

Transient Temperature Measurement of Unburned Gas in an Engine Cylinder Using Fiber-Optic Heterodyne Interferometry

by

Nobuyuki Kawahara, Eiji Tomita, Hiroshi Kamakura, Mitsuru Ichimiya

Department of Mechanical Engineering, Okayama University
Tsushima-Naka 3, Okayama 700-8530 JAPAN

Abstract

Various global environmental issues are related to the use of internal combustion engines, including air pollution and energy concerns. With homogenous charge compression ignition (HCCI) engine, it is possible to operate with ultra lean premixed mixtures and to lead low NO_x and soot-particle emissions. The combustion process in the HCCI engine is due to auto-ignition of an unburned mixture. The occurrence of auto-ignition is dependent on the temperature and pressure histories of the unburned mixtures. Therefore, it is necessary to measure the temperature history of the unburned mixture in the HCCI engine. In the present study, the temperature of the unburned mixture in a homogeneous charge compression ignition (HCCI) engine, fueled with dimethyl ether (DME), was measured using fiber-optic heterodyne interferometry. The technique is based on refractive index measurements using laser interferometry along a line of sight. The temperature history of gas can be determined from the pressure history in the engine, the gas composition, and the laser interference intensity. The measurement accuracy of the developed system was sufficient to determine the temperature history of unburned mixture in HCCI operation. The uncertainty of this method is within ± 15 K. The resolution of temperature measurements is approximately 0.5 K, and is dependent on both the sampling clock speed of the A/D converter and the length of the test section.

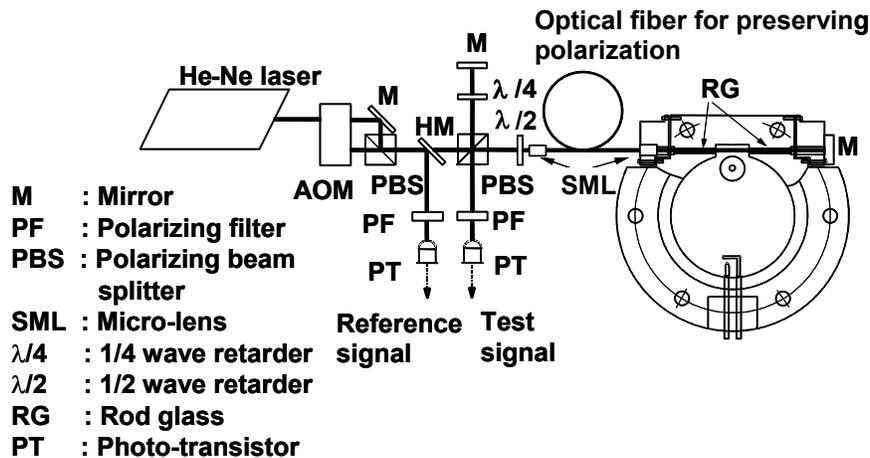


Fig. Developed fiber optic heterodyne interferometer

1. Introduction

Temperature measurements of turbulent combustion processes can provide important information about chemical kinetics controlling fuel oxidation and pollutant formation, and the optimization of practical devices. However, an accurate time-resolved temperature history of gas is difficult to obtain experimentally. Traditionally, sound velocity and infrared emission absorption methods have been used to measure the unburned mixture temperature in internal combustion engines. Livengood (1958) and Gluckstein and Walcutt (1961) used a sound-velocity method to measure the gas temperature in a cylinder. The unburned mixture temperature has also been measured using iodine absorption spectra (Chen et al., 1954), a two-wavelength infrared method (Agnew, 1960), and an infrared radiation pyrometer (Burrows et al., 1961).

More recently, a light-scattering method that uses spontaneous vibrational and rotational Raman scattering, laser Rayleigh scattering, coherent anti-Stokes Raman spectroscopy (CARS) and laser-induced fluorescence (LIF) has been developed (Chiger, 1991, Eckbreth, 1996, Zhao and Ladommatos, 2001). Several researchers have used CARS method to determine the unburned mixture temperature (Lucht, et al., 1987, Bood, et al., 1997, Nakada, et al., 1990, Akihama and Asai, 1993). technique is particularly well suited to engines, because it produces a strong signal. However, the accuracy of CARS in an engine cylinder is only ± 40 K (Akihama and Asai, 1993) and it is limited to single-point and single-shot measurements. Two-dimensional temperature measurements have become possible using fluorescence thermometry because of its intrinsically high signal-to-noise ratio. Schulz et al., (1996) used LIF with a tunable KrF excimer laser to obtain quantitative imaging of the nitric oxide concentration distribution and temperature field in an SI engine. Kaminski et al. (1998) used a two-line atomic fluorescence (TLAF) technique to measure the temperature inside an internal combustion engine. These methods have the potential to provide quantitative two-dimensional temperature distribution, but time-series analysis is limited by the laser repetition rate.

