on the two-line excitation LIF technique, ketones such as acetone or 3-pentanone were used as fluorescence tracers with a pair of excitations at 248 and 308 nm.[12-14] However, the quantum efficiency of ketones is 10% or less of that of aromatic hydrocarbon (HC) molecules,[15] so that a much larger fraction of the tracer in the base fuel is required to achieve sufficient LIF intensity. Therefore, we have investigated a new combination of a fluorescent tracer and a pair of excitation lines that provides significant improvements to address these problems. The two-line excitation LIF technique has been applied to a temperature stratification field, and the decay process in that field was examined.

The second topic under investigation is internal EGR behavior. Because internal EGR measurements are difficult, the behavior of the internal EGR has not been clarified so far. A variable valve timing (VVT) system makes it possible to change the amount of internal EGR by variation of the valve timing in accordance with the operating conditions, while reducing the pumping loss and NOx and HC emissions. The adoption of the VVT system began with the intake valves of commercialized engines. However, there is now an example where the VVT system is adopted for both intake and exhaust valves to expand the adjustment range of the amount of EGR and attain higher levels of power.[16] To use EGR effectively, internal EGR measurements have been attempted using gas sampling,[17] Raman scattering,[18,19] and IR absorption.[20] However, these measurements are limited to point or line averaged measurement, so that it has remained difficult to measure the internal EGR distribution in a cylinder. The LIF method, which can measure two-dimensional fuel distributions, is widely used,[21,22] but it is difficult to measure the CO_2, H_2O and CO combustion products because they cannot be excited by the UV laser that is usually employed in the LIF method. Although LIF measurement of H_2O using two-photon absorption has been proposed,[23] there remain problems in that the fluorescence intensity is weak and the concentration is not in proportion to the intensity. Two-photon fluorescence has also been used to measure CO concentrations in a diesel engine;[24] however, similar problems remain, in that the fluorescent intensity is weak. Therefore, the LIF method has not become a practically applicable technique. Therefore, to establish a method for diagnosis of the internal EGR distribution, we have developed a new method referred to as the tracer-producing LIF technique, which enables two-dimensional measurement of the internal EGR in an engine cylinder. Here, the principles of this technique, the fluorescent tracers, and the fuel additives that generate the fluorescent tracers are described. Furthermore, we have applied this technique to an optically accessible gasoline engine in which the entire pent-roof area can be observed from the side of engine. As a result, the gas exchange process between a burned gas and fresh air, as well as the influence of the valve timing on this process have been clarified.

2. Principle of Measurement

2. 1 Temperature Measurement

To determine the best combination of fluorescent tracer and excitation wavelength that gives a high LIF intensity ratio, a fluorescent tracer was poured into a constant volume vessel. A schematic of the constant volume vessel apparatus is shown in **Fig. 1**. The capacity of the vessel is 368 cm^3, the temperature adjustment range is from room temperature to 523 K, and the pressure range is up to 1.0 MPa. This vessel has four quartz windows for optical diagnostics and over thirty electric rod heaters in a stainless steel block to heat the entire vessel. A fan is rotated inside the vessel to maintain a uniform temperature. The gas temperature at three different points is monitored using thermocouples located in the vessel. The temperature and pressure in the vessel are set to the test conditions after injection of a predetermined amount of pure fluorescent tracer into the vessel using a microsyringe. High-pressure air from a gas cylinder is used to increase the pressure in the vessel. Three excitation

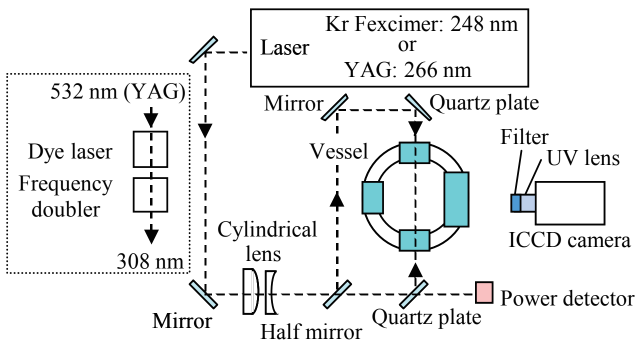


Fig. 1 Schematic of constant volume vessel apparatus.

