Feature Article

Development of Spark-Plug Sensor System for Fuel/ Residual Gas Concentration

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Cycle-resolved measurements of the fuel/ residual gas concentration near a spark plug in a practical spark-ignition (SI) engine have been developed. An *in situ* laser infrared (IR) absorption method was applied using a spark plug sensor and a 3.392-μm He-Ne laser or an infrared lamp as the light source. The newly developed IR spark plug sensor had a higher signal-to-noise ratio than its previous version due to the optimization of its sapphire lens and two optical fibers. Mixture formation process near the spark-plug and relationship between fuel concentration and combustion characteristics could be investigated in Wankel rotary engine, and high boost diesel engine using developed IR sensor system.

Introduction

A stratified-charge lean-burn engine has great potential for achieving higher thermal efficiency and lower exhaust emissions[1]. There are two ways to achieve the stratified charge condition in the cylinder: in-cylinder gasoline direct injection and port injection with late injection timing. Gasoline direct-injection engines are operated unthrottled in an ultra-lean condition by distinctively stratifying the charge and by preparing a fuel-rich mixture around the spark plug. Fuel consumption can be improved by reducing pumping and heat losses. One of the major problems of stratified-charge lean-burn engines are the unstable combustion due to the difficulty in controlling stratified-charge combustion under the required operating range. The fuel concentration around the spark plug and fluid motion strongly influence the duration of combustion initiation. This causes cycle-to-cycle variation, which can become large in lean-burn engines. To better understand how to achieve both an appropriate local mixture around the spark plug and to optimize the large-scale stratification, it would be useful to have a diagnostic tool that can indicate the gasoline distribution near the spark plug in practical engines. Here, In-cylinder mixture consists of fresh fuel-air mixture and residual gas from the previous cycle. Internal Exhaust Gas Recirculation (EGR) is one of the key features to understand the mixture formation process in a spark-ignition engine. Cyclic variations in the residual gas and the homogeneity of mixture with residual gas can significantly affect the initial period of flame propagation and the results in cyclic variations in IMEP. Instantaneous fuel/ residual gas (CO_2 or H_2O) concentration measurements in firing engines would greatly aid in the effort to design, optimize, and actively control an engine by electronic means. I am developing an infrared optical spark plug sensor with a double-pass measurement length for hydrocarbon fuel/ CO_2 gas concentration measurements[2-8].

A 3.392 μm He-Ne laser was used to obtain the fuel concentration for combustion diagnostics. Infrared absorption method was also applied and an infrared lamp and optical filter (center wavelength: around 4.29 μm) that coincides with the absorption line of CO_2 was used as a light source. The spark plug sensor was also applied to a practical SI engine using gasoline as fuel, and we confirmed that the fuel concentration measured using the sensor agreed with the preset concentrations under firing conditions. The spark-plug sensor was already developed, however light sources should be considered for residual gas concentration measurements with infrared absorption method.

Previously, we developed an IR optical spark-plug sensor with a double-pass measurement length. The measurement accuracy was confirmed by measuring the concentration of a homogeneous methane-air mixture in a compression-expansion engine. Our spark-plug sensor was also applied to a commercial SI engine using gasoline as fuel, and we confirmed that the fuel concentration measured using the sensor agreed with the preset concentrations under firing conditions. In order to measure the gasoline concentration accurately using the infrared absorption method, the molar absorption coefficient of gasoline is required. The molar absorption coefficient of a fuel is dependent on both pressure and temperature; therefore, the effects of coinciding conditions must be investigated. We also developed an optical spark-plug sensor with a double-pass measurement length using an infrared absorption technique for measuring hydrocarbon fuel concentrations, and we applied it to a motorcycle engine and a Wankel rotary engine[7]. Fuel concentration measurements were also carried out in SI engine with ethanol blended gasoline, and effects of evaporation on mixture formation process were investigated[9].

Firstly, the measurement principle using IR spark-plug sensor system was explained. Here, problems and tips for developing spark-plug sensor were explained. I showed experimental results obtained in port-injected spark-ignition engine, and carried out discussion between air-fuel ratio near the spark-plug and combustion characteristics. Finally, residual gas (CO_2) concentration measurements were also discussed in a sprak-ignition engine.

