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Unburned Gas Temperature Measurement in an SI Engine Using Fiber-Optic Laser Interferometry

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Abstract

A heterodyne interferometry system with a fiber-optic sensor was developed to measure the temperature history of unburned gas in a spark-ignition(SI) engine. A polarization-preserving fiber and metal mirror were used as the fiber-optic sensor to deliver the test beam to and from the measurement region. This fiber-optic sensor can be assembled in an engine cylinder head without a lot of improvements of an actual engine. Adjustment system in the sensor was revised to face the distributed index lens with metal mirror. Before the flame arrived at the developed fiber-optic sensor, measured temperature was almost same with the temperature history after the spark, assuming that the process that changes the unburned gas is adiabatic. In situ unburned gas temperature measurements before knocking in a commercially produced SI engine can be carried out using developed fiber-optic heterodyne interferometry system. Although the heterodyne interferometry with the developed fiber-optic sensor provides the mean temperature along the line of sight, the feasibility of our system was sufficient to be applied to temperature history measurement of an unburned gas compressed by flame propagation in an engine cylinder. The developed heterodyne interferometry with fiber-optic sensor has a good feasibility to measure the unburned gas temperature history in the commercially produced SI engine.

1 INTRODUCTION

Requirements of spark-ignition (SI) engine are lower fuel consumption and reduction of pollutants. The simple strategy of higher thermal efficiency of SI engine is to increase the compression ratio. Higher compression ratio leads to higher unburned end-gas temperature and pressure which produces the spontaneous ignition of a portion of the unburned end-gas mixture in connection with engine knocking [1, 2]. Spontaneous auto-ignition is based on the low-temperature chemical kinetics under the cool flame conditions [3]. Although it is very important to know the temperature history of the unburned gas, it is not easy to determine the transient temperature of gas in a commercially produced spark ignition engine.

For the in-cylinder gas temperature measurement, newer technique with high accuracy and high temporal resolution has been required. Since thermocouples typically lack the temporal resolution, in-cylinder gas temperature measurements have been dominated by optical diagnostics [4, 5]. Orth et al. presented two-dimensional temperature measurement using a combination of 2D laser-induced fluorescence (LIF) of hydroxyl radicals and 2D

Rayleigh scattering [6]. They measured a significant dependence of the temperature on the mixture composition, and confirmed the validity of the flamelet assumption from the analysis if OH radicals and temperature profiles. Schulz et al. used a tunable KrF excimer laser for LIF to obtain the quantitative imaging of the nitric oxide concentration distribution and temperature field in an SI engine by Rayleigh scattering [7]. Kaminski et al. applied two-line atomic fluorescence (TLAF) to internal combustion engine [8]. Precision of 14% on temperature distribution was obtained in high temperature and pressure condition. LIF method has the potential to provide quantitative two-dimensional temperature distribution, but time-series analysis is limited by the laser repetition rate. Sanders et al. applied the wavelength-agile absorption spectroscopy to determine the in-cylinder gas temperature in an HCCI engine [9]. Several researchers have used coherent anti-Stokes Raman spectroscopy (CARS), which is particularly well suited to engines, since it produces a strong signal, to determine the unburned mixture temperature in a single-point [10-14]. Bradley et al. checked measurement accuracy of CARS system using high-temperature/ high-pressure cell and firing engine. The accuracy of CARS in an engine cylinder is up to ±25 K [11] and it is limited to single-shot measurements. Additionally these techniques are not feasible for the application in production engines due to the need of optical window to access into the cylinder. Moreover, there is intensive demand to know the time-history of unburned gas temperature in practical engines especially.

Laser interferometry [15] offers both high potential resolution and non-intrusive temperature measurement. Several researchers have applied this technique to temperature measurements [16, 17]. In general, it is considered that laser interferometry has problems, which are sensitivity to mechanical vibrations, and inapplicability to an actual engine. However, Hamamoto et al. [17] and Tomita et al. [18, 19] installed Mach-Zehnder interferometry with polarization preserving fibers and Kster prisms into the spacer of cylinder. They measured the temperature change of a compressed unburned gas during flame propagation and investigated the knock phenomenon. However application of this system was restricted due to the special-type spacer. Therefore, a fiber-optic heterodyne interferometry system has been developed to provide non-intrusive measurements of the temperature history for an unburned end-gas in an engine cylinder during flame propagation with a high temporal resolution [20, 21]. Fiber optical heterodyne interferometry is fairly insensitive to the fluctuations in signal intensity caused by mechanical vibration. Measurement accuracy was discussed in consideration of the accuracy of pressure measurements, the stability of the AOM system, the gas composition, and the relationship between the beat and sampling frequencies. The uncertainty of this method is within ±10 K. Moreover, the feasibility of a temperature sensor probe that uses a polarized fiber and mirror was demonstrated. A fiber-optic sensor with the polarized fiber and metal mirror, which is involved in heterodyne interferometry system, were developed in order to install into a test engine [22]. Measurements of unburned gas in engine cylinder under the condition of motoring and firing were performed. The feasibility and measurement accuracy of this developed sensor for the use in a test engine was discussed.

