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

by

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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 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 changes of an actual engine. Adjustment system in the sensor was revised to face the distributed index lens with metal mirror. 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 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 in a commercially produced SI engine can be carried out using developed fiber-optic heterodyne intereferometry 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.

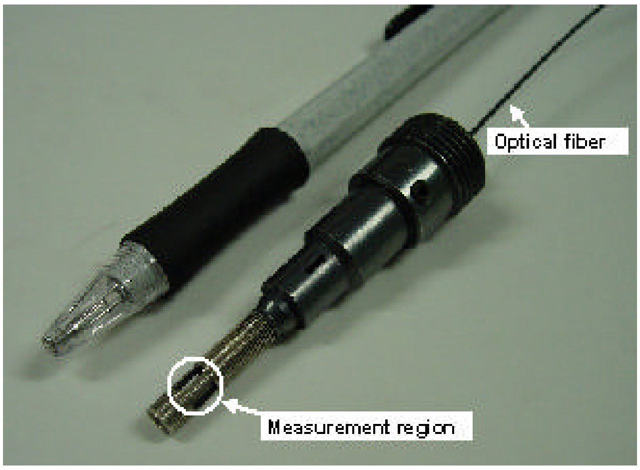


Fig. 2 Photograph and schematic diagram of developed fiber-optic sensor

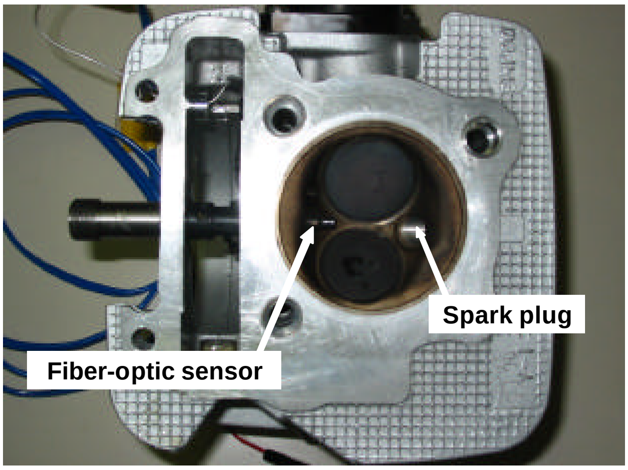


Fig. 6 Photographs of the spark-ignition engine with fiber-optic sensor

1. INTRODUCTION

Higher thermal efficiency and reduction of pollutant are of particular interest in improving the environmental acceptance of internal combustion engines (Heywood, J.B. 1988.). There have recently been intensive efforts at developing thermal efficiency of internal combustion engines. Better thermal efficiency can be achieved by making a compression ratio of engine higher. However, knocking prevents thermal efficiency being attained for a spark-ignition engine (Heywood, J.B. 1988; Pilling, M.J. 1997.). When a homogeneous fuel-air mixture burns in a spark ignition engine, the pressure and temperature of the unburned mixture rise with flame propagation. Much attention has focused on the spontaneous ignition of a portion of the unburned end-gas mixture in connection with engine knocking. The spontaneous auto-ignition phenomena of the end-gas that causes engine knocking is governed by the temperature and pressure history of the end-gas. Spontaneous auto-ignition is based on the low-temperature chemical kinetics under the cool flame conditions (Bäuerle, B., et al., 1994). 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 (Zhao, H, and Ladommatos, N., 2001; Eckbreth, A.C. 1996). Orth et al. presented two-dimensional temperature measurement using a combination of 2D laser-induced fluorescence (LIF) of hydroxyl radicals and 2D Rayleigh scattering (Orth, A., et al. 1994.). They measured a significant dependence of the temperature on the mixture composition, and confirmed the validity of the flamelet assumption from the analysis if IH 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 (Schulz, C., et al. 1996.). Kaminski *et al*. applied two-line atomic fluorescence (TLAF) to internal combustion engine (Kaminski, C. F., et al. 1998.). 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 (Sanders, S.T., et al. 2003.). 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 (Lucht, R.P., et al. 1987; Bradley, D., et al. 1994; Bood, J., et al. 1997; Nakada, T, et al. 1990; Akihama, K., and Asai, T. 1993). 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 (Bradley, D., et al. 1994) 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 (Garforth, A.M. 1976) offers both high potential resolution and non-intrusive temperature measurement. Several researchers have applied this technique to temperature measurements (Achasov, O., et al. 1993; Hamamoto, Y., et al. 1994). 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. (1994) and Tomita et al. (1994, 2000) installed Mach-Zehnder interferometry with polarization preserving fibers and Köster 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 (Kawahara , N., et al. 2001; Kawahara, N., et al. 2002). 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 (Kawahara, N., et al. 2002). 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 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 conditions with propane as fuel. 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_s 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. These beams meet at the polarized beam splitter and create a beat frequency of 25.0 kHz. The difference between the initial frequencies can be altered to create other beat frequencies (12.5 ~ 100 kHz), if desired. 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 delivery of the test beam poses a possible problem in heterodyne interferometry since, any change in the position of the optical system in relation to the combustion chamber affects the results due to the sensitivity of the signal. 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-optic sensor, which is explained in the next section. The 1/2 wave retarder was used in the fiber-optic system, so that the polarization angle of the fiber coincides with the test beam. Manipulator of LDV system was used to enter the beam into the fiber. A distributed index lens is fixed at the other end of the fiber to generate a collimation beam and to introduce the beam into the fiber. This distributed index lens has an anti-reflection coating to decrease the cross-talk effect. The test beam passes through the fiber and meets the reference beam at the polarized beam splitter, where the two beams interfere with each other. The frequency stabilized He-Ne laser used in these tests has a long coherence length (over 10 km); thus, the difference between the path lengths of the test and reference beams is insignificant. The interfering light is guided to a phototransistor, and changes in the intensity are detected. Fiber-optic heterodyne interferometry system without developed fiber-optic sensor were 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.

