Unburnt Gas Temperature Measurements Using Single Shot CARS in a Spark Ignition Engine

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ABSTRACT

Coherent anti-stokes Raman spectroscopy (CARS) measurements of the gas temperature ahead of the flame front in the unburned end gas have been carried out in a spark ignition engine. The engine used in this study was fueled with gasoline (RON91.3) and air and operated under knocking and non-knocking conditions. Temperatures were determined by fitting the theoretical CARS spectra to the experimental measurements. Several methods to compensate the CARS signal for the dye laser fluctuations were tried to improve the accuracy; the final estimated accuracy in temperature is ±4 percent. Unburned end gas temperatures were measured for compression ratios of 10 and 12.

INTRODUCTION

Recently, some production gasoline engines have compression ratios greater than 10 to 1 in an effect to improve the thermal efficiency. However, for a given fuel octane number, the extent to which the compression ratio can be increased is restricted by the occurrence of autoignition in the unburned gas region. For the purpose of improving the anti-knock characteristics of the engine designs it would be helpful to understand the correlation between the unburned gas temperature and the parameters affecting knocking, such as the compression ratio. Since knocking is a very complex phenomena, and further more, 'the knocking intensity changes cycle by cycle, it is necessary to use a high temporal and spatial resolution technique to obtain the unburned gas temperature.

The CARS technique is a powerful method for analyzing the relationship between knocking and the end gas temperature in an S.I. engine. Although temperature measurement in an engine using CARS have been reported previously (1) (2), there are still many difficulties, especially when CARS is applied to the S.I. engine. In this report first the improvement of the accuracy of CARS is described through changing the laser optics, correcting for variations in a reference signal,etc. Second, the measurement of the unburned gas temperature in a spark ignition engine which has general specifications similar to production engines are described. The effect of the compression ratio increasing from 10 to 1 to 12 to 1 on the unburned gas temperature were examined. Additionally, temperatures measured using CARS were compared with temperatures calculated by a two-zone combustion model.

CARS EXPERIMENTAL APPARATUS

Optical set up

A block diagram to show an optical set up of the CARS system is shown in Fig.1. The pump beam is provided by the 532nm second harmonic of a Nd:YAG laser (Spectron SL803). Part of the 532nm laser radiation is also used to pump a broadband dye laser system centered at 607nm (Komatsu). The dye laser oscillator is transversely pumped and the amplifier is longitudinally pumped.

An intensified double diode array detector is used for measurement of the CARS spectrum. This system obtains both the CARS signal and a reference signal from CO_2 gas. The CARS signal

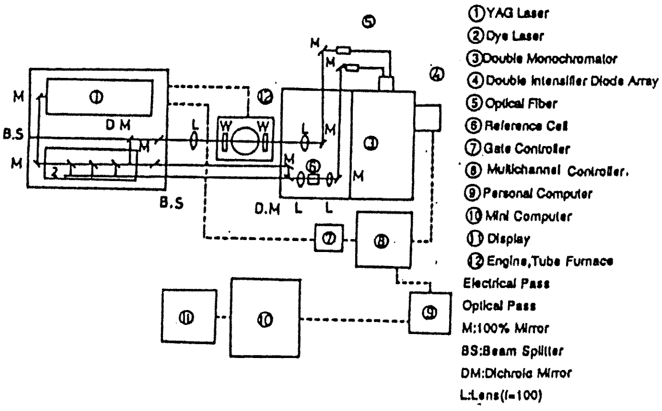


Fig.1 CARS Experimental Apparetus

can be normalized by the reference signal to minimize the effect of shot to shot fluctuation in the dye laser spectrum.

Measuring point in the combustion chamber

A schematic of the measurement geometry and location of the measurement point is shown in Fig.2. This measuring location was chosen because high speed shadowgraph pictures showed that autoignition normally began near this region as is previously reported (3). A distance from the cylinder wall to the measuring point is around 3 mm and from the cylinder head to the measuring point is around 5 mm.