lines, which are 248 nm (KrF excimer laser, Lambda Physik LPX150T with broadband operation), 266 nm (the 4th harmonic of a Nd:YAG laser, Spectra Physics PRO290-10) and 308 nm (the 2nd harmonic of a dye laser, Spectra Physics WEX-1, excited by 532 nm, the 2nd harmonic of the Nd:YAG laser), are used for excitation. The temperature and pressure dependence of the LIF intensity for each excitation wavelength of three fluorescent tracers (acetone, 3-pentanone and toluene) was measured using an intensified CCD (ICCD) camera (Hamamatsu Photonics C5987) equipped with a UV lens (Nikon UV-Nikkor) under different temperature and pressure conditions. **Figure 2** shows the results for the temperature dependence of the LIF intensity ratio. All data was normalized at 373 K. As a result, the combination of toluene with 266/248 nm was selected for measurement of the in-cylinder temperature distribution with the new combination of a fluorescent tracer and the pair of excitation wavelengths. The reason why this combination was selected is that the quantum efficiency of toluene is much higher than that of the ketones (acetone and 3-pentanone), so that toluene gives comparable LIF intensity with a quantity that is 10% or less than that required with the ketones. In addition, the closer excitation lines (between 248 and 266 nm) also enables ease of optical handling. The observation wavelength was set to more than 275 nm using an edge filter to minimize the effect of LIF light re-absorption by the fluorescent tracers. **Figure 3** shows the temperature dependence of the LIF intensity ratio for toluene with 266/248 nm excitations at various pressures. The standard condition with a LIF intensity ratio of 1.0 is a temperature and pressure of 373 K and 0.1 MPa, respectively. The temperature dependence is clearly different among the various pressures. However, if the pressure is known, then the LIF intensity ratio becomes a function of only the temperature. Therefore, in the case of the temperature distribution measurement in an engine, simultaneous in-cylinder pressure measurement is required, which is commonly conducted using a pressure sensor. The temperature can then be determined using the database shown in Fig. 3 and the measured in-cylinder pressure. The calibration curves can be extrapolated when the measured value is beyond the range of the database.

2. 2 Internal EGR Distribution Measurement

For the internal EGR distribution measurement in a cylinder, the use of LIF emissions from combustion products of regular hydrocarbon fuel is difficult. **Figure 4** shows the concept used to solve this problem. A non-fluorescent fuel additive is added to a non-fluorescent fuel. If the additive generates a highly fluorescent material as a result of combustion chemical reactions, then the internal EGR distribution can be measured. This is the principle behind the

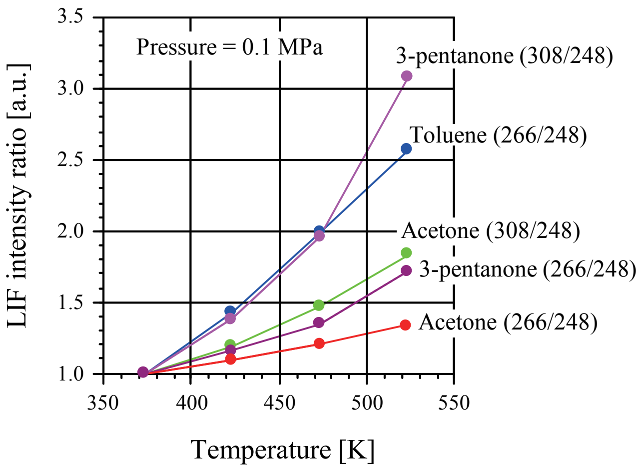


Fig. 2 Temperature dependence of LIF intensity ratio. The parameter expresses the combination of a tracer and a pair of excitation lines indicated in parenthesis. Intensity ratio is normalized at 373 K in temperature.

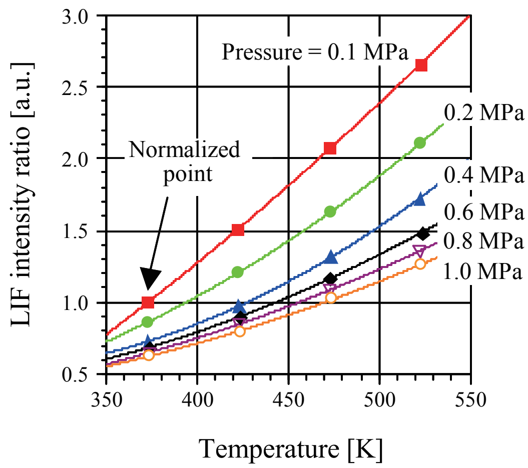


Fig. 3 Temperature dependence of LIF intensity ratio of toluene with 266/248 nm excitations for various pressure. Intensity ratio is normalized at the value of 373 K in temperature and 0.1 MPa in pressure.