Principle of Laser Infrared Method

Assuming that light at a certain wavelength and intensity, I_0, decays to I when the light passes through a gas with concentration c (mol/cm^3), along a measurement length L, then, the transmissivity, I/I_0, is expressed by Lambert-Beer's law as follows:

$$\log (I/I_0) = -\varepsilon C L \quad (1)$$

where ε denotes the molar absorption coefficient. When the measurement length L is constant, the concentration can be determined from measuring the transmissivity. The absorption bands of methane calculated using the HITRAN database[10] are shown in Figure 1. This shows that methane absorbs light at four wavelengths, 7.6, 3.4, 2.3, and 1.6 μm, especially around 3.4 μm, and each wavelength corresponds to one methane absorption line. This absorption is caused by single C-H bond stretching in the hydrocarbon molecular structure. All hydrocarbons have similar absorption characteristics because they contain many C-H bonds. A strong absorption coefficient is desired when measuring the local fuel concentration in a SI engine because of measurement length limitations.

In this study, an infrared 3.392 μm He-Ne laser was used due to its stable wavelength and output power.

The absorbance (1 - I/I_0) of methane was calculated from the HITRAN database[10], as shown in Figure 2. The absorption lines are sharp when the pressure and temperature are 100 kPa and 300 K, respectively (Figure 2(a)). However, as the pressure and temperature increase to 2,000 kPa and 600 K, respectively, which are similar to values found in an engine just before ignition, the absorption lines merge and form a broad spectrum due to collisional broadening (Figure 2(b)). Because the absorbance value depends on the pressure and temperature of the methane, the fuel absorption coefficients were measured in advance at different ambient pressures and temperatures up to normal engine conditions.

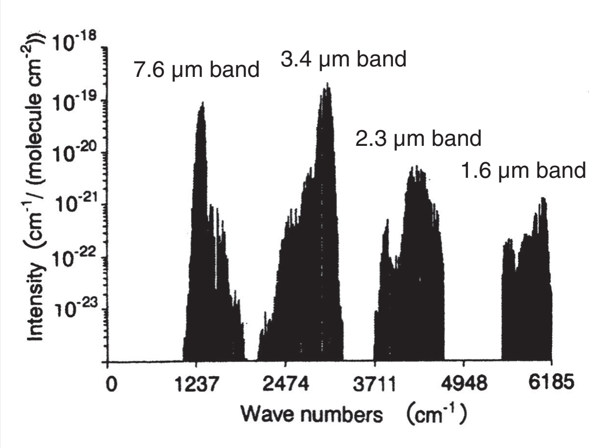

Figure 1 Absorption lines of methane calculated with HITRAN database

CO_2 absorbs IR light at three wavelengths: 4.3, 2.7, and 2.0 μm. This absorption is caused by the C-O vibrational-rotational band in CO_2. The strongest absorption line has a wavelength of 4.3 μm. The burned gas includes CO_2 and H_2O; therefore, the effect of H_2O on the absorption line can also be examined. Very few absorption characteristics were observed for H_2O near a wavelength of 4.3 μm. Near the wavelength of 2.7 μm, absorption of H_2O is stronger than CO_2. Near the wavelength of 2.0 μm, absorptions of H_2O and CO_2 were same tendency in wavelength of 2.7 μm, and show very week absorption of CO_2. A strong absorption coefficient is desired when measuring the local CO_2 concentration, therefore a wavelength of 4.3 μm was chosen as light source.