In this study, the developed fiber-optic sensor with the polarized fiber and metal mirror, which is involved in heterodyne interferometry system, was revised in order to install into a practical spark-ignition engine. An optical system for an in-situ heterodyne interferometry system for unburned gas temperature measurement in a spark-ignition engine was developed and tested under firing condition. Measurements of unburned gas in the cylinder of compression-expansion engine under the firing conditions were performed. Moreover, the developed fiber-optic sensor was applied to a commercially produced spark ignition engine under the firing condition. The feasibility of this developed sensor for the use in a production spark ignition engine was discussed.

2 METHOD OF UNBURNED GAS TEMPERATURE MEASUREMENT

2.1 Laser Heterodyne Interferometry system with fiber-optic sensor

Figure 1 shows the configuration of heterodyne interferometry with the fiber-optic sensor. A frequency stabilized He-Ne laser, with a wavelength λ of 632.8 nm and an output power of 1 mW, provides a linear polarized beam for the measurements. The AOM system for heterodyne interferometry produces two beams. In this experiment, the frequency of the first beam is shifted by 80.100MHz, and that of the second by 80.125 MHz. The stability of our AOM is within 0.02ppm.These beams meet at the polarized beam splitter and create a beat frequency of 25.0 kHz. After the polarized beam splitter, the beam is split into two by the half mirror. One beam is detected by a photo-transistor as a reference signal; the other is used for modified Michelson interferometry. The reference signal beam passes outside the combustion chamber and is reflected by a mirror. The beam used for modified Michelson interferometry passes through the test section, is reflected by a mirror, and then passes back through the test section again. The polarization of the signal is important; therefore, a 1.5 m polarization-preserving fiber is used to deliver the test beam to and from the fiber-

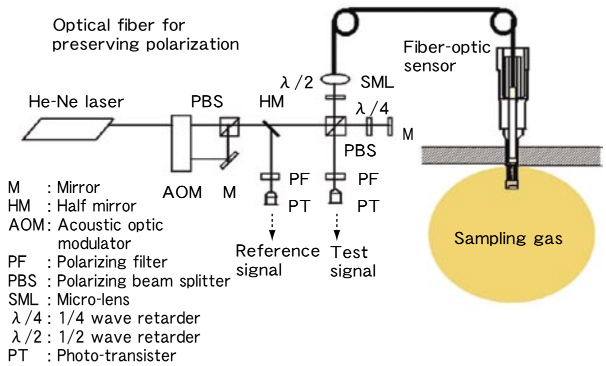


Figure 1. Heterodyne interferometrywith fiber-optic sensor

optic sensor. Manipulator of LDV system was used to enter the beam into the fiber. Fiber-optic heterodyne interferometry system without developed fiber-optic sensor was set on a vibration isolator. The reference signal, test signal and pressure data are collected using an A/D converter (maximum sampling rate: 500 kHz). These data are then analyzed using in-house software.

2.2 Principle of temperature measurement

When the unburned gas mixture is compressed by the piston or the flame development, the density of the gas in the combustion chamber change will change. This results in the change of the refractive index. The refractive index is influenced simultaneously by both temperature and changes in species concentrations. The difference between the optical paths of the test and reference beams varies, and corresponds to changes in the refractive index in unburned mixture and the interference light intensity [17]. The temperature of the mixture can be expressed by this equation [22],

$$T_t = \frac{2\pi P_t R_{Gt} L_t}{2\pi P_{t_0} R_{Gt} L_t + \Delta\Psi_t T_{t_0} R_0 \lambda} \qquad (1)$$

Where $\Delta\Psi_t$ is the change of phase shift of the heterodyne signal over a given time t, Lt is the length of the test section, λ is the wavelength of the test beam, R_0 denotes the mean gas constant, R_{Gt} is the Gladstone-Dale constant (cm^3/mol)[23], which is determined by the wavelength of the laser and the gas species. The value of the Gladstone-Dale constant for each gas is given in detail for each laser wavelength in reference [23]. When the pressure P_{t0} and temperature T_{t0} of the initial state are known, the temperature of the gas can be calculated from measurements of the pressure and the change in beat frequency of the interfering light.