tracer-producing LIF technique. Here, SO_2 was selected as a fluorescent material and di-tert-butyl sulfide (DtBS) was chosen as the fuel additive. An SO_2 analyzer, which is one type of exhaust analysis meter, can detect small amounts of sulfur in fuel or oil with sufficient sensitivity from the fluorescence by UV excitation; therefore, SO_2 can be estimated to have a certain fluorescence quantum efficiency. However, it has also been reported that the LIF of SO_2 can be measured in areas of both burned and unburned gas that were seeded with a small amount of SO_2 and then irradiated with an UV laser sheet.[(25)] This shows that SO_2 can exist stably from room temperature to the high temperature range of combustion gas, which makes it ideal as a burned gas tracer. Therefore, SO_2 was adopted as a burned gas tracer. Absorption measurements using the constant volume vessel revealed that SO_2 has a strong absorption band at wavelengths of 330 nm and less. Therefore, LIF emissions from SO_2 can be obtained if SO_2 molecules are excited using a strong pulse laser with this wavelength band. Using an excitation wavelength of 248 nm from the KrF excimer laser, it was confirmed that LIF emission was observed over a wide range of wavelengths from 280 to 400 nm. Next, a fuel additive that contains sulfur atom(s) was selected that would produce SO_2 during the combustion process. This additive would have to satisfy the following requirements:

・The additive itself is non-fluorescent.

・No materials other than SO_2 are produced during combustion.

・The boiling point of the additive is close to the distillation temperature of gasoline.

・The toxicity of the additive is low.

Two candidate additives were thus selected with consideration of these requirements. The LIF emissions of the additives themselves (which become noise) were investigated. As a result, DtBS was selected as the fuel additive for the tracer-producing LIF technique.

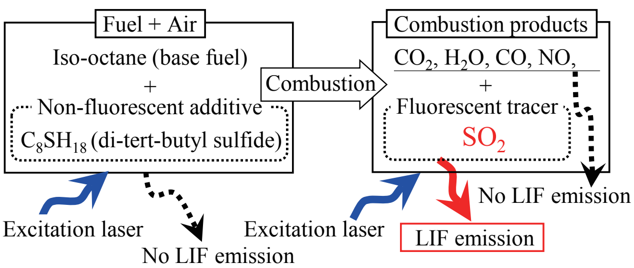


Fig. 4 Principle of tracer-producing LIF technique.

3. Experimental Apparatus

Laser diagnosis of an optically accessible engine with a glass cylinder can be classified into two types: a bottom-view system and a side-view system, according to the observation target (**Fig. 5**). The engine specifications used for this measurement and the experimental conditions are listed in **Table 1**. The bottom-view system was applied for the temperature measurement, while the side-view system was applied for the EGR measurement. Both engines have a quartz cylinder and a quartz piston. It should be noted that the engines used for both measurements were not the same.

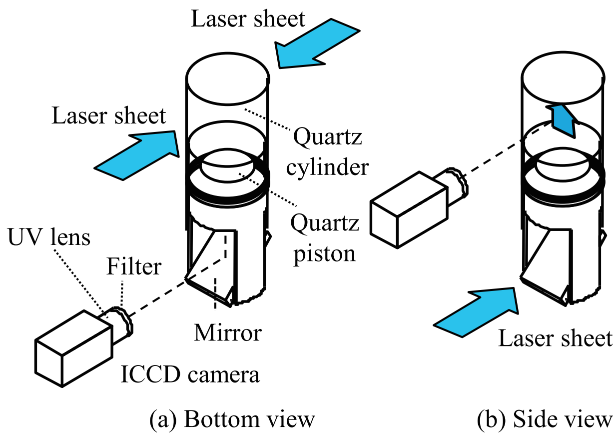


Fig. 5 Optical setup.

Table 1 Engine specifications and operating conditions.