An optical fiber as shown in Fig.2 was used to identify the flame arrival at the measuring point. For this purpose, a small aperture was used to limit the field of view of the fiber. This light emission signal was used to judge the location of the flame front to determine if the measurement was in the unburned gas region. Pressure transducer is installed in the cylinder wall near this measuring point.

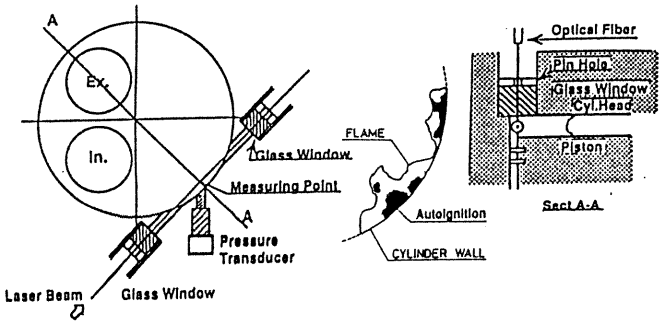


Fig.2 Combustion Chamber Configuration

Temperature measurement by CARS

A block diagram of the CARS temperature acquisition system is shown in Fig. 3. The upper portion shows an example of timing of CARS spectrum, flame arrival, knocking occurrence obtained by the high-pass filtering the pressure and a pressure in the combustion chamber. To obtain the temperature the measured CARS spectrum was compared with the theoretical spectrum using the codes CARP-3 and QUICK-2D developed by the Harwell Laboratory (4). CARP-3 includes the collisional narrowing effect, the doppler broadening effect and the cross-coherence effect. CARP-3 was used to prepare a spectrum library for the pressure at the timing of the measurement, and QUICK-2D was used to find a best match from this library with the measured spectrum. This method reduces the calculation time for comparison with the experimental data.

The measured temperature is determined by finding the minimum deviation between the measured CARS spectrum and the library of theoretical spectra calculated for different temperatures at the engine pressure.

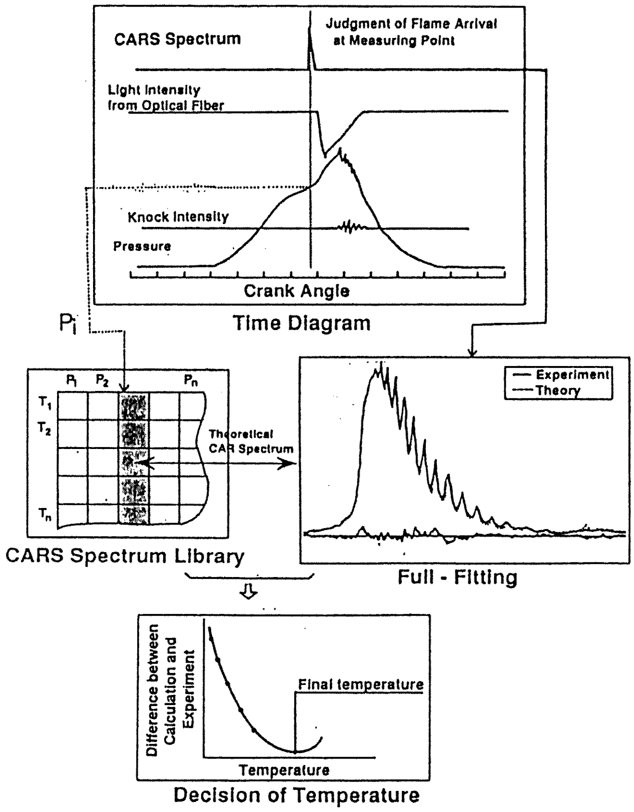


Fig.3 Block Diagram of Temperature Accquisition System

TEMPERATURE PREDICTION BY A TWO-ZONE FLAME PROPAGATION MODEL

A schematic diagram of the two-zone flame propagation model used in this study is shown in Fig. 4 (5). This model uses measured pressure data and the following assumptions; (i) the flame propagates spherically from the ignition point and the gas in the combustion chamber is divided into the unburned and burned zones by the flame front, (ii) the pressure within the combustion chamber is uniform and the temperature of the gas in both the unburned and burned zones respectively are uniform, (iii) a single constant value for the wall temperature is assigned to the cylinder head, cylinder and piston and Woschni's equation for the heat

