Lake Louise, September 20-24, 2009 31st IEA/TLM –1.4G

Mixture Formation Process in a Spark-Ignition Engine with Ethanol Blended Gasoline

Okayama University

Nobuyuki KAWAHARA

Eiji TOMITA

kawahara@mech.okayama-u.ac.jp
tomita@mech.okayama-u.ac.jp

➢ Ethanol

	Gasoline	Ethanol
RON	92	111
Density [g/cm³]	0.74	0.79
Lower Heating value [MJ/kg]	42.4	$\boxed{26.8}$
Stoichiometric A/F	14.3	$\boxed{9.0}$
Boiling Point [□]	□	78.5
Latent Heat of Evaporation [kJ/kg]	420	$\boxed{845}$

- Biomass fuel (CO_2 free)
- High antiknock quality

- Low heat of combustion
- Low stoichiometric A/F
- High latent heat

➢ Ethanol Blended Gasoline

Ex : Ethanol *x* vol% mixture

Antiknock quality
- High efficiency
- Low emissions

Background

- **Ethanol Blended Gasoline** (E*10* = Ethanol *10 vol%* mixture)

Merits → Biomass, High antiknock quality

Problems → Evaporation characteristics

↓

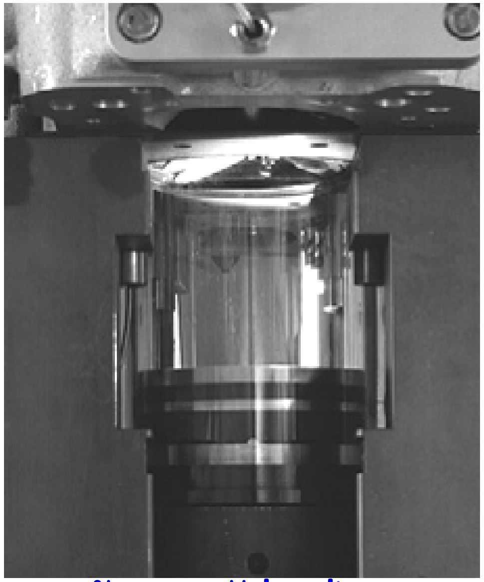
Mixture formation process

Transparent Engine

× Heat loss is very different from that in a practical engine.

Practical Engine

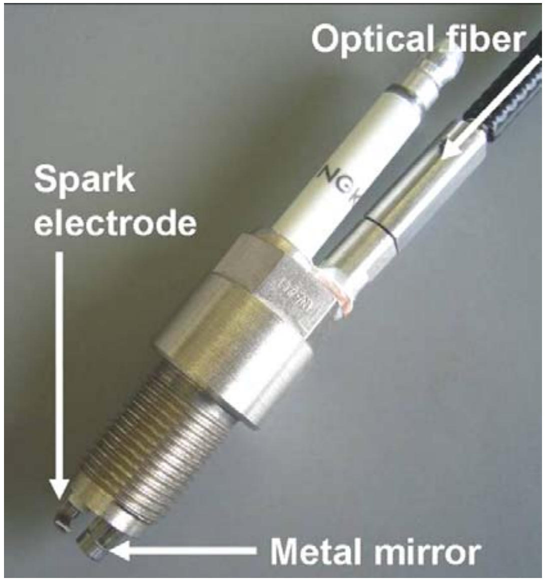
Time-series of local fuel concentration can be measured by *in situ* infrared absorption method.



Background

Purpose

Effect of ethanol blending on mixture formation process is investigated by fuel concentration near the spark plug in a practical spark-ignition engine.

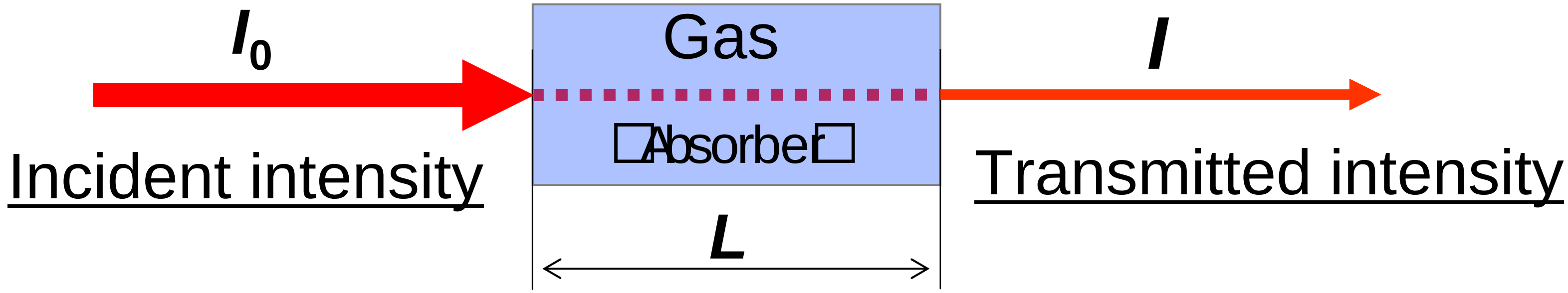


Experimental process

1. Molar absorption coefficient of ethanol blended gasoline was measured by a constant volume vessel.
2. Fuel concentration near the spark plug was measured in a practical SI engine under standard injection timing and under late injection timing.

Purpose of this study

Infrared Absorption Method



Law of Lambert-Beer

$$\log_{10}\left(\frac{I}{I_0}\right) = -\varepsilon C L$$

$\frac{I}{I_0}$: Transmissivity [ ]

ε : Molar absorption coefficient [cm^2/mol]

C : Molar concentration [mol/cm^3]

L : Length of measurement [cm]

Light source : **3.392 μm He-Ne laser**

Hydrocarbons have absorption bands around 3.4 μm

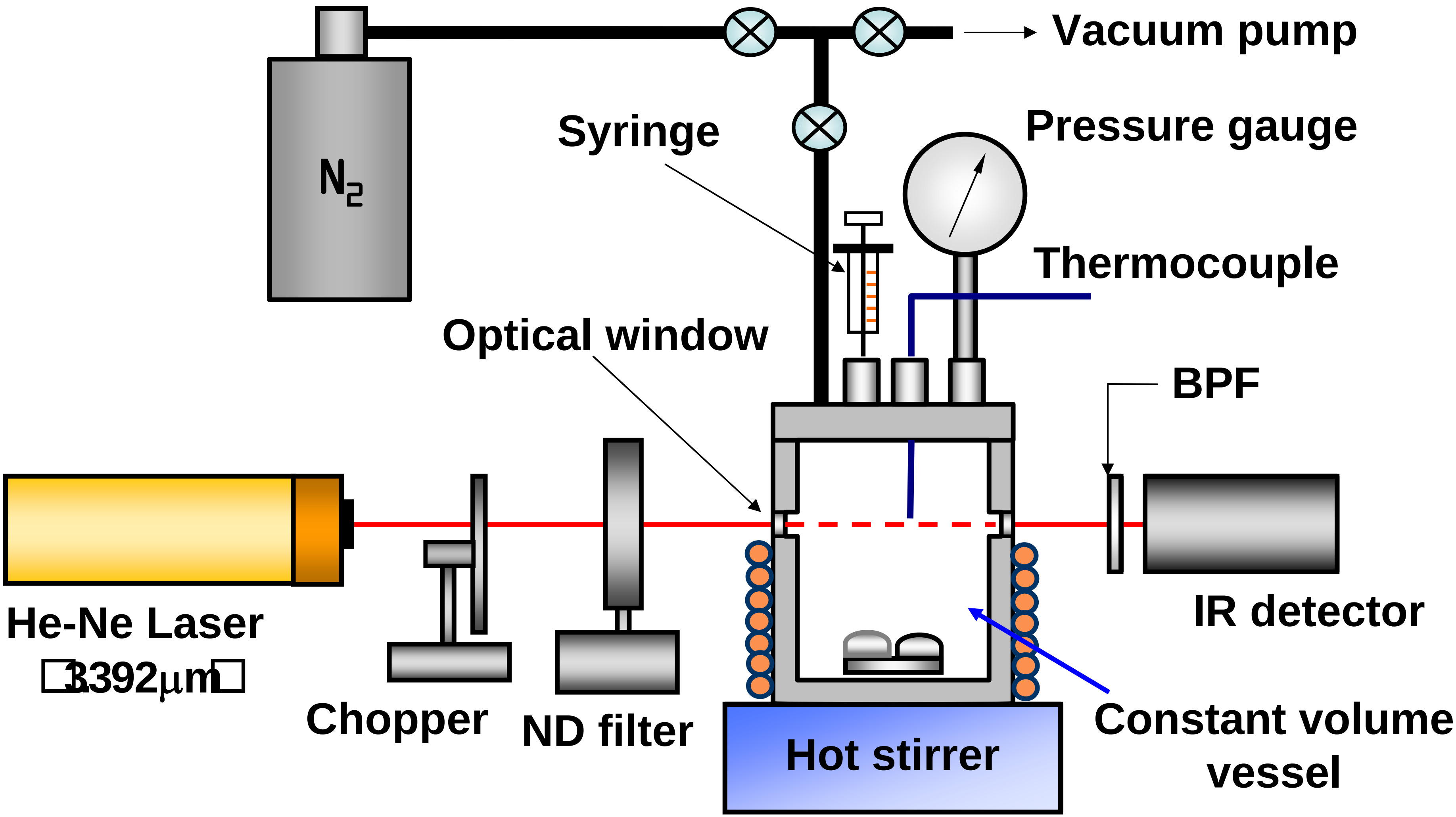
Molar absorption coefficient : Pressure and temperature dependence