2.3 Developed fiber-optic sensor

Photograph and schematic diagram of developed fiber-optic sensor are shown in **Figure 2.** Developed fiber-optic sensor is consisted with the polarized fiber and metal mirror. The fiber-optic sensor comes in contact with high temperature burned gas. Therefore sapphire glass as window and metal mirror as mirror section were used in order to resist heat from burned gas. Adjustment system in the sensor for

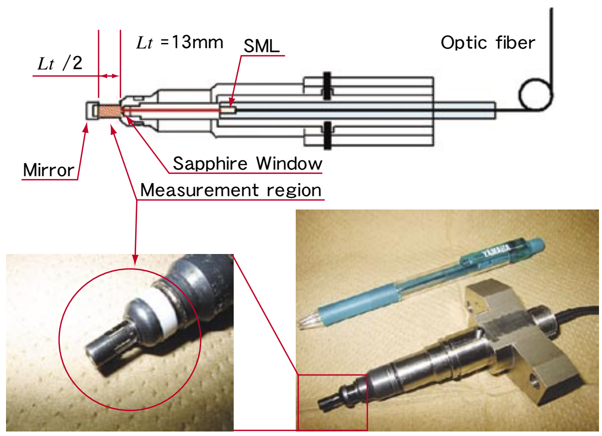


Figure 2. Photographs of developed fiber-optic sensor

matching the laser beam from and to the test region was revised. The developed sensor could be assembled easily using the new adjustment system.

Temperature measurement system using heterodyne interferometry is the line of sight measurement method. Since longer length of measurement region makes phase shift larger, signal to noise ratio and measurement accuracy will be better using longer length of measurement region. However, measured temperature is averaged value inside the measurement region so that short length should be better. When the developed fiber-optic sensor is settled in a production engine, length of sensor should be shorter due to the contact of intake and exhaust valve. The trade-off relationship between the length of measurement region and measurement resolution should be optimized. The developed sensor has a double-pass measurement length. In consideration of the sensor length inside cylinder and the resolution of temperature measurement, the length of measurement region was determined as 13.0 mm using double-pass measurement length. It was very difficult to determine the thermal boundary layer in the measurement path so that the effect of thermal boundary layer on the measurement length was not considered.

3 TEMPERATURE MEASUREMENT OF UNBURNED END-GAS IN A TEST ENGINE

A specially designed test engine that could only be fired once was used for the experiments [21, 22]. The engine had a bore and stroke of 78 and 85 mm, respectively, and the compression ratio was 8.9:1. The combustion chamber of this engine is pancake-type. The engine was operated at 600 rpm, and spark timing was 20 degrees before TDC. The sensor was located at 64 mm left from spark electrode and length of the sensor inside cylinder was 8.8 mm.

The cylinder and mixture tank were initially charged with a homogeneous methane-air mixture (equivalence ratio ϕ=1.0, P0 = 100 kPa, T0 = 291 K). The temperature of the fuel-air mixture at the start of compression (base state) had to be determined in advance, because only the change in temperature from the base state was measured by the fiber-optic heterodyne interferometry system. In this experiment, the valve was closed at BDC of a certain cycle. Using a resistance wire as a thermometer, the temperature at BDC of the valve closure cycle was found to be 3.8 K lower than the initial gas temperature in the mixture tank [18]. This value was used for the temperature at the start of compression.

The compression-expansion engine provided optical access via an extended piston and a quartz window. Combustion inside the cylinder was visualized using a high-speed video camera (4,500 frames/sec) with an image intensifier. By gating the intensifier synchronously with the engine, we were able to acquire an image at a specific crank angle. Unburned gas temperature measurement using heterodyne interferometry system with developed fiber-optic sensor and visualization of flame propagation were obtained simultaneously during one cycle.

