An optical sensor instrumented in spark plug for in-situ fuel concentration measurement in an engine cylinder by 3.39 μm infrared absorption method

by

Eiji Tomita[(1)], Nobuyuki Kawahara[(1)], Masahiro Shigenaga[(1)], Sadami Yoshiyama[(1)],
Yoshisuke Hamamoto[(2)], Akihiro Kakuho[(3)], Teruyuki Itoh[(3)], Robert W. Dibble[(4)],

(1) Okayama University, Dept. of Mechanical Engineering, Tsushima-Naka 3, Okayama 700-8530 Japan,
Email: tomita@mech.Okayama-u.ac.jp
(2) The University of Kitakyushu
(3) Nissan Motor Co. Ltd.
(4) University of California at Berkeley

ABSTRACT

A fiber optic system linked to the optical sensor installed in the spark plug, in which light can pass through the combustion chamber, was developed to determine the fuel concentration near the spark-plug successively using an infrared absorption method. A He-Ne laser with a wavelength of 3.39 μm that coincides with the absorption line of hydrocarbons was used as a light source. By exchanging an ordinary spark plug into this spark plug with the optical sensor, successive measurement of fuel concentration before the spark timing near the spark-plug was performed in a test engine. Figure 1 shows a schematic diagram of experimental apparatus and optical arrangement. This optical sensor shown in Fig.2 has a pair of sapphire rod whose tip is cut at an angle of π/4 radian to pass a laser light through the combustion chamber in an engine. A light from the 3.39μm laser is introduced into a fiber and passes through a sapphire rod. After being reflected at the corner, the light passes through the measurement region in the cylinder of the engine and enters another sapphire rod again. The light goes back to another fiber and is determined with an IR-detector. It was found that the concentration just before the spark timing near the spark plug showed almost correct value.

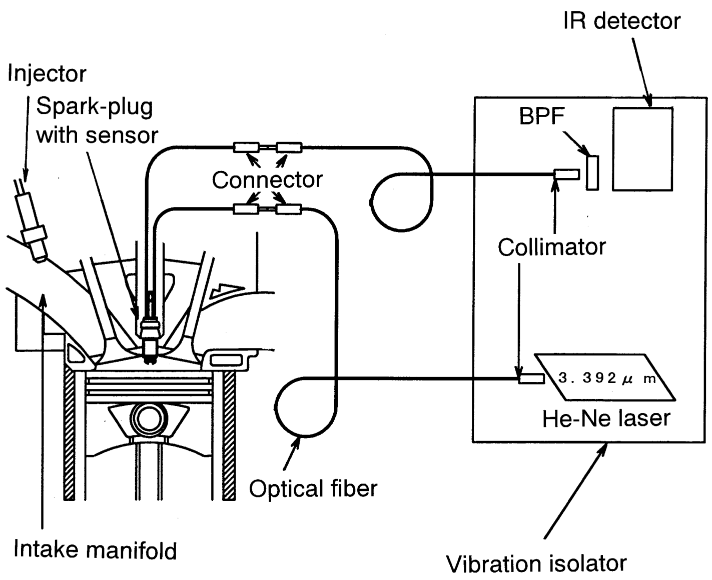


Fig.1 Optical arrangement and experimental apparatus

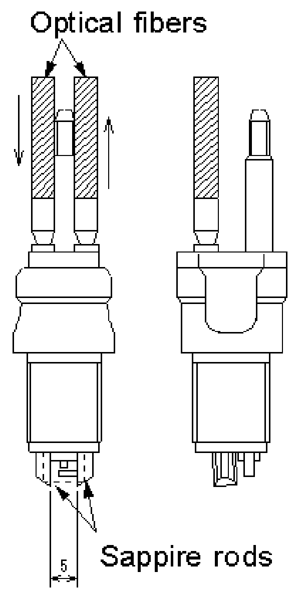


Fig.2 Optical sensor in spark plug

1. INTRODUCTION

It is well known that the emission line of 3.392 μm He-Ne laser is very close to the line of IR-ν3 band of methane, which has a relation to C-H stretching bands of aliphatic hydrocarbons. Therefore, this infrared laser is often applied to determine hydrocarbon concentration. Fundamental studies on absorption lines of methane have been done by many researchers (eg. Edwards and Burch, 1965, Hubbert et al., 1969, Mcmahon et al., 1972, Varanasi et al., 1974, Heffington et al., 1976, Mallard and Gardiner, 1978, Perrin and Hartmann, 1989, Tsuboi et al., 1985, 1990).

There are some applications of this laser to thermal fluid phenomena. For example, hydrocarbon vapor measurements were performed in fuel sprays or jets (eg. Emmerman, 1980, Chraplyvy, 1981, Adachi et al., 1990, Winklhofer and Plimon, 1991, Drallmeier and Peters, 1991, Drallmeier, 1994(1)(2)). Local fuel concentration was determined near the outlet of a burner with the help of infrared fibers and the inhomogeneity forced the NOx emissions to increase in lean mixture of overall equivalence ratio of 0.6. (Mongia et al., 1996(1), (2))