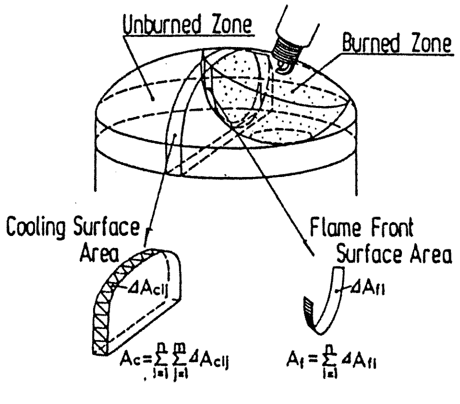


Fig.4 Schematic of the Two-zone Flame Propagation Model

transfer coefficient is used to obtain the cooling losses.

ENGINE SPECIFICATION AND OPERATING CONDITION

The test engine specifications used in this study are shown in Table 1. The fuel used is unleaded gasoline with a research octane number(RON) of 91.3. And the operating conditions are also summarized in Table 1. To obtain equivalent knocking condition at 10 to 1 and 12 to 1 compression ratio the ignition timing was set at +1° and -2° BTDC, respectively.

MODIFICATION OF TEMPERATURE MEASUREMENT ACCURACY

Tube furnace used in calibration

For testing the CARS system the tube furnace shown in Fig.5 is used. This tube furnace is controlled by an IR radiation thermometer and the accuracy is within ±15K at 1000K. The temperature in this tube furnace can be varied from 300K to 2200K and the maximum pressure allowed is 10 MPa.

Effect of CARS signal intensity

In Fig.6 the error in CARS temperature measurement is shown as a function of the reciprocal of the intensity of the CARS spectrum. These measurements were made in the tube furnace and power of YAG laser was changed to obtain different CARS intensities. Decreasing the signal intensity causes the measured CARS temperature to be lower and a correspondingly larger temperature error. The CARS signal intensity depends primarily on two parameters, the phase matching geometry and the pump laser power. The phase matching geometry is the most important because the laser power and other parameters are not practically variable for our engine experiments. The BOX-CARS geometry has higher spatial resolution but result in signal intensity about twenty times less than the co-linear geometry. To minimize the temperature error, the lower spatial resolution of the co-linear geometry was accepted. For this geometry the probe volume can be described as a cylinder of about 1cm long, diameter of 300μm (6). That is why the probe volume was set parallel to the flame front in order to avoid this volume crossing the flame front.

Dye laser spectrum shape

For accurate single shot CARS measurements it is necessary to take account of the variation in the spectral shape of the dye laser shot by shot. Two kinds of typical dye laser spectral shapes are shown in Fig.7. The difference between these spectra results from the configuration of the dye laser resonator; flat to flat and concave to wedge. As even in the modified dye laser spectrum cycle variation is still existed, the normalization by reference spectrum is necessary. Three kinds of reference methods shown in Fig.8-(a) are examined below.