The unburned gas temperature after the valve closes can be obtained from the data concerning the pressure and the heterodyne signal in one experimental run. The temperature history of the unburned end-gas from a crank angle of 210° till the flame arrival time at the sensor was calculated using Eq. (2) and plotted with solid line in **Figure 3.** For comparison, another method for obtaining the temperature was presented with broken lines. For the mixture, a polytropic change was assumed to be generated by the spark timing whereas an adiabatic change was assumed after the spark timing because the unburned gas was compressed due to there being almost no heat loss. The polytropic index from BDC to the spark timing was calculated with the measured pressure and the volume of the cylinder. It was 1.270 from BDC to the spark timing. The mean value of the ratio of the specific heats of the unburned mixture, within a temperature range of 300 - 800 K and a pressure range of 0.1 - 3.0 MPa, was 1.380. This value was estimated with the mixture composition. As shown in Figure 3, the temperature under the assumption of polytropic and adiabatic change was approximately equal to the measured temperature with developed system.

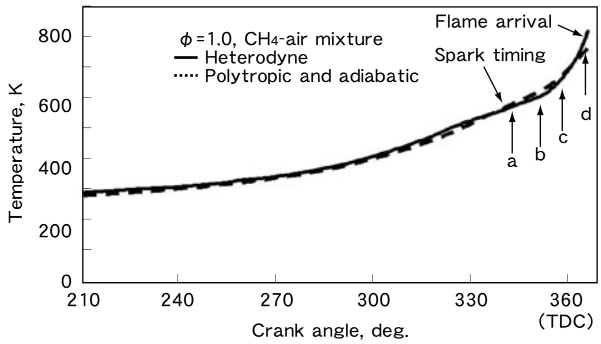


Figure 3. Temperature change of unburned gas in a compression-expansion engine

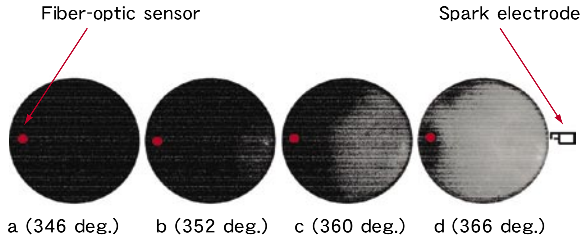


Figure 4. Flame propagation in a compression-expansion engine

Figure 4 indicates the flame propagation photographs at a specific crank angle. Circles in images indicated the position of developed fiber-optic sensor. The obtained crank angles were shown in **Figure 3**. Spark electrode was set in the right hand side of the pictures. The diameter of visualization area was 52 mm. The flame propagated from right to left. The obtained pictures indicate that the flame front broadens with the distance from the spark point, because the flame front is not planar. When the flame first reaches the test beam, the beam is refracted so much that the interference signal is temporarily weakened; the flame arrival time can be determined from this phenomenon. Before the flame arrived at the developed sensor, measured temperature was almost the same as the temperature history after the spark, assuming that the process that changes of the unburned gas is adiabatic as shown in **Figure 3**.

As described above, the system of this measurement technique was confirmed to be valuable for in-situ temperature history measurement in a simple test engine.

4 TEMPERATURE MEASUREMENT OF UNBURNED GAS IN A PRODUCTION ENGINE

4.1 Experimental Set-up

Next, the developed fiber-optic sensor was applied to a commercially produced engine. A schematic diagram of experimental set-up is shown in **Figure 5**. A four-stroke cycle spark-ignition engine with 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. Throttle valve was almost closed at idling condition. When the gaseous fuel is used as fuel, the gas was introduced into the intake pipe approximately 1 m from the engine intake manifold. The gaseous fuel flow rate was measured with a laminar flow meter and adjusted with a needle valve. Electric heater was used for changing mixture temperature. A static mixer was placed in the intake pipe to produce a homogeneous mixture of propane-in air. When the liquid fuel, such as gasoline, n-heptane, is used, the port-injection system is applied. The inlet airflow rate was measured with another laminar flow meter. **Figure 6** indicates photographs of a spark-ignition engine with the developed fiber-optic sensor.

The fiber-optic sensor was set in the cylinder head against the spark plug. The measurements of unburned gas temperature compressed by the flame propagation could be carried out. The window of measurement region was enough to enter unburned gas.