$$\varepsilon = f\,(P, T)$$

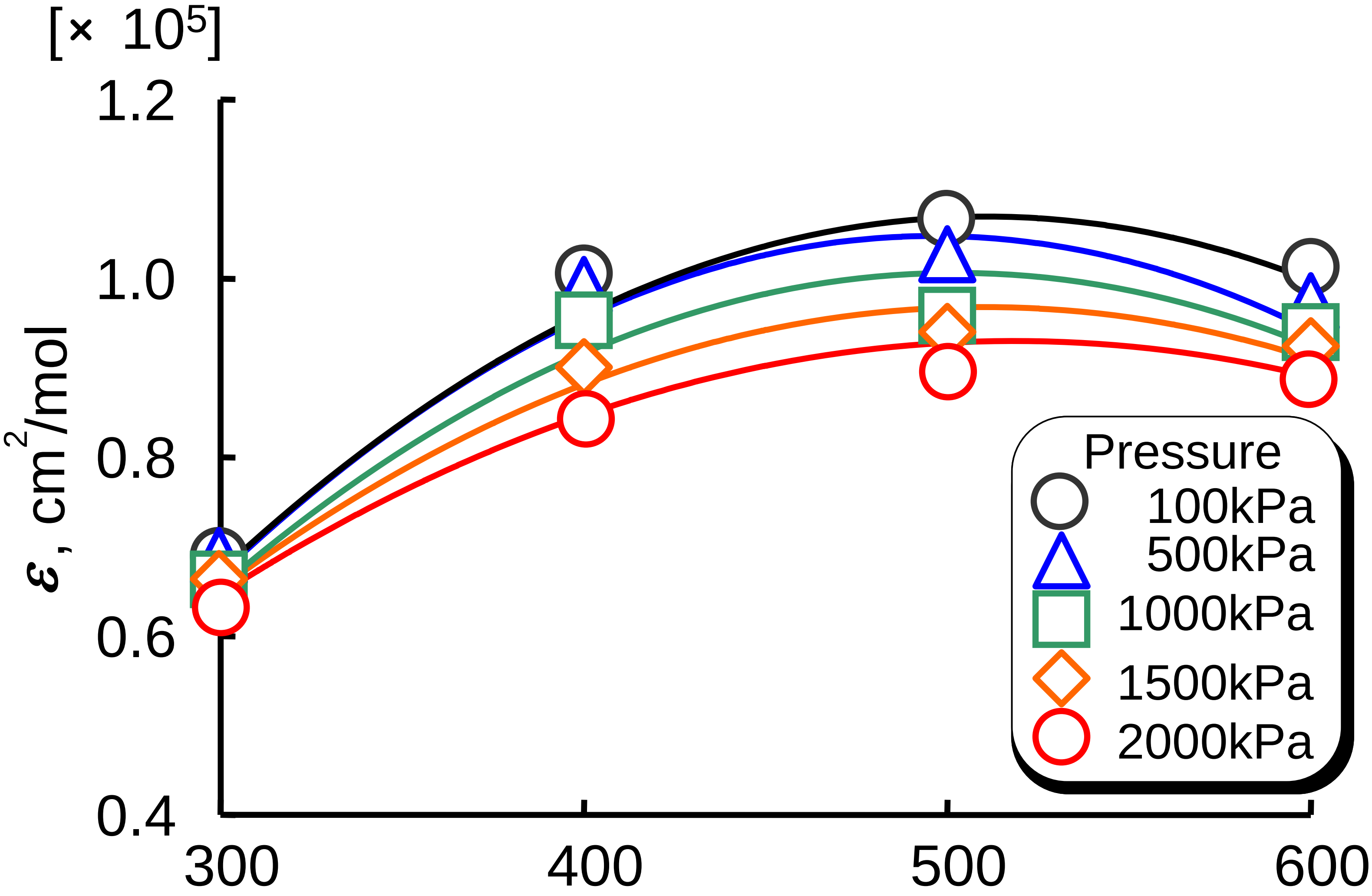
- Molar absorption coefficient of ethanol blended gasoline was measured by a constant volume vessel.

- Fuel concentration near the spark plug was measured in a practical SI engine under standard injection timing and under late injection timing.

Contents

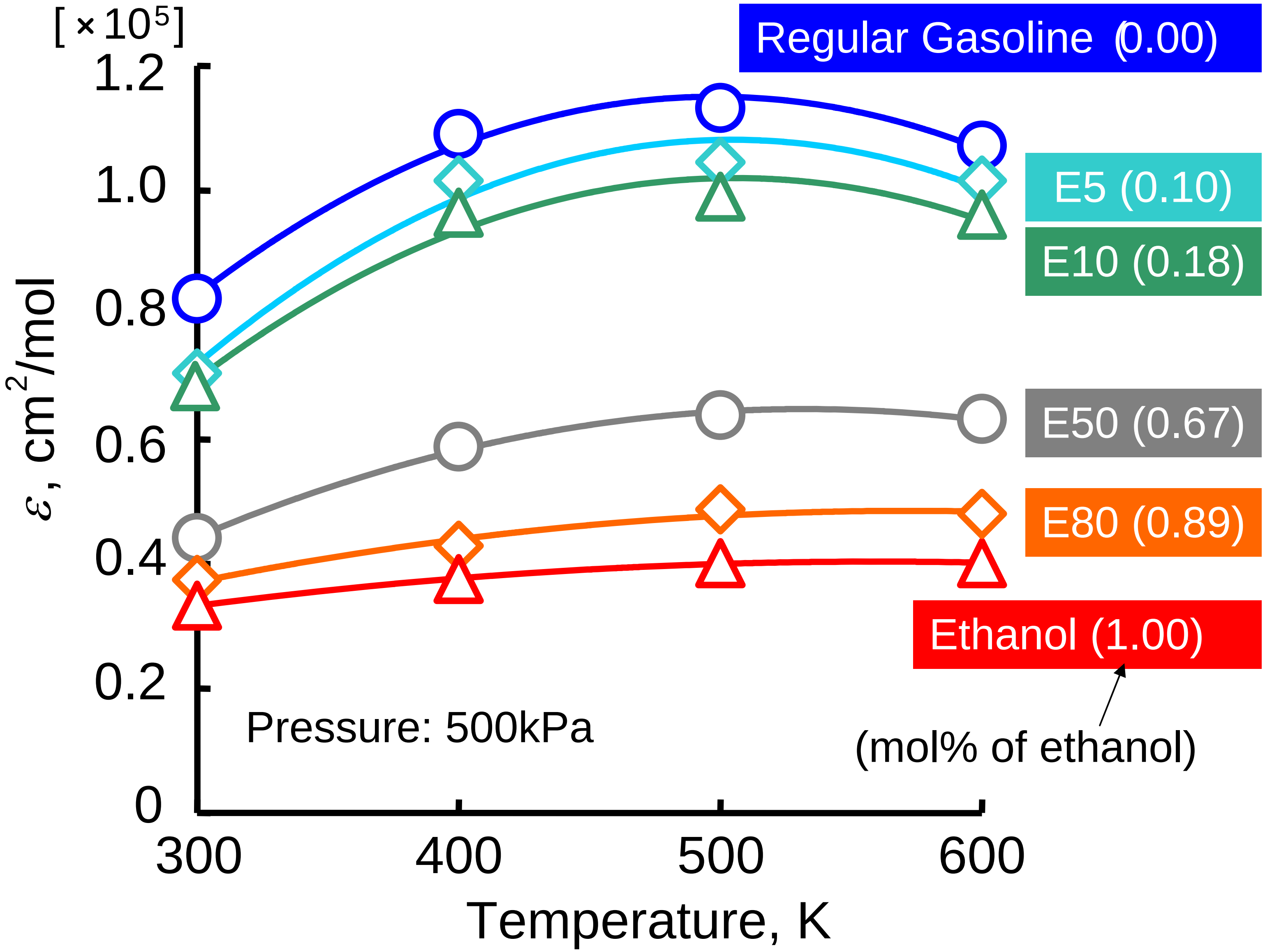


Experimental Apparatus for Determining ε



Okayama University

Molar absorption coefficient of E10



Okayama University

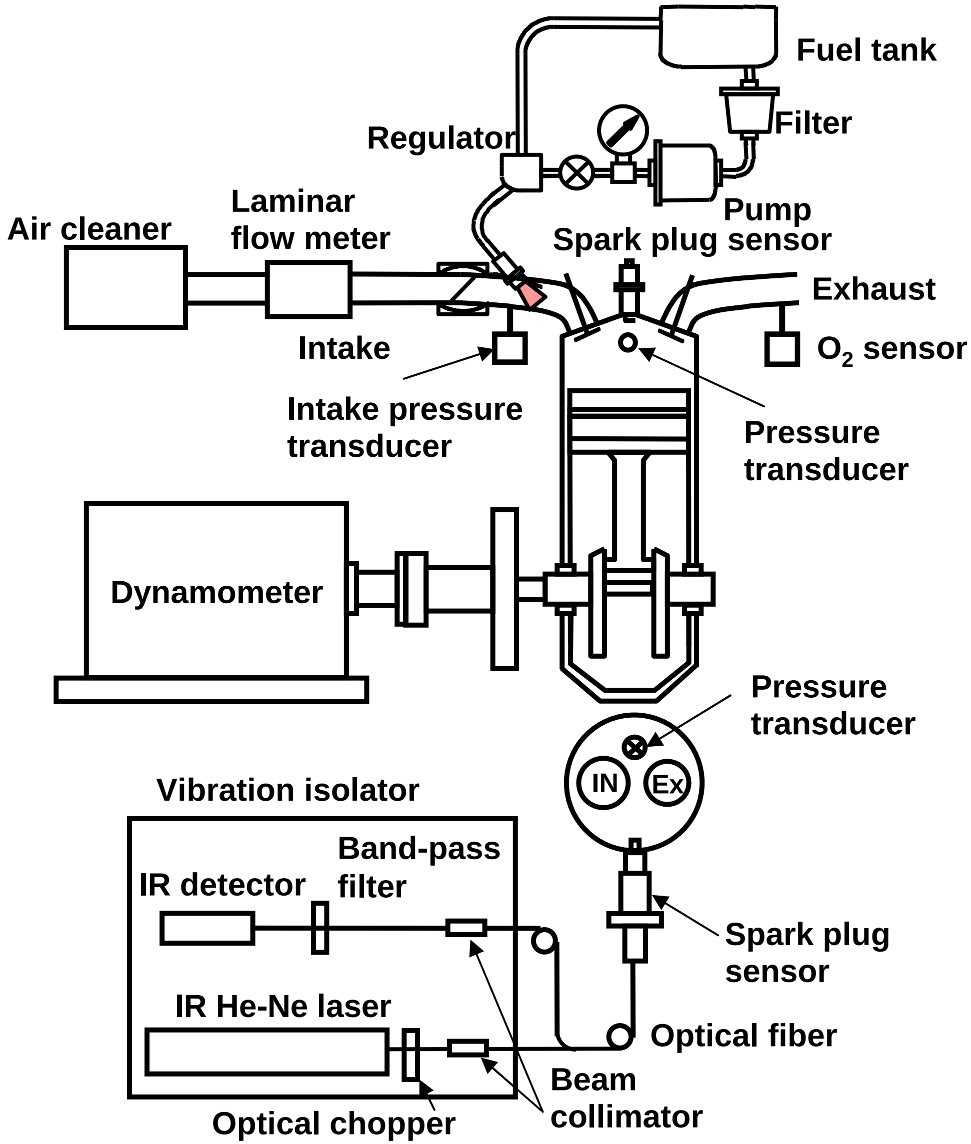
Molar absorption coefficient

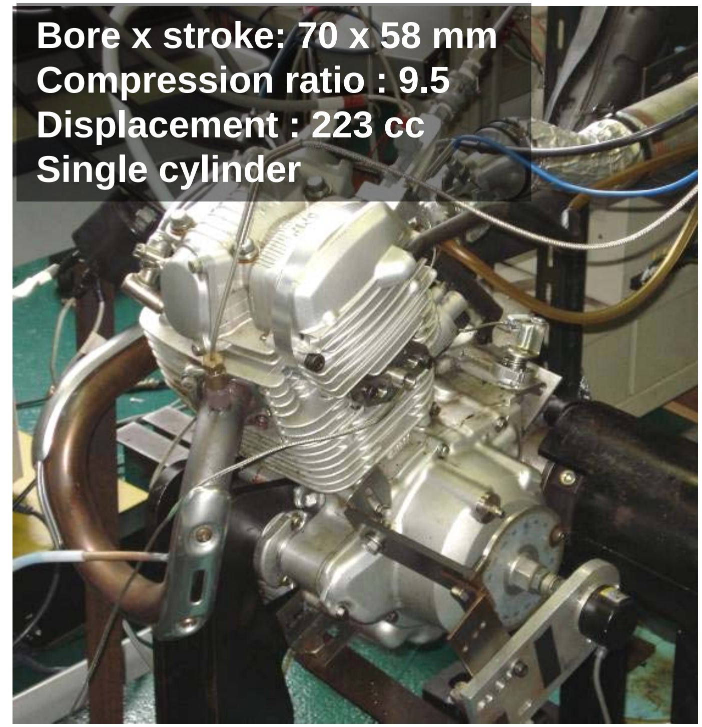
- Molar absorption coefficient of ethanol blended gasoline was measured by a constant volume vessel.

