Simultaneous CARS Measurements of Temperature and CO_2 Concentration applied to the Study of the Effect of the Residual Gas Fraction on Combustion in an S.I. Engine

M.Lebel-Simon and M.J.Cottereau
CORIA, U.R.A. CNRS 230, Université de ROUEN
76821 Mont Saint Aignan Cedex
France

ABSTRACT

Local simultaneous measurements of temperature and CO_2 concentration (tracer of the residual gas) have been performed in a spark ignition engine using CARS technique in order to study the effect of the residual gas fraction on combustion.

The measurements were made either very near the spark plug (1 mm) or at a larger distance (2.4 or 4.3 cm), varying the equivalence ratio, the speed and the load of the engine.

Various correlations were studied. The CO_2 concentrations and the temperatures correlate well giving confidence on the validity of the measurements. The correlations found between the CO_2 concentration and the maximum pressure, and those between the concentration and the crank angle of maximum pressure, indicate that the residual gas fraction influences the combustion processes differently during the ignition period and during the flame propagation period.

INTRODUCTION

Reduction of cycle-to-cycle variations is an important issue to improve the performances of modern S.I. engines. Actually, the various parameters controlling the engine (spark timing, air/fuel ratio, injection timing ...) are optimised for the average cycle and due to cycle-to-cycle variations they are always compromises which are not optimized for a given cycle.

Three factors (1) have been found to influence the cycle-to-cycle variations of the cylinder pressure versus time:

* The variation in gas motion in the cylinder : mean flow velocity and turbulence structures.

* The variation in the amounts of fuel, air and recycled exhaust gases.

* The variation in mixture composition within the cylinder, especially near the spark plug. These variations are actually consequences of the two first causes.

A limited number of studies have been devoted to the effect of the variations of the residual gas amount and mixing, probably due to the lack of experimental techniques to measure the residual gas local concentrations. In these studies (2, 3, 4, 5) rapid acting sampling valves have been used.

For a few years we have applied the CARS (Coherent Anti-Stokes Raman Spectroscopy) technique to simultaneously measure the temperature and the CO_2 concentration in an engine (6). In a previous paper (7) we have shown that the method can be used to study the effect of the residual gas fraction on the combustion in an S.I. engine. The measurements were performed in an engine fueled with isooctane by a carburettor. Therefore a large part cycle-to-cycle variations was due to variations in the amount of fuel supplied to the cylinder each cycle. In the experiments reported in this paper the engine have been fueled with propane. Much better stable operating conditions have been achieved and the residual gas variations effects could have been studied more accurately.

EXPERIMENTAL

Engine

The engine has been developed by GSM (Groupement Scientifique Moteur) from a production four cylinder engine block. Only one cylinder is active. An elongated piston bolded over the original piston slides into a chrome cylinder liner. Carbon rings are used, without any lubricating oil. The combustion chamber has a cylindrical shape (flat cylinder head and flat piston) except in a crosspiece which holds the rectangular windows (20 mm wide and 11.8 mm high). The engine specifications and operating conditions are given in Table 1.

TABLE 1 Operating conditions

N° of cylinders : 1 Bore : 86.15 mm
Capacity : 466 cm^3 Compression ratio : 4.7 : 1
Fuel : Propane Spark advance : 26° before TDC
Ratio of connecting rod length to crank radius : 3.341
Equivalence ratio : 0.8 , 1.0 and 1.2
Speed : 1200 and 1800 rpm
Load : 15% , 50% and 100%

Three types of ignition have been used :

* Usual ignition, a conventional spark plug is located on the cylinder head. In that case the volume probed by CARS, which is always at the center of the clearance volume of the combustion chamber, is at 2.4 cm away from the spark.

* Multiple ignition, three spark plugs are regularly spaced around the circumference of the crosspiece which holds the windows. The distance between the probe volume and the spark is then d = 4.3 cm (Fig 1).

* Central ignition, in order to have the spark close to the probe volume the spark plug is equiped with elongated electrodes. The spark is located at 1 mm of the center of the probe volume (Fig 1).