Table 1 Engine Spec. and Operating Condition

Bore&Stroke:	85mm&106mm	Engine Speed:	1200 rpm
Displacement:	601.5cm	ϕ	: 1.18 (A/F=12.5)
Compression Ratio:	10:1 , 12:1	ηc	: 75 %
Combustion Chamber:	Disk	Ignition Timing:	1° and -2° BTDC
		Fuel	: Gasoline (91.3 RON)

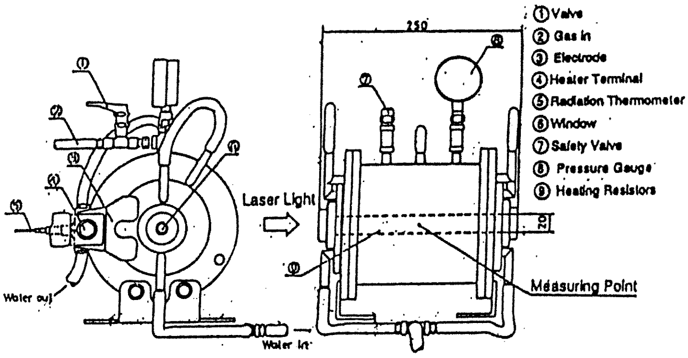


Fig.5 Tube Furnace

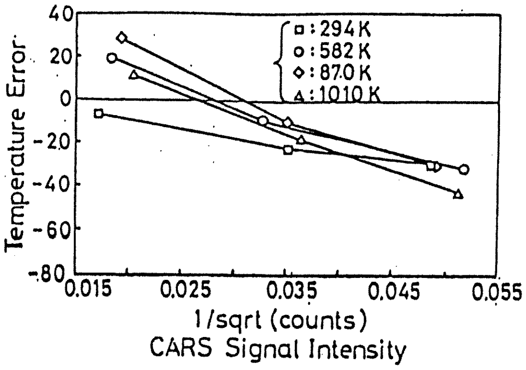


Fig.6 Average Temperature Error

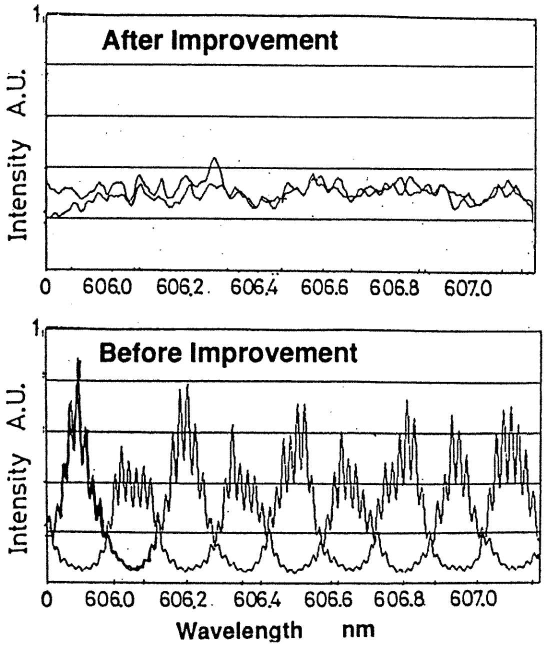


Fig.7 Dye Lser Spectrum

(i) The CARS signal is normalized by an averaged dye laser spectrum to compensate for fluctuations, (Average method).

(ii) The CARS signal is normalized by the dye laser spectrum for each shot (Single shot method).

(iii) The CARS signal without normalization.

The temperature accuracy was determined for the six cases of these three technique and two dye laser configurations shown in Fig.8-(b). In this figure the vertical axis is the minimum square difference between experimental and calculated CARS spectrum, while the horizontal axis is the temperature error between the tube furnace and the CARS measurement. Two conclusion can be obtained as stated below.

(a) The variation of the intensity of the dye laser with wavelength should be as small as possible. Thus a concave mirror and a wedge out put coupler should be used as the resonator of dye laser (7).

(b) Since the spectral shape of the CARS measurement depends on the dye laser spectrum, the CARS spectrum should be normalized by the reference spectrum for each shot.' However, as is seen in Fig.8-(b), a lower precision is actually found by this method compared to using an averaged dye laser reference spectrum. This is caused by the temporal fluctuations of the YAG laser, and it would be necessary to reduce the fluctuations of the YAG laser, for example by use of an injection seeder (8). As this equipment was not available, the best results for this experiment are obtained by normalization of the CARS spectrum by the averaged dye laser spectrum.