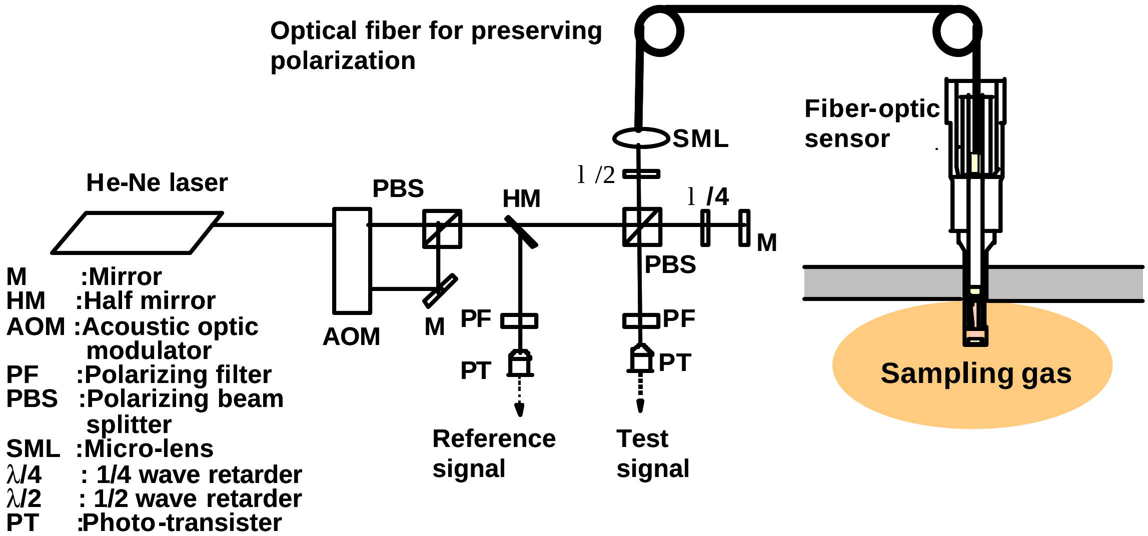


Fig. 1 Heterodyne interferometry with fiber-optic sensor

2.2 Principle of Temperature Measurement

Interferometric methods allow variation in the refractive index along the line of sight to be measured. When the unburned gas mixture is compressed by the piston or the flame development, the density of the gas in the combustion chamber changes affecting 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.

The change of phase shift of the heterodyne signal over a given time t, y_t is expressed by

$$y_t = \int_0^t 2pf_{bt}(t)dt - \int_0^t 2pf_{br}(t)dt \tag{1}$$

where f_{br} and f_{bt} denote the beat frequency of the reference and test sections, respectively. The change of phase in the test section, y_t, is also expressed by

$$y_t = 2p\Phi_t / l_s = 2pn_t L_t / l_s \tag{2}$$

where F_t is the change in the optical path length, L_t is the length of the test section, l_s is the wavelength of the test beam, and n_t is the change in the refractive index in the test section.