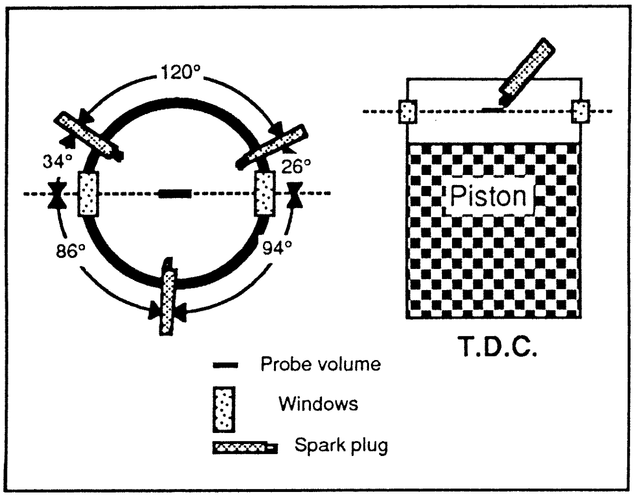

Fig 1 Locations of the spark plugs.

CARS System

A frequency doubled single-mode Nd-Yag laser provides the pump beam and synchronously pumps two dye lasers. One, which is broadband (centered at 607 nm), is used to determine the temperature from the N_2 spectra. The other is narrowband and is tuned to a Raman active transition of CO_2 (571.3 nm).

Shot-by-shot, four signals are collected on an ISIT Vidicon camera at the exit of a spectrograph. Two of them, generated in a reference cell filled with 4 bars of argon, are send to the upper part of Vidicon target. The other two issued from the engine are send to the lower part of the target.

In order to obtain good single-shot measurements the collinear beam configuration is used in detriment to spatial resolution. The probe volume is cylindrical, approximately 1 cm in length and 100 µm in diameter. To eliminate the non-resonant background the crossed polarization technique is used.

Processing. The detailed description of the procedure used to process the four signals collected on the camera is given in reference (7). The measurements signals from the engine are divided channel by channel by the reference signals from the argon cell in order to correct for the dye lasers spectral fluctuations. Then the nitrogen signal is compared to theoretical spectra (at the pressure simultaneously measured in the engine) to obtain the temperature.

Once the temperature known the CO_2 concentration relative to the nitrogen concentration is determined : the ratio of the experimental CO_2 signal by the N_2 signal is compared to computed values using theoretical N_2 and CO_2 CARS spectra. With this in-situ referencing technique most of the shot-by-shot intensity fluctuations of the signals are eliminated.

RESULTS

Accuracy of the temperature measurements

In order to check the accuracy of the temperature measurements, the temperature was measured during the compression stroke of the motored engine. Figure 2 gives an example of the histogram of the measured temperature. The experimental values are compared in Figure 3 with the temperature evolution computed from the measured pressure (in order to take into account heat and mass losses). The errors bars are the standard deviation of the measurements ($\sigma_T \leq 50$ K).

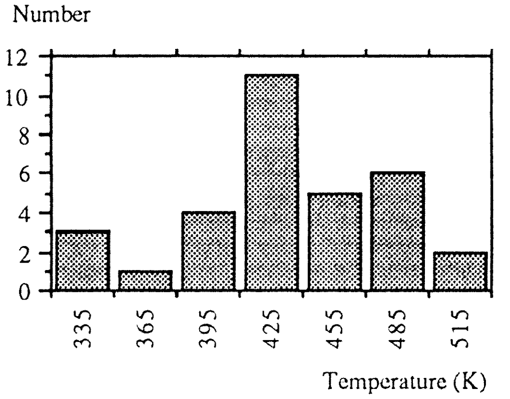

Fig 2 : Histogram of temperature, the measurements were performed at 10 deg before T.D.C., the engine is motored.