	Bottom view (Temperature meas.)	Side view (EGR meas.)
Specifications		
Engine	Optically accessible single cylinder engine	
Engine displacement volume	500 cm^3	
Number of valve	Intake:2, Exhaust:1	Intake:2, Exhaust:2
Bore × Stroke	86 mm × 86 mm	
Compression ratio	9.0	7.2
Piston top geometry	Flat	
Steady tumble ratio	0.13	0.46
Operating conditions		
Engine speed	1200 rpm	
Volumetric efficiency	30%	55%
Fuel	Isooctane ＋ Toluene (5 wt.%)	Isooctane ＋ DtBS (20 wt.%)
Fuel supply	PFI (Port fuel injection)	
Coolant temperature	80℃	

To observe the gas exchange process between fresh gas and internal EGR during the intake and exhaust valve overlap period, and to determine the internal EGR distribution at the end of the compression stroke, it is necessary to observe the entire pent-roof area from the side. For this reason, a new optically accessible single-cylinder gasoline engine was developed. The entire pent-roof area of this engine can be observed from the side, as shown in **Fig. 6**. The bonded surface of the cylinder (glass) and the cylinder head (metal) is a complex pent-roof shape rather than simply being flat; therefore, particularly careful attention must be given to prevent cracking of the glass by stress concentration. To overcome such problems, high-precision glass processing with a CNC grinding machine was employed, in addition to high-precision positioning between the cylinder head and glass cylinder, and a highly elastic gasket was used between the metal and glass components.

4. Experimental Procedure and Results

4. 1 Temperature Measurement

At first, with the engine in the stopped state, the mixed fuel was supplied into the engine cylinder to obtain reference images at known temperature (353 K) and pressure (0.1 MPa) for each excitation line. To reduce the influence of absorption of the laser sheet by the fluorescent tracer, the combustion chamber was irradiated from both sides (front and rear) by laser sheets, as indicated in Fig. 5(a). Twenty LIF images were captured for each excitation line by switching the excitation lines between 248 and 266 nm. Sets of 20 images were then averaged to reduce the shot-to-shot fluctuation of the laser intensity pattern. This averaging is possible because the relationship between the temperature and LIF intensity ratio is approximately linear, as shown in Fig. 3. The LIF images were not captured simultaneously for the 248 and 266 nm lines; therefore, special care was paid to keep the thermal conditions of the engine identical for each LIF measurement. Periodic motored and fired operations were adopted, and each 20-LIF image set was captured at the same timing from the start of firing operation. From consideration of the homogeneous temperature field, the accuracy of this technique was estimated to be 8% at maximum. A stratified temperature field was then formed in the engine cylinder and measured using the two-line excitation LIF technique. A heated intake passage is connected to only the front (Fr)-side intake port. Intake air can be heated up to 450 K at the cylinder head entrance. This engine has two straight intake ports that generate weak tumble flow with no swirl in the cylinder. Before the temperature measurements, the mixture formation process in the cylinder was determined under the heated Fr-port condition. Fuel is injected to only the Fr-port, so that the fuel-air mixture is introduced into the cylinder only from the Fr-intake valve (as indicated by the distribution for −210 deg ATDC shown in **Fig. 7**(b)). The intake air from the rear (Rr)-side valve contains no fuel; therefore, no LIF signal was detected from the rear-half of the cylinder. The LIF signal plays a role as the tracer for the mixture introduced from the Fr-intake port. During the intake stroke, the in-cylinder airflow from each port is completely separated, which clearly stratifies the fuel in the cylinder. At the latter half of the compression stroke, the degree of stratification becomes weak but still remains even at −30 deg ATDC.

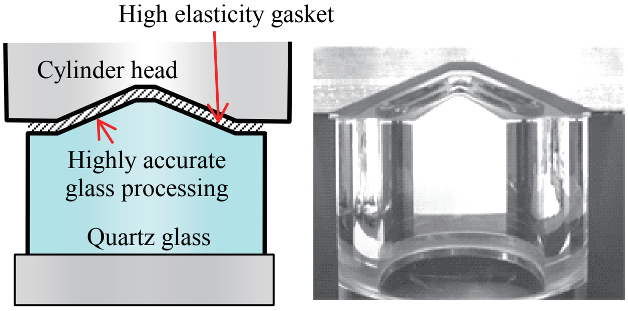


Fig. 6 Structure of optically accessible single cylinder engine in which the pent-roof area can be observed from the side.

Figure 7(a) shows the temperature distribution determined using the two-line excitation LIF technique for the same intake system with the mixture formation measurements. The same amount of fuel is injected to both intake ports in this experiment. Temperature stratification, where the front half is higher than the rear half in the cylinder, is observed clearly at −210 deg ATDC. However, the temperature stratification decays during the compression stroke and cannot be recognized at −30 deg ATDC. Histories of the average temperature for the Fr and Rr square regions in the test plane indicated in Fig. 7 are shown in **Fig. 8**. The maximum temperature difference between the Fr and Rr regions is observed at approximately 50 K for −210 deg ATDC.