Recently, improving thermal efficiency and reducing exhaust emissions have been very crucial for internal combustion engines. It is very important to grasp the fuel concentration in the vicinity of the spark plug near the spark timing because initial stage of combustion affects the following main stage of combustion in spark-ignition engines. Gas sampling method is one of the most popular methods to investigate the fuel concentration in the actual engine (eg. Matsui et al., 1979, Collings, 1988, Galliot et al., 1990). However, some time delay occurs because the sampling tube has some length. Although laser diagnostics, such as laser induced fluorescence (LIF), Rayleigh scattering, and Raman scattering (eg. Eckbreth, 1996), can provide two-dimensional information of the fuel concentration, optical windows are needed. They can not be settled in actual engines so that LIF measurement is limited to apply to the test engine in which combustion chamber is sometimes different from actual engines. These methods for investigating mixture formation are summarized in the recent literature (eg. Zhao and Ladommatos, 2001). With regard to an in-situ optical method for obtaining fuel concentration near the spark plug, fluctuations in air/fuel ratio (A/F) were determined with an optical probe in a spark plug by detecting CH and C_2 radicals in the burned gas (eg. Ohyama et al., 1990), and both temperature and A/F were measured with a special optical probe (eg. Sohma et al., 1991). An optical sensor with fibers was developed to investigate the flame kernel and the rate of flame growth with the direction of flame propagation (eg. Witze et al., 1988). And optical fibers have often been used for detecting flame and chemiluminescence (eg. Spicher et al., 1988, Shoji et al., 1995).

Some efforts have been made to utilize absorption method as in-situ measurement for determining hydrocarbon concentration near the spark plug. Absorption of ultraviolet light was tested (eg. Morishita and Asai, 1992). The concentration measurements were performed near the spark plug in a test engine (eg. Yoshiyama et al., 1995), near the spark plug in a gasoline engine without combustion (eg. Kawamura et al., 1998) and with combustion (eg. Iiyama et al., 1998). The infrared lamp filtered near 3.4 μm instead of 3.392 μm laser was also used to determine the concentration of hydrocarbons (eg. Hall and Koenig, 1996, Koenig and Hall, 1997 and 1998, Koenig et al., 1997, Alger et al., 1999). Air/fuel ratio was tried to measure the stratification using a spark plug type sensor in a constant volume vessel (eg. Tor et al., 1997).

In this study, a fiber optic system linked to the optical sensor installed in the spark plug, in which light can pass through the combustion chamber, was developed to determine the fuel concentration near the spark plug successively using in-situ infrared absorption method. The 3.392 μm He-Ne laser was used as an incident light. By exchanging one of ordinary spark plugs in four cylinders in an engine for this special spark plug, successive measurement of fuel concentration before the spark timing near the spark plug was performed. Methane was homogeneously mixed with air with a static mixer under the conditions of motoring and firing. Isooctane was injected into the intake port in firing. Absorption coefficient of the fuel was also measured for high pressure and temperature in advance.

2. PRINCIPLE OF MEASUREMENT

Assuming that the intensity of a light with a certain wavelength, I, decays to I_0 when the light passes through a gas with concentration, C, along measurement length, L, the transmissivity, I/I_0 is expressed from Lambert-Beer's law as follows:

$$\log(I/I_0) = -\varepsilon CL, \qquad (1)$$

where ε denotes molar absorption coefficient. When the measurement length, L, is constant, the concentration can be determined form measuring the transmissivity. Absorption bands of methane are presented in Fig.3, which is calculated with HITRAN database (eg. Rothman et al., 1996). According to this result, methane absorbs the light in four ranges of wavelength, (7.6, 3.4, 2.3 and 1.6 μm), especially strong around 3.4μm. Each wavelength coincides well with one of the absorption line of methane. This is in conjunction with the C-H stretching bands in the molecule structure of the hydrocarbon. Therefore all hydrocarbons have similar absorption characteristics because they have many C-H bonds. When the local concentration of the fuel in spark-ignition engines is measured, it is desirable that the absorption coefficient is stronger because of the limitation of the measurement length.

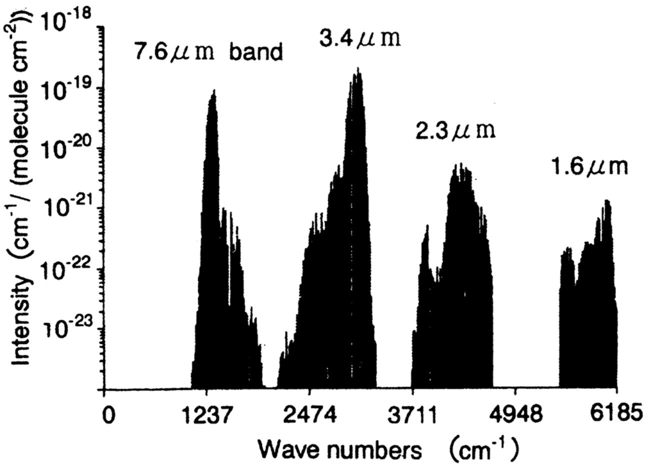
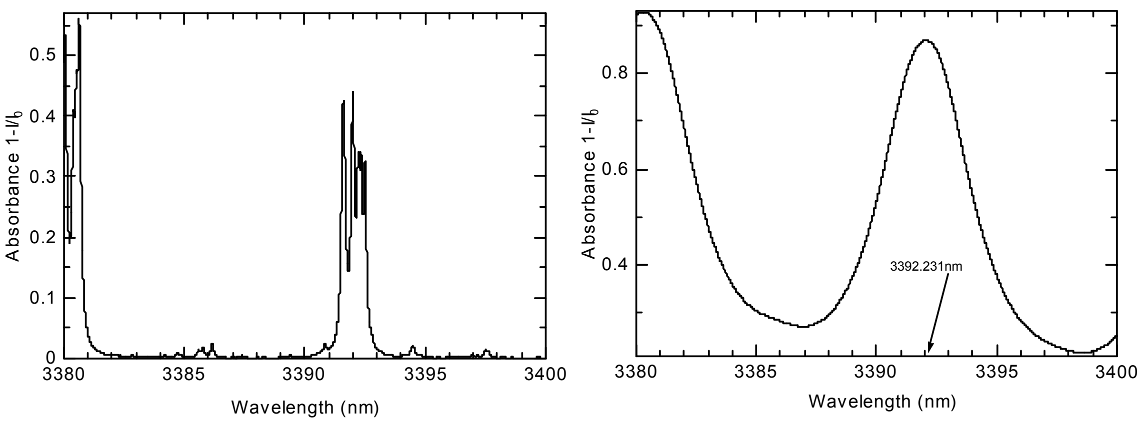