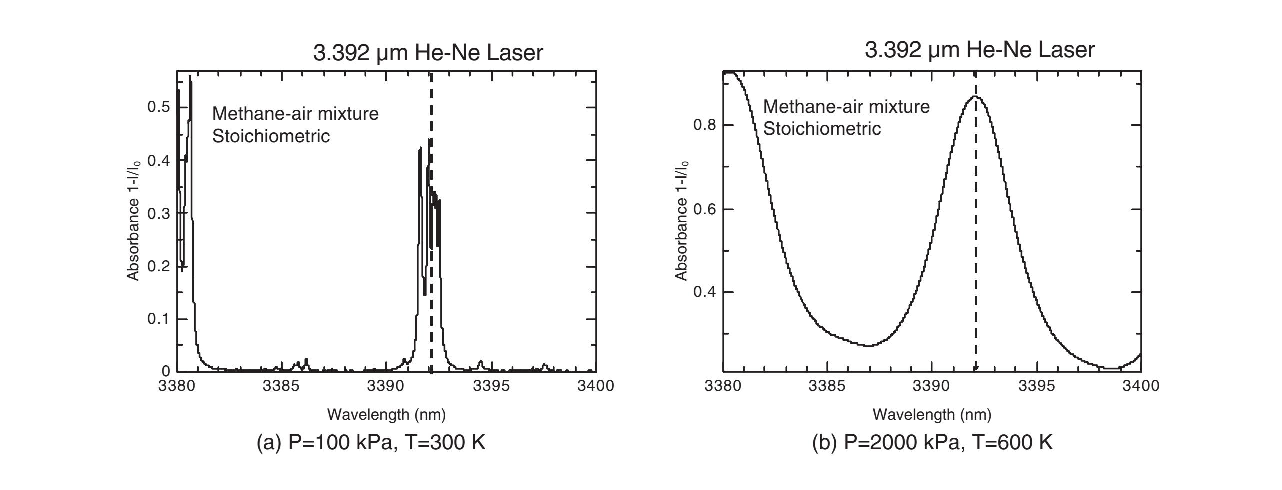

Figure 2 Effects of surrounding pressure and temperature on absorbance of methane

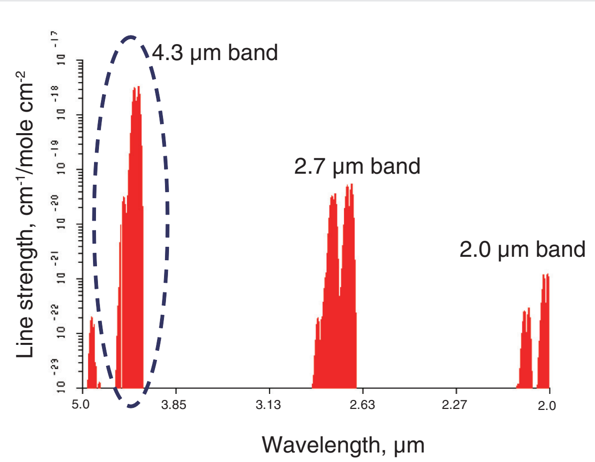

Figure 3 Absorbance line strength of CO_2 (2-5 μm, 300 K)

Spark-plug Sensor System for Fuel/ Residual Gas Concentration Measurement

Spark-plug Sensor

Figure 4 shows the optical sensor installed in a spark plug. This sensor was constructed by modifying a commercial instrumented spark plug. Consequently, it is possible to measure the fuel concentration near the spark plug under firing conditions by replacing a standard spark plug with this spark plug sensor. The optical setup consists of two optical fibers, a sapphire lens, and a metal mirror. The sapphire lens protects the end faces of the fibers from burned gas at high pressures and temperatures. One of the optical fibers guides light from the laser to the sensor. The light passes through the sapphire lens and is reflected by the mirror. The reflected light then passes through the sapphire lens again, and is transmitted to the detector through the second fiber. The measurement region is the gap between the sapphire lens and the metal mirror. The measurement length is twice longer than the gap length, because the light traverses the gap in both directions.

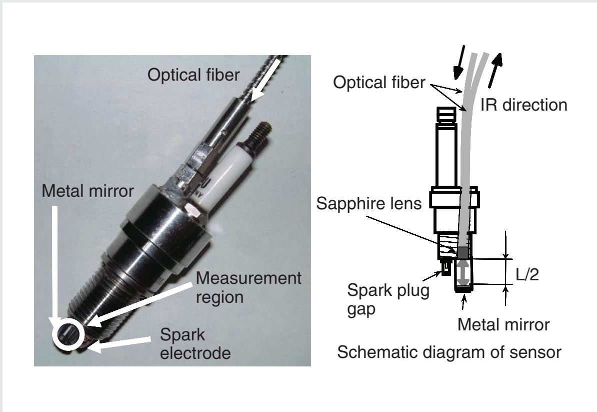

Figure 4 Schematic diagram and photograph of an IR spark plug sensor

The measurement length *L* is the factor that most affects the absorption sensitivity close to the time of the spark. Figure 5 shows the relationship between the transmissivity and the measurement length in a stoichiometric fuel mixture (methane, iso-octane, and premium gasoline) under specific spark conditions (400 kPa, 600 K). The transmissivity of all fuels decreases as the measurement length increases because of stronger absorption, and the transmissivity of premium gasoline is higher than that of other fuels, which explains the difficulty in measuring the gasoline concentration accurately. In this study, the measurement length was set to 10.0 mm to incorporate both the geometry of the sensor and the intensity of the absorption. Developed IR spark plug sensor can detect the signal during some hours because of use of Ni related material as the metal mirror. It is possible to clean up the metal mirror and the sapphire lens and continue the next experiments. Effect of deposits on the metal mirror or the quarts lens on the life time of measurement was not needed to consider under our experimental conditions. This newly developed IR spark plug sensor has a higher signal-to-noise ratio than a previous version due to the optimization of the quartz lens and the two optical fibers.

