Studies of Temperature Elevation Due to the Pre-flame Reaction in a Spark-ignition Engine with CARS Temperature Measurements Using Fuels of Various Octane Numbers*

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The unburned end-gas temperatures in a combustion chamber of a conventional 4-cylinder DOHC spark-ignition engine were measured using the broadband CARS temperature measurement technique. The test engine was fueled with primary reference fuel 80 and gasoline with research octane numbers of 70.9, 83.4, 91.5 and 100.4. The measured CARS temperatures were compared with the adiabatic core temperatures calculated from the measured pressures. Significant heating by pre-flame reaction in the end gas zone was observed in the late part of compression stroke under both knocking and non-knocking conditions. The measured CARS temperatures when the cylinder pressures were above 1 400 kPa were higher than the calculated adiabatic core temperatures. These results indicate that some exothermic reactions exist in relatively low pressure and temperature regions. The CARS temperatures began to be higher than the adiabatic core temperature when the end-gas temperatures reached 700 K. The temperature elevation due to the pre-flame reaction correlated well with the unburned gas CARS temperature for different research octane number fuels tested.

Key Words: Knock, Autoignition, CARS, End-gas Temperature, Pre-flame Reaction

1. Introduction

Autoignition is defined as the rapid combustion reaction without any external ignition source and it is generally accepted that knocking originates from the autoignition of a portion of or the entire end-gas during the later stages of the combustion process⁽¹⁾. Temperature of the end-gas, which is a mixture of fuel/air/residual-gas ahead of the flame, increases due to the compression both by the piston and by the expansion of fuel-air mixture as it burns. As a result of increasing temperature, pre-flame exothermal oxi-

dation of the unburned end-gas begins to occur⁽²⁾. The pre-flame reaction accelerates itself because the rate of reaction increases as a function of the temperature. In consequence, autoignition of the end-gas occurs.

In a knocking cycle, autoignition occurs in one or several locations in the end-gas ahead of the flame before the flame propagation is complete. It usually results in a rapid local pressure rise followed by pressure oscillations inside the cylinder, which cause higher heat loss, vibration and noise. In the last few decades, great progress has been made in developing fundamental chemical kinetic models of autoignition of hydrocarbon fuels⁽³⁾⁻⁽⁷⁾. The temperature history of the unburned gas is a critical input to such chemical kinetic models. To test different chemical kinetic models, it is necessary to measure the unburned gas temperature accurately in the engine combustion chamber.

Under the engine combustion condition, tempera-

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tures vary rapidly in the time and space and it is difficult to measure the temperature using intrusive methods, such as thermocouple, without influencing in-cylinder flow and combustion. Therefore, the laser based techniques play an important role in the diagnostics of combustion in internal combustion engines because they give spatially and temporally resolved information of temperature⁽⁸⁾. One of the most widely used laser diagnostic techniques is the coherent anti-Stokes Raman spectroscopy (CARS), which has several merits for the diagnostics in hostile combustion environments. CARS temperature measurements have fine temporal and spatial resolution and CARS experiment requires little modification of test engine because windows with diameter of a few millimeters are sufficient for the technique. The CARS signal is generated as a beam of high intensity, and consequently the background noises can be easily suppressed. Since the first report on CARS experiment within the cylinder of an internal combustion engine was published by Stenhouse et al.⁽⁹⁾, many engine researchers have adopted the CARS technique because of the merits mentioned above^{(10)–(17)}. Nowadays, many researchers interested in knock use CARS to measure the temperature rise due to the rapid heat release before the autoignition^{(18)–(22)}.

In the present study, the end-gas temperatures in a combustion chamber of a conventional 4-cylinder DOHC spark-ignition engine with fuels of various octane numbers was measured simultaneously with the cylinder pressure by the CARS technique. Knock characteristics of the engine were determined from the measured cylinder pressure using the band pass-filter method. In order to investigate the effect of the pre-flame reaction on the end gas temperature, the measured CARS temperatures were compared with the adiabatic core temperatures calculated from the measured pressures.