Fig.3 Absorption lines of methane calculated with HITRAN database.



(a) P=100 kPa, T=300 K (b) P=2000 kPa, T=600 K

Fig.4 Absorbance lines for methane calculated from HITRAN database

The absorbance for methane was calculated from HITRAN database as shown in Fig.2. When the pressure and temperature are 100 kPa and 300 K, respectively, shown in Fig.4(a), the absorption lines are sharp. However, as pressure and temperature increases 2000 kPa and 600 K, respectively, like in an engine near the spark timing, the absorption lines gathers with each other and shows broad spectrum due to Doppler broadening as shown in Fig.4(b). The value of absorbance depends on the concentration of methane.

The absorption coefficient depends on pressure and temperature. However, the absorption coefficient of a fuel, such as gasoline, is not known. Therefore, in general, the absorption coefficient of the fuel was measured with changing ambient pressure and temperature up to the conditions in engines in advance.

3. MOLAR ABSORPTION COEFFICIENT

3.1 Experimental apparatus

The value of the molar absorption coefficient depends on the pressure and temperature of the gas. However, there is almost no data for isooctane. Therefore, in this study, the value of the molar absorption coefficient was determined using a constant-volume vessel. Figure 5 shows a schematic diagram of the experimental apparatus. A He-Ne laser with a wavelength of 3.392 μm was used as an incident light. A convex lens and a chopper make the light thin and intermittent, respectively. The intensity of the light was adjusted with an ND filter. The waisted light chopped as 250 Hz frequency and passed through an optical window into a test region (L=64.0 mm) in the vessel. The light was absorbed by hydrocarbon in the vessel under the condition of a certain pressure and temperature. The light passes through another window again to an IR detector (PbSe) of which temperature is controlled to be constant. A band-pass-filter (full width at half maximum, FWHM=127nm) was set in front of the IR detector. After nitrogen is supplied to the vessel up to atmospheric pressure, isooctane that was used as fuel was aspirated with a syringe. Nitrogen was added to a certain pressure and temperature was controlled with heaters on the side and bottom of the vessel. Isooctane was vaporized and mixed very well with nitrogen by a special magnetic stirrer with a blade. When molar absorption of methane was investigated, methane was introduced into the vessel and mixed with nitrogen with a stirrer. The initial temperature in the vessel was measured with a thermocouple. The experimental condition of temperature was between 300 and 600 K while pressure in isooctane and methane were set between 100 and 2000 kPa and between 30 and 2000 kPa, independently.

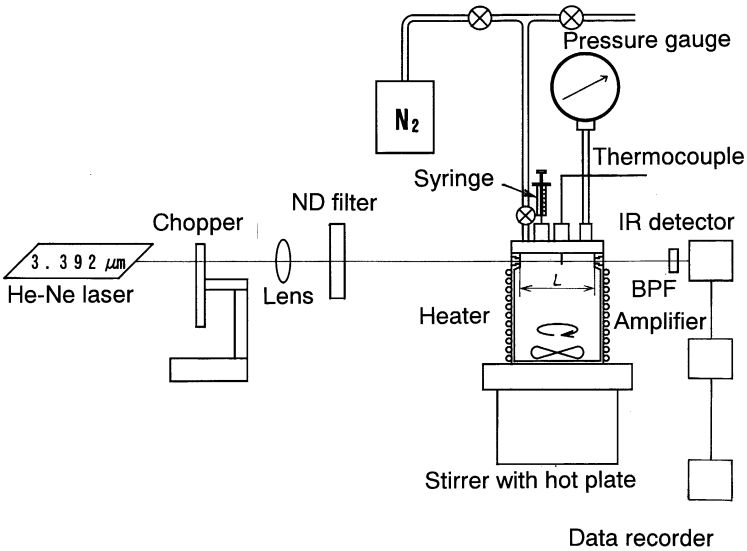
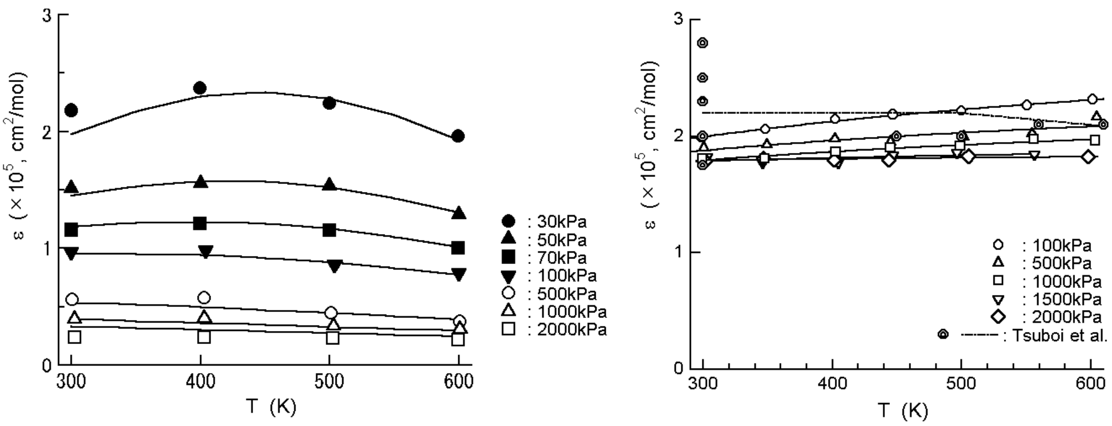