The relationship between the refractive index and density can be approximated using the Gladstone-Dale equation,

$$n_t = 1 + \frac{\rho_t R_{Gt}}{M_t} = 1 + \frac{P_t R_{Gt}}{R_0 T_t} \tag{3}$$

where R_{Gt} is the Gladstone-Dale constant (cm^3/mol) (Gardiner, W.C.Jr, , et al. 1980), which is determined by the wavelength of the laser and the gas species. The variables M_t, R_0, P_t, and T_t denote the mean molecular weight, mean gas constant, pressure, and temperature in the test section, respectively. The value of the Gladstone-Dale constant for each gas is given in detail for each laser wavelength in reference (Gardiner, W.C.Jr, , et al. 1980).

The temperature of the mixture can be obtained from Eqs. (1), (2), and (3),

$$T_t = \frac{2pP_t R_{Gt} T_{t_0} L_t}{2pP_{t_0} R_{Gt} L_t + y_t T_{t_0} R_0 l} \tag{4}$$

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

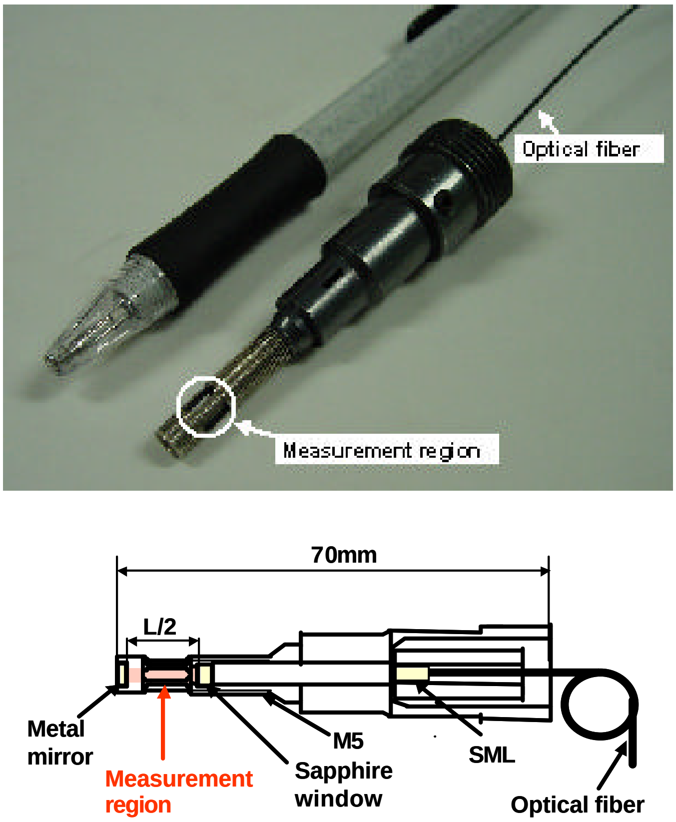


Fig. 2 Photograph and schematic diagram of developed fiber-optic sensor

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. EXPERIMENTAL RESULTS

3.1 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 (Kawahara , N., et al. 2001; Kawahara, N., et al. 2002). 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 f = 1.0, P_0 = 100 kPa, T_0 = 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 (Tomita, e., et al. 1994). 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. 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. (4) and plotted with solid line in Fig. 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. As shown in Fig. 3, the temperature under the assumption of polytropic and adiabatic change was approximately equal to the measured temperature with developed system.

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 Fig. 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 Fig. 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.