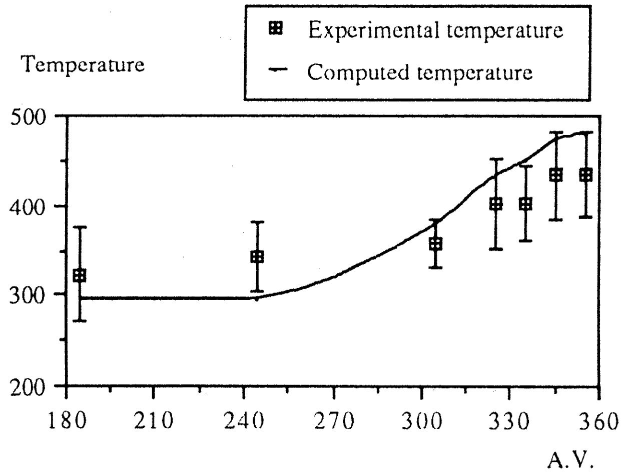

Fig 3 Comparison between experimental and computed temperatures during the compression stroke of the motored engine.

When the engine is fired the temperatures are higher, the standard deviations increase to $\sigma_T \geq 80$ K and the histograms are quite different (Fig 4). The temperature depends on the residual gas fraction, the higher the residual gas fraction, the higher the temperature as shown, for example, in Fig 5. A good correlation is found between the measured temperature and the measured CO_2 concentration which is a tracer of the residual gas. The larger dispersion of the single shot measurements compared to the motored case is due to cycle-to-cycle variations of the residual gas fraction (RGF) and/or variations in the mixing between the fresh and the residual gases. We have compared the measured temperatures and their standard deviations to computed temperature evolutions, assuming that the residual gas at 1000 K is homogeneously mixed with the fresh gas at 300 K. An example of such a comparison is shown in Fig 6. Two curves are computed, they correspond to the RGF determined from the measured

CO_2 concentration plus or minus one standard deviation. The comparison is good both in terms of absolute values and in terms of variations. Figure 7 shows an other example of the comparison. The load is in this case 15% and as it is well known the residual gas fraction is larger.

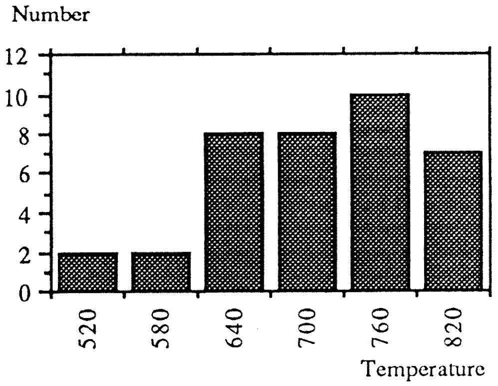

Fig 4 Histogram of temperature, the measurements were performed at 8 deg before T.D.C., the ignition was accomplished by an usual spark plug, the load was 50%, the rotational speed was 1200 rpm, ϕ = 1.0, the fuel was propane.

Correlations

The purpose of this work was to further study the effects of the residual gas on the cycle-by-cycle pressure history. As in Reference (7) we have studied the correlations between the CO_2 concentrations and either the maximum pressure P_{max} reached in the cycle, or the crank angle Apm of occurence of the maximum pressure.

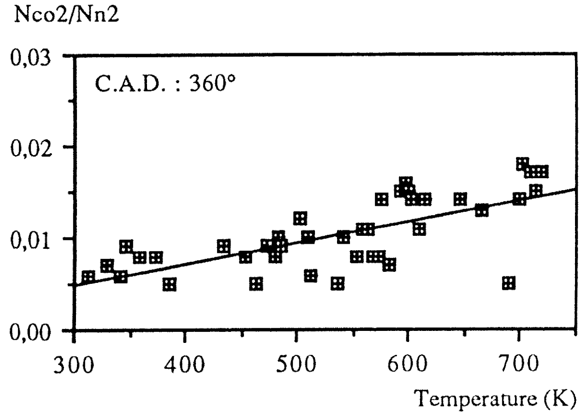

Fig 5 Scatter plots of [CO2] versus T, the measurements were performed at T.D.C., the ignition was accomplished by an usual spark plug, the load was 50%, the rotational speed was 1800 rpm, ϕ = 1.0, the fuel was propane, a correlation coefficient of $\rho = 0.682$ is found.