Laser interferometry (Goldstein, 1983, Fomin, 1998) offers high potential resolution and provides a non-intrusive temperature measurement technique. Garforth (1976) used modified Michelson interferometry to measure the transient density in the unburned gas region of a spherical combustion chamber, and obtained the transient gas temperature from the equation of state and pressure data. Hamamoto et al. (1989) measured the unsteady temperature change of a gas during compression and expansion using Mach-Zehnder interferometry; however, they encountered difficulties because the measurements were usually sensitive to mechanical vibration. Hamamoto et al. (1994) and Tomita et al. (1994, 2000) addressed some of these problems by using modified Mach-Zehnder interferometry with polarization-preserving fibers and Köster prisms to measure the temperature change of a compressed unburned gas during flame propagation and to investigate the knock phenomenon. However, it is difficult to apply this system to another combustion system due to the special optical arrangement. Heterodyne interferometry (Kawahara, et al. 2000) is more fairly insensitive to fluctuations in signal intensity caused by mechanical vibration. Thus, a fiber-optic heterodyne interferometry system was developed to measure the temperature history of the unburned end-gas in an engine cylinder during flame propagation (Kawahara, et al., 2002). A polarization-preserving fiber was used to deliver the test beam to and from the test section in order to improve the applicability of this system.

In the present paper, the same fiber-optic heterodyne interferometry system was used to measure the temperature of the unburned mixture in a homogenous charge compression ignition (HCCI) engine (Thring, 1989) fueled with dimethyl ether (DME). With HCCI it is possible to operate with ultra lean premixed mixtures and to lead low NO_x and soot-particle emissions. The combustion process in the HCCI engine is due to auto-ignition of an unburned mixture. The occurrence of auto-ignition is dependent on the temperature and pressure histories of the unburned mixtures. Therefore, it is necessary to measure the temperature history of the unburned mixture in the HCCI engine. Moreover, DME (CH₃OCH₃), one of the oxygenated fuels, is an attractive alternative fuel because of smoke-free combustion, reduction of NO_x and easy compression ignition. Since DME shows very strong low temperature oxidation, the HCCI study of DME may give useful information on the general role of cool flame in HCCI operation.

2. Experimental Method and Procedure

2.1 Principles of Temperature Measurement

The principles of using optical interferometry to measure gas temperature are shown in Fig. 1. 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, 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.

When the reference and a test beam have intensity I_0 , the interference intensity, I , is expressed as

$$I = 2 \cdot I_0 \left[1 + \cos(2\pi f_b t + \psi_t) \right] \quad (1)$$

where f_b and ψ_t denote the beat frequency and the change of phase shift in the test section, respectively. The change of phase shift of the heterodyne signal over a given time t , ψ_H , is related to ψ_t by

$$\psi_t = \int_0^t 2\pi f_{bt}(t) dt - \int_0^t 2\pi f_{br}(t) dt \quad (2)$$

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, ψ_t , is also expressed by