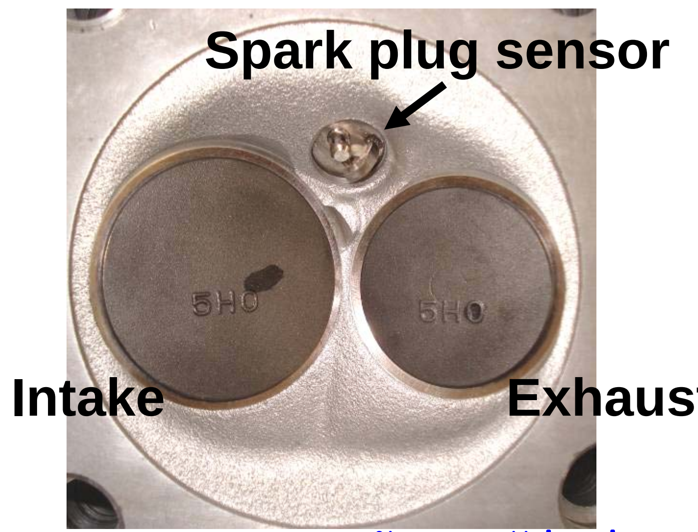
- Fuel concentration near the spark plug was measured in a practical SI engine under standard injection timing and under late injection timing.

