

2-D Internal EGR Distribution Measurements in an Engine by Laser-Induced Fluorescence

Kenji Fukui, Taketoshi Fujikawa, Mamoru Tohyama, Yoshiaki Hattori and Kazuhiro Akihamu
Toyota Central R&D Labs Inc

ABSTRACT

A novel diagnostic technique named a "Tracer-Producing LIF technique" which enables 2-dimensional measurement of an internal EGR within an engine cylinder, has been developed. The main feature of this technique is the utilization of a fuel additive that does not itself emit an LIF signal by irradiation of UV-light but whose combustion products radiate strong LIF emissions by UV-light irradiation. Internal EGR behaviors can be measured by observing LIF images that are excited by a UV-laser sheet. Firstly, principles of this technique were confirmed and fuel additives were selected. Then, the "Tracer-Producing LIF technique" was applied to an optically accessible single-cylinder gasoline engine in which the entire pent-roof area can be observed from the side of the engine. The internal EGR behaviors were measured through the entire engine cycle, from intake to exhaust. As a result, gas exchange process between burned gas and fresh air, as well as the influence of the valve timing on the above process, were clarified. It was also confirmed that non-homogeneous internal EGR distribution was still present at the ignition timing. Furthermore, by compensating for the influence of pressure and temperature dependency on LIF intensity, a relative internal EGR concentration measurement has been developed. So evaluation of non-uniformity of the internal EGR in different crank angles has become possible.

CITATION: Fukui, K., Fujikawa, T., Tohyama, M., Hattori, Y. et al., "2-D Internal EGR Distribution Measurements in an Engine by Laser-Induced Fluorescence," *SAE Int. J. Engines* 6(1):2013, doi:10.4271/2013-01-0556.

INTRODUCTION

In an internal-combustion engine, it is necessary to achieve high levels of efficiency and output power, while maintaining low levels of exhaust emissions. A Variable Valve Timing (VVT) mechanism is a powerful tool of attaining this. This mechanism sets out to change the amount of internal EGR by varying the valve timing in accordance with operating conditions, while reducing pumping loss and NO_x, and HC emissions. Here, the internal EGR is a combustion gas from the previous cycle which remains in the cylinder, and a gas exhausted from the cylinder once and drawn back into the cylinder during the valve overlap. To date, the VVT mechanism has been adopted only for the intake valves of commercialized engines. There is now, however, an example where the VVT mechanism is adopted for intake and exhaust valves in order to further improve its effect and attain higher levels of power [1]. On the other hand, in a research phase, there have been many studies of ignition controls for a Homogeneous Charge Compression Ignition (HCCI) engine in which this internal EGR is carefully controlled [2, 3, 4, 5]. In addition, there has been research that has attempted to control the self-ignition combustion rate by intentionally distributing the internal

EGR [6]. To date, an in-cylinder gas sampling method has been used as this internal EGR measurement technology [7]. Moreover, as an optical technique, Raman scattering has been utilized [8-9]. However, these are all point measurements, and it has remained difficult to measure the internal EGR distribution in a cylinder. Although a technique using infrared ray absorption has been proposed [10], this method involves measuring the average information on the optical path and it is difficult to measure the internal EGR distribution. Planar Laser-Induced Fluorescence (PLIF) method is widely used for two-dimensional distribution measurement [11-12], but it is difficult to measure CO₂, H₂O and CO which are combustion products, because these combustion products cannot be excited by UV laser which is usually employed by the LIF method. Though LIF measurement of H₂O that uses two-photon absorption has been proposed [13], there remain problems in that the fluorescent intensity is weak and the concentration is not in proportion to the intensity, etc. Two-photon fluorescence has also been used to measure CO concentrations in diesel engine [14], there remain similar problems in that the fluorescent intensity is weak. So, the LIF method has not become a practicable technique. As described above, a method for diagnosing the internal EGR distribution

in a cylinder has not yet been established, so that the behavior of the internal EGR cannot be clarified. For the purpose of establishing a method for diagnosing the internal EGR distribution, we have developed a new method named the “Tracer-Producing LIF technique”, which enables the 2-dimensional measurement of the internal EGR within an engine cylinder. In this paper, 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 single-cylinder gasoline engine in which the entire pent-roof area can be observed from the side of engine. As a result, a gas exchange process between a burned gas and a fresh air, as well as the influence of the valve timing on the above process has been clarified. It is also confirmed that non-homogeneous internal EGR distribution was still presented at the instant immediately before ignition.