To be informative the measurements have to be done just before the flame arrival at the volume probed by CARS. Due to cycle-by-cycle variations, although the spark advance is constant, this does not happen exactly at a given crank angle. The CARS measurements being made at a given crank angle, chosen as close as possible of the flame arrival, it happens that a few measurements are performed with burned gases present in the probe volume. This is evident in Fig 8, where for a few measurements temperature and CO_2 concentration are too high. To keep only the measurements made in the unburned gas we have arbitrarily rejected the values for which [CO_2] exceeds the mean value by more than one standard deviation and for which T> 850 K. T = 850 K corresponds to the theoritical temperature, computed for the measured [CO_2] maximum, increased by one standard deviation. In most cases as in example given in Figure 8 the two conditions are fulfilled simultaneously.

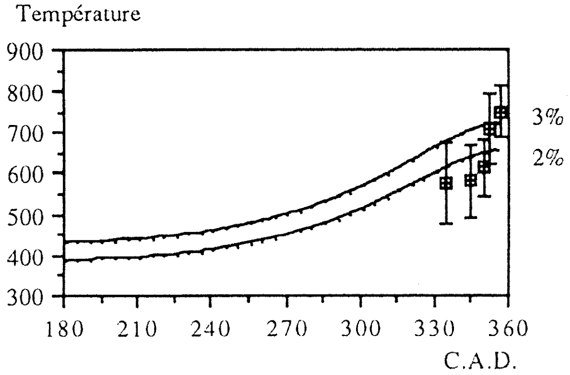

Fig 6 Comparison between experimental and computed temperatures during the compression stroke of the fired engine, the ignition was accomplished by an usual spark plug, the load was 50%, the rotational speed was 1200 rpm, ϕ = 1.0, the fuel was propane.

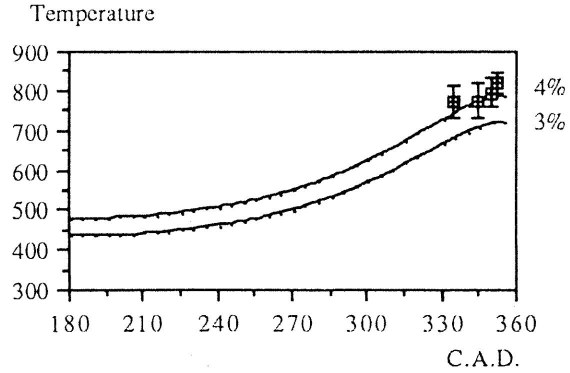

Fig 7 Comparison between experimental and computed temperatures during the compression stroke of the fired engine, the ignition was accomplished by 1 spark plug with elongated electrodes, the probe volume was at 4 mm under the spark, the load was 15%, the rotational speed was 1200 rpm, ϕ = 1.0, the fuel was propane.

Figures 9, 10, 11 and 12 show examples of scatter plots of [CO_2] versus P_{max} or Apm and the correlations found. Table 2 gives the values of the correlations ([CO_2]-P_{max}) found in all the experimental conditions studied.

DISCUSSION

Table 2 shows that the correlations between [CO_2] and P_{max} are negative for lean and stoechiometric mixture and are null for the rich mixture, when the measurements are made at 1 mm from the spark plug. On the contrary for the measurements made at a larger distance from the spark plug the correlations are positive (or null for the lean mixture).

The signs of the correlation coefficients (Apm - [CO_2]) were found in each case opposite to the ones in Table 2.

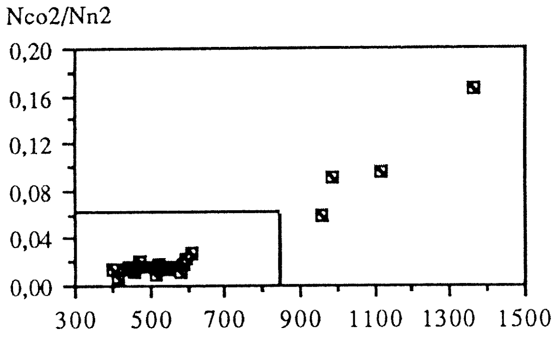

Fig 8 Scatter plots of [CO2] versus T, the measurements were performed at 20 deg before T.D.C., the ignition was accomplished by 1 spark plug with elongated electrodes, the probe volume was at 1 mm under the spark, the load was 50%, the rotational speed was 1200 rpm, $\phi = 1.0$, the fuel was propane.