Contents

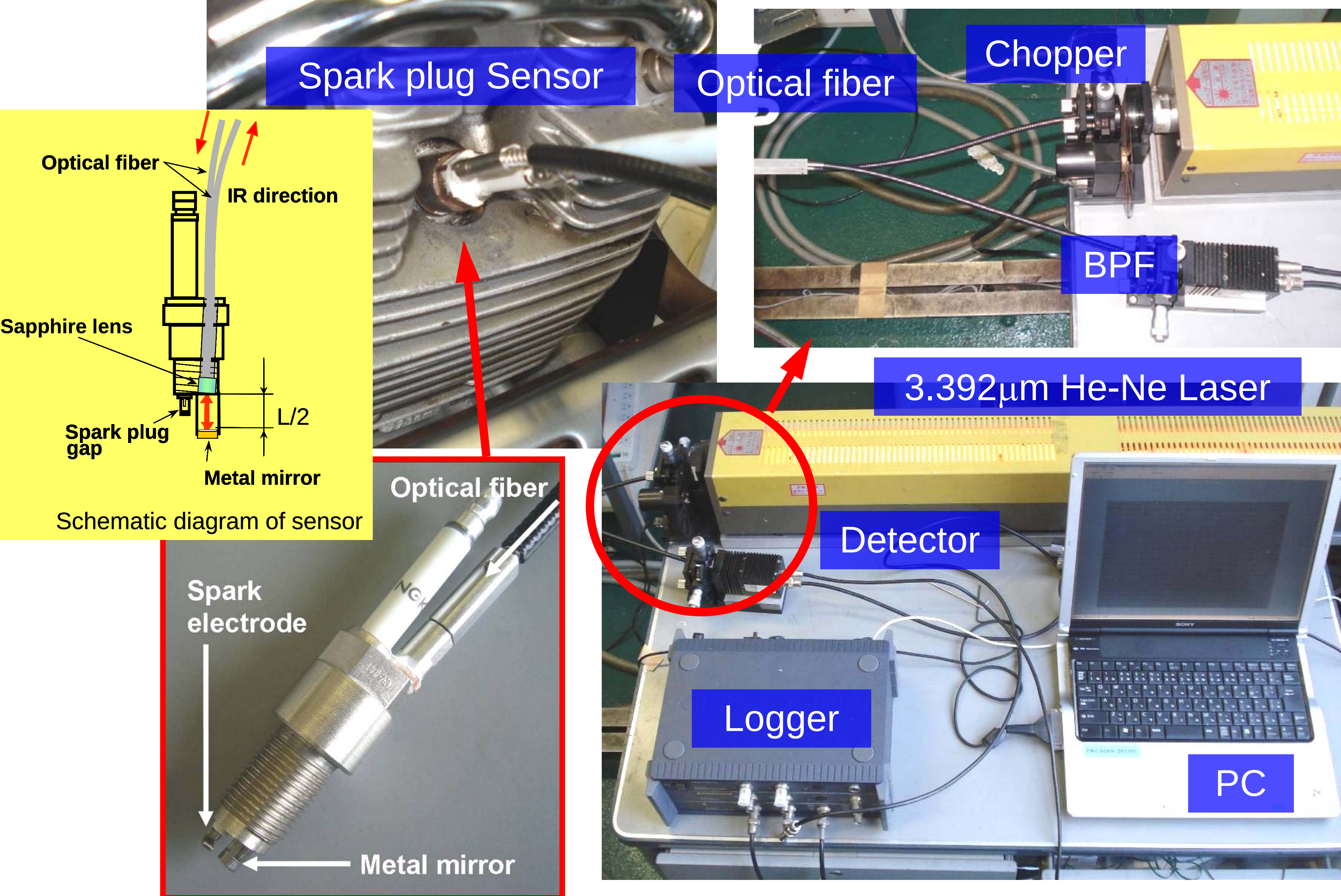
Fuel : E0 (Regular gasoline)□E20



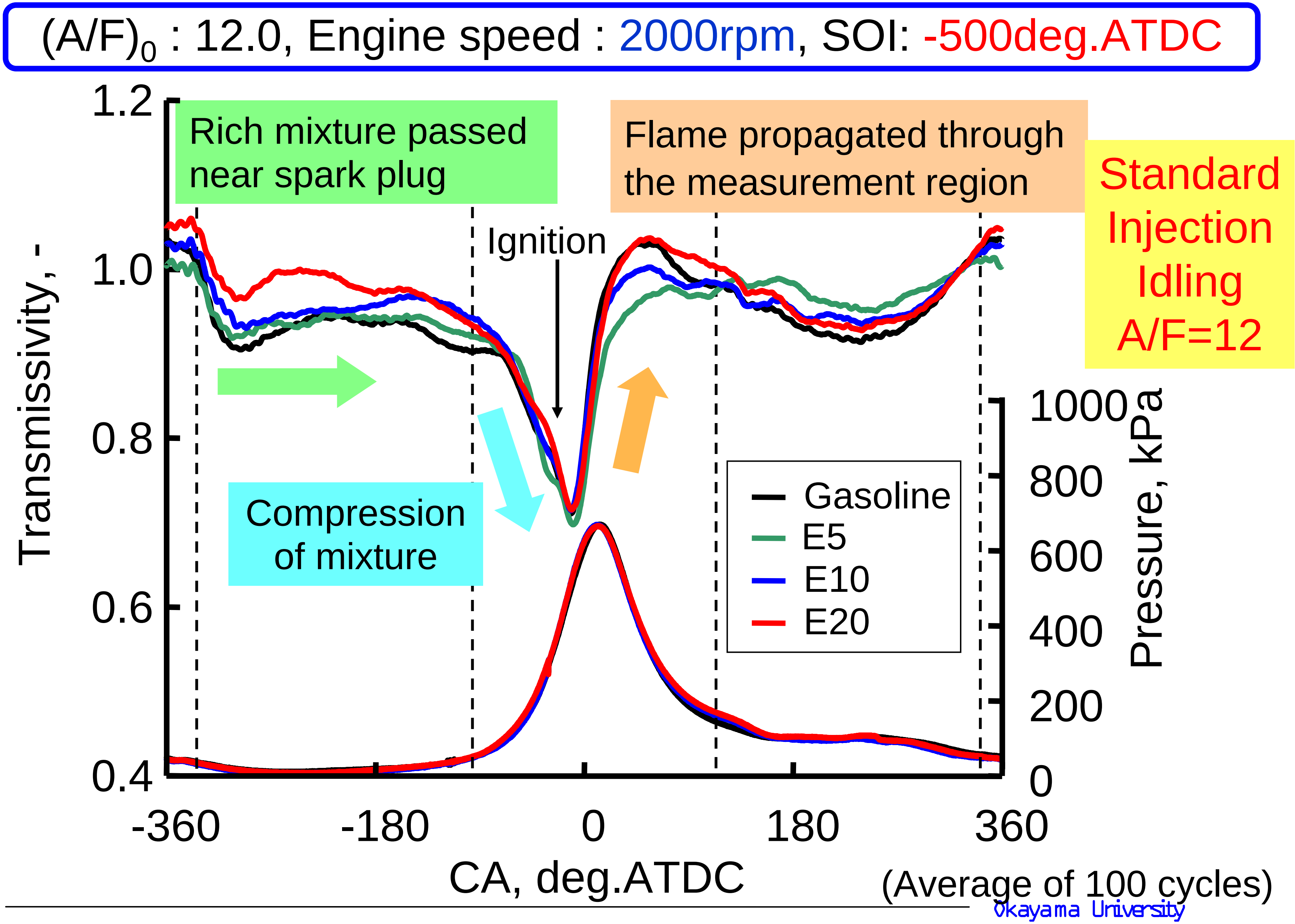




Experimental setup and optical arrangement

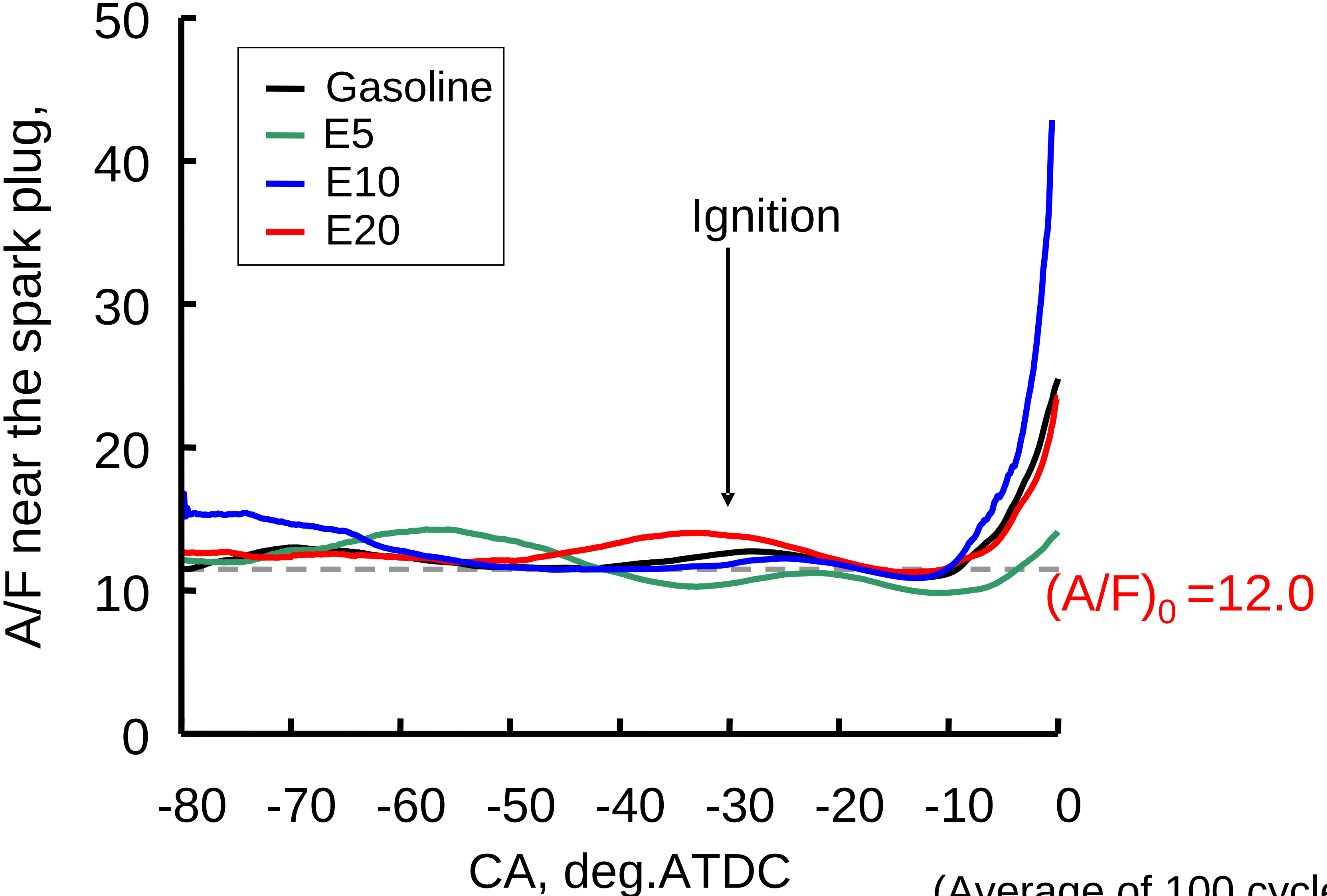


Optical setup



Transmissivity history

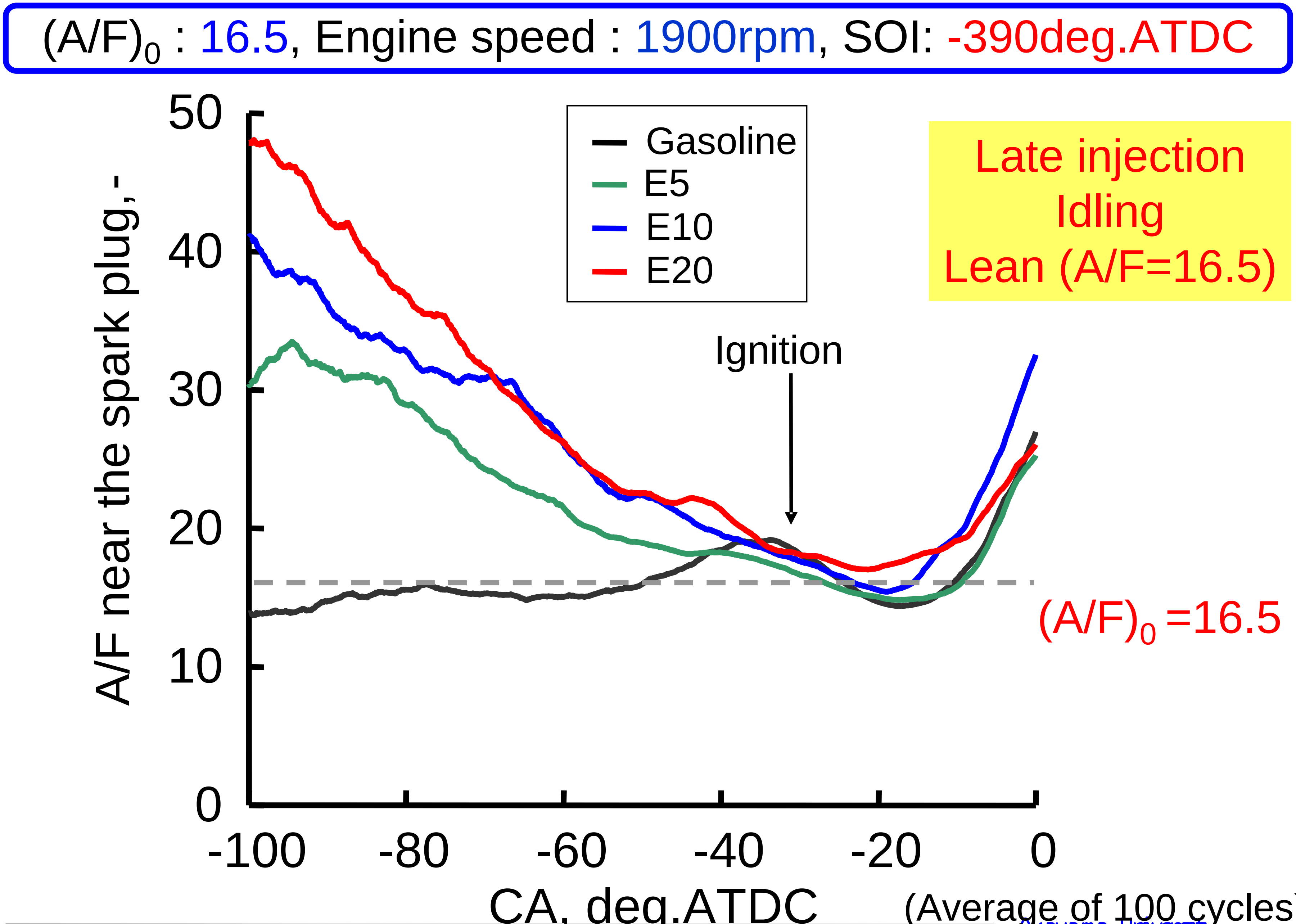
(A/F)$_0$: 12.0, Engine speed : 2000rpm, SOI: -500deg.ATDC



(Average of 100 cycles)