TRACER-PRODUCING LIF TECHNIQUE

Principle of Measurement

For LIF measurement in an engine, an excitation wavelength that is usually used is in excess of 190 nm to alleviate the influence of absorption by atmospheric oxygen. When hydrocarbon fuel is burned as described before, however, CO_2 , H_2O , and CO , which are the main combustion products, do not have an absorption band at this wavelength area, so LIF measurement for these molecules within a cylinder is difficult. Because NO molecules have an absorption band at 226 nm or in the vicinity of 248 nm, LIF measurement is possible [15–16]. The NO density resulting from the combustion greatly depends on the equivalent ratio. Furthermore, its fluorescent intensity is very weak, so it is not easy to detect NO even immediately after combustion. Particularly, it becomes very difficult to measure the distribution of NO which has become mixed with fresh air and is thus highly diluted. As described above, for the internal EGR distribution measurement in a cylinder, the use of LIF emissions from the combustion products of regular hydrocarbon fuel is difficult. Figure 1 shows the idea to solve the above problems. A non-fluorescent fuel additive was added to a non-fluorescent fuel. If the fuel additive generates highly fluorescent material as a result of combustion, we can measure the internal EGR distribution. This is the principle behind the “Tracer-Producing LIF technique.”

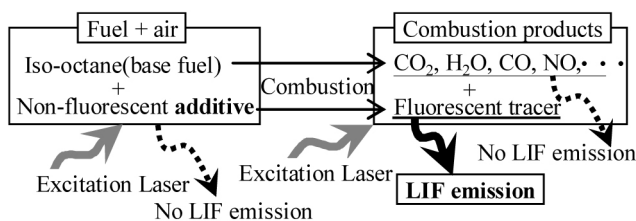


Figure 1. Principle of tracer-producing LIF technique

Next, fluorescent material that could be used as a burned gas tracer in this technique was selected. Since 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 ultraviolet excitation, SO_2 can be estimated that it has certain fluorescence quantum efficiency. On the other hand, it has also been reported that the LIF of SO_2 can be measured in both the burned and unburned gas areas, which were seeded with a small amount of SO_2 and then irradiated with an ultraviolet laser sheet [17]. This shows that SO_2 can exist stably from the room temperature to the high temperature range of combustion gas, making it ideal as a burned gas tracer. Therefore, SO_2 was adopted as the burned gas tracer.

Absorption and Emission Spectra of SO_2

Firstly, the absorption and emission spectra were measured in order to examine the excitation wavelength and observation wavelength with a constant volume vessel. Figure 2 shows the experimental apparatus. The constant vessel consists of a stainless steel cylinder with a quartz window. To measure the absorption spectrum, SO_2 -air mixture was sealed into this vessel. The incident light was guided into the vessel from the light source (heavy hydrogen (D2) lamp (Otsuka electron MC-964)), and the transmitted light was measured with a photodiode array addition spectroscopy (Otsuka electron IMUC-7000). To measure the LIF spectrum, laser light was formed into a sheet by passing the laser through a cylindrical lens, and was made to be incident from a direction perpendicular to the detection system, and then measurement was performed in the same way. Figure 3 shows the results. The upper part in the figure is the absorption spectrum of SO_2 . SO_2 has a strong absorption band at wavelengths of 330 nm and less, as can be seen from the figure. Thus, the LIF emissions of SO_2 can be obtained if SO_2 molecules are excited with a strong pulse laser of this wavelength band. The SO_2 LIF emission spectrum is shown in the lower part in Figure 3, when SO_2 is excited by a KrF excimer laser (Lambda Physik LPX-150) with a wavelength of 248 nm. It was confirmed that LIF emission is seen over a wide range of wavelengths from 280 nm to 400 nm at least, although background light became superimposed at wavelengths of less than 280 nm because it was not possible to remove sufficient stray incident light. From this result, we can conclude that the detection wavelength for SO_2 -LIF should be longer than 280 nm.