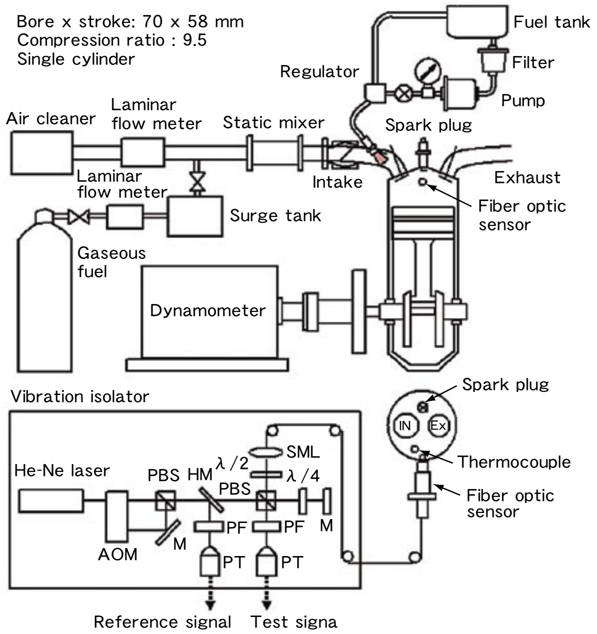
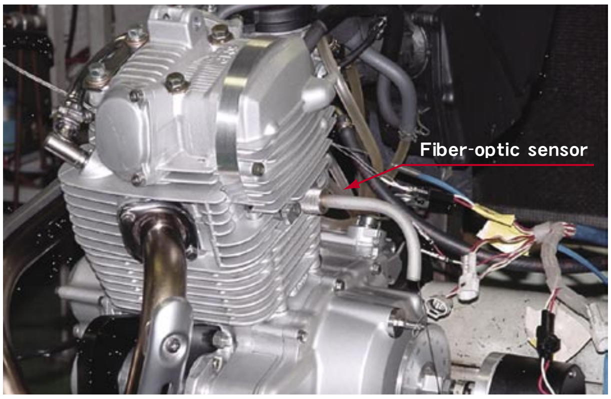


Figure 5. Experimental set-up



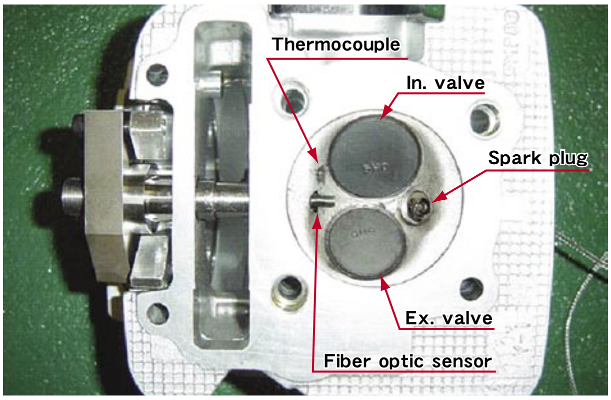


Figure 6. Photographs of spark-ignition engine with fiber-optic sensor

Intake and exhaust valve did not contact with housing of measurement region. The crank angle and TDC from a rotary encoder were used for changing spark timing and port-injection timing, and recorded by the A/D converter. In-cylinder pressure was obtained using a pressure transducer set in the spark plug. History of in-cylinder pressure was very important for the evaluation of unburned gas temperature using developed fiber-optic heterodyne system.

4.2 the case of n-Butane

Figure 7 indicates the measured temperature history and pressure history with n-butane as fuel. In these experiments, intake mixture temperature was changed from room temperature to 403 K. Experiments were done under the engine speed 1,560 rpm, the equivalence ratio 0.7, the spark timing 30 deg. before TDC.

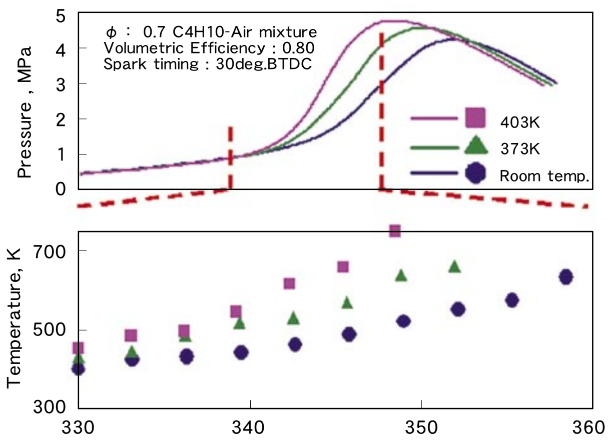


Figure 7. Unburned temperature history (n-butane)