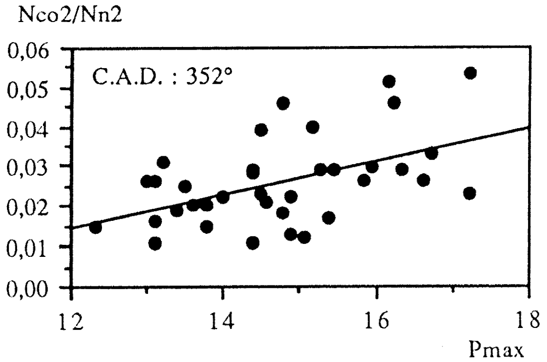

Fig 9 Scatter plots of [CO2] versus P_{max}, the measurements were performed at 8 deg before T.D.C., the ignition was accomplished by an usual spark plug, the load was 50%, the rotational speed was 1200 rpm, $\phi = 1.0$, the fuel was propane, a correlation coefficient of $\rho = 0.479$ is found.

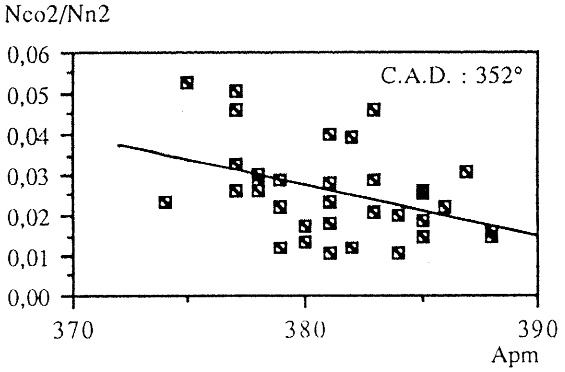

Fig 10 Scatter plots of [CO2] versus Apm, the measurements were performed at 8 deg before T.D.C., the ignition was accomplished by an usual spark plug, the load was 50%, the rotational speed was 1200 rpm, $\phi = 1.0$, the fuel was propane, a correlation coefficient of $\rho = -0.406$ is found.

In the following we propose an explanation to these apparently contradictory results.

The effects of the RGF on the pressure trace, i.e. on the combustion process, must be studied in two steps : during the initiation of the flame and during the propagation of the flame.

During the initiation period the electric energy supplied by the spark is transformed into thermal and chemical energies until a stable self-propagating flame is established (8). At this time the diameter of the flame is of the order of a few millimeters. The temperature in the spark plasma is very high and does not depend on the mixture initial temperature. The composition of the mixture is very important and a minimum radius is required for inflammation of the fuel-air mixture to occur. This radius increases rapidly as the mixture is leaned out or diluted.

Table 2 Correlations $[CO_2]$ - Pmax

Spark configuration	Equivalence ratio											
	$\phi = 0.8$				$\phi = 1.0$				$\phi = 1.2$			
Usual ignition one spark plug d = 2.4 cm			Rotational speed				Rotational speed				Rotational speed	
			1200 rpm	1800 rpm			1200 rpm	1800 rpm			1200 rpm	1800 rpm
	load	50 %	0.016	0.208	load	50 %	0.479	0.158	load	50 %	0.363	//////
		100 %	0.068	//////		100 %	0.487	//////		100 %	0.814	//////
Multiple ignition 3 sparks plug d = 4.3 cm			Rotational speed				Rotational speed				Rotational speed	
			1200 rpm	1800 rpm			1200 rpm	1800 rpm			1200 rpm	1800 rpm
	load	50 %	0.161	- 0.148	load	50 %	0.241	0.262	load	50 %	0.274	0.47
Central ignition one spark plug with elongated electrodes d = 1 mm			Rotational speed				Rotational speed				Rotational speed	
			1200 rpm				1200 rpm				1200 rpm	
	load	50 %	- 0.241		load	50 %	- 0.512		load	50 %	0.085	
fuel : Propane												