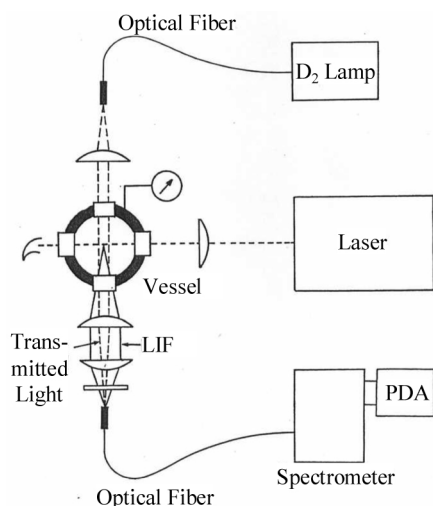


Figure 2. Schematic of absorption and LIF emission measurement apparatus

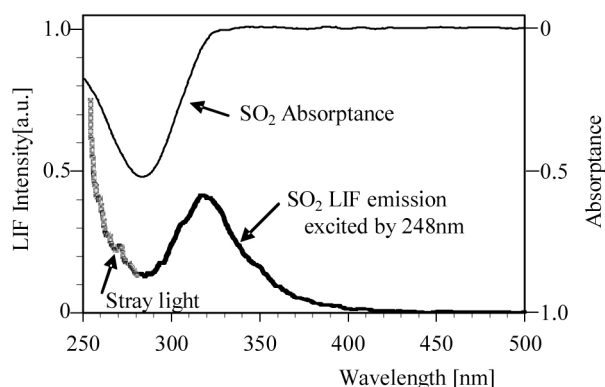


Figure 3. Absorption and LIF emission spectra of SO₂

Selection and Evaluation of Fuel Additive for Tracer Production

Next, we selected a fuel additive which contains sulfur atom(s) and which would produce SO₂ generated in combustion processes. This additive would have to satisfy the following requirements.

- The additive itself is non-fluorescent.
- No materials other than SO₂ are produced in combustion.
- The boiling point of the additive is close to the distillation temperature of gasoline.
- The toxicity of the additive is low.

In view of the foregoing, we selected and evaluated the following two compounds that contain S atom(s) with a linear coupling of CH as their basic structure:

- di-tert-butyl sulfide (DTBS)
- di-tert-butyl disulfide (DTBDS)

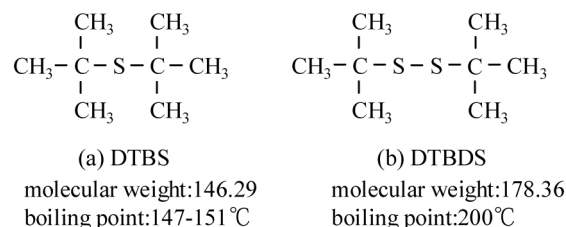


Figure 4. Test Additives

Figure 4 shows these molecular structures and their physical properties. With this measurement technique, it is essential that the fuel additive does not fluoresce before it burns. This is confirmed by using the vessel that is shown in Figure 2. The temperature in the vessel was raised to 353K with the electric heater in the vessel wall. Here, prescribed amounts of -

- isooctane(100%)
- DTBS(10wt.)/isooctane
- DTBDS(10wt.)/isooctane
- toluene(10wt.)/isooctane

were injected into the vessel and the LIF image was captured by an ICCD camera (Hamamatsu Photonics C8484) by the irradiation of laser. Wavelength of observation range was set by using optical filters (Sigma Koki UTF-30U, UTVAF-34U) from 280nm to 380nm. Here, since it is known that isooctane in case(i) does not fluoresce under the incidence of ultraviolet light, the intensity of the LIF light of the isooctane can be regarded as being a noise level, and was thus assumed to be the standard intensity. And, toluene in case (iv) is a fluorescent substance used for concentration measurement etc. and was used for the comparison of fluorescent intensity. Laser wavelengths of 248 nm (KrF excimer laser; Lambda Physik LPX-150), and 266 nm (4th harmonic of YAG laser; Spectra Physics PRO290-10) were used as the excitation wavelengths, and laser light was formed into a sheet by passing the laser through a cylindrical lens, before it enters the vessel.

Figure 5 shows the measured LIF intensity for each fuel additive. The LIF intensity is normalized for each excitation wavelength by the intensity of the isooctane, which is the noise level. From the figure, it turns out that the intensity of the fluorescence of DTBS is equivalent level to the non-fluorescent isooctane. On the other hand, the LIF intensity of DTBDS is low enough relative to the toluene, which is usually used as a fluorescent substance, but emissions in excess of the noise level can be clearly observed. Given these results, DTBS was chosen as the fuel additive for the Tracer-Producing LIF technique.