Fig. 5 Schematic diagram of the experimental apparatus for determining molar absorption coefficient

3.2 Molar Absorption Coefficient

The molar absorption coefficient of methane was determined from Eq.(1), which increases with increasing temperature and decreases with increasing pressure as shown in Fig.6(a). In low pressure under atmospheric pressure, the molar absorption coefficient increases very much. The dependence of temperature shows negative over atmospheric pressure and the value dose not change monotonously in low pressure. The molar absorption coefficient of isooctane increases with increasing temperature and decreases with increasing pressure as shown in Fig.6(b). The degrees of increase and decrease are less in higher pressure and temperature. For isooctane, there is little data except Tsuboi et al. indicated with double-circle (eg. Tsuboi et al., 1985). They measured the absorption coefficient from 300 K to 1200 K using a shock tube, however, the number of the data is very less and their data fluctuated very much from 1.8 to 2.8×10^5 cm^2/mol as shown in Fig.6. On the contrary, the standard deviation of each data obtained in this study is about 2%. The result certificates the reliability of our method.



(a) Methane (b) Isooctane

Fig.6 Molar absorption coefficient of hydrocarbons

4. FUEL CONCENTRATION NEAR THE SPARK PLUG IN A SPARK-IGNITION ENGINE

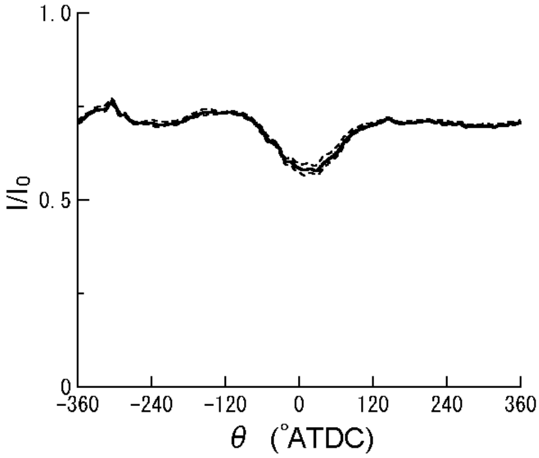
4.1 Optical arrangement and experimental apparatus

Figure 1 presents the optical arrangement and schematic diagram of the experimental apparatus for the spark-ignition engine. The light source with wavelength of 3.392μm was introduced into an optical fiber that infrared light can pass through. The light was guided to a spark plug through a connector. The spark plug had a pair of sapphire rods 5mm apart from each other and the edges were cut at an angle of $\pi/4$ radian so that the light passed through one of the rods and went back to the other rod as shown in Figure 2. The first generation of this sensor, which is almost the same configuration, was used for trial measurement of gasoline concentration (eg. Iiyama et al., 1998). However, the accuracy was not enough because of short measurement length of 3mm. The laser light was detected with an InSb detector through a band-pass-filter. The IR detector and TDC signals are recorded at every crank angle. According to Lambert-Beer's law presented in Eq.(1), the fuel concentration near the spark plug was determined when the transmittance signal was measured. In this study, the data was obtained successively during one experiment about 10 seconds. The light was cut off before and after the data instead of a chopper. The signals before and after the data were almost the same, so that this method is useful as far as some emission lights is not added to the signal during the experiment. This effect was confirmed not to occur in this experimental range.

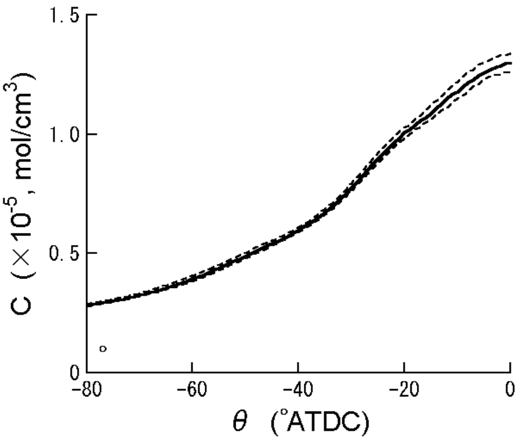
A four-stroke cycle spark-ignition engine with four cylinders in line was prepared to investigate the measurement method of this technique. The bore and stroke are 89 and 96 mm, respectively. One of the spark plugs was exchanged for the special spark plug with optical arrangement. Two kinds of fuels, that is, homogeneously mixed gaseous fuel and liquid fuel injected into the intake port, were used.