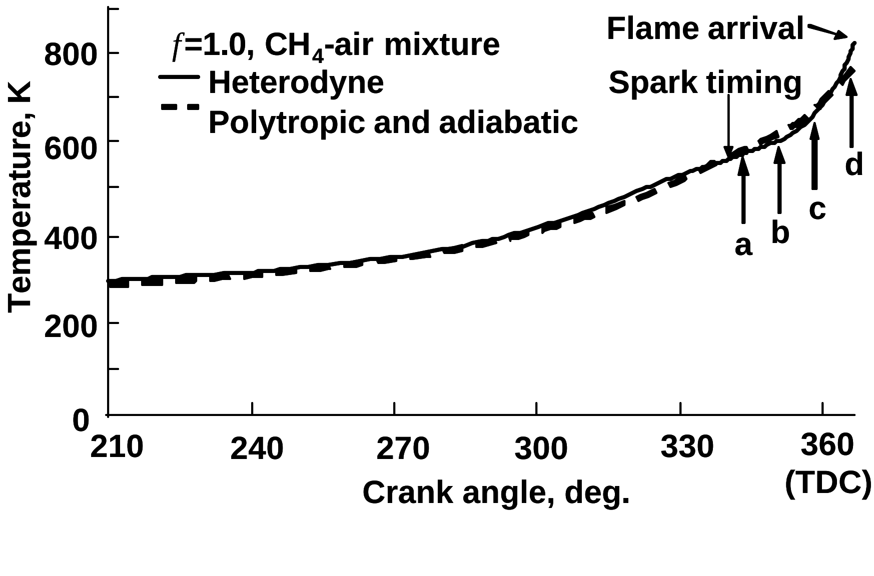


Fig. 3 Temperature change of unburned gas under firing condition in the test engine

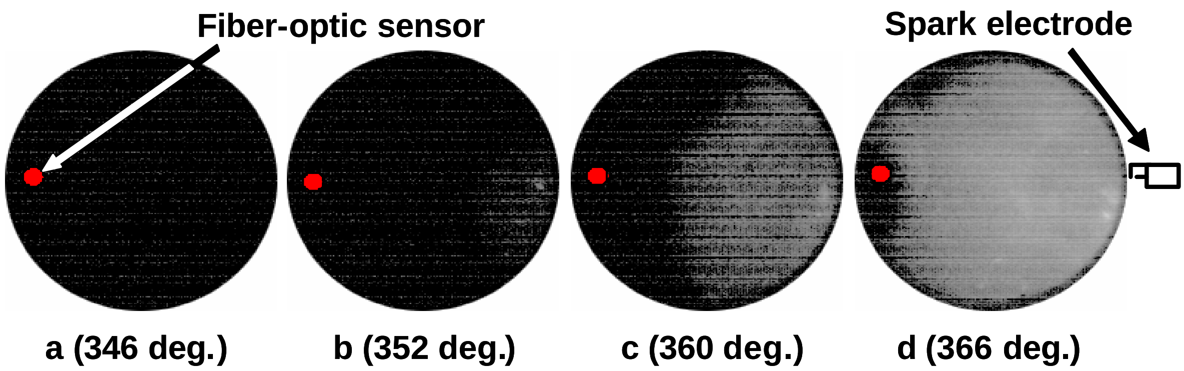


Fig. 4 Flame propagation in the test engine

3.2 Temperature Measurement of Unburned Gas in a Prpduction Engine

Next, the developed fiber-optic sensor was applied to a commercially produced engine. A schematic diagram of experimental set-up is shown in Fig. 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. Propane was introduced into the intake pipe approximately 1 m from the engine intake manifold. A static mixer was placed in the intake pipe to produce a homogeneous mixture of propane-in air. The inlet airflow rate was measured with a laminar flow meter. The propane fuel flow rate was measured with another laminar flow meter and adjusted with a needle valve. 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. Intake and exhaust valve did not contact with housing of measurement region. 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. The engine was operated at 1,500 rpm. Intake valve was closed at 251°. The spark timing was 20 degree before TDC. In situ unburned gas temperature measurements were carried out in the spark-ignition engine under firing conditions.