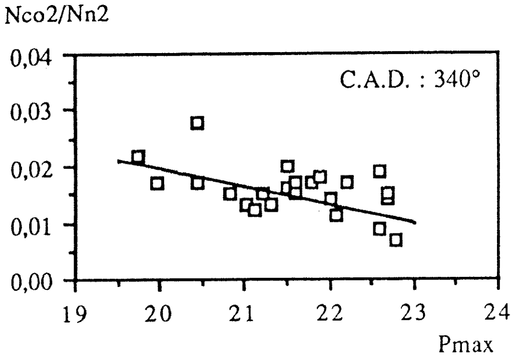

Fig 11 Scatter plots of [CO_2] versus P_{max}, the measurements were performed at 20 deg before T.D.C., the ignition was accomplished by 1 spark plug with elongated electrodes, the probe volume was at 1 mm under the spark, the load was 50%, the rotational speed was 1200 rpm, ϕ = 1.0, the fuel was propane, a correlation coefficient of $\rho = -0.512$ is found.

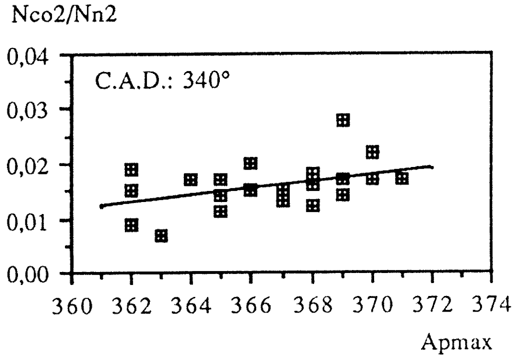

Fig 12 Scatter plots of [CO2] versus Apm, the measurements were performed at 20 deg before T.D.C., the ignition was accomplished by 1 spark plug with elongated electrodes, the probe volume was at 1 mm under the spark, the load was 50%, the rotational speed was 1200 rpm, ϕ = 1.0, the fuel was propane, a correlation coefficient of $\rho = 0.426$ is found.

Therefore the larger the amount of residual gas present within the spark plug at the time of the spark, the more difficult is the inflammation. As a consequence the burning time will increase with the residual gas fraction unless it is conteracted by an opposite effect. For $\phi = 0.8$ and $\phi = 1.0$ the correlation coefficient [CO_2] - Apm is effectively positive showing that the larger the RGF the larger the burning time. As a consequence the peak pressure decreases with the RGF and the correlation coefficient [CO_2] - P_{max} is negative. For the $\phi = 1.2$ the two correlation coefficients are null, the lengthening of the inflammation time is compensated by a shortening of the flame propagation time.

The residual gas fraction influences the flame velocity by two opposite effects. The increase of the dilution of the mixture with the increase of the RGF decreases the flame velocity. On the contrary the increase of the mixture temperature with the increase of the amount of hot residual gas increases the flame velocity.

Actually, the two effects have been studied independantly in bomb experiments (9 to 14). The dilution by residual gas have been studied by adding to a fuel-air mixture at room temperature a mixture of N_2-CO_2 also at room temperature. The effect of temperature have been studied by heating, before inflammation, fuel-air mixtures. These bomb experiments give the variations of the laminar flame velocity. It is assumed than, in the engine, the turbulent flame velocity is proportional to the laminar flame velocity. The relations given by the various autors are the following :

$$S_l = S_{lo}\left(\frac{T}{298}\right)^{\alpha} (P)^{\beta} \quad (9) \qquad S_l = 27\ p^{-0.16}\left(\frac{T}{298}\right)^{2.18} \quad (10)$$

$$S_l = \left(404 \log T - 1008\right) p^{(-0.39 - 0.0004\ T)} \quad (11)$$

$$S_l = 2965.5\ p^{-0.051}\ e^{-\left(\frac{2008.8}{T}\right)} \quad (12)$$

$$S_l = 12.1 + 21.9\left(\frac{T}{298}\right)^{2.19} \quad (13)$$

$$\frac{S_l(f)}{S_l(0)} = 1 - 2.5\ f \quad (12)$$

$$\frac{S_l(f)}{S_l(0)} = 1 - 2.1\ f \quad (10) \qquad \frac{S_l(f)}{S_l(0)} = 1 - 3\ f \quad (14)$$

T and P are, respectively, the unburned mixture temperature (K) and pressure (atm). Slo is the laminar flame velocity at 298 K and 1 atm. f is the residual gas mass fraction. α and β are coefficients depending on fuel and equivalence ratio.