2. Experimental Setup

Figure 1 shows a schematic diagram of the experimental setup. The CARS system and the test engine were separated into two different rooms in order to suppress the effect of vibrational and electrical noise from the engine.

The CARS system measured a full CARS spectrum on shot by shot basis. The system consisted of a frequency doubled Nd:YAG laser (Continuum Surlite II), broadband modeless dye laser and a monochromator equipped with an optical multichannel analyzer (EG & G 1420). According to our previous study⁽²³⁾, the uncertainty of the temperature measurements under engine-like condition of the CARS system used in this study was ± 40 K.

Fig. 1 Schematic diagram of the experimental setup

Two lenses with a focal length of 25 cm were used to make CARS signal in a combustion chamber of the engine. A Pellin-Broca prism was used to separate CARS signal from the other laser beams. The cylinder pressure was measured simultaneously with the CARS signal using a flush mounted pressure transducer (Kistler 6053) and was used as a parameter on fitting the measured CARS spectrum to theoretical spectra. The temperatures were determined by finding the minimum deviation between every single CARS spectrum and the library of theoretical spectra calculated for different temperatures at the engine pressure. Knock characteristics were determined from the measured cylinder pressure using the band-pass-filter method.

Configuration of the combustion chamber and CARS measurement location are shown in Fig. 2. A plate spacer was inserted between the engine head and block to make windows for optical access, and the pistons were elongated to compensate the compression ratio decrease. Original compression ratio of the engine was 9.5, but it was changed to 8.3 because of the modification.

The test engine was fueled with primary reference fuel 80 (PRF80) and gasoline with research octane numbers of 70.9, 83.4, 91.5 and 100.4. The properties of test fuels are shown in Table 1. The engine was operated under 1200 rpm, wide-open throttle condition and spark ignition timing was varied. Specifications of the test engine and the engine operating conditions are in Table 2.

3. Results and Discussion

Knock characteristics were determined from the

Table 1 Properties of test fuels

RON	70.9	83.4	91.5	100.4
Specific Gravity	0.6821	0.6945	0.6979	0.8082
H/C Atomic Ratio	2.23	2.20	2.20	1.50
LHV (kcal/kg)	10613	10596	10606	9961

Table 2 Specifications and operating conditions of the test engine

Cylinder / Stroke	4 / 4
Combustion Chamber Type	Pentroof
Bore $\times$ Stroke (mm)	76.5 $\times$ 81.5
Displacement Volume (cc)	1498
Compression Ratio	9.5 (8.3)
Engine Speed (rpm)	1200
Load (%)	100
Coolant Temperature ($^{\circ}\text{C}$)	88

Fig. 2 Engine combustion chamber configuration and CARS measurement location

measured pressure using the band-pass-filter method⁽²⁴⁾. The range of the band pass filter method was 5 – 10 kHz.

Under the given operating conditions, the percentage of cycles in which knock occurred increased from 0 to 100%. Figure 3 shows knock occurrence percentage and cycle averaged knock occurrence crank angle as a function of spark timing for PRF80 experiments. The mean knock occurrence angle became earlier as spark timing was advanced.

At each temperature measuring crank angle, CARS spectra of 100 – 150 consecutive cycles were stored and 10 – 15% of the spectra were rejected because of low signal intensity or poor fitting result. Figure 4 shows a scatter plot of the measured temperatures of PRF80 for spark timing of 30° BTDC as a function of simultaneously measured cylinder pres-

Fig. 3 Knock occurrence probability and average knock occurrence crank angle as a function of spark timing (1 200 rpm, WOT, used fuel : PRF80)

Fig. 4 Measured CARS temperatures as a function of simultaneously measured cylinder pressure (1 200 rpm, WOT, used fuel: PRF80, spark timing: BTDC 30°, CA: temperature measurement crank angle)

ures.