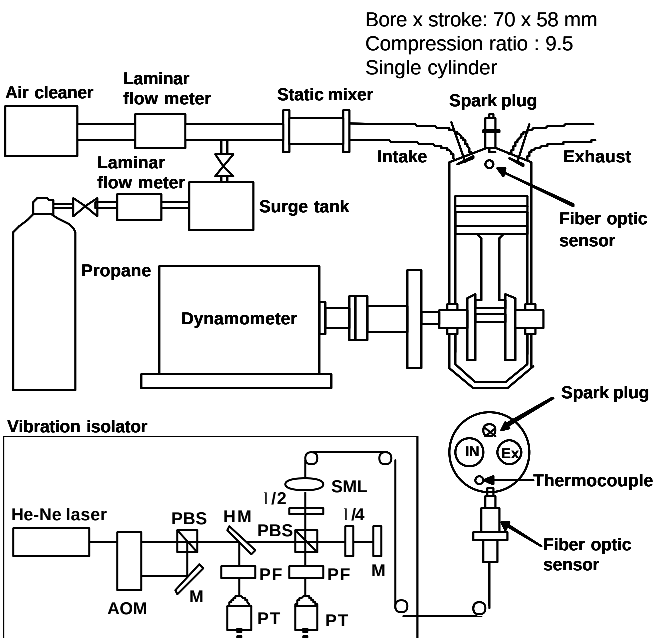
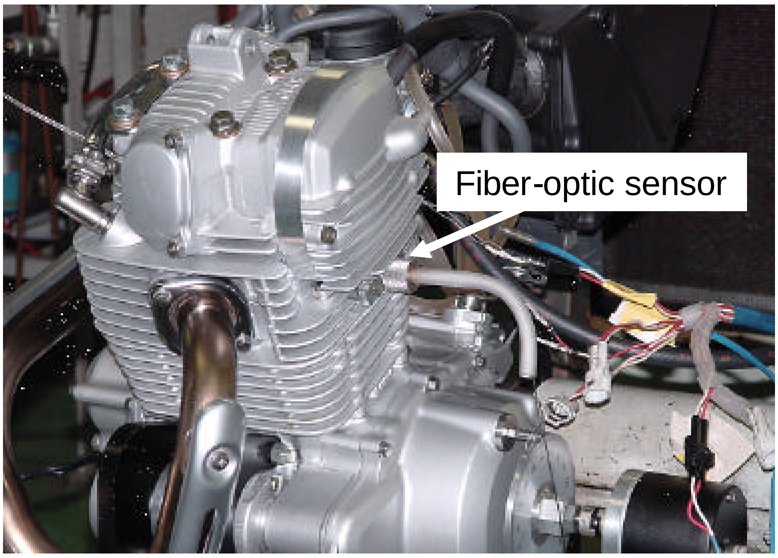
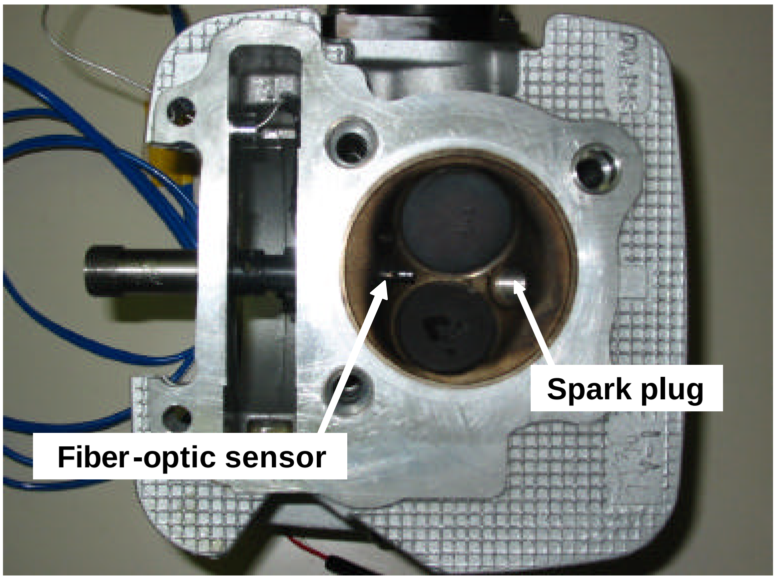


Fig. 5 Schematic diagram of experimental set-up using the spark-ignition engine



(a) Spark-ignition engine with fiber-optic sensor



(b) Engine cylinder head with fiber-optic sensor

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

Figure 7 indicates the pressure history and the measured phase shift between the reference and test signals under conditions pertaining to an engine speed of 1,500 rpm. The phase shift is calculated from the difference between the reference and test signals using Eq. (1). TDC corresponds to a crank angle of 360°. The phase shift increases slightly with the pressure rise at the first stage of compression; as the pressure increases after the spark, the phase shift becomes larger. At the first stage of compression (crank angle from 240° to 300°), the phase shift fluctuated due to the mechanical vibration of firing engine. During the first stage of compression, pressure in the cylinder rises slightly. The effect of mechanical vibration on the fiber cannot be neglected. However, the phase shift became smooth line due to the large pressure rise from the crank angle of 300°. Although the noise from mechanical vibration contributed to the interference signal during the flame propagation, the effect was within the limits allowed for measurement. The effect of the impact at the valve closure and the operating vibration of the engine were therefore sufficiently restrained to permit accurate heterodyne interferometry measurement.

