Simultaneous Temperature and CO_2 Concentration Measurements by CARS in an Engine

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ABSTRACT

Simultaneous CO_2 concentration and temperature have been performed inside a fired engine. A model has been developed to accurately compute the theoretical CO_2 CARS spectra at high pressure and high temperature needed to process the experimental data. To overcome the main difficulties encounted when achieving measurements into an engine (i.e cycle-to-cycle variations and beam steering by density gradients), the shot-by-shot referencing technique and the in-situ referencing technique using N_2 to determine $[CO_2]$ were used.

In the burnt gas the CO_2 CARS signal is weak and only a rough estimation of the concentration has been achieved so far.

During the compression stroke the signal is much stronger (due to the lower temperature) despite the weak amount of CO_2 and accurate measurements could be performed. The correlations found between temperature and CO_2 concentration and the variation of $[CO_2]$ with the crank angle, suggest that the mixture of fresh and residual gases is inhomogeneous.

INTRODUCTION

Optimizing the balance between fuel economy, emissions and performance is the challenge met when designing modern IC engine. Without doubt the success will result thanks to a better understanding of the process which control the combustion. As a part of the research effort aimed at this goal, new optical diagnostic techniques have been adapted to engine as soon as they became available. CARS, in particular was very early applied to engine, mainly for thermometry purpose [1,4].

Measurements by CARS into an engine is complicated, compared to measurements performed into less hostile devices, by the following specific features :

-The size of the chamber is small and has to be accessed through windows.
-Strong temperature and density gradients are likely.
-The ranges of temperature, pressure and species concentration encounted are large.

-Cycle-to-cycle variations add difficulties to the unsteady and turbulent characters of the combustion process.

To overcome the problems one has to develop his own strategy which would mainly depend upon the answer given to the last point.

Unlike most of the authors we have chosen to perform single-shot measurements. In the next paragraph, devoted to the experimental approach, we will analyse the implications of such a choice.

The last paragraph is devoted to presentation and discussion of the results we have obtained in measuring simultaneously the temperature and the concentration of CO_2 into an engine.

EXPERIMENTAL

Engine

The measurements have been performed in an engine developed by G.S.M. ("Groupement Scientifique Moteur") which has the needed optical access. An elongated piston, bolted over the piston of a production engine crank case, slides into a chrome cylinder liner without lubricating oil. The combustion chamber has a cylindrical shape (flat cylinder heat and flat piston) except in a crosspiece holding rectangular windows (20mm wide and 11.8mm high). The compression ratio is 4.7 : 1 and the engine is fueled with isooctane thanks to a commercial carburettor. In the experiment reported here the engine was ignited with three spark plugs fired simultaneously at 21 degrees before TDC. The plugs are regularly spaced around the circumference of the crosspiece which holds the windows.

The CARS measurements are performed at a given crank angle about every 1 second. The pressure is measured by a transducer as function pressure traces of the crank angle, at each cycle, but only cycles during which a CARS measurements occurs are stored.

CARS systems

The CARS system was developed in collaboration with ONERA and SOPRA. It consists

of a frequency-doubled single-mode Nd:YAG laser which generates the pump beam and of two independant dye lasers, pumped synchroneously by parts of the YAG laser output. One of them is a broadband laser ($60 cm^{-1}$) allowing determination of the temperature on N_2 , the other one is a narrowband laser ($0.25 cm^{-1}$) tuned on a Raman-active transition of the second species to be studied, CO_2 in the present work.

The beams are first focused by a 0.3m focal length achromat into a cell filled with 3bars or Argon. The two non-resonant anti-Stokes signals (reference signals) generated in the cell are isolated from the laser beams with dicroic filters and send to the upper part of the slit of a spectrograph. The laser beams are then focused again by a 0.2m focal length achromat into the center of the combustion chamber, and the two anti-Stokes signal (one from N_2, the other from CO_2) are send to the lower part of the slit of the spectrograph. At the exit of the spectrograph four signals (two references and two signals) are received on four distinct locations on an ISIT Vidicon camera. Two mirrors inside the spectrograph allow the CO_2 and N_2 spectra to be collected on the same receptor with the spectral dispersion needed to obtain the good spectral resolution ($1.2 cm^{-1}$) required for accurate determination of the temperature, despite the spectral gap between the two spectra. Figure 1 shows an example of the four signals registred on the camera.
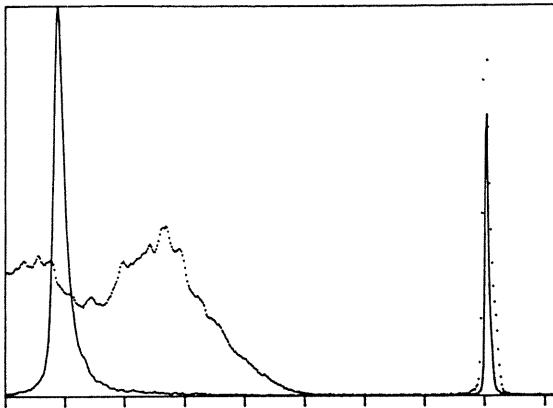
SIGNAL & REFERENCE

Fig.1 -Reference and Measurement signals on the camera

The choice of a short focal length (0.2m) lens to focus the lasers beams inside the combustion chamber is imposed by the presence of the windows because it is necessary to keep the size of the beams large enough when they cross the windows to avoid optical damages. As a consequence the size of the volume of interaction if the BOXCARS configuration was used would be very small. The CARS signals would be very weak and the signal-to-noise ratio too poor to allow good single-shots measurements. To perform single-shot measurements it is therefore necessary to have recourse to the colinear beam configuration in detriment to the spatial resolution. The probe volume is cylindrical, 1cm in length and 100µm in diameter. With this configuration it was possible to eliminate the non-resonant background, using the crossed polarization technique (which decreases the

signal by a factor of 16). This procedure which is very useful for obtaining a good determination of the temperature (otherwise accurate knowledge of the non-resonant background is necessary [5]) was absolutely needed for the concentration measurements.