$$\psi_t = 2\pi\Phi_t / \lambda_s = 2\pi n_t L_t / \lambda_s \quad (3)$$

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

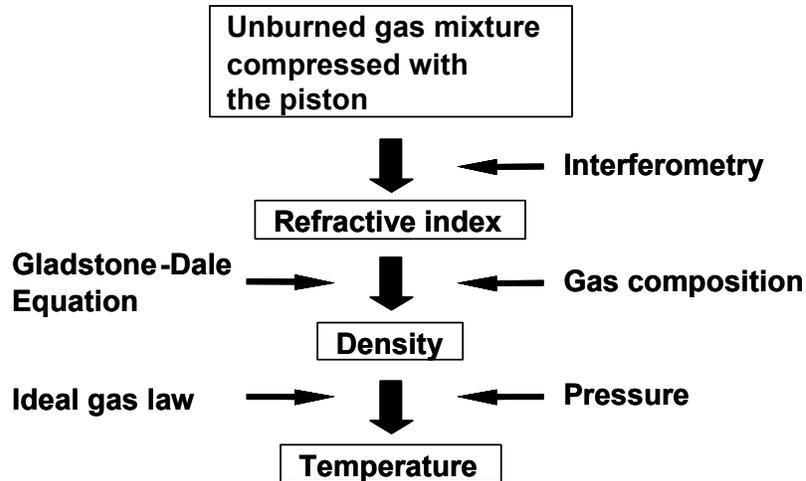


Fig.1 Principle of temperature measurement using laser interferometry

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

$$n_t = 1 + \frac{\rho_t R_{Gt}}{M_t} = 1 + \frac{P_t R_{Gt}}{R_0 T_t} \quad (4)$$

where R_{Gt} is the Gladstone-Dale constant (cm^3/mol)(Gardiner, 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, et al., 1980). When the gas mixture is composed of many species, the Gladstone-Dale constant of the mixture is expressed as

$$R_{Gt} = \sum R_{Gi} x_i \quad (5)$$

where x is the mole fraction of each gas and the subscript i indicates the i -th species of the mixture.

The temperature of the mixture can be obtained from Eqs. (2), (3), and (4),

$$T_t = \frac{2\pi P_t R_{Gt} T_{t_0} L_t}{2\pi P_{t_0} R_{Gt} L_t + \psi_t T_{t_0} R_0 \lambda} \quad (6)$$

When the pressure P_{t_0} and temperature T_{t_0} 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.

2.2 Fiber-Optic Heterodyne Interferometry

Figure 2 shows the configuration of the fiber-optic arrangement in the combustion chamber. 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 80.1 MHz, 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 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 test section in the combustion chamber. The 1/4 wave retarder, used previously for a test beam without the fiber system (Kawahara, et al., 2000), is replaced by a 1/2 wave retarder in the fiber-optic system, so that the polarization angle of the fiber coincides with the test beam. A distributed index lens is fixed at each 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 interfering light is guided to a phototransistor, and changes in the intensity are detected. The main problem of this system is coherence length of laser due to the different length of the test and reference beams. 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 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.