The temperature history of the unburned gas from 300° to the flame arrival time at the developed sensor was plotted with solid line in Fig. 8. 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 Fig. 8. Initial temperature is very important for the measurement method using laser interferometry. The evaluated temperature using polytropic index at a crank angle of 300° was used for the initial temperature of laser interferometry. Measured temperature was lower than evaluated mean temperature using in-cylinder pressure. One of the reasons is that the measurement location was near the wall, where the temperature is expected to be lower than the mean temperature. Unburned gas temperature could be quantified using developed fiber-optic sensor in a spark-ignition engine.

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. 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.

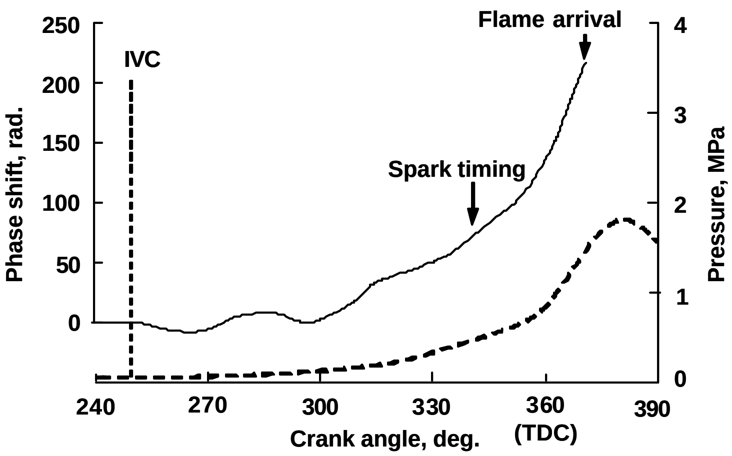


Fig. 7 Measurement phase shift and pressure under firing condition in the spark-ignition engine

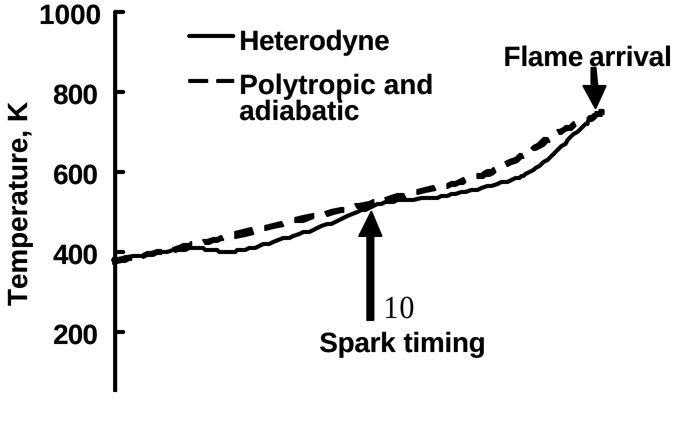


Fig. 8 History of unburned gas temperature obtained in spark-ignition engine

4. CONCLUSIONS

Temperature measurement system of unburned gas in a commercially produced engine was developed using laser heterodyne interferometry with a fiber-optic sensor. 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 the engine cylinder or the cylinder head without a lot of changes of an actual engine. The feasibility of our system was sufficient to be applied to temperature history measurement of an unburned gas compressed by the flame propagation in an engine cylinder. The measured value was almost the same as the averaged temperature estimated using the in-cylinder pressure. The developed heterodyne system may also be used for other applications that require a fast response time to measure the density and pressure of a gas, and thereby obtain a transient temperature record.

REFERENCES

Akihama, K., Asai, T. (1993). “Improvement in Temperature Measurement Accuracy of Q-Branch CARS Thermometry (Effects of Spectral Resolution of Detection System)”, JSME International Journal, B 36-2, pp.364.

Achasov, O., Fomin, N., Penyazkov, O., Oznobishin, A., and Fisson, F. (1993). “Interferometric Study of Combustion in a Spark Iginition Engine”, Proc. of the Int. Symp. on Internal Comb. Engines, KONES'93, pp. 553-562.

Bäuerle, B., Hoffmann, F., Behrendt, F., and Warnatz, J. (1994). “Detection of Hot Spots in the End Gas of an Internal Combustion Engine Using Two-dimensional LIF of Formaldehyde”, Proc. Combust. Inst., 25, pp.135-141.