4.2 Experiment in a spark-ignition engine inducted with homogeneously mixed methane-air

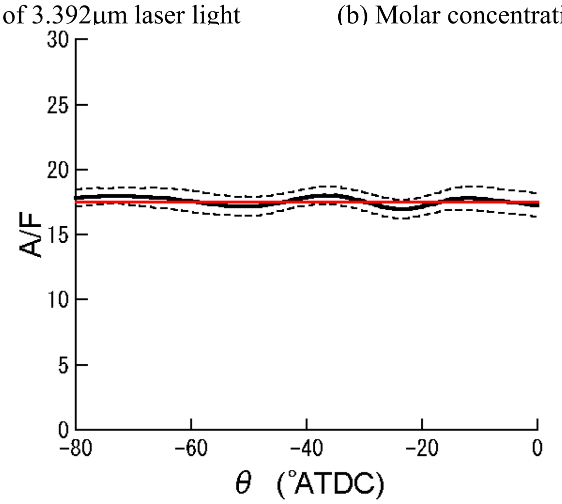
Methane was supplied from the intake pipe that is connected to the intake manifold and mixed homogeneously with air using a static mixer equipped to the intake pipe. Two laminar flow meters were also installed to determine the flow rates of methane and air, individually. The engine speed was 800rpm controlled with a DC electric dynamometer and the boost pressure was –52kPa with preset air/fuel ratio (A/F) of 17.5. Figure 7 shows the results averaged over 50 cycles. Solid lines illustrate the averaged values and dashed ones the standard deviations. The transmissivity of 3.392 μm laser light, I/I_0, decreased near the compression TDC as shown in Fig.7(a), because the piston moved toward the compression TDC (crank angle, θ=0 °BTDC) and the molarity, C, increased gradually due to increase in density. The molarity was determined from Eq.(1) in consideration for the dependence of molar absorption coefficient on pressure and temperature shown in Fig.6(a). In this case, the tranmissivity did not return to unity as shown in Fig.7(a) because the engine operated without firing and methane-air mixture remained in the combustion chamber all the time. The air/fuel ratio (A/F) keeps almost constant of 17.5, which coincides with the preset value. The fluctuation of the averaged air/fuel ratio and its standard deviation were within air/fuel ratio of 1.0



(a) Trasmissivity of 3.392μm laser light



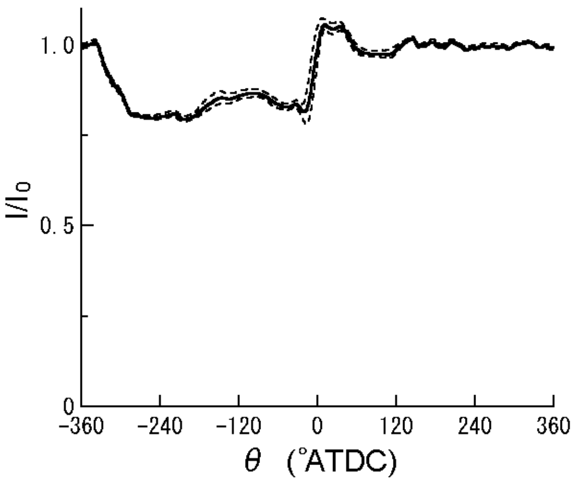
(b) Molar concentration history of methane

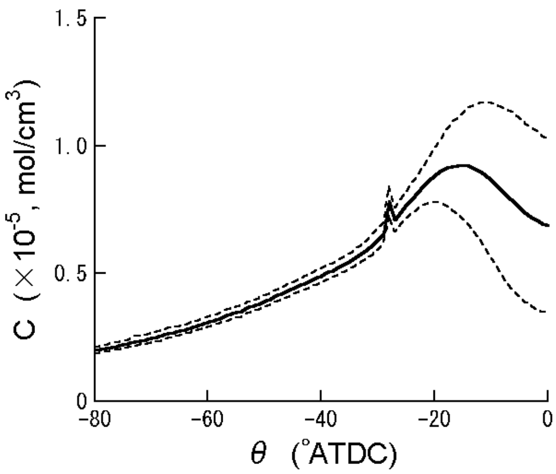


(c) Air/fuel ratio (Preset value = 17.5)

Fig.7 Results without combustion (Homogeneously mixed methane-air)