Table 3 Relative variations of the laminar flame velocity for a given variation of the residual gas fraction (see text).

	Equivalence ratio		
	$\phi = 0.8$	$\phi = 1.0$	$\phi = 1.2$
	Effect of temperature		
Metghalchi (1980)	39.7 %	30.1 %	37 %
Metghalchi (1982)	37.8 %	30.8 %	39.1 %
Babkin (1967)	30.8 %	26.7 %	32.2 %
Ryan (1980)	52.8 %	46.5 %	55.8 %
Heimel (1957)	34 %	27.8 %	32.3 %
	Effect of dilution		
Metghalchi (1980)	- 25 %	- 21 %	- 26.8 %
Ryan (1980)	- 32.4 %	- 25.4 %	- 33.8 %
Cho (1992)	- 42 %	- 30.6 %	- 43.9 %

In Table 3 we have reported the relative variations of the laminar flame velocity computed using the above relations for a variation of the residual gas fraction corresponding to the CO_2 concentration relative to nitrogen varying from 0.014 to 0.026 (which is the mean range of variation measured in the experiments). Only the relations given in reference (9) explicitly depend on the equivalence ratio. The other relations have been established for a stoechiometric mixture. The values reported in Table 3 for $\phi = 0.8$ and $\phi = 1.2$ have been computed using these unique relations. It can be seen in Table 3 that the results significantly depend on the relation used. However when the two influences are studied by the same author, the effect of temperature is always larger than the effect of dilution.

The correlations found in Table 2 for the measurements made at 4.3 cm or 2.4 cm can therefore be explained. The measured CO_2 concentration represents the mean conditions encounted by the flame during its free propagation. Therefore the larger the temperature (larger the CO_2 concentration) the fastest the combustion and the correlation coefficient [CO_2] - P_{max} is positive (and the correlation coefficient [CO_2] - Apm is negative). The increase of the flame velocity with the temperature overcomes on average the larger inflammation time. For a lean mixture the effect on the inflammation time is larger and is just compensated by the increase of the velocity with temperature. Inversely for a rich mixture, even for a large amount of residual gas near the spark plug, the increase of velocity with temperature compensates the larger inflammation time and the correlations for the measurements made at 1 mm are null.

Comparable results have been already found in the measurements reported in reference (7), dealing with the engine fuelded with iso-octane with an equivalence ratio of 1.1. Due to the larger variations, in that case, of the amount of fuel provided at each cycle the coefficient of correlations were smaller (0.1 - 0.2). The results found in the present study therefore confirm the tentative explication given in reference (7) which have been developped here.

Analogous results have been reported by Gardiner (15). In this study hot recycled exhaust gas (using prompt exhaust gas recirculation, Prompt EGR) are added to the mixture by a brief reoppening of the exhaust valve. Up to a Prompt EGR of 11% an improvement of the peak pressure is observed, contrary to the observations with usual EGR.

SUMMARY and CONCLUSIONS

Simultaneous single-shot measurements of local CO_2 concentration and temperature have been performed in a fired S.I. engine during the compression stroke. The measured temperatures compare well with the temperature computed from the mixture of fresh gas and the amount of hot residual gas deducted from the CO_2 measured concentration.

The correlations found between the CO_2 concentration and the crank angle of maximum pressure or the value of this maximum can be analysed by the following plausible explanation:

Cycle-by-cycle variations in the mean residual gas fraction and in the mixing of the residual gas with the fresh mixture affect the combustion processes in two ways :

- The larger the local amount of residual gas near the spark plug the more difficult the inflammation.
- The larger the mean amount of residual gas the fastest the combustion, due to an increase of the flame velocity with the temperature, which overcomes the decrease with the dilution.

The net effect on the combustion depends on the equivalence ratio. It can be thought that with the residual gas fractions (RGF) encounted in this study, a larger RGF gives a larger peak pressure unless a poor mixing gives a high residual gas fraction near the spark plug. This effect is more important for lean mixtures.

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