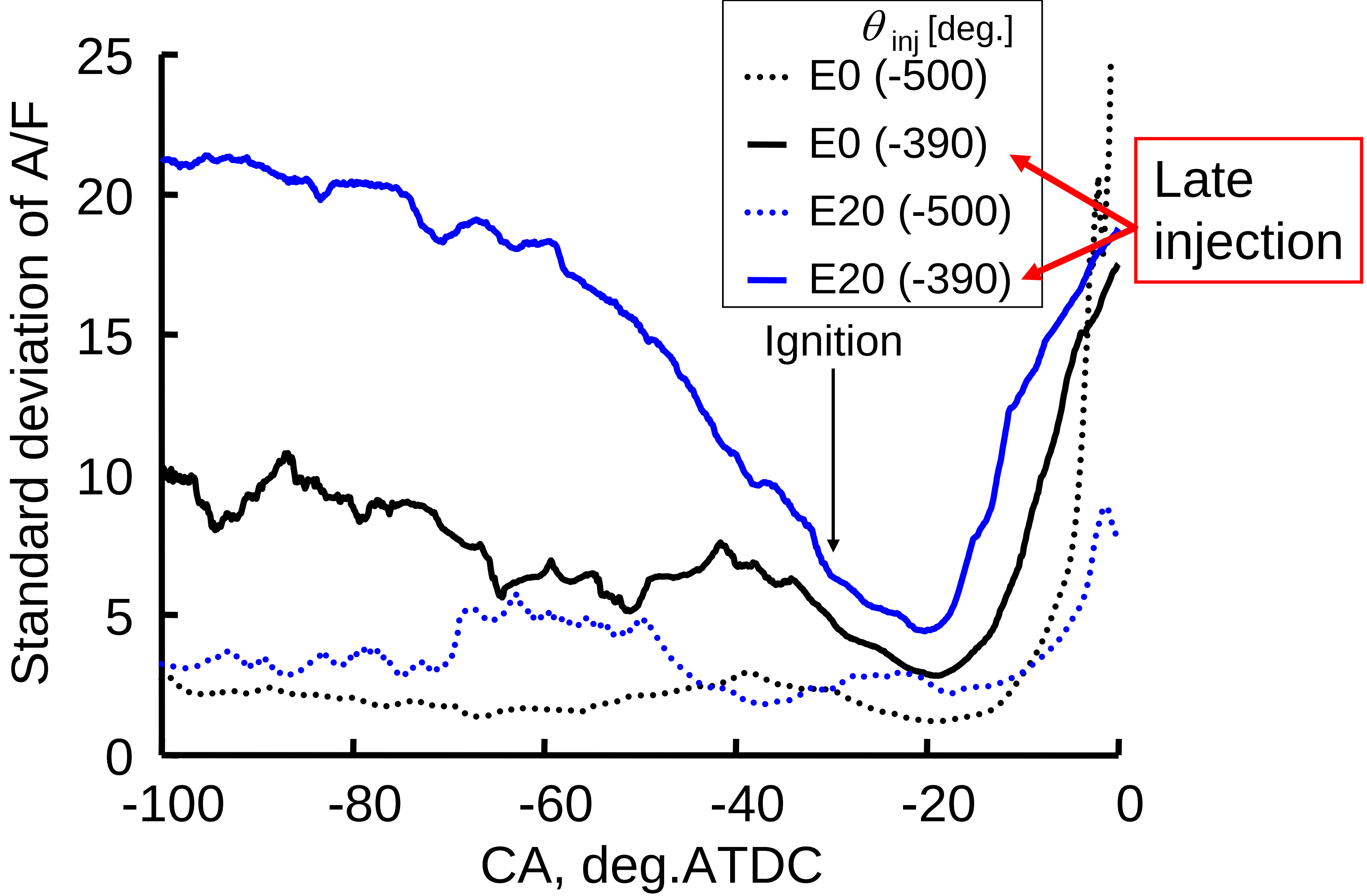
Okayama University

A/F near the spark plug



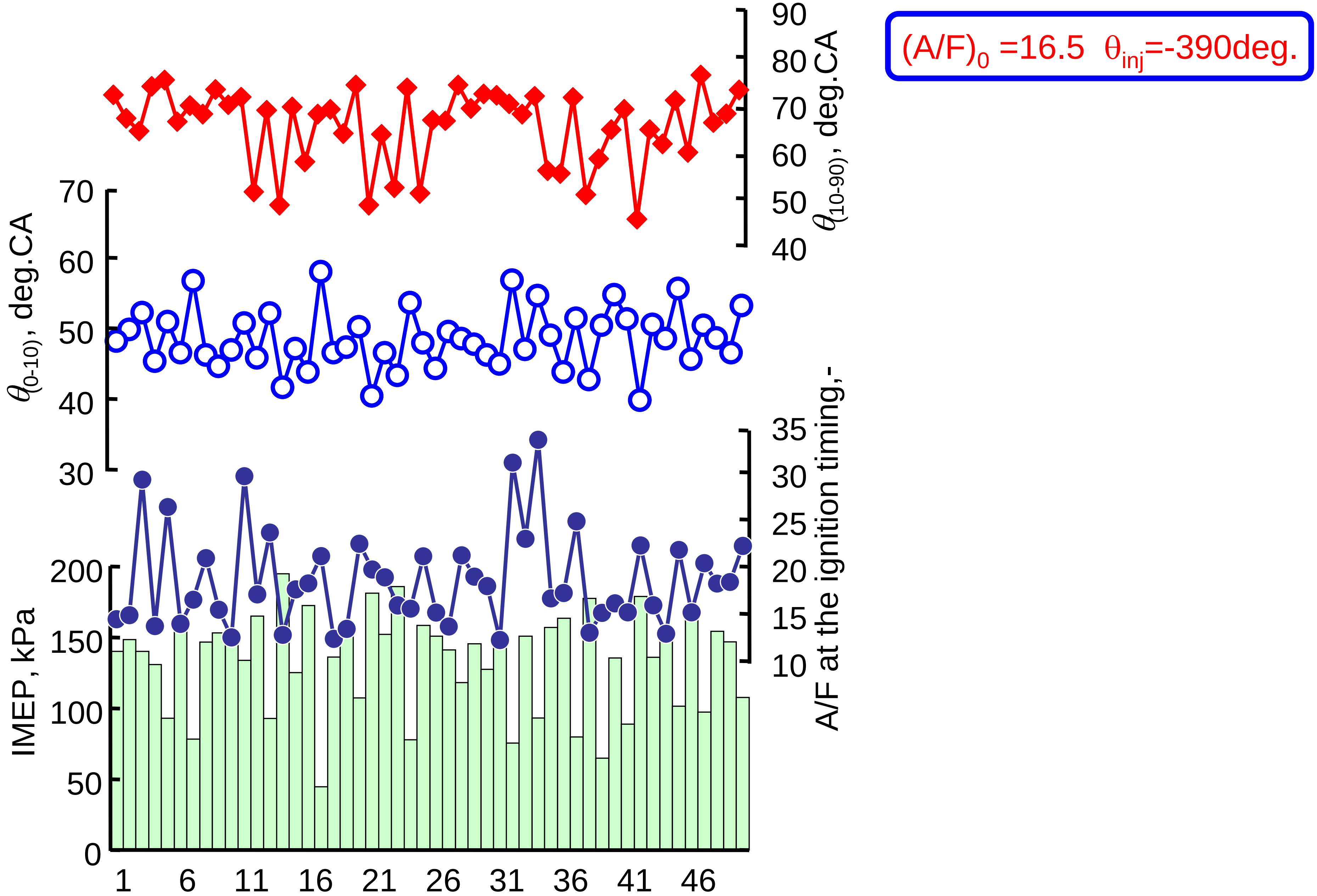
Okayama University

A/F near the spark plug

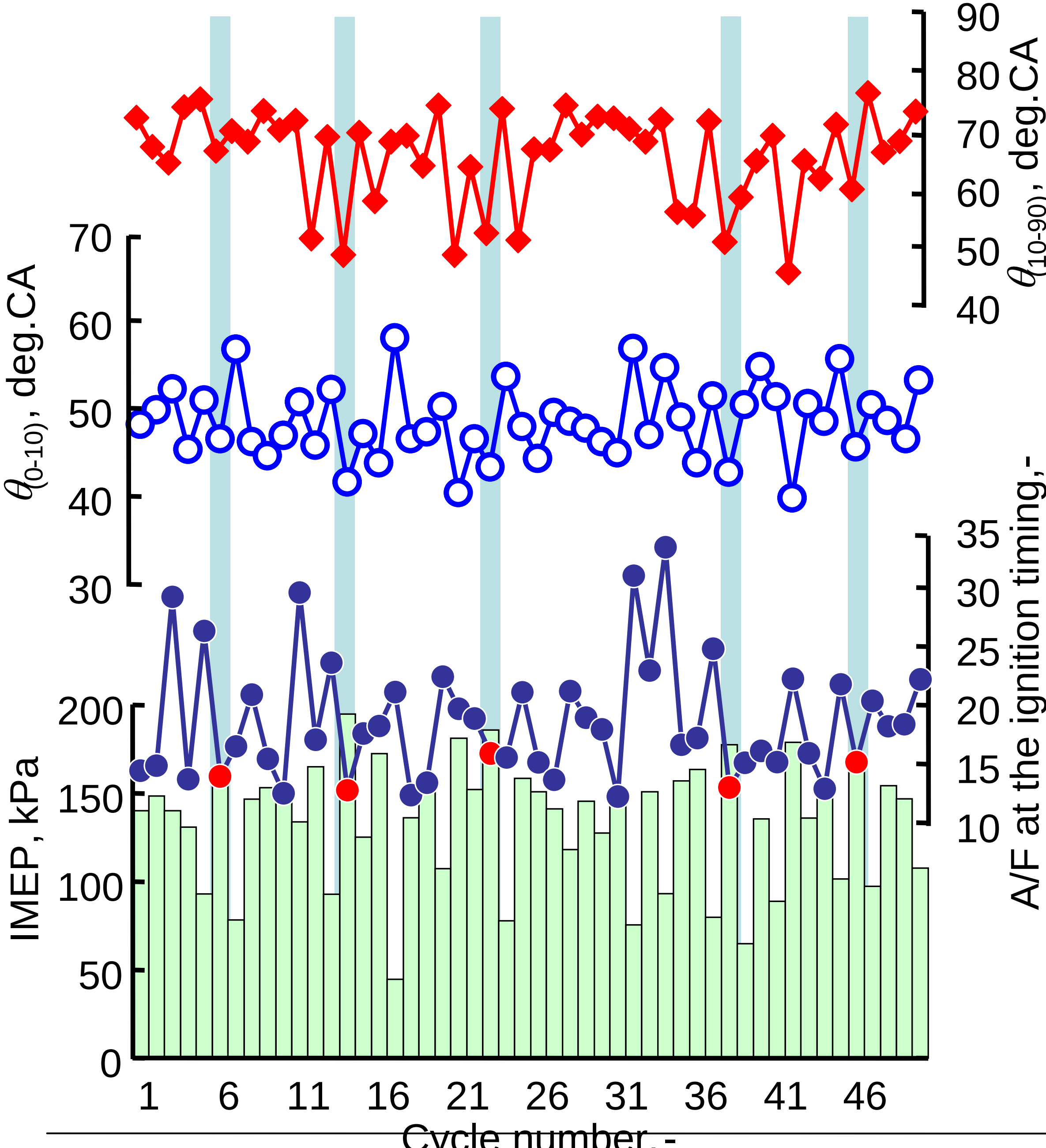


Ethanol blending → **Cycle to cycle fluctuation of mixture formation became higher under late injection and lean A/F**

Standard deviation of local A/F



Cycle-to-cycle fluctuation of E20

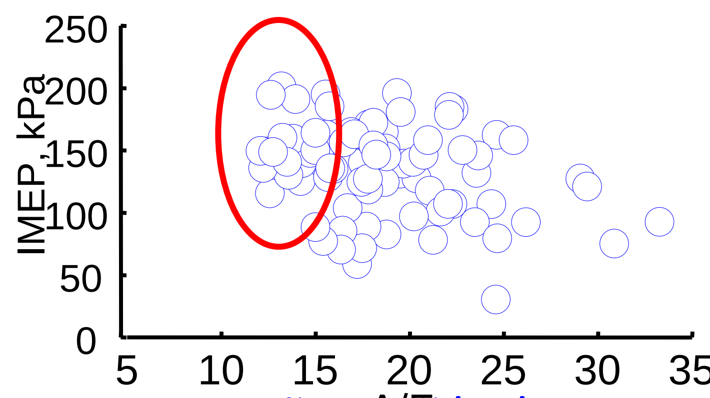


$(A/F)_0$ =16.5 θ_{inj}=-390deg.

Fuel concentration near the spark plug was rich.

Initial and main combustion period became shorter.