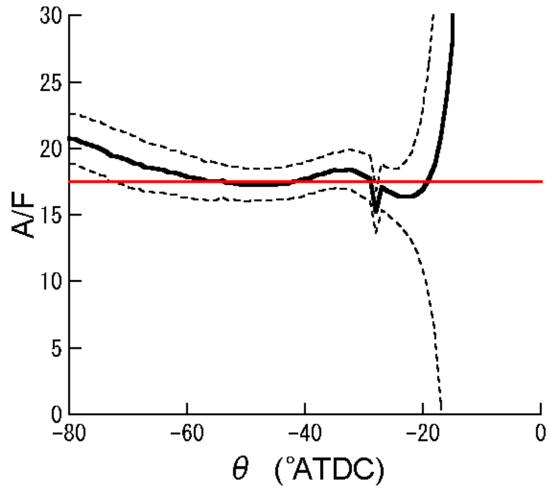
Next, the engine operated in firing with engine speed of 1000rpm, boost pressure of –72kPa and preset air/fuel ratio (A/F) of 17.5. The ignition timing was advanced at 28 °BTDC to achieve stable combustion. As shown in Fig.8(a), the transmissivity of the laser light returned 1.0 in the exhaust stroke when the gas is almost constructed of burned gas. When a flame touches the laser light and unburned gas changes into burned gas, the transmissivity returns to unity rapidly while the averaged data of transmissivity in Fig.8 returns to unity gradually. This phenomenon informs us of the timing of the flame arrival to the laser beam. The molarity was determined from Eq.(1) as shown in Fig.8(b). The standard deviation becomes very large after the spark because cycle-to-cycle fluctuation in the formation of initial flame occurs. Figure 8(c) presents the air/fuel ratio, which coincides with the preset value between 60 °BTDC and the spark timing. Before the crank angle of 60 °BTDC, the air/fuel ratio (A/F) is somewhat apart from the preset value. The accuracy decreases gradually when the molarity is smaller because the relative error in molarity becomes to affect air/fuel ratio very much.





(a) Trasmissivity of 3.392μm laser light

(b) Molar concentration history of methane



(c) Air/fuel ratio (Preset value = 17.5)

Fig.8 Results with combustion (Homogeneously mixed methane-air)

This study focuses on the concentration measurement before the ignition timing so that the information after the ignition timing is not discussed here. The information of fuel concentration near the spark plug at spark timing is very useful to design the engine performance. After a flame front passes through the measurement region, fuel concentration cannot be determined. However, the signal might imply a lot of information for a future work.

4.3 Experiment in a spark-ignition engine fueled with isooctane injected into intake port

Isooctane was injected into the intake port in the same spark-ignition engine. Isooctane is liquid fuel so that it may be considered that isooctane does not vaporize enough and liquid droplets remains in the combustion chamber. Assuming that liquid droplets exist in the gas, the light with 3.39μm wavelength detected with a sensor decreases due to the scattering of the droplets. The light is not only absorbed but scattered under such condition. When the light with another wavelength that is not absorbed by hydrocarbons is used, only the effect of scattering can be extracted. Figure 9 shows the transmissivity of the light through an interference filter from a visible He-Ne laser of which the wavelength is 0.6328 μm instead of the 3.392 μm laser. The throttle was almost closed near idling operation at engine speed of 840 rpm. In this case, no existence of the liquid droplets could be observed because the signal showed almost the same level. The HITRAN database also indicates that the wavelength of 0.6328 μm has no absorption line of hydrocarbons.

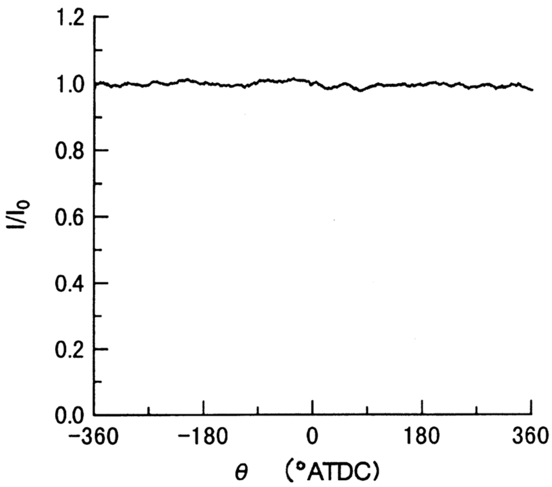


Fig.9 Transmissivity with 0.6328nm He-Ne laser that does not have absorption line for hydrocarbons

The engine operated at 850 rpm under near idling condition with preset air/fuel ratio of 16 and ignition timing of 14 °BTDC. When both pressure and temperature increase, the molar absorption coefficient estimated from Fig.6(b) presents almost constant for isooctane.

Figure 10 shows the result of the air/fuel ratio (A/F) from 50 till 10 35 °BTDC. Here, the mass flow of air was determined with the averaged data for four cylinders from an air flow meter. The concentration just before the spark timing near the spark plug almost agrees with the mean value that is obtained from the measurement of the flow rate with a buret. At the crank angle from 50 to 35 °BTDC, a solid line of the air/fuel ratio shows much larger than the preset value of 16. It may be considered that the fuel cloud moves with the gas flow and the air/fuel ratio near the spark plug shows that air is richer before 35 °BTDC. As the piston moves up toward the cylinder head, the fuel is mixed homogeneously. However, this reason of air rich before 35 °BTDC does not have certainty in the present stage because the molar density is small and the standard deviation of A/F drawn in dashed lines shows very large, as described in the previous section.