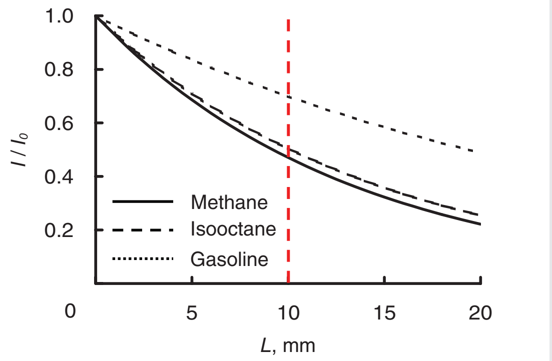

Figure 5 Relationship between I/I_0 and L at the time of the spark. (P = 400 kPa, T = 600 K, stoichiometric mixture)

Optical Arrangement and Experimental Apparatus

Figure 6 shows the experimental setup used to measure the concentration in a port-injected lean-burn engine employing the laser infrared absorption method with our spark plug sensor. A four-stroke cycle SI engine with a single cylinder was used to test this measurement technique; the bore and stroke were 70 and 58 mm, respectively, and the compression ratio was 9.5:1. The throttle valve was closed almost completely while idling, and the gasoline fuel was injected into the intake port using the port-injection system. The crank angle and top dead center (TDC) from a rotary encoder were used to change the spark timing and port-injection timing in the engine control unit (ECU), and were recorded using an analog/digital (A/D) converter. The in-cylinder pressure was obtained using a pressure transducer set in the spark plug. The history of the in-cylinder pressure is critical for evaluating the molar absorption coefficient of fuel using our IR sensor system.