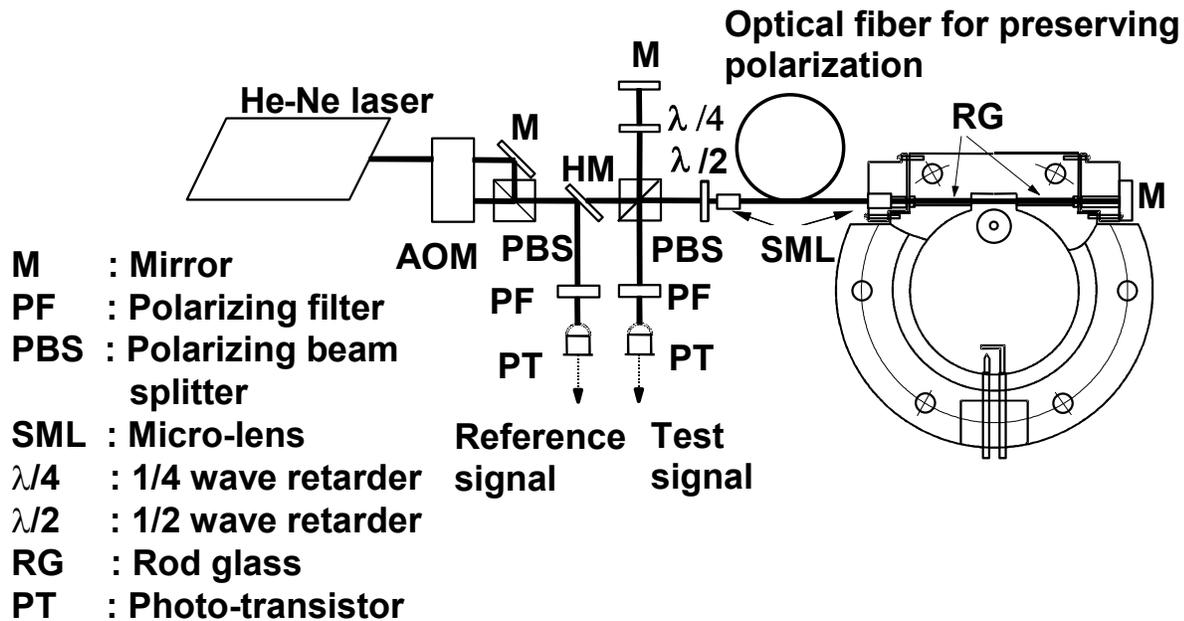


Fig. 2 Developed fiber-optic heterodyne interferometer

3. Unburned Mixture Temperature Measurement in a HCCI Engine Cylinder

This experiment used a specially designed compression-expansion engine that can only auto-ignite once. With this engine can observe the phenomena of one cycle in one experimental run. A schematic diagram of the engine is shown in Fig. 3. The engine had a bore and stroke of 78 and 85 mm, respectively, and the compression ratio was 10.1:1. The constant volume combustion chamber in this engine was the same as that described in (Kawahara, et al., 2002). The laser beam used for fiber-optic heterodyne interferometry passed through glass rods in the combustion chamber. The glass rods are fixed with liquid packing and thin Teflon gaskets in order to prevent leakage of the fuel-air mixture. The axis of the laser beam in the test region was 4.3 mm from the upper wall and 2.7 mm from the side wall; this position was chosen to be outside the thermal boundary layer near the wall. The length of the gas layer in the test region, L_t , was 18.74 mm.

The engine cylinder was connected to a mixture tank by a pipe. Initially, a homogeneous mixture was introduced into the tank and cylinder through an open valve, with the piston set at top dead center (TDC). The engine was driven by an electric motor while the valve was open. After a given time, the valve was closed when the piston was at bottom dead center (BDC). The mixture was then compressed sufficiently to raise the mixture temperature above its ignition point. Auto-ignition was distributed throughout the cylinder volume, starting at the hottest regions. The mixture was introduced without swirl, because the valve was located at the center axis of the cylinder. The engine was operated at 600 rpm. The pressure signals in the cylinder, interference intensity, crank angle, TDC, BDC, and valve closure were recorded by an A/D converter, with a sampling time of 2 microseconds and data resolution of 12 bits. The cylinder and mixture tank were initially charged with a homogeneous dimethyl ether (DME)-air mixture (equivalence ratio $\phi = 0.3$).

DME-air mixture was initially heated up at 348K by the electric heater. The temperature of the fuel-air mixture at the start of compression (base state) had to be determined in advance, because the fiber-optic heterodyne interferometry system measured only the change in temperature from the base state. In this experiment, the valve was closed at