The histories for the degree of temperature stratification and the fuel concentration defined by Eqs. (1) and (2) are shown in **Fig. 9**.

$$S_T = (T_{\mathrm{Fr}} - T_{\mathrm{Rr}})/T_{\mathrm{av}}, \qquad (1)$$

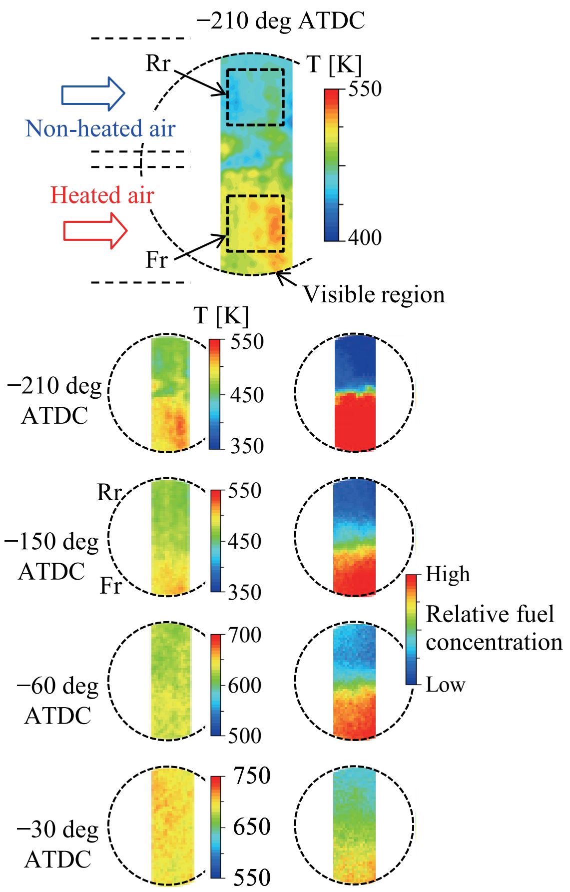
$$S_C = (C_{\mathrm{Fr}} - C_{\mathrm{Rr}})/C_{\mathrm{av}}, \qquad (2)$$

where

- S_T: degree of temperature stratification.
- S_C: degree of fuel concentration stratification.
- T : temperature.
- C: fuel concentration.

Subscripts (see Fig. 7):

- Fr: average for the Fr-square region in the test plane.
- Rr: average for the Rr-square region in the test plane.
- av: average for the Fr and Rr square regions.



(a) Temperature Fuel injection: Fr&Rr-port (b) Fuel concentration Fuel injection: Fr-port

Fig. 7 2-D temperature and fuel distribution taken by LIF technique in heated Fr-port system.

During the compression stroke, the temperature difference and the degree of temperature stratification (S_T) both decrease, as shown in Fig. 9. The principal reason for this temperature decay is considered to be turbulent gas mixing in the cylinder because both S_T and S_C show similar tendencies in Fig. 9. It was revealed that at least the temperature stratification can be evaluated using the two line excitation LIF technique. However, no temperature stratification can be clearly observed at −30 deg ATDC, so it is not certain whether it disappears at this

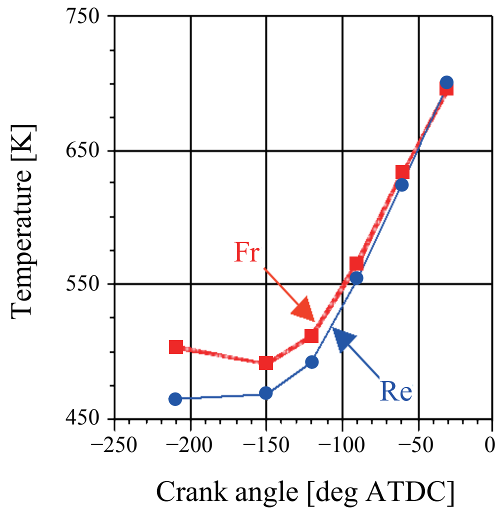


Fig. 8 Temperature histories at the Fr and the Rr region in the laser sheets plane with heated Fr-port system. Both temperature are averaged value in the square regions indicated in Fig. 7.