Experimental Results

Fuel Concentration near the Spark-plug

We investigated the mixture formation process near the

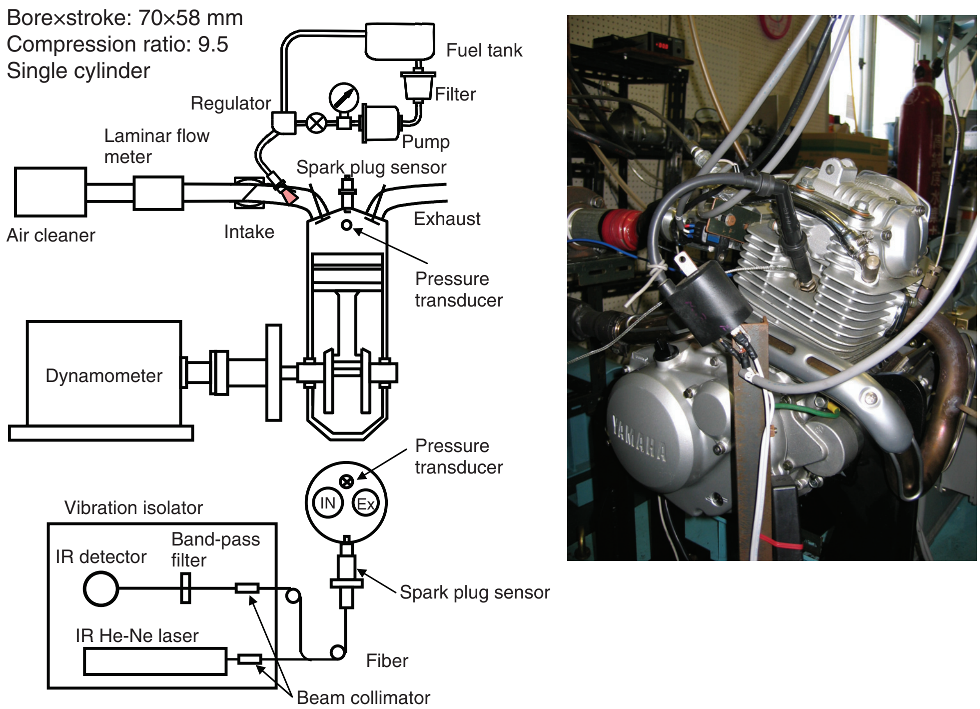

Figure 6 Experimental set-up

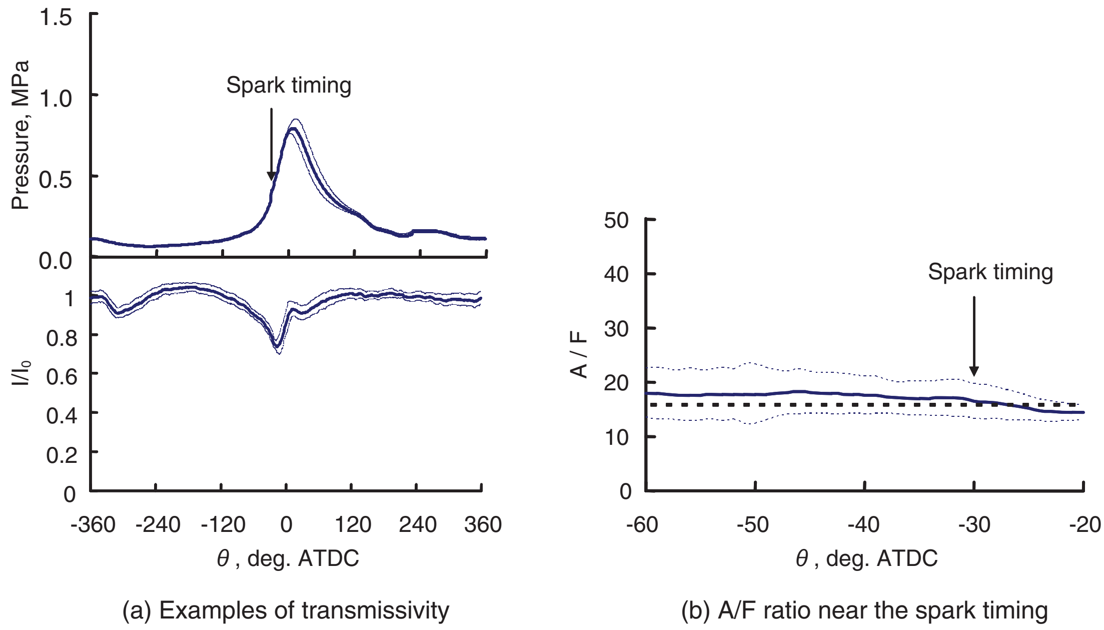

Figure 7 Air/fuel (A/F) ratio during the latter part of compression stroke

spark plug in the spark-ignition engine using the laser infrared absorption method with a 3.392 μm He-Ne laser as the light source. Figure 7(a) shows an example of the transmissivity, I/I_0, when $(A/F)_0 = 16.0$ and engine speed at 2,000 rpm. These are the average results for 100 cycles. During the intake stroke, the transmissivity decreased as the fuel flowed into the cylinder from the intake port and passed near the spark plug. During the compression stroke, the transmissivity decreased as the in-cylinder volume decreased and the molar concentration of the mixture increased. With the spark, the transmissivity decreased suddenly due to the greater absorption of gasoline. After the spark, the transmissivity increased suddenly because the flame propagated through the measurement region and removed hydrocarbons. Figure 7(b) shows the A/F ratio during the latter part of the compression stroke. The molar concentration was converted into the A/F ratio using the mass flow of air measured by a laminar flow meter installed upstream from the intake manifold. Here, we assumed that the residual gas mixed with the fresh air homogeneously. Measured A/F ratio decreased slightly until the spark timing and approached preset $(A/F)_0$ (16.0). We could determine the fuel concentration near the spark plug using our IR sensor system.

CO_2 Concentration Measurement near the Spark-plug

Figure 8(a), (b) indicate the experimental results of transmissivity, I/I_0, under several preset A/F ratio condition. The engine was operated at 1,200 rpm, and intake manifold pressure is about 30 kPa; which is almost idling condition. Figure 8(a) indicates the raw signal of transmitted infrared light intensity from IR detector under A/F=14.7, (b) A/F=17.0. Upper of raw IR signal decreases due to increase of CO_2 density and molar concentration before spark timing. However, baseline of raw IR signal slightly increases due to the background radiation of CO_2. Figure 8(c) indicates the history of transmissivity, I/I_0, as difference between upper and baseline of raw IR signal under both conditions. These transmissivities under both cases decrease due to the absorption of CO_2 inside residual gas before spark timing during compression stroke. CO_2 absorption of A/F=14.7 increases slightly than A/F=17.0 due to the larger amount of CO_2 inside residual gas. These experimental results perform the feasibility and applicability of in-situ CO_2 concentration measurement inside residual gas in commercial engine cylinder using developed spark-plug sensor system. This research is currently in progress, and the results, including the cyclic variability and quantitative measurements of residual gas fraction in commercial spark-ignition engines, are being prepared for forthcoming publications.