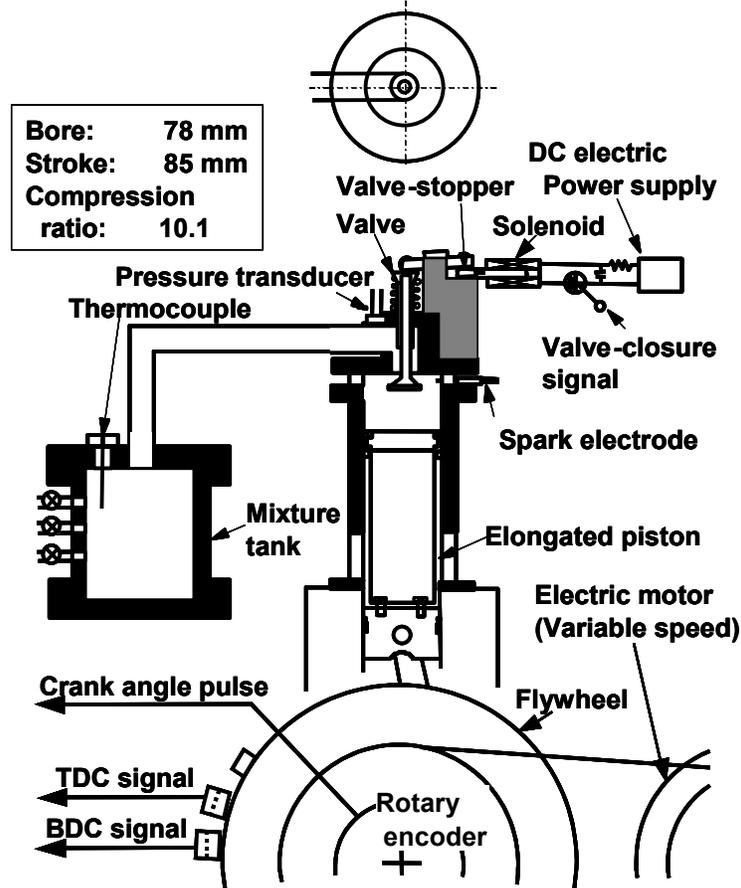


Fig. 3 A schematic diagram of the test engine

BDC of a certain cycle. Using a resistance wire as a thermometer, the temperature at BDC of the valve closure cycle was 3.8 K lower than the initial gas temperature in the mixture tank (Tomita, et al., 1994). This value was used for the temperature at the start of compression.

The temperature after valve closure was obtained from the pressure data and the heterodyne signal, as given by Eq. (6). Figure 4 indicates the pressure history and the heat-release rate in the cylinder of the test engine. The combustion of the DME-air mixture was characterized by a clearly distinguished two-stage ignition, which is visible from the two peaks in the heat release rate curve. The first peak indicates the heat released during the first stage of ignition, which is also described by the low temperature ($T < 1000$ K) chemical kinetics. The main ignition stage follows the first stage. At lower temperatures (up to 900 K), the ignition is controlled by degenerative chain branching processes. The figure shows clearly that HCCI combustion occurred in the test engine, using an ultra-lean premixed mixture and DME as fuel.

Figure 5 indicates the pressure history and the measured phase shift between the reference and test signals at an engine speed of 600 rpm. BDC corresponds to a crank angle of 180° and TDC corresponds to 360° . The phase shift increased slightly with the pressure rise during the first stage of compression. Although noise from mechanical vibration contributed to the interference signal when the valve was closed at BDC, the effect was within the limits