Bood, J., Bengtsson, P-E., Mauss, F., Burgdorf, K., and Denbratt, I. (1997). “Knock in Spark-ignition Engines: End-gas Temperature Measurements using Rotational CARS and Detailed Kinetic Calculations of the Autoignition Process”, SAE paper 971669.

Bradley, D., Kalghatgi, G.T., Morley, C., Snowdon, P., and Yeo, J. (1994). “CARS Temeprature Measurements and the Cyclic Dispersion of Knock in Spark Ignition Engines”, Proc. Combust. Inst. 25, pp.125-133.

Eckbreth, A.C. (1996). “Laser Diagnostics for Combustion Temperature and Species”, 2nd Ed., Gordon and Breach Publishers.

Gardiner, W.C.Jr, Hidaka, Y., and Tanzawa, T. (1980). “Refractivity of Combustion Gases”, Combust. and Flame, 40, pp. 213-219.

Garforth, A.M. (1976). “Unburnt Gas Density Measurements in a Spherical Combustion Bomb by Infinite-fringe Laser Interferometry”, Combust. and Flame, 26, pp. 343-352.

Hamamoto, Y., Tomita, E., and Jiang, D. (1994). “Temperature Measurement of End Gas under Knocking Condition in a Spark-Ignition Engine by Laser Interferometry”, JSAE Review, 15-2, pp. 117-122.

Heywood, J.B. (1988). “Internal Combustion Engine Fundamentals”, McGraw-Hill, Inc.

Kaminski, C. F., Engstroem, J. and Alden, M. (1998). “Spark ignition of Turbulent Methane/Air Mixtures Revealed by Time-Resolved Planar Laser-Induced Fluorescence and Direct Numerical Simulations”, Proc. Comb. Inst. 27, pp.85.

Kawahara, N., Tomita, E., and Kamakura, H. (2001). “Transient Temperature Measurement of Gas Using Fiber Optic Heterodyne Interferometry”, SAE paper No.2001-01-1922.

Kawahara, N., Tomita, E., and Kamakura, H. (2002), “Unburned Gas Temperature Measurement in a Spark-ignition Engine Using Fiber-Optic Heterodyne Interferometry”, Meas. Sci. Technol., 13-1, pp.125-131.

Lucht, R.P., Teets, R.E., Green, R.M., Palmer, R.E., and Ferguson, C.R. (1987). “Unburned Gas Temperature in an Internal Combustion Engine. I: CARS Temperature Measurements”, Combust. Sci. and Technol., 55, pp.41.

Nakada, T, Ito, T., and Takagi, Y. (1990). “Unburnt Gas Temperature Measurements Using Single Shot CARS in a Spark Ignition Engine”, Proc. of Int. Symp. on COMODIA 90, pp. 393-399.

Orth, A., Sick, V., Wolfrum, J., Maly, R.R., Zahn, M. (1994). “Simultaneous 2D Single-Shot Imaging of OH Concentrations and Temperature Fields in an SI Engine Simulator”, Proc. Combust. Inst., 25, pp.143-150.

Pilling, M.J. (1997). “Low-Temperature Combustion and Autoignition”, Elsevier Science.

Sanders, S.T., Kim, T., and Ghandhi, J.B. (2003). “Gas Temperature Measurements During Ignition in an HCCI Engine”, SAE Paper No. 2003-01-0744.

Schulz, C., Sick, V., Wolfrum, J., Drewes, V., Zahn, M., and Maly, R. (1996). “Quantitative 2D Single-Shot Imaging of NO Concentrations and Temperatures in a Transparent SI Engine”, Proc. Comb. Inst. 26, pp.2597.

Tomita, E., Hamamoto, Y., and Jiang, D. (1994). “Temperature and Pressure Histories of End Gas under Knocking Condition in a S.I. Engine”, Proc. of Int. Symp. on COMODIA 94, pp. 183-188.

Tomita, E., Hamamoto, Y., and Jiang, D. (2000). “Measurement of Temperature History of Unburned Gas Before Knocking in a Spark-Ignition Engine Using Laser Interferometry”, Meas. Sci. Technol., 11-6, pp. 587-593.

Zhao, H, and Ladommatos, N. (2001). “Engine Combustion Instrumentation and Diagnostics”, Society of Automotive Engineers, Inc.