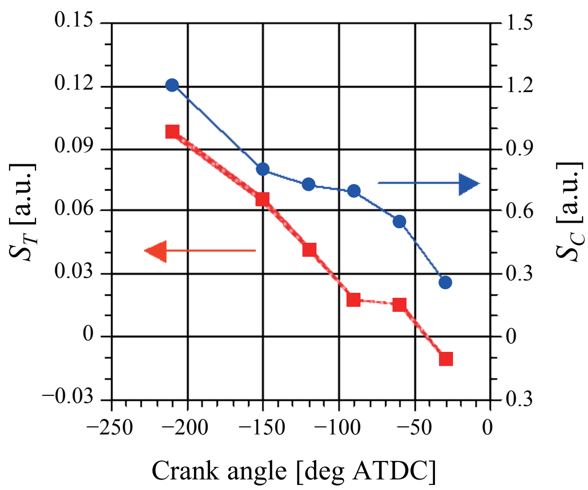


Fig. 9 Histories of stratification degree for temperature (S_T) and fuel concentration (S_C).

crank angle or not. The temperature difference is small while the absolute value is high (ca. 700 K): therefore, this may be below the measurable limit. Further investigation is required to conclude this problem with an experimental setup that can produce a larger initial temperature difference.

4. 2 Internal EGR Distribution Measurement

4. 2. 1 Measurement of the Burned Gas Region in the Combustion Process

Firstly, it was confirmed that SO_2 was formed in the cylinder by combustion of the DtBS fuel additive, and also that SO_2 emits an LIF signal by irradiation with the laser sheet. DtBS was mixed at 20 wt% to isooctane as a base fuel. **Figure 10** shows representative single-shot images extracted at each crank angle. At −10 deg ATDC, the LIF intensity from SO_2 generated by combustion is high in the burned gas region. However, in the unburned gas region, the LIF signal is barely observed, which implies that distinct separation of the burned and unburned gas regions is possible. When the crank angle advances, the flame first propagates toward the exhaust valve, then toward the intake valve along the piston, and then finally spreads throughout the entire combustion chamber. Given this flame propagation pattern, it is clear that a tumbling flow exists at the compression TDC. As described previously, the unburned gas area including the fuel additive does not fluoresce; however, SO_2 is formed by the combustion and can become the burned gas tracer, which allows flame propagation to be observed.

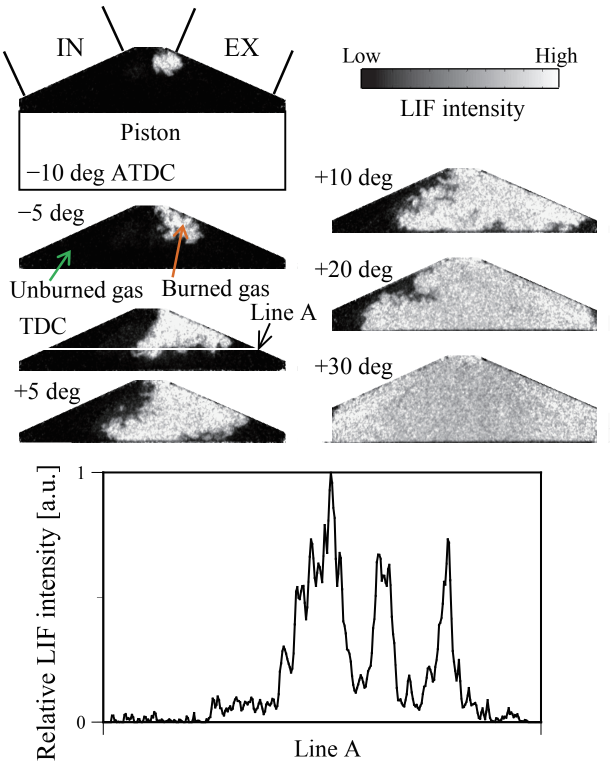


Fig. 10 LIF images and intensity profile on line A.

4. 2. 2 Measurement from the Last Half of the Exhaust Stroke to the First Half of the Intake Stroke