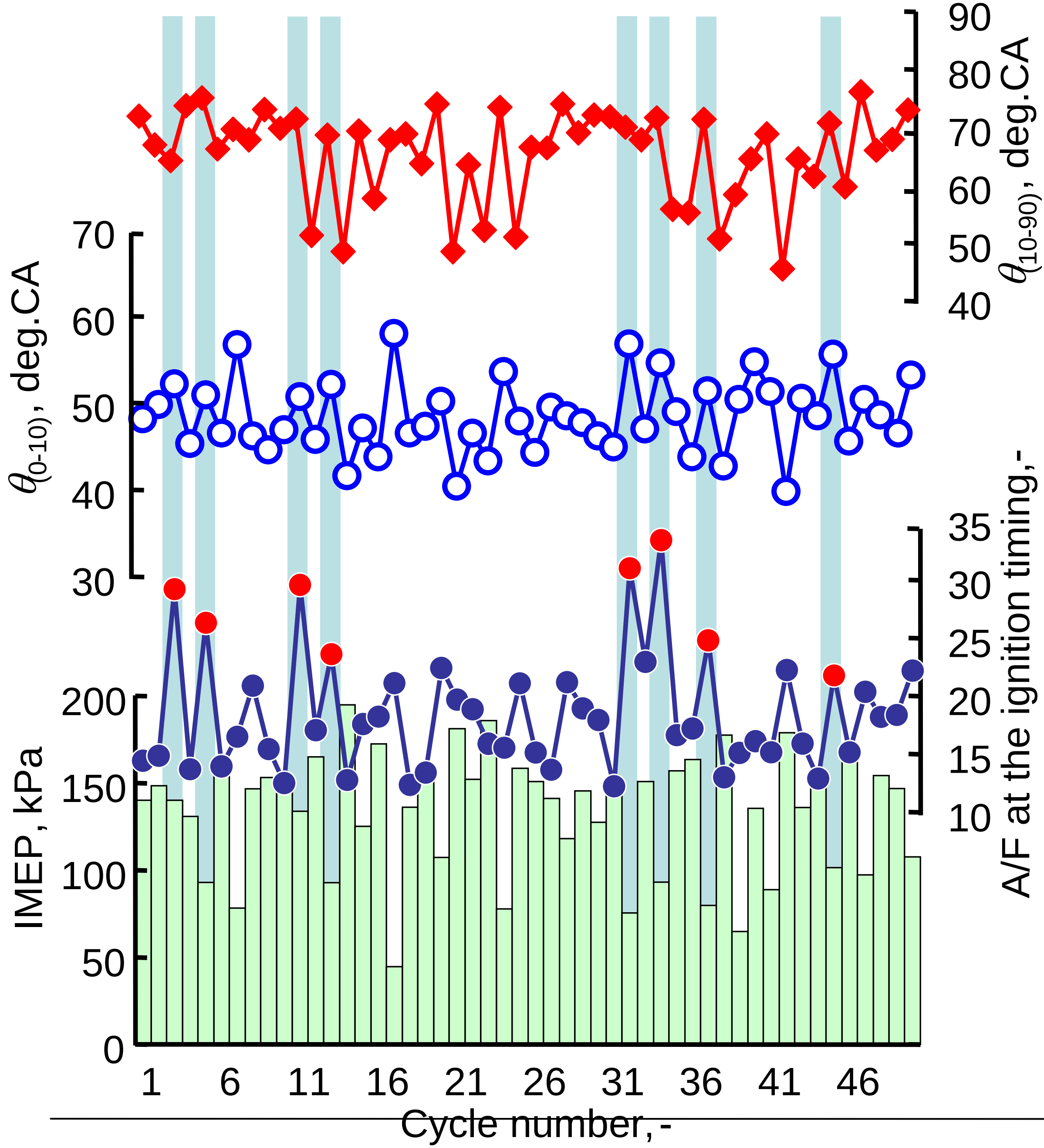
IMEP was high.



Okayama University

Cycle-to-cycle fluctuation of E20

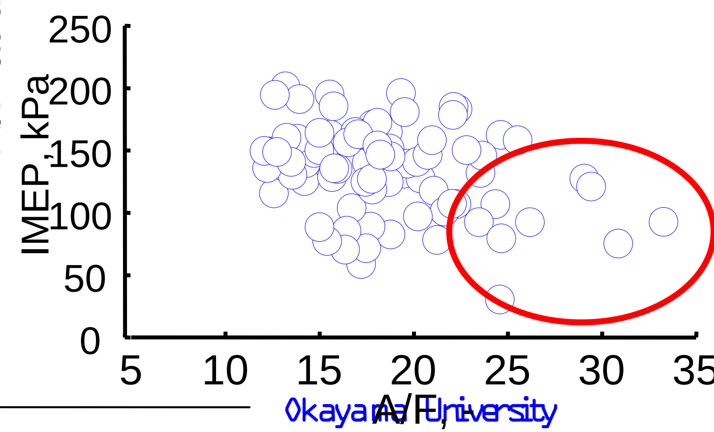
$(A/F)_0 = 16.5$ $\theta_{inj} = -390$deg.



Fuel concentration near the spark plug was lean.

Initial and main combustion period became longer.

IMEP was low.



Cycle-to-cycle fluctuation of E20

The effect of ethanol blending on mixture formation was investigated by fuel concentration near the spark plug in a practical SI engine.

1. The molar absorption coefficients of an ethanol blended gasoline were estimated by considering the molar fraction of ethanol and gasoline.

2. Delaying fuel injection of ethanol blended gasoline caused leaner fuel concentration around the spark plug at the early stage of compression stroke due to higher latent heat of ethanol.

3. Cycle-resolved measurements were made to investigate the effects of lower evaporation of ethanol on combustion characteristics of late fuel injection under lean air-fuel ratio condition.

Conclusions

Mixture Formation Process in a Spark-Ignition Engine with Ethanol Blended Gasoline

Nobuyuki Kawahara and Eiji Tomita (Okayama University)

ABSTRACT

In this study, fuel concentration measurements in a spark-ignition (SI) engine with ethanol blended gasoline were carried out using an optical sensor installed in the spark plug with laser infrared absorption technique. The spark plug sensor for in-situ fuel concentration measurement was applied to a port injected SI engine. The molar absorption coefficients of ethanol blended gasoline were determined for various pressures and temperatures in advance using a constant volume vessel with electric heating system. Ethanol blended gasoline with high volumetric ratios shows lower molar absorption coefficients due to lower molar absorption coefficients of ethanol. The molar absorption coefficients of ethanol blended gasoline can be estimated by considering the molar fraction of each component. Mixture formation processes of ethanol blended gasoline were investigated using spark-plug sensor installed in a spark plug in a port-injected SI engine with changing the fuel injection timing in an intake port. Delaying injection of ethanol blended gasoline caused a leaner fuel concentration around the spark plug and cycle-to-cycle fluctuation of combustion.

INTRODUCTION

In order to reduce global CO2 emissions, biomass fuel, such as ethanol, methanol, MTBE (methyl tertiary-butyl ether), ETBE (ethyl tertiary-butyl ether), have been focused as an attractive alternative fuel instead of gasoline in an SI engine [1-3]. Alcohol fuels can be produced from renewable energy sources, such as agricultural feed stocks. Although the emission of aldehyde will increase when we use ethanol as fuel, the damage to the environment by the emitted aldehyde is far less than that by the poly-nuclear aromatics emitted from burning gasoline. Alcohol fuels particularly ethanol has a several features as fuel for the SI engines, such as high octane number: 107 (RON), oxygenate fuel, high flame speed, low stoichiometric air-fuel ratio, high enthalpy of vaporization.

Ethanol can be used in a spark-ignition engine as pure fuel or as gasoline-ethanol blends. Although using ethanol alone requires some modification on fuel system, it can be used without any modification by blending with gasoline, generally in the ratio of 10% [2, 4]. Ethanol or ethanol-gasoline blends has higher octane number, thus it can lead to operation at higher compression ratio with reducing engine knocking [5]. However, ethanol has higher latent heat of vaporization, therefore vaporization of the intake mixture may be reduced and affect the mixture formation process inside cylinder, especially near spark plug [6]. To better understand how to achieve both an appropriate local mixture and to control the large-scale stratification, it is useful to have a diagnostic tool that gives the mixture formation process in practical engines.

Methods for measuring the fuel concentration in engines have been proposed [7], and gas sampling methods have often been used in commercial engines; however, successive data cannot be obtained. Although fast-flame ionization detector (FID) systems that measure the instantaneous hydrocarbon concentration inside the cylinder are available, the time lag problem is quite serious due to the sampling tube [2, 8]. Several papers have reported the relationship between an ion current and the air/fuel (A/F) ratio [9, 10]. It is easy to detect the ion current using the spark plug; however, the measurement accuracy is poor because unaccounted disturbances, such as fuel deposits, fuel additives, and air humidity, affect the ion current. Laser diagnostics have recently been developed, including Raman scattering, Rayleigh scattering, and laser-induced fluorescence (LIF) methods [2, 11, 12]. In particular, LIF measurements have been widely used because the LIF signal is relatively strong and provides two-dimensional fuel concentration information at a specified time. However, these optical methods require changes in the engine combustion chamber design because of the need for optical windows. Therefore, these methods are difficult to apply to commercial engines.

Recently, fuel concentrations have been measured in situ using infrared absorption [13–22]. In particular, a 3.392 μm He–Ne laser was used to obtain the fuel concentration for combustion diagnostics. Previously, we developed an IR optical spark plug sensor with a double path measurement length [20]. The measurement accuracy was confirmed by measuring the concentration of a homogeneous methane–air mixture in a compression expansion engine. The spark plug sensor was also applied to a practical SI engine using isooctane 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 [21]. Authors also developed an optical spark-plug sensor with a double-path measurement length using an infrared absorption technique for measuring hydrocarbon fuel concentrations [21, 22].

In this study, fuel concentration measurements in an SI engine with ethanol blended gasoline were carried out using an optical sensor installed in the spark plug [21, 22]. The spark plug sensor for in-situ fuel concentration measurement was applied to a port injected SI engine. Laser infrared absorption method was applied and a 3.392μm He-Ne laser that coincides with the absorption line of hydrocarbons was used as a light source. The molar absorption coefficients of ethanol blended gasoline were determined for various pressures and temperatures in advance using a constant volume vessel with electric heating system. Mixture formation processes of ethanol blended gasoline were investigated using spark-plug sensor installed in a spark plug in a port-injected SI engine with changing the fuel injection timing in an intake port. We discuss the effect of injection timing on the fuel concentration near the spark plug and the relationship between the fuel concentration and combustion characteristics.

PRESSURE AND TEMPERATURE DEPENDENCE OF THE MOLAR ABSORPTION COEFFICIENT OF ETHANOL BLENDED GASOLINE EXPERIMENTAL APPARATUS AND 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:

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

where ε denotes the molar absorption coefficient. When the measurement length L is constant, the concentration can be determined from measuring the transmissivity.

We first determined the molar absorption coefficients of ethanol blended gasoline at various pressures and temperatures using a constant-volume vessel [18]. Ethanol and gasoline blended with the volumetric ratios of 0-100% were investigated. A 3.392 μm He–Ne laser provided the incident light, and commercial premium or regular gasoline in use in Japan was supplied to the vessel with a micro-syringe. The light passed through an optical window into the test region of the vessel, and was absorbed by the gasoline vapor inside the vessel. The remaining light passed through another window to an IR detector. A band-pass filter was placed in front of the IR detector. Nitrogen was added until the desired vessel pressure was reached. The temperature inside the constant-volume vessel was controlled. The liquid fuel was vaporized and mixed very well with the nitrogen by stirring. The experimental temperatures and pressures were set independently between 300 and 600 K, and between 100 and 2000 kPa, respectively. The molar absorption coefficients of the ethanol blended gasoline were obtained from the transmissivity and the ethanol blended gasoline input volume using Lambert–Beer's law shown in Eq. (1).