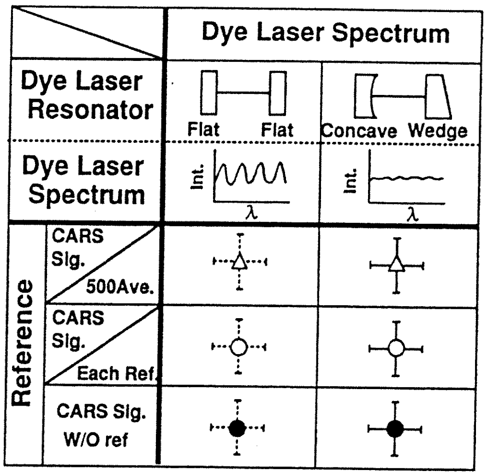


Fig.8-(a) Examined Dye Laser Spectrum and Normalization

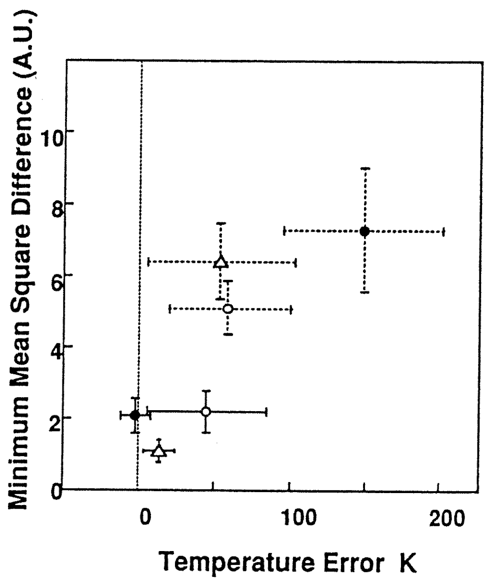


Fig.8-(b) Temperature Error due to Dye Laser Spectrum and Normalized Methord

Non-resonant background susceptibility

Under engine conditions the nonresonant susceptibility of the fuel has a significant effect on the measured CARS temperature. The value of this susceptibility was obtained from the experiment to minimize the spectra difference.

Accuracy of single shot CARS

Fig.9 shows the improvement in accuracy resulting from the increased signal intensity and single shot normalization of the spectrum. These data were taken using the tube furnace. Averaging 80 single shot measurements gives an accuracy of ±4%.

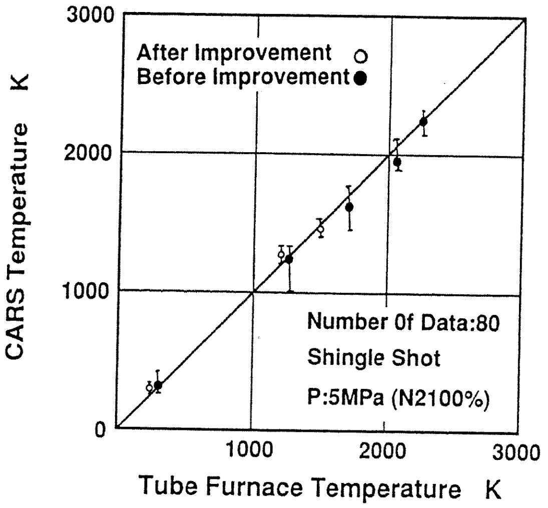


Fig.9 Temperature Accuracy of CARS

RESULTS AND DISCUSSION

A typical time diagram of the supporting measurements for the CARS temperature is shown in Fig.10. This figure shows the pressure in the combustion chamber, the knock intensity, and the light emission as a function of the crank angle. The frequency of knocking occurrence under the both driving condition such as the compression ratio of 10 and 12 is the same as shown in Table 2. The principal results of this study are shown in Fig.11, where temperature is shown as a function of crank angle for several different conditions. Also shown on this figure are the predictions from the two-zone flame model.