Processing

Four signals are collected on the ISIT camera.

Two reference signals

$$P^{ref}_{CO_2 \omega_{AS}} = C_1 P_L^2 P_{CO_2 \omega_S} \left| \chi^{Ar}_{NR} \right|^2 N_{ref}^2 \qquad (1)$$

$$P^{ref}_{N_2 \omega_{AS}} = C_2 P_L^2 P_{N_2 \omega_S} \left| \chi^{Ar}_{NR} \right|^2 N_{ref}^2 \qquad (2)$$

and two measurement signals

$$P^{mes}_{CO_2 \omega_{AS}} = A\, C_3 P_L^2 P_{CO_2 \omega_S} \left| \chi_{\omega, CO_2} \right|^2 N_{CO_2}^2 \quad (3)$$

$$P^{mes}_{N_2 \omega_{AS}} = A\, C_4 P_L^2 P_{N_2 \omega_S} \left| \chi_{\omega, N_2} \right|^2 N_{N_2}^2 \qquad (4)$$

P_L, $P_{CO_2 \omega_S}$ $P_{N_2 \omega_S}$ are respectively the pump power and the Stokes powers.

χ^{AR}_{NR} is the non-resonant susceptibility of Argon.

N_{CO_2}, N_{N_2}, N_{ref} are the molecular density of CO_2, N_2 and Argon respectively.

C_1, C_2, C_3, C_4 are constants.

A is a factor taking into account the attenuation of the measured signals due to various effects in the engine : beam steering effects, optical transmission. The basis of the method is to assume that A is the same for the nitrogen signal and for the CO_2 signal.

The N_2 spectra are first processed to determine the temperature. Ratio

$$R_{N_2 \omega_{AS}} = \frac{P^{mes}_{N_2 \omega_{AS}}}{P^{ref}_{N_2 \omega_{AS}}}$$ is computed as function of $\omega^{N_2}_{AS}$ in

dividing channel by channel the measurement signal by the reference signal. It represents the rovibrational spectra of N_2, in relative value, free of inhomogeneity of the dye laser. It can be compared, according to a well established routine to theoretical spectral of N_2 (at the pressure measured simultaneously in the engine), and the temperature is obtained. The theoretical N_2 spectra and the fitting procedure are those developed by ONERA[6].

Figure 2 gives an example of temperature determination. The experimental curve has been taken in the engine at 660 crank angle degrees.
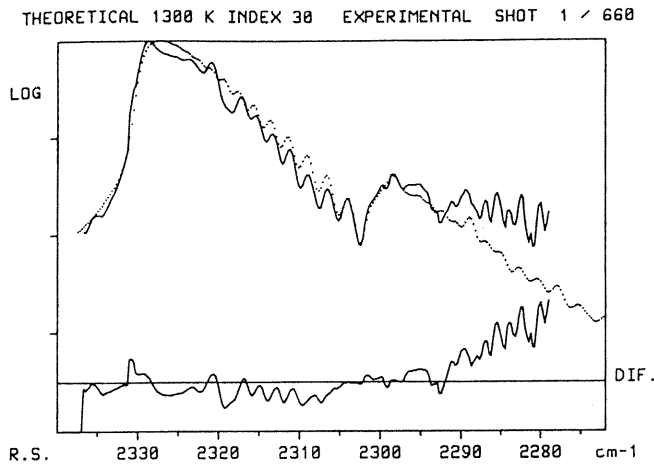
THEORETICAL 1300 K INDEX 30   EXPERIMENTAL SHOT 1 / 660

Fig. 2 -Determination of the temperature
Experimental (dots) and theoretical
(solid line) N_2 spectra.

Once the temperature known the CO_2 concentration can be determined. Summations (normalized by the reference signals) over the bandwiths of the dye lasers are then computed :

$$R_{N_2} = \sum_{\text{modes } \omega_{AS}^2} R_{N_2} \quad \text{and} \quad R_{CO_2} = \frac{\sum_{\text{modes } \omega_{AS}^2} P_{CO_2}^{mes}}{\sum_{\text{modes } \omega_{AS}^2} P_{CO_2}^{ref}}$$

They do not depend on the laser intensities but they still depends on beam steering effects. The in situ referencing concept is used in computing R :

$$R = \frac{R_{CO_2}}{R_{N_2}} = \frac{N_{CO_2}^2}{N_{N_2}^2} \cdot \frac{\int_{\Delta\omega_S} |\chi_{\omega,CO_2}|^2 f(\omega)d\omega}{\int_{\Delta\omega_S} |\chi_{\omega,N_2}|^2 g(\omega)d\omega} K \quad (5)$$

Experiment   Deduced   Calculated   Calibration constant

Constant K is determined by calibration in a known mixture of N_2 and CO_2 at ambient temperature. The integrals are computed using theoretical spectra taking into account the apparatus functions $f(\omega)$