MOLAR ABSORPTION COEFFICIENT OF ETHANOL BLENDED GASOLINE

First, the pressure and temperature dependence of the molar absorption coefficients for ethanol is shown in Fig.1. In this figure, symbols indicate the measurement results. The molar absorption coefficient of ethanol increased with temperature and decreased with increasing pressure. At pressures below atmospheric, the molar absorption coefficient increased rapidly. The temperature dependence was negative at pressures greater than atmospheric. The molar absorption coefficient of regular and premium gasoline showed the same tendency as that of ethanol, and was higher than that of ethanol [21]. The solid, dashed, and broken lines in Fig. 1 correspond to the curves predicted by empirical equations based on the measured data. Molar absorption coefficients of ethanol blended gasoline (E0: gasoline, E5, E10, E50, E80, E100) are shown in Fig. 2.

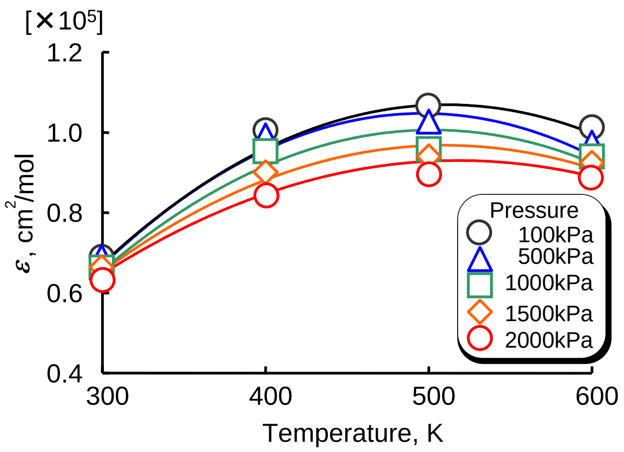


Fig.1 Molar absorption coefficient of ethanol

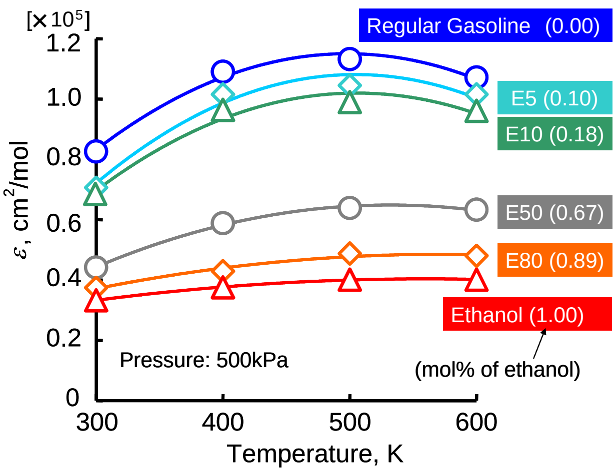


Fig.2 Molar absorption coefficient of each ethanol blended gasoline

EXPERIMENTAL APPARATUS THE DEVELOPED SPARK PLUG SENSOR

Figure 3 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. One of the optical fibers guides light from the laser to the sensor. 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. This newly developed IR spark plug sensor has a higher signal-to noise ratio than a previous version due to the optimization of the sapphire lens and the two optical fibers [22].

OPTICAL ARRANGEMENT AND EXPERIMENTAL APPARATUS

Figure 4 shows the experimental setup used to measure the concentration in a port-injected SI engine employing the laser infrared absorption method with our spark plug sensor. A four-stroke cycle engine with a single cylinder was used; the bore and stroke were 70 and 58 mm, respectively. The throttle valve was closed almost completely while idling, and the gasoline fuel was injected into the intake port using the port-injection system. Ethanol blended gasoline of gasoline, E5, E10, and E20 were used as fuel. The spark plug was replaced with the spark plug sensor. A 3.392 μm He–Ne laser and an IR detector were set on a vibration isolator. Simultaneously, the pressure in the cylinder was measured with a pressure transducer.

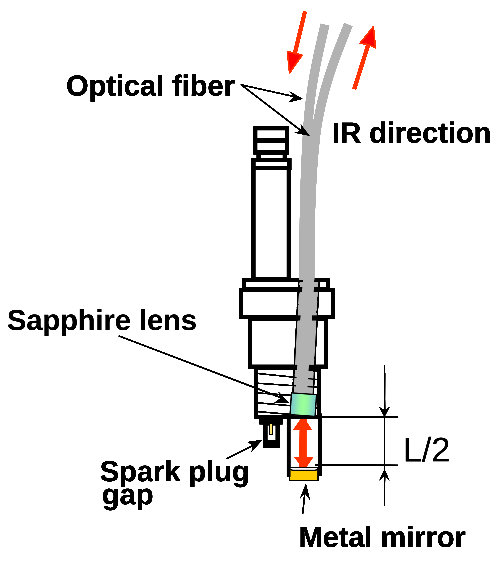


Fig.3 Schematic diagram and photograph of an IR Spark plug sensor

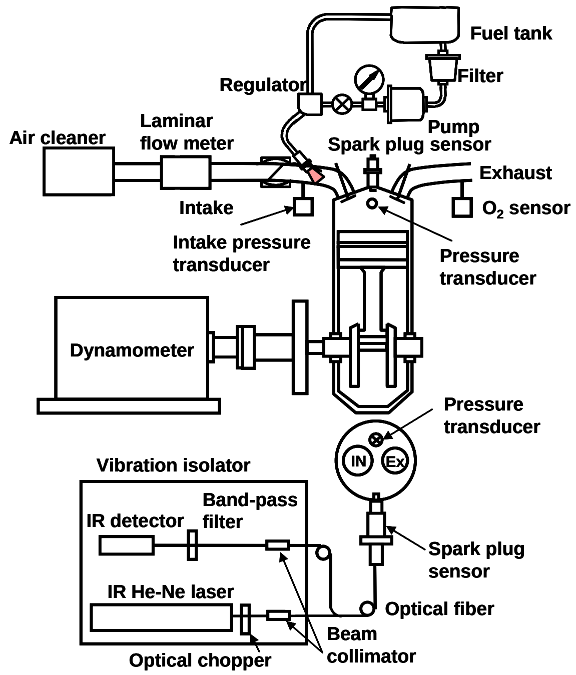


Fig. 4 Experimental apparatus and optical system

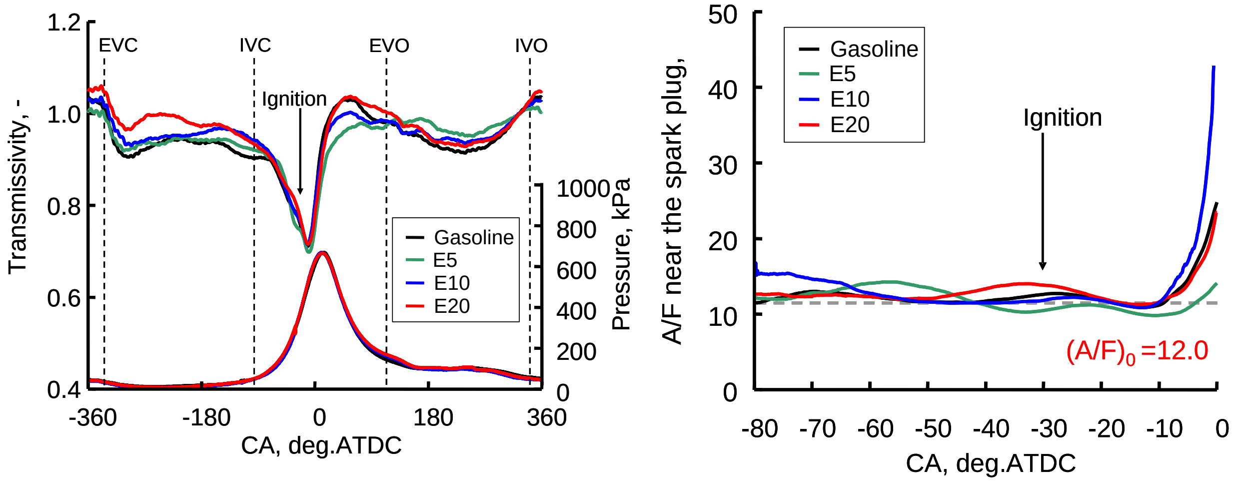
MIXTURE FORMATION PROCESS OF ETHANOL BLEDED GASOLINE IN SI ENGINE

Figure 5 shows (a) the transmissivity, I/I_0, and in-cylinder pressure of each fuel, (b) the measured air-fuel ratio by infrared absorption technique, when $(A/F)_0$ (Preset A/R ratio) = 12.0, θ_{inj} = –140° ATDC intake, engine speed =2,000 rpm and idling condition. 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 ethanol blended gasoline. After the spark, the transmissivity increased suddenly because the flame propagated through the measurement region and removed hydrocarbons. The timing of the decrease in transmissivity during the intake stroke depended largely on the mole fraction of ethanol in ethanol blended gasoline. When only gasoline was used, transmissivity indicates lower value than ethanol blended gasoline due to higher molar absorption coefficient of gasoline than ethanol.

Figure 5 (b) shows the A/F ratio during the latter part of the compression stroke. Here, we assumed that the residual gas mixed with the fresh air homogeneously. Measured air-fuel ratio of each ethanol blended gasoline is almost constant and was fitted with preset air-fuel ratio. Under this condition (θ_{inj} = –140° ATDC intake), homogeneous mixture can be formed inside engine cylinder with each ethanol blended gasoline.

Effect of ethanol blended gasoline on mixture formation process cannot be investigated under early fuel injection condition.

Next, mixture formation process of ethanol blended gasoline under late fuel injection and lean mixture condition were investigated. Figure 6 indicates the A/F ratio during the latter part of the compression stroke when $(A/F)_0$ = 16.5, θ_{inj} = –30° ATDC intake, engine rotating speed =2,000 rpm and idling condition. E0: gasoline used as fuel indicates the constant value of air fuel ratio near the spark plug. In this case (E0), homogenous mixture was formed inside engine cylinder during the compression stroke. However, for ethanol blended gasoline, the air-fuel ratio decreased gradually until the spark timing and approached preset $(A/F)_0$ (16.5). Higher mole fraction of ethanol blend indicates leaner air-fuel ratio at -100° ATDC. Air-fuel ratio of higher mole fraction of ethanol at the spark timing was leaner than E0: gasoline. Under this condition (θ_{inj} = –30° ATDC intake), effects of vaporization of ethanol may affect the mixture formation process inside engine cylinder. Delaying fuel injection caused leaner fuel concentration around the spark plug due to higher enthalpy of vaporization of ethanol. Injected fuel forms liquid film around intake valves, cylinder wall and piston top [23]. High enthalpy of vaporization of ethanol affects the vaporization of ethanol blended gasoline, and forms thicker liquid film around intake valves, cylinder wall and piston top. These liquid films can form leaner mixture inside engine cylinder at the early stage of compression stroke.