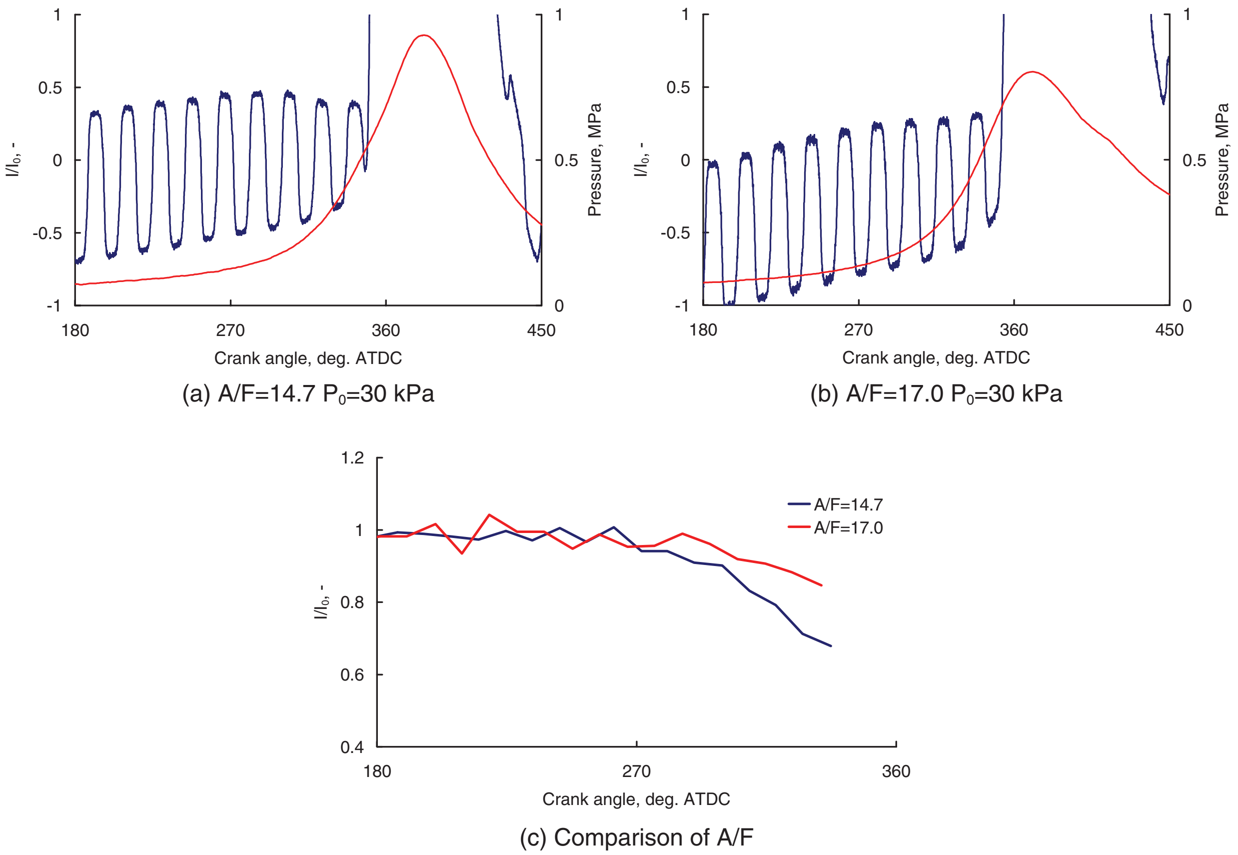

Figure 8 Measurement of CO_2 absorption in commercial spark-ignition engine

Conclusions

This report describes the development and application of a spark plug sensor using a 3.392 µm infrared absorption technique to quantify the instantaneous fuel/ residual gas concentration near the spark plug. We developed an *in situ* laser infrared absorption method using a spark plug sensor and a 3.392 µm He-Ne laser as the light source; this wavelength coincides with the absorption line of hydrocarbons. It was possible to quantify the fuel/ residual gas concentration during the compression stroke using the developed IR spark-plug sensor system with optimization of optical fibers, materials of lens and metal mirror, and measurement length. Fuel/ residual gas concentration measurements potentially allow us to understand the differences in the mixture formation processes inside the combustion chamber and to increase fuel consumption and to reduce exhaust emissions.

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