First, under motoring conditions, it can be seen that the temperature at TDC for 12 to 1 is a bit higher than for 10 to 1, as is predicted by the two-zone flame propagation model. When fuel is added, under motoring conditions, the temperature is a bit higher than without fuel even in the same compression ratio. This temperature increase is thought to be the result of partial chemical reaction and oxidation of the fuel.

Second, under combustion condition temperatures measured by CARS at TDC are around 100K higher than the temperatures calculated by the two zone flame propagation model in which non-heat release in the unburned gas is estimated. Again, the occurrence of partial chemical reaction in the unburned mixtures is responsible for the temperature difference between experiment and model calculation.

Third, the temperatures just before autoignition occurrence are about 150K higher than the temperature at TDC. This is also due to further partial chemical reaction of the fuel under compression by the flame expansion. Also, by increasing the compression ratio from 10 to 1 to 12 to 1, the unburned gas temperature just before the occurrence of autoignition rises from about 1020K to 1100K.

Also shown in Fig.11 are some single shot data at same crank angle. The standard deviation of the temperature obtained by single shot CARS is larger than the standard deviation of the cycle-averaged CARS and the mean value of the one shot CARS is 50 deg. higher than the cycle-averaged CARS. And also the cycle to cycle fluctuations in temperature are considerably larger than the 4% accuracy measured for the CARS temperature under calibration conditions. Thus these measurements reflect the true state of the unburned gas and are not due to errors in the measured CARS temperatures. Fig.12 shows the cyclic variation of autoignition location by means of high speed shadowgraph pictures. Each picture belongs to the same crank angle and comes from the different cycle under the same experiment. Black portion corresponds to the flame front and autoignition location in unburned area. Autoignition location is different from each other, therefore, the deviation of temperature by single shot CARS and cycle-averaged CARS will depend on the cyclic variation of autoignition location.

SUMMARY

CARS temperature measurements in the unburned gas region of an internal combustion engine under knocking condition have been obtained. When this compression ratio is increased from 10 to 12, unburned gas temperature just before autoignition increases from about 1020K to 1100K.

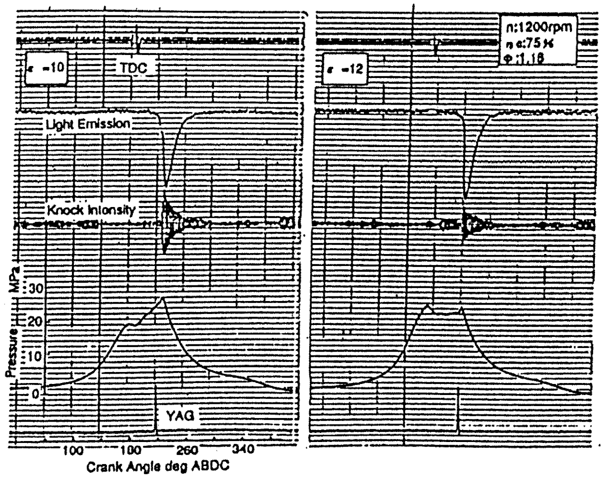


Fig .10 Time Diagram of Temperature Measurment

Table 2 Frequency of Knocking Occurrence

DrivingCondition	Number of Cycle		Ratio
	Knocking Occurred	Without Knocking	
ε=10,I.A.=1°BTDC	103	53	2 : 1
ε=12,I.A.=-2°BTDC	109	47	2 : 1