Figure 11 shows the internal EGR behavior of the center cross-section of the front valve during the period from the exhaust stroke to the intake stroke. The motion of the internal EGR (bright area) and fresh air (dark area) for each crank angle is indicated by the arrows. The valve timing of (a) is the standard condition for this engine, and that of (b) is retarded 20 deg (exhaust valve) and advanced 20 deg (intake valve) from (a). The pressure in the intake port is negative when the intake valve opens, e.g., in case (a) with standard valve timing; therefore, the internal EGR gas in the cylinder is rapidly drawn toward the intake valve (arrows in the figure from 374 deg BTDC to 360 deg BTDC). Case (b) has a longer intake duration and the exhaust valves are open together with the intake valves for a longer time than in case (a) because the overlap period of case (b) is 40 deg larger than (a). During this time, at 366 deg BTDC (enlarged view in the lower part of Fig. 11), the motion of internal EGR blowing back into the cylinder from the exhaust valve is observed as (1) in Fig. 11. The internal EGR then spreads, as (2) in Fig. 11. This is because there is little internal EGR at 370 deg BTDC, which corresponds to the area of (2) in Fig. 11. It was also possible to capture the phenomenon where part of the internal EGR gas is blown back directly into the intake port ((3) in Fig. 11). Although the brightness of burned gas under the intake valve is so high, this is because the brightness level of the image has been adjusted to easily observe under the exhaust valve. After the intake TDC, the inflow of gas from the intake port begins with the descent of the piston. In case (b), gas flow into the cylinder begins at 330 deg BTDC, where the brightness of the inlet gas is slightly higher ((4) in Fig. 11). This is because the inlet gas is a mixture of internal EGR and fresh air. In the case of (a), the valve overlap period is short and the amount of internal EGR gas blowing back into the intake port is small, so that almost no fluorescence from the inflow of fresh air can be detected at 300 deg BTDC ((5) in Fig. 11). On the other hand, at the same timing, in the case of (b), where the opening timing of the intake valve is earlier, the brightness of the inlet gas of mixed fresh air and internal EGR is slightly stronger ((6) in Fig. 11). This is because the valve overlap is large and a large amount of internal EGR gas blows back to the intake port. In this case, the full-blown inflow of fresh air will be delayed further. The gas exchange process between burned gas and fresh air could be clearly observed from the exhaust stroke to the intake stroke. In addition, a difference in the amount of internal EGR carried over for the next cycle could be observed from the LIF images.

4. 2. 3 Measurement from the Intake Stroke to the Compression Stroke

Figure 12 shows the results of measurement from the intake stroke to the compression stroke. Here, the laser sheet is positioned to irradiate the center of the Fr-valve and the valve timing is standard. At 310 deg BTDC, fresh air, of which the SO_2-LIF emission is not significant, is flowing into the cylinder. With the inflow of this fresh air, the internal EGR gas in the cylinder is swept away to the lower right side. Even if it becomes a compression stroke, the EGR motion with rotation in a clockwise direction could be captured. Here, at 30 deg BTDC in the vicinity of