(a) (b)

Fig.5 In-cylinder pressure, transmissivity and measured air fuel ratio in early injection timing (Preset A/F=12.0)

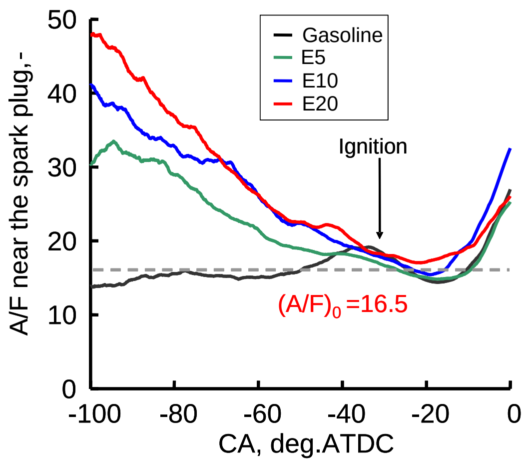


Fig.6 Measured air fuel ratio near the spark plug in late injection timing and lean burn condition (Preset A/F =16.5)

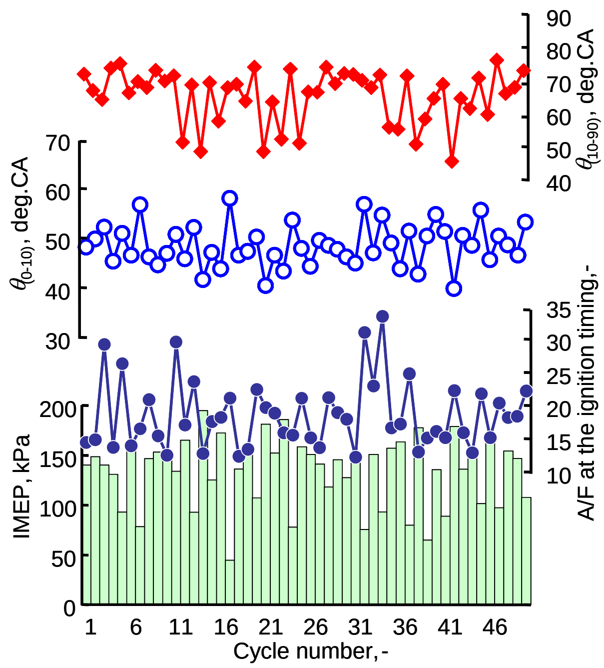


Fig.7 Cycle-to-cycle fluctuation of air fuel ratio, initial/main combustion period, and IMEP with E20 under late injection and lean burn condition.

E20 with late injection condition shows higher fluctuation of IMEP. Figure 7 shows the cycle-to-cycle fluctuations of the IMEP, initial/ main combustion period and the air fuel ratio near the spark plug at the spark timing. There was a very slight correlation between the fuel concentration and IMEP: the IMEP increased and initial/main combustion period indicates shorter period when a leaner fuel concentration existed at the spark timing (cycle number #14). Next cycle after lower IMEP indicates the higher IMEP when leaner mixture existed near the spark plug because the unburned hydrocarbon fuel remained in residual gas due to high enthalpy of vaporization of ethanol (cycle number #33). Effect of lower evaporation of ethanol blended gasoline makes inhomogeneous mixture around spark plug and affects the cyclic fluctuation of IMEP and initial/ main combustion period.

The fuel concentration measurement system with spark plug sensor permits us to measure the mixture formation process and the cycle-to-cycle fluctuations of the fuel concentration of ethanol blended gasoline around the spark plug in a commercial motorcycle engine. We could obtain detailed information about effects of vaporization of ethanol on mixture formation process around the spark plug and investigate key features of cyclic variability.

CONCLUSIONS

Fuel concentration measurements in a spark-ignition engine with ethanol blended gasoline were carried out using an optical sensor installed in the spark plug. The molar absorption coefficients of ethanol blended gasoline were determined for various pressures and temperatures in advance using a constant volume vessel with electric heating system. We discuss the effects of ethanol blended gasoline on mixture formation process around the spark plug and the results obtained from this study can be summarized as follows:

1. First, we independently determined the pressure and temperature effects on the molar absorption coefficient of ethanol in advance using a constant volume vessel. The coefficient decreased with increasing pressure. The molar absorption coefficients of an ethanol blended gasoline were estimated by considering the molar fraction of ethanol and gasoline.
2. Delaying fuel injection of ethanol blended gasoline caused leaner fuel concentration around the spark plug at the early stage of compression stroke due to higher enthalpy of vaporization of ethanol.
3. Cycle-resolved measurements were made to investigate the effects of lower evaporation of ethanol on combustion characteristics of late fuel injection under lean air-fuel ratio condition. The system of developed measurement technique was confirmed to be valuable for cycle-to-cycle fluctuation of ethanol blended gasoline around the spark plug.

REFERENCES

1. Stone, R, Introduction to Internal Combustion Engines, 3rd Ed., Society of Automotive Engineers, Inc, Warrendale, 1999.
2. Heywood, J. B., Internal Combustion Engine Fundamentals, McGraw–Hill Books, 1988.
3. Wagner, T.O., Gray, D.S., Zarah, B.Y., Kozinske, A.A., Practicality of Alcohols as Motor Fuel, SAE Paper No. 790429, 1979.
4. Thring, R.H., Alternative Fuels fro Spark-Ignition Engines, SAE Paper No. 831685, 1983.
5. Celik, M.B., (2008). Experimental Determination of Suitable Ethanol-Gasoline Blend Rate at High Compression Ratio for Gasoline Engine, Applied Thermal Engineering, 29, pp. 396-404.
6. Kar, K., Last, T., Haywood, C., Raine, R.R., M, Measurement of Vapor Pressures and Enthalpies of Vaporization of Gasoline and Ethanol Blends and their Effects on Mixture reparation in an SI Engine, SAE Paper No. 2008-01-0317, 2008.
7. Zhao, H., and Ladommatos, N., Engine Combustion Instrumentation and Diagnostics, Society of Automotive Engineers, 2001.
8. Summers, T., and Collings, N., Modelling the Transit Time of a Fast Response Flame Ionisation Detector During In-Cylinder Sampling, SAE Paper No.950160, 1995.
9. Reinman, R., Saitzkoff, A., Mauss, F., Local Air–Fuel Ratio Measurements Using the Spark Plug as an Ionization Sensor, SAE Paper No. 970856, 1987.
10. Wickstrom, N., Byttner, S., Holmberg, U., Robust Tuning of Individual Cylinders AFR in SI Engines with the Ion Current, SAE Paper No. 2005-01-0020, 2005.
11. Egermann, J., Koebcke, W., Ipp, W., Leipertz, A., (2000). Investigation of the Mixture Formation Inside a Gasoline Direct Injection Engine by Means of Linear Raman Spectroscopy, Proceedings of the Combustion Institute, 28, pp. 1145–1152.
12. Han, D., and Steeper, R. R., (2002). An LIF Equivalence Ratio Imaging Technique for Multicomponent Fuels in an IC Engine, Proceedings of the Combustion Institute, 29, pp. 727–734.
13. Hall, M. J., and Koenig, M., (1996). A Fiber-Optic Probe to Measure Pre-Combustion In-Cylinder Fuel–Air Ratio Fluctuations in Production Engines, Proceedings of the Combustion Institute, 26, pp.2613–2618.
14. Koenig, M., and Hall, M. J., Measurements of Local In-Cylinder Fuel Concentration Fluctuation in a Firing SI Engine, SAE Paper No. 971644, 1997.
15. Kawamura, K., Suzuoki, T., Saito, A., Tomoda, T. Kanda, M., (1998). Development of Instrument for Measurement of Air–Fuel Ratio in Vicinity of Spark-Plug (Application to DI Gasoline Engine), JSAE

Review, 19-4, pp. 305–310.
16. Yoshiyama, S., Hamamoto, Y., Tomita, E. Minami, K., (1996). Measurement of Hydrocarbon Fuel Concentration by Means of Infrared Absorption Technique with 3.39 μm He–Ne Laser, JSAE Review, 17, pp. 339–345.
17. Tomita E., Kawahara, N., Shigenaga, M., Nishiyama, A., Dibble, R. W., (2003). In Situ Measurement of Hydrocarbon Fuel Concentration Near a Spark Plug in an Engine Cylinder by 3.392 μm Infrared Laser Absorption Method: Discussion of Applicability with a Homogeneous Methane–Air Mixture, Measurement Science and Technology, 14, pp.1350–1356.
18. Tomita, E., Kawahara, N., Nishiyama, A. Shigenaga, M., (2003). In Situ Measurement of Hydrocarbon Fuel Concentration near a Spark Plug in an Engine Cylinder by 3.392 μm Infrared Laser Absorption Method-Application to Actual Engine, Measurement Science and Technology, 14, pp.1357–1363.
19. Tomita, E., Kawahara, N., Yoshiyama. S., Kakuho, A., Itoh, T., and Hamamoto, Y., (2002). In-Situ Fuel Concentration Measurement near Spark-Plug in Spark-Ignition Engines by 3.39 μm Infrared Laser Absorption Method, Proceedings of the Combustion Institute, 29, pp. 735–741.
20. Nishiyama, A., Kawahara, N., and Tomita, E., In-Situ Fuel Concentration Measurement near Spark Plug by 3.39 μm Infrared Absorption Method (Application to Spark Ignition Engine), SAE Paper No.2003-01-1109, 2003.
21. Kawahara, N., Tomita, E., Nishiyama, A., Hayashi, K., In-Situ Fuel Concentration Measurement near Spark Plug by 3.392 μm Infrared Absorption Method─Pressure and Temperature Dependence of the Gasoline Molar Absorption Coefficient, SAE Paper No. 2006-01-0182, 2006
22. Kawahara, N., Tomita, E., Hayashi, K., Tabata, M., Iwai, K., Kagawa, R., (2007). Cycle-Resolved Measurements of the Fuel Concentration near a Spark Plug in a Rotary Engine Using an in situ Laser Absorption Method, Proc. Combust. Inst., 31, pp.3033-3040.
23. Miyagawa, H., Nagaoka, M., Akihama, K., Fujikawa, T., Numerical Analysis on Multi-Component Fuel Behaviors in a Port-Injection Gasoline Engine, SAE Paper No. 1999-01-3642, 1999.

The contents in this paper are described in detail in SAE paper No.2009-01-1957 (2009).