Pressure history indicates that a higher intake mixture temperature resulted in larger pressure increase and larger maximum pressure. The temperature histories of the unburned gas from 330◦ to the flame arrival time at the developed sensor were shown in **Figure 7**. Initial temperature is very important for the measurement method using laser interferometry. The evaluated temperature using polytropic index at a crank angle of 330◦ was used for the initial temperature of laser interferometry. The polytropic index from Intake valve closure timing to the spark timing was calculated with the measured pressure and the value of the cylinder volume. The mean value of the ratio of the specific heats of the unburned mixture is estimated in consideration with mixture components. A higher intake mixture temperature causes the larger temperature gradient on measured temperature. This result demonstrates that the developed heterodyne interferometry system can measure the transient temperature of the air-fuel mixture in a cylinder under the firing condition.

4.3 the case of gasoline

When the gasoline is used as fuel, Gladstone-Dale constant of gasoline and air mixture should be estimated. Gasoline is multi-component fuel, therefore it is very difficult for determination of Gladstone-Dale constant form reference [23]. Representative Gladstone-Dale constants are summarized in **Table 1**. Here, Gladstone-Dale constants of propane-air mixture, n-butane-air mixture and n-octane-air mixture were used instead of Gladstone-Dale constant of gasoline-air mixture for analyzing unburned gas temperature in the case of gasoline as fuel.

Table1. Gladstone-Dale constant

Species	Ar	N_2	H_2	O_2	CO_2	Air
R_G, cm³/mol	6.298	6.689	2.583	6.053	9.968	6.552
Species	CH_4	C_3H_8	n-C_4H_{10}	n-C_6H_{14}	n-C_8H_{18}	
R_G, cm³/mol	9.864	24.069	30.942	44.773	58.611	

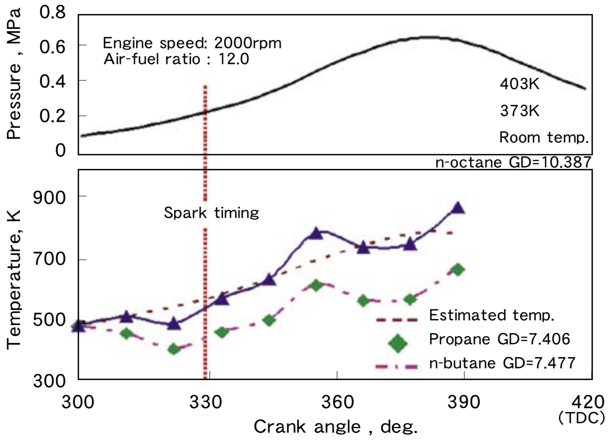


Figure 8. Effect of Gladstone-Dale constant on temperature of gasoline-air mixture

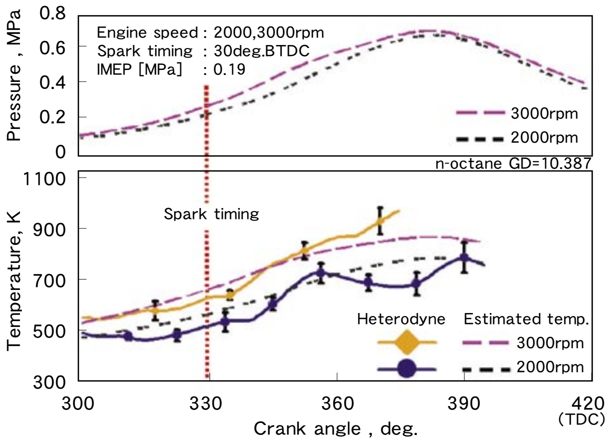


Figure 9. Effect of engine speed on temperature of gasoline-air mixture

Figure 8 indicates the effect of Gladstone-Dale constant on measured unburned gas temperature. Experiments were done under the condition of engine speed 2,000 rpm, air-fuel ratio 12.0, the spark timing 30 deg. before TDC. The case of propane indicates the diamond plot, dashed line the case of n-butane, and solid line with triangle plot is the case of n-octane. The unburned gas temperature before the spark timing, calculated using the polytropic index, and after the spark timing, which is assumed by an adiabatic change, is shown with a dashed line in **Figure 8**. The case of n-octane indicates a good agreement with the temperature evaluated from in-cylinder pressure history with an adiabatic change, therefore Gladstone-Dale constant of n-octane and air mixture is used for the case of gasoline.