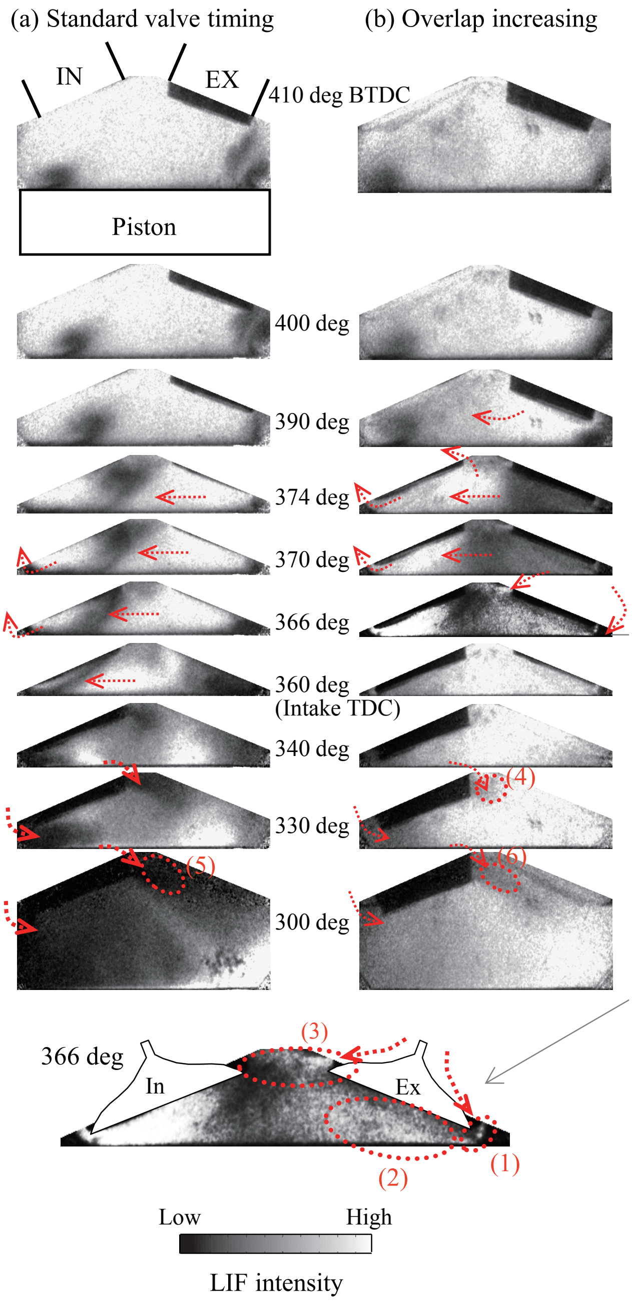


Fig. 11 Process of gas exchange between fresh air and internal EGR.

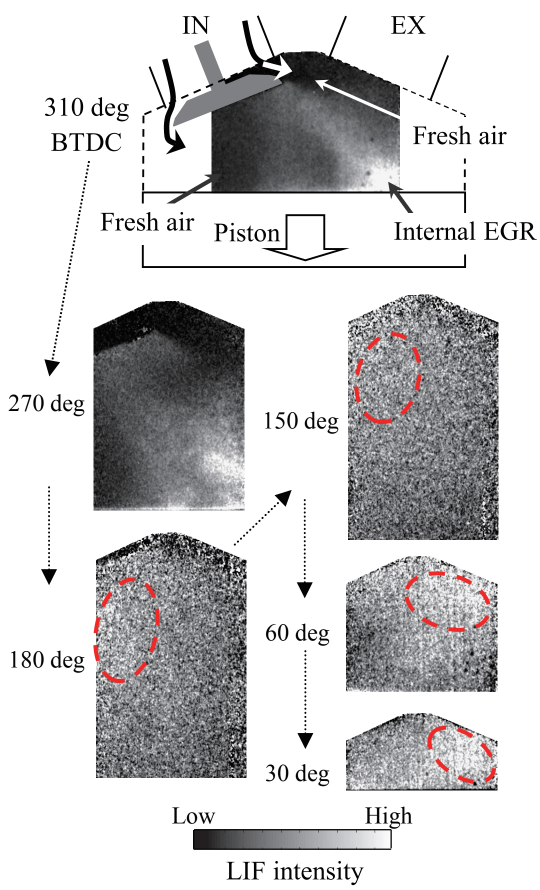


Fig. 12 Internal EGR behaviors in intake and compression strokes.

TDC, internal EGR is not completely homogeneous but somewhat distributed. To date, it has not been possible to clarify whether non-homogeneous internal EGR distribution remains at the end of the compression stroke. However, using the developed technique has enabled confirmation that an inhomogeneous distribution of the internal EGR also exists at the end of the compression stroke, immediately before the time of ignition under the experimental conditions.

5. Conclusion

In an optically accessible single cylinder engine, temperature measurement application using a two-line excitation LIF technique, and internal EGR distribution measurement using a tracer-producing LIF technique were developed. Typical measured images were presented and the following results were obtained:

(1) A combination of toluene tracer with 248 and 266 nm excitation lines was selected for temperature measurement. The advantage of this combination is high LIF quantum efficiency, which gives high measurement accuracy with a high intensity ratio for the two-line excitation, as well as a low tracer fraction to the base fuel. Closer excitation lines enable ease of treatment for incident optics.

(2) The stratified temperature field generated by heated air supplied only one of two intake ports could be clearly observed in the cylinder. The decay process of temperature stratification was also observed during the compression stroke.

(3) SO_2 was selected as a burned gas tracer for internal EGR measurement considering the fluorescence intensity and the temperature stability of the molecule. In addition, DtBS (di-tert-butyl sulfide) is suitable as a fuel additive for the production of SO_2 by combustion because it does not fluoresce itself.

(4) Application of this technique to an optically accessible single-cylinder gasoline engine provided strong LIF emissions from the burned gas region and flame propagation could be captured. Thus, the principles of the tracer-producing LIF technique were confirmed for measurement in an engine cylinder.

(5) From the end of the exhaust stroke to the start of the intake stroke, the burned gas returned to the intake port and cylinder due to the negative pressure in the intake port when the intake valve opened. The gas exchange process between burned gas and fresh air was also clearly captured.

(6) From the intake stroke to the compression stroke, a highly concentrated area of internal EGR gas was rotating by tumble flow. An inhomogeneous distribution of the internal EGR also exists at the end of the compression stroke, immediately before the time of ignition under the experimental conditions.

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