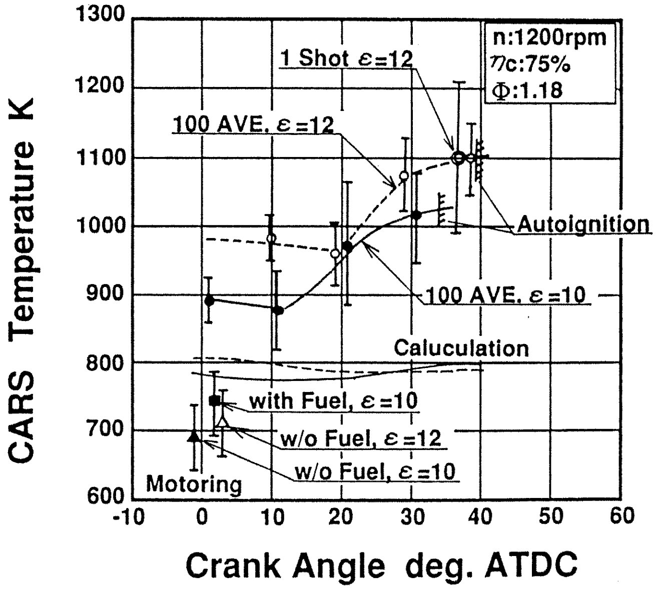
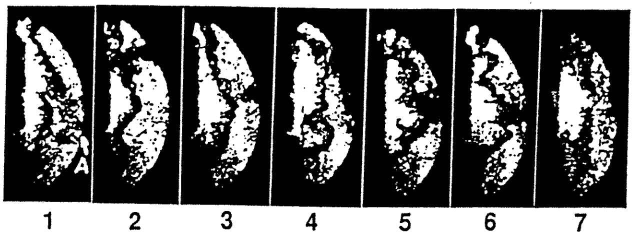


Fig.11 Evorution of Unburned Gas Temperature



ε =10:1
Ne=1200rpm
η_c=80%
I.A.=16°BTDC(Light Knock)
Fuel:Gasoline(RON91.3)
Film Speed:32000fps
Exposure Time:0.8μsec

Fig.12 Cycle Variation of Autoignition Location

Under motoring condition there is partial reaction of the fuel, which results in the higher temperatures measured with fuel compared to without fuel. In each cycle, the autoignition location is different, and sometimes obscure, so the deviations of temperature measured are a result of engine cycle variation.
The higher the compression ratio increases, the higher the pressure becomes. In general, the ignition timing is retarded in order to decrease the knock intensity. Therefore, the thermal efficiency decreases under W.O.T. condition in spite of the higher compression ratio. When the ignition timing is retarded, the pressure at the autoignition occurrence gets lower and the temperature gets higher as shown in Fig.11. This phenomena is described by the theory of explosion limit described below.

$\ln P = A/T + B$; p:pressure, T:temperature, A,B:constant

Additionally, the two stage exothermic reaction at TDC and 35° ATDC seems to be due to the chemical reaction, so called a two-stage chemical reaction already reported by the rapid compression machine.(9)

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REFERENCES

1.D.A.Greenhalh,D.R.williams and C.A.Baker, Proc.Autotech.Conference,1.Mech.E.(1985)
2.D.Klick,K.a.Marko and L.Rimai,Appl.Opt.20, 1178(1981)
3.T.Itoh,Y.Takagi,T.Iijima,Y.Nakagawa, S.A.E.845001
4.D.A.Greenhalh,W.A.England and F.M.Porter, Comb and Flame 44,171(1983)
5.S.Muranaka,Y.Takagi and T.Ishida, S.A.E.870548
6.J.J.Marie,M.J.Cottereau, Symp JRC-Comb 23-24 Sept.,(1985)
7.D.A.Greenhalh and S.T.Whittley, Appl.Opt., 24,907, (1985)
8.D.R.Snelling,R.A.Sawchuk and G.J.Smallwood, Appl.Opt.,23,4083,(1984)
9.J.F.Griffiths,S.M.Hasko, Proc.R.Soc.Lond.,(1984)