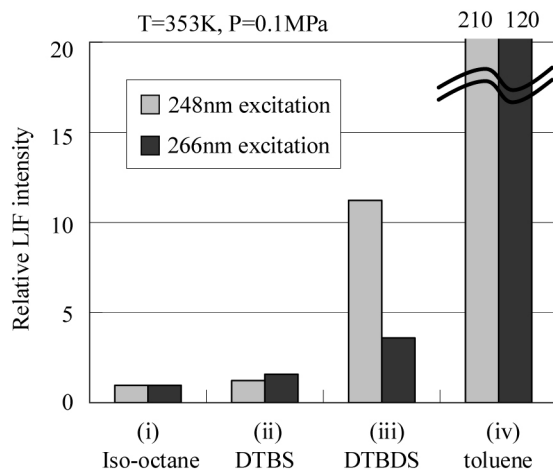


Figure 5. Relative LIF intensity of test fuels

EXPERIMENTAL SETUP

Optically Accessible Engine, in Which the Entire Pent-Roof Area Can be Observed

Based on the considerations described in the previous chapter, the Tracer-Producing LIF technique with DTBS was applied to the optically accessible engine for measuring internal EGR distributions. In order to observe the gas exchange process between fresh gas and internal EGR during the intake and exhaust valve overlap period, as well as 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, we developed the new optically accessible single-cylinder gasoline engine (optical engine for short). The entire pent-roof area of this engine can be seen from the side, as shown in Figure 6. Since the bonded surface of the cylinder (glass) and the cylinder head (metal) is a complex pent-roof shape rather than simply being flat, we have to pay particularly careful attention to preventing cracking of the glass by stress concentration. To overcome these problems, we used high-precision glass processing with a CNC grinding machine, high-precision positioning between the cylinder head and the glass, and a highly elastic gasket between the metal and the glass.

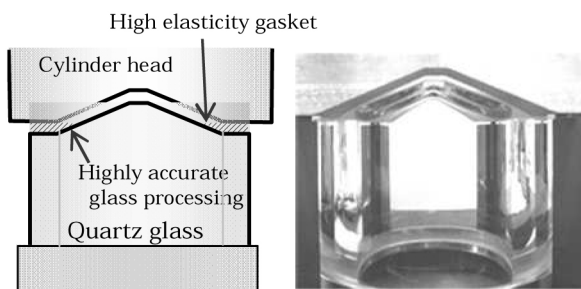


Figure 6. Structure of optical engine in which the pent-roof area can be observed from the side

Measurement of Internal EGR Behavior

Using the optical engine described in figure 6, the internal EGR behavior was measured by applying the Tracer-Producing LIF technique. The optical engine and the location of the incident laser sheet are shown in Figures 7 and 8. Table 1 lists the main specifications of the engine. Table 2 lists the engine operating conditions. 20 wt.% DTBS was mixed into isooctane as the base fuel. The optical engine has two intake and two exhaust valves, and is designed so that a quartz piston can be mounted, in addition to a quartz cylinder. The excitation wavelength is 248 nm, applied by a KrF excimer laser (Lambda Physik LPX-150). The laser light was formed into a sheet by passing the laser through a cylindrical lens, guided into the cylinder via a mirror from below the piston, with imaging performed from the side. The laser sheet was positioned to either the center of the cylinder or the center of the valve (Figure 8). When we wished to observe the entire cylinder, a quartz glass piston with a lower surface in the form of concave lens was used, with the laser sheet spread throughout the cylinder. Although the observed field of view was narrower, to attain a higher S / N ratio, we also took observations where the laser sheet did not spread throughout the cylinder. In this case, the lower surface of the quartz glass piston was flat. To capture an image, we used the same ICCD camera with UV lens for selection and evaluation of fuel additive. The optical filter for cutting the visible and laser light (the measurement wavelength band is from 280 nm to 380 nm) was changed to an edge filter. Its transmittance at shorter wavelengths is higher so that the maximum amount of SO₂-LIF can be collected. The gate width of the ICCD camera was 1μs. Figure 9 shows the image processing method. 20 consecutive cycles in firing and motoring condition were captured at the same crank angle. After averaging each image, by subtracting the image of motoring condition from the firing condition, LIF images in engine operating state are obtained. The results described in this paper are those for an average cycle, unless otherwise indicated. Here, to eliminate the influence of the light intensity distribution in the laser sheet, reference images of a homogeneous concentration of toluene (acting as a fluorescent tracer) were taken in advance, with the engine stationary at each crank angle. These images are also averaged by 20 cycles and by subtracting absence of toluene image (20 cycles averaged), LIF images in engine stationary state are obtained. Then, by dividing the LIF image of engine operating state by the reference image, a corrected image was obtained. In addition, taking the LIF images in the stationary state are performed in each experiment. In the image processing of single-shot measurement, LIF image of averaged firing condition was replaced by a single shot measurement of the same condition.