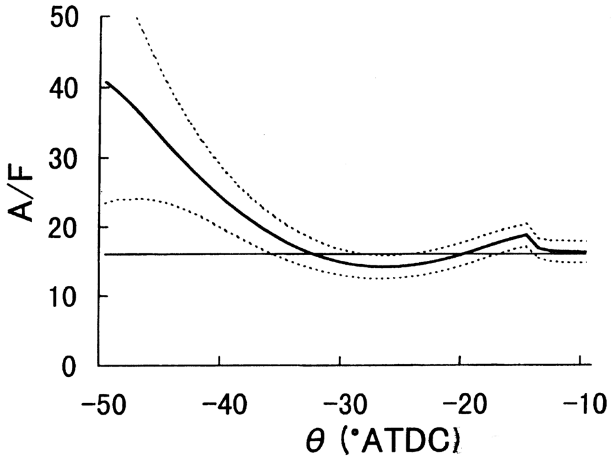


Fig.10 Air/fuel ratio with combustion fueled with isooctane injected into intake port

5. SUMMARY

A special optical sensor in a spark plug was developed for a spark-ignition engine. Fuel concentration history near the spark plug was obtained in a spark-ignition engine. Two kinds of fuel and methods were performed. Methane was homogeneously mixed with air in the intake pipe while isooctane was injected into the intake port.

The effects of pressure and temperature on the molar absorption coefficient of methane and isooctane were independently determined with a constant-volume vessel in advance. The molar absorption coefficient of methane shows higher in lower pressure and decreases with increasing temperature and pressure over atmospheric pressure. The molar absorption coefficient of isooctane shows almost the same value in compression stroke. The effects of temperature and pressure are offset with each other because the effect of temperature is positive and that of pressure is negative. When this optical sensor was used, the air/fuel ratio near the spark plug before the ignition timing agreed with the value obtained from other stationary methods in three cases, that is, motoring and firing with methane, and firing with isooctane. Laminar flow meters were used for methane and air, individually while buret and air flow meter were used for isooctane and air. As a result, it was found that this optical sensor is a strong tool for determining fuel concentration history in a spark-ignition engine.

ACKNOWLEDGEMENT
Financial support for parts of this work has been granted from Iwatani Foundation in fiscal year 2001.

REFERENCES

Adachi, M., Mcdonell, V.G. and Samuelsen, G.S. (1990), “Nonintrusive measurement of gaseous species in reacting and non-reacting sprays”, Combustion Science and Technology, 75, pp.179-194.

Alger, T., Hall, M. and Matthews, R., “Fuel Spray Dynamics and Fuel Vapor Concentration Near the Spark Plug in a Direct-Injected 4-Valves SI Engine”, SAE Paper, (1999), No.1999-01-0497.

Chraplyvy, A.R. (1981), "Nonintrusive measurements of vapor concentrations inside sprays", Applied Optics, 20, pp.2620-2624.

Drallmeier, J.A. (1994 (1)), "Hydrocarbon-vapor measurements in pulsed fuel sprays: a simplification of the infrared extinction technique", Applied Optics, 33-30, pp.7175-7179.

Drallmeier, J.A. (1994 (2)), "Hydrocarbon-vapor measurements in pulsed fuel sprays", Applied Optics, 33-33, pp.7781-7788.

Drallmeier, J. A. and Peters, J. E. (1991), "An experimental investigation of fuel spray vapor phase characterization", Atom. Sprays, 1, pp.63-88.

Eckbreth, A.C. (1996), "Laser Diagnostics for Combustion Temperature and Species (2nd Edition)", Gordon and Breach Publications.

Edwards, B.N. and Burch, D.E. (1965), "Absorption of 3.39-Micron Helium-Neon Laser Emission by Methane in the Atmosphere", Journal of the Optical Society of America, Vol.55, No.2, (1965), pp.174-177.

Emmerman, P. J., Goulard, R., Santoro, R.J. and Semerjian, H.G. (1980), Multiangular Absorption Diagnostics of a Turbulent Argon-Methane Jet, J. Energy, 4-2, pp.70-77.

Hall, M.J. and Koenig, M. (1996), "A Fiber-Optic Probe to Measure Precombustion In-Cylinder Fuel-Air Ratio Fluctuations in Production Engines", Proc. of 26th Symp. (Int.) on Combustion, pp.2613-2618, The Combustion Institute.

Heffington, W. M., Parks, G. E., Sulzmann and Penner, S. S. (1976), "High Temperature Absorption Coefficient of Methane at 3.392μ", J. Quant. Spectrosc. Radiat. Transfer, 16, pp.839-841.

Hubbert, G., Kyle, T. G., and Troup, G. J. (1969), "An Investigation of Self-Broadening in Methane Using a Single-Frequency 3.39μ Laser", J. Quant. Spectrosc. Radiat. Transfer, 9, pp.1469-1476.

Iiyama, A., Itoh, T., Muranaka, S., Takagi, Y., Iriya, Y., Noda, T., Urushihara, T. and Naitoh, K. (1998), "Attainment of High Power with Low Fuel Consumption and Exhaust Emissions in a Direct-Injection Gasoline Engine", FISITA F98T048.

Kawamura, K., Suzuoki, T., Saito, A., Tomoda, T. and Kanda, M. (1998), "Development of Instrument for Measurement of Air-Fuel Ratio in Vicinity of Spark-Plug (Application to DI Gasoline Engine)", JSAE Review, Vol.19, No.4, pp.305-310.