The solid line in Fig. 4 is a path that the unburned gas experienced if it would be compressed adiabatically from the initial condition of 1 bar, 350 K. The temperature on this line is called the adiabatic core temperature. In this calculation, specific heat ratios as a function of temperature and air-fuel ratio⁽²⁵⁾ were used. As shown in Fig. 4, the measured CARS temperatures were higher than the adiabatic core temperature at high-pressure region. The discrepancy was no less than 200 K at the pressure of 3 000 kPa. Uncertainty of CARS temperature measurements under engine-like condition was ± 40 K. Therefore, it is clear that there were some heating effects caused by chemical reactions other than the compression which resulted in the temperature discrepancy.

The measured CARS temperatures were compared with the adiabatic core temperatures calculated from the measured cylinder pressure under assumption that the compression process is isentropic. Figures 5 and 6 show the differences between the mea-

Fig. 5 Difference between measured CARS temperature and adiabatic core temperature as a function of measured cylinder pressure for different spark timings (1 200 rpm, WOT, used fuel: PRF80, S/T: spark timing)

Fig. 6 Difference between measured CARS temperature and adiabatic core temperature as a function of CARS temperature for different spark timings (1 200 rpm, WOT, used fuel: PRF80, S/T: spark timing)

sured and adiabatic temperature as a function of cylinder pressure and CARS temperature at various spark timing conditions of PRF 80. Trend lines and R^2 values in figures were calculated from the data after temperature difference occurrence only. Each point of CARS temperature is the average of effective CARS temperatures.

As shown in Fig. 5, the temperature elevation began to occur at cylinder pressure of 1 400 kPa and the R^2 value between the temperature increase and cylinder pressure was 0.850 7. Even though no knock occurred under spark timing 15° BTDC condition, the result shows almost same heat release as other spark timing conditions. In the late part of the compression stroke, the measured temperature was higher than the adiabatic core temperature due to the heating effect by pre-flame reactions without regard to knock occurrence, and these results are in accordance with the results from other researchers^{(12),(18),(19)}.

(a) RON of fuel: 70.9

(b) RON of fuel: 83.4

(c) RON of fuel: 91.5

(d) RON of fuel: 100.4

Fig. 7 Difference between measured CARS temperature and adiabatic core temperature as a function of CARS temperature for different spark timings (1 200 rpm, WOT, S/T: spark timing)

Figure 6 shows the differences between the measured and adiabatic temperature as a function of average CARS temperature. The temperature elevation due to the pre-flame reaction began to occur when unburned end-gas temperature reached about 700 K under all spark timing conditions. The temperature elevation due to the pre-flame reaction correlated better with the CARS temperature than with the cylinder pressure ($R^2=0.927$).

Figure 7 shows the differences between the measured CARS temperature and the adiabatic temperature as a function of CARS temperature at various spark timing conditions and with gasoline of various research octane numbers.

With all fuels except fuel of RON 100.4, the temperature elevation due to the pre-flame reaction began to occur when the unburned gas temperature reached at 700 K, and the temperature elevation showed very good correlation with the unburned gas temperature without regard to the research octane number of fuel.

It is clear that there are some exothermic reactions in the end gas region starting at temperature of 700 K without regard to the knock occurrence. This low temperature reaction should be included in the chemical simulation to predict unburned gas temperature and occurrence of autoignition in combustion chamber of internal combustion engines accurately.

4. Conclusions

Coherent anti-stokes Raman Spectroscopy was used to measure the end-gas temperature in a conventional DOHC spark-ignition engine. The results can be summarized as follow.

1) End-gas Temperatures were measured by CARS technique in a conventional 4 cylinder DOHC spark-ignition engine fueled with PRF 80 and gasoline of various research octane numbers.

2) Significant heating effect by pre-flame reaction in the end gas zone was observed under both knocking and non-knocking conditions.

3) Pre-flame exothermic reaction began to occur when the cylinder pressure reached 1 400 kPa and the unburned gas temperature reached 700 K.

4) The temperature elevation due to the pre-flame reaction correlated better with the CARS temperature than with the cylinder pressure.

5) The temperature elevation showed very good correlation with the unburned gas temperature with all different research octane number fuel except the fuel of RON 100.4.

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