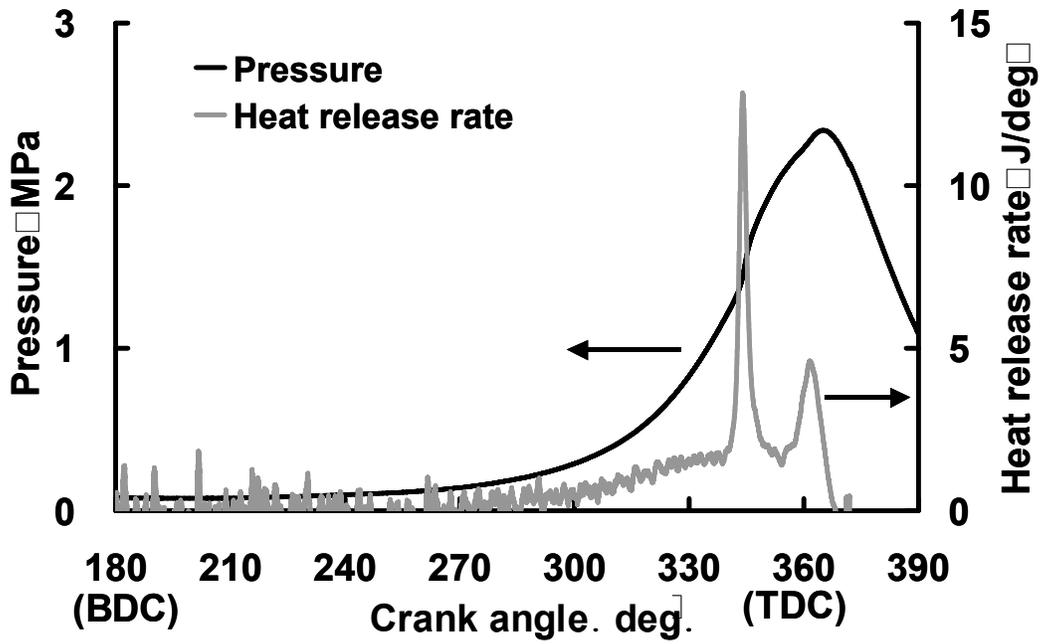


Fig. 4 Measured pressure and heat release rate in the cylinder of test engine

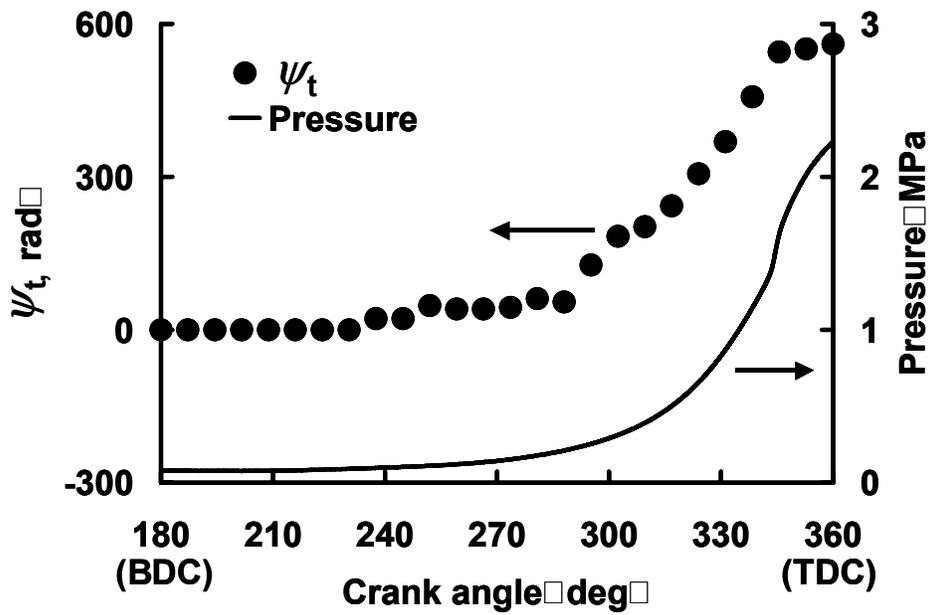


Fig. 5 Measured phase shift and pressure of unburned mixture in the cylinder of test engine

allowed for measurement. The effect of the impact when the valve closed and the operating vibration of the engine were therefore sufficiently restrained to permit accurate heterodyne interferometry measurements.

The temperature history of the unburned mixture from a crank angle of BDC to the first ignition stage was calculated using Eq. (6) and is plotted with black circles in Figure 6. The transient temperature determined by heterodyne interferometry was compared with the temperature calculated using the mean temperature from the state equation for an ideal gas. The mean temperature is also the bulk temperature in the engine cylinder. The mean temperature was similar to that measured by interferometry before a crank angle of 300° , but the temperature obtained by the present system was lower than the mean temperature before the first stage of ignition. This was because the measurement location was near the wall, where the temperature is expected to be lower than the mean temperature.

Heterodyne interferometry provided the mean temperature along a line of sight, and the present results demonstrate that this method can measure the temperature history of the unburned mixture in a HCCI engine.

4. Measurement Accuracy

The accuracy of the developed fiber-optic heterodyne interferometry system depends on (1) the accuracy of pressure measurements, (2) the stability of the AOM system, (3) the gas composition, and (4) the relationship between the beat and sampling frequencies.

(1) Accuracy of pressure measurements

The pressure history of the combustion chamber is required in order to estimate the temperature of the gas. The accuracy of pressure measurements depends on that of the pressure transducer, which has a specified non-linearity of less than 1% at full scale. Even if the pressure measurement had an error of ± 2.5 kPa, which would be an over-

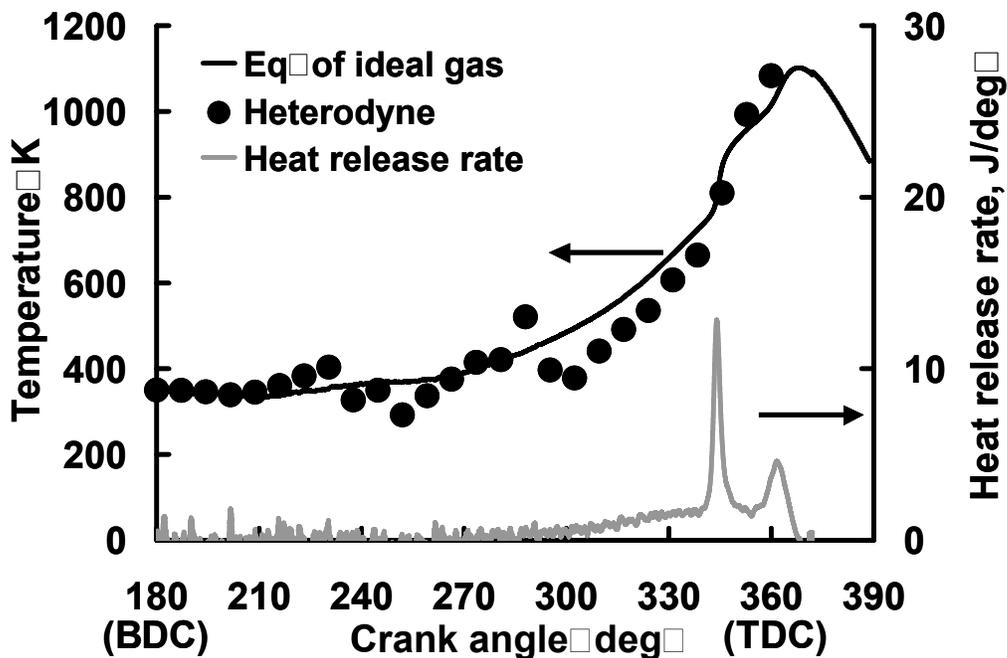


Fig. 6 Temperature change of unburned mixture in the cylinder of test engine

estimate, the accuracy of the temperature data would still be $\pm 2.0\%$. The accuracy of the heterodyne interferometry system was found to be largely dependent on the accuracy of the pressure measurements.

(2) Stability of the AOM system

If the beat frequency of the AOM system is unstable, the gas temperature estimates will be poor. In this system, the stability of the AOM system was 0.02 ppm; therefore, the stability effects of the AOM system were negligible.

(3) Gas composition

The Gladstone-Dale constant varies with gas composition. In this analysis, the composition of the unburned mixture was assumed to be constant. In an HCCI engine, ignition is controlled by degenerative chain branching processes at low temperature. Low-temperature oxidation processes occur in an engine cylinder during first stage combustion. Therefore, the effect of the Gladstone-Dale constant must be considered. For example, if the equivalence ratio of the test gas (DME-air mixture) varies from 0.3 to 0.25, the Gladstone-Dale constant changes from 6.823 to 6.779 cm^3/mol , respectively. In this case, the error introduced by assuming a constant equivalence ratio of 0.3 was approximately 0.6%.

(4) Relationship between the beat and sampling frequencies

The relationship between the beat and sampling frequencies affects the temperature measurement resolution. Optimization of the two frequencies improves the accuracy of a system. In this study, the initial beat and sampling frequencies were 25 and 500 kHz, respectively. A total of 20 sampling points were obtained during one period of the beat frequency before the spark. However, during the compression by the piston, only 18 sampling points were obtained, owing to an increase in the beat frequency of the test signal. If 1/18 of the beat signal period is considered to be the resolution of the temperature measurements, then the measurement resolution, which changes with density, is about 0.5 K. Fig. 8 indicates the change in the measurement resolution, ΔT , with pressure, P_t , for temperature

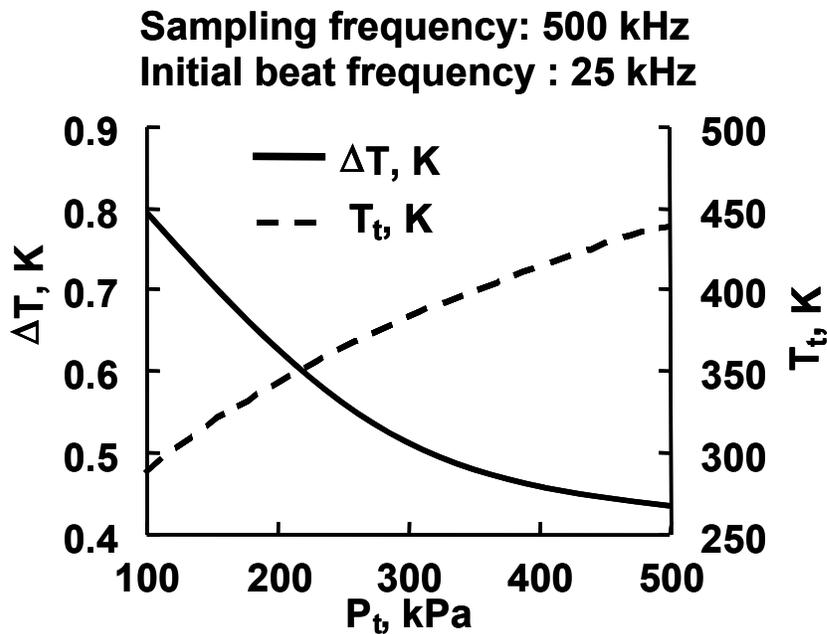


Fig. 7 Resolution for temperature of unburned mixture

measurements of the unburned gas mixture compressed by the piston. The value of ΔT changes with density; it was approximately 0.45 ~ 0.8 K for these tests. These values indicate that our system can measure temperature at a better resolution than reported for the Mach-Zehnder optical system with polarization-preserving fibers and Köster prisms (Tomita, et al., 1994). The resolution of temperature and time could be improved by using an A/D converter with a higher sampling rate, and by increasing the length of the test section.

5. Conclusions

Non-intrusive measurement of transient gas temperatures was successfully developed with a fiber-optic heterodyne interferometry system. The measurement accuracy of the developed system was sufficient to determine the temperature history of unburned mixture in HCCI operation. There was good agreement between the measured temperature and the mean temperature calculated from the state equation for an ideal gas. The uncertainty of this method is within ± 15 K. The resolution of temperature measurements is approximately 0.5 K, and is dependent on both the sampling clock speed of the A/D converter and the length of the test section. Fiber-optic heterodyne interferometry systems would be useful in studies of auto-ignition kinetics in HCCI engines. This method can also be used for other applications that require a transient temperature record with a fast response time.

Acknowledgments

Financial support of this research by the Industrial Technology Research Grant Program of the New Energy and Industrial Technology Development Organization (NEDO) of Japan is gratefully acknowledged.

References

- Livengood, J.C., Taylor, C.F., and Wu, P.C. (1958). "Measurement of Gas Temperature in an Engine by Velocity of Sound Method", SAE Trans, 66, 683-699.
- Gluckstein, M.E., and Walcutt, C. (1961). "End-gas Temperature-pressure histories and their relation to knock", SAE Trans., 69, 529-531.
- Chen, S.K., Beck, N.J., Uyehara, O.A., and Myers, P. (1954). "Compression and End-Gas Temperature from Iodine Absorption Spectra", SAE Trans., 62, 503-513.
- Agnew, W.G. (1960). "End Gas Temperature Measurement by Two-Wavelength Infrared Radiation Method", SAE Trans, 68, 495-513.
- Burrows, M.C., Shimizu, S., Myers, P.S., and Uyehara, O.A. (1961) "The Measurement of Unburned Gas Temperature in an Engine by an Infrared pyrometer", SAE Trans., 66, 514-528.
- Chiger, N. (1991). "Combustion Measurements", Hemisphere Publishing Corp.
- Eckbreth, A.C. (1996), "Laser Diagnostics for Combustion Temperature and Species, 2nd Ed.", Gordon and Breach Publishers.
- Zhao, H. and Ladommatos, N. (2001), "Engine Combustion Instrumentation and Diagnostics", Society of Automotive Engineers, Inc.
- 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, 41.

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.

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, 393-399.

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: 364-370.

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. 26:2597-2604.

Kaminski, C. F., Engstroem, J. and Alden, M. (1998), "Spark Ignition of Turbulent Methane/ Air Mixtures Revealed by Time-Resolved Planer Laser-Induced Fluorescence and Direct Numerical Simulations", Proc. Comb. Inst. 27, 399-405.

Goldstein, R.J. (1983). "Fluid Mechanics Measurements", Hemisphere Publishing Corp.

Fomin, N.A. (1998). "Speckle Photography for Fluid Mechanics Measurements", Springer-Verlag.

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

Hamamoto, Y., Tomita, E., and Okada, T. (1989). "The Measurement of the Transient Temperature of Gas by Laser Interferometry, JSME Int. J., Ser. II, 32-2, 247-251.

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, 117-122.

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, 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, 1-7.

Kawahara, N., Tomita, E., Kamakura, H. (2000). "Transient Temperature Measurement of Unburned Gas Using Optic Heterodyne Interferometry", 10th Int. Symp. on Appl. of Laser Meas. on Fluid Mech., in CD-rom, (2000).

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

Thring, R.H. (1989), "Homogeneous Charge Compression Ignition (HCCI) Engines", SAE Paper 892068.

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