Koenig, M. and Hall, M.J. (1997), "Measurement of Local In-Cylinder Fuel Concentration Fluctuations in a Firing SI Engine", SAE Paper, No.971644.

Koenig, M. H., Stanglmaier, R.H., Hall, M.J. and Matthews, R.D. (1997), "Mixture Preparation During Cranking in a Port-Injected 4-Valve SI Engine", SAE Paper, No.972982.

Koenig, M. and Hall, M., "Cycle-Resolved Measurements of Pre-Combustion Fuel Concentration near the Spark Plug in a Gasoline SI Engines", SAE Paper, (1998), No.981053.

Mallard, W. G. and Gardiner, Jr., W. C. (1978), "Absorption of the 3.39μm He-Ne Laser Line by Methane From 300 to 2400 K", J. Quant. Spectrosc. Radiat. Transfer, 20, pp.135-149.

McMahon, J., Troup, G. J. and Hubbert, G. (1972), "The Effect of Pressure and Temperature on the Half-Width of the Methane Absorption at 3.39μ", J. Quant. Spectrosc. Radiat. Transfer, 12, pp.797-805.

Mongia, R., Tomita, E., Hsu, F., Talbot, L. and Dibble, R. (1996 (1)), “Optical Probe For In-Situ Measurements of Air-To-Fuel Ratio In Low Emission Engines”, 34th Aerospace Sciences Meeting & Exhibit, pp.1-8 (Paper No.AIAA 96-0174).

Mongia, R., Tomita, E., Hsu, F., Talbot, L. and Dibble, R. (1996 (2)), “Use of an Optical Probe for Time-Resolved in Situ Measurement of Local Air-to-Fuel Ratio and Extent of Fuel Mixing with Applications to Low NOx Emissions in Premixed Gas Turbines”, 26th Symp. (Intern.) on Combustion, pp.2749-2755, The Combustion Institute.

Morishima, R. and Asai, K. (1992), “Mixture Strength at Cranking Cycles of Gasoline Engine Starting”, SAE Paper, No.920235.

Ohyama, Y., Ohsuga, M. and Kuroiwa, H. (1990), “Study of Mixture Formation and Ignition Proces in Spark Ignition Engine Using Optical Combustion Sensor”, SAE Paper, No.901712.

Perrin, M.Y. and Hartmann, J.M. (1989), “High temperature absorption on the 3.39μm He-Ne laser line by methane”, J. Quant. Spectrosc. Radiat. Transfer, 42-6, pp.459-464.

Rothman, L. S., et al. (1996), “The HITRAN Molecular Spectroscopic Database and HAWKS (HITRAN Atmospheric Workstation):1996 Edition” (http://www.hitran.com/).

Shoji, H., Shimizu, T., Toshida, K. and Saima, A. (1995), “Spectroscopic Measurement of Radical Behaviour under Knocking Operation”, SAE Paper, No.952407.

Sohma, K., Yukitake, T., Azuhata, S. and Takaku, Y. (1991), “Application of Rapid Optical Measurement to Detect the Fluctuations of the Air-Fuel Ratio and Temperature of a Spark Ignition Engine”, SAE Paper, No.910499.

Spicher, U., Schmitz, G. and Kollmeiner, H. (1988), “Application of a New Optical Fiber Technique for Flame Propagation Diagnostics in IC Engines”, SAE Paper, No.881673.

Tor, J.L., Mongia, R. and Dibble, R.W. (1997), “Fiber Optic Instrumented Spark Plug for Time Resolved Measurement of Air-Fuel Ratio”, Spring Meeting of Western State Sect. of Combust. Institute, Paper No.97S-010.

Tsuboi, T., Inomata, K., Tsunoda, Y., Isobe, A. and Nagaya, K. (1985), “Light Absorption by Hydrocarbon Molecules at 3.392μm of He-Ne Laser”, Japanese Journal of Applied Physics, 24-1, pp.8-13.

Tsuboi, T., Arimitsu, N., Ping D. and Hartmann, J.-M. (1990), “Temperature, Density, and Perturber Dependences of Absorption of the 3.39 μm He-Ne Laser by Methane”, Japanese Journal of Applied Physics, 29-10, pp.2147-2151.

Varanasi, P., Pugh, L.A., Bangaru, B.R.P. (1974), “Measurement of Multiplet Intensities and Noble Gas-Broadened Line Widths in the ν3-Fundamental of Methane”, J. Quant. Spectrosc. Radiat. Transfer, 14, pp.829-838.

Winklhofer, E. and Plimon,A. (1991), “Monitoring of hydrocarbon fuel-air mixture by means of a light extinction technique in optically accessed research engines”, Optical Engineering, Vol.30, No.9, pp.1262-1268.

Witze, P.O., Hall, M.J. and Wallace, J.S. (1988), “Fiber-Optic Instrumented Spark Plug for Measuring Early Flame Development in Spark Ignition Engines”, SAE Paper, No.881638.

Yoshiyama, S., Hamamoto, Y., Tomita, E. and Minami, K. (1996), "Measurement of Hydrocarbon Fuel Concentration by means of Infrared Absorption Technique with 3.39µm He-Ne Laser", JSAE Review, 17-4, pp.339-345.

Zhao, H. and Ladommatos, N. (2001), "Engine Combustion Instrumentation and Diagnostics", Society of Automotive Engineers, Inc., pp.337-394.