Figure 9 shows the effect of engine speed on temperature measurement under gasoline, firing condition. Plots indicate the measured temperature, and the dashed lines the estimated temperature. Measured data were averaged value during several cycles. It is emphasized that the unburned gas temperature history can be obtained under the engine speed 3,000 rpm using developed fiber-optic sensor. Measured temperature is fluctuated near TDC due to the mechanical vibration. Main problem in robustness for long time experiment is blurred mirror with gasoline vapor. Obtained signal is very low due to the little reflection of blurred mirror. However, unburned gas temperature can be obtained during several hundreds of cycles. This result demonstrates that developed fiber-optic sensor can survive under the production engine conditions.

4.4 Under the knocking condition

By using n-heptane as liquid fuel, the knocking phenomena can be observed in this engine. It is very important to know unburned gas temperature measurements before knocking due to the auto-ignition phenomena. Therefore, unburned gas temperature measurements were tried under the knocking condition.

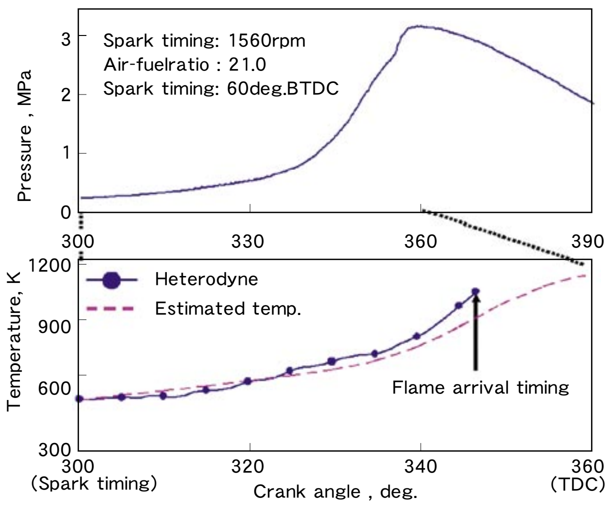


Figure 10. Unburned temperature history under knocking condition

Figure 10 indicates the pressure histories under the knocking condition. Engine speed is 1,560 rpm, air-fuel ratio 21.0, and the spark timing 60 deg. before TDC. The weak knocking phenomena can be seen at the TDC of in-cylinder pressure history. The measured unburned gas temperature history is plotted with solid circle after the spark timing until the flame arrival timing on fiber- optic sensor. Measured data were averaged value during several cycles. The measured temperature before the flame arrival timing indicates slightly higher temperature than the adiabatic mean temperature. There are a number of several reasons for this result. One is that developed fiber-optic sensor measures local region inside the cylinder. The adiabatic temperature shows mean temperature of unburned gas inside cylinder. Another reason is chemical reaction of unburned. Moreover, it is difficult to obtain unburned gas temperature just before knocking due to difficulty of understanding of knocking position inside cylinder and measurement volume of developed sensor.

Although heterodyne interferometry with the developed fiber-optic sensor provides the mean temperature along the line of sight, this result demonstrates that this method can measure the temperature history of unburned gas locally in an engine cylinder before knocking. It must be emphasized that the developed heterodyne interferometry with fiber-optic sensor has a good feasibility to measure the unburned gas temperature history in the commercially produced spark-ignition engine.

5 CONCLUSIONS

Temperature measurement system of unburned gas in a commercially produced engine was developed using laser heterodyne interferometry with a fiber-optic sensor. The results obtained in this work are summarized as follows:

(1) The system of developed measurement technique was confirmed to be valuable for in-situ temperature history measurement in a compression-expansion test engine. Before the flame arrived at the developed sensor, measured temperature was almost the same as the temperature history after the spark, assuming that the process that changes of the unburned gas is adiabatic.

(2) The developed fiber-optic sensor with the polarized fiber and metal mirror, which is involved in heterodyne interferometry system, was revised in order to install into a practical spark-ignition engine. Developed fiber-optic sensor can survive under the production engine conditions.

(3) Although the heterodyne interferometry with the developed fiber-optic sensor provides the mean temperature along the line of sight, the feasibility of our system was sufficient to be applied to temperature history measurement of an unburned gas compressed by flame propagation in the commercially produced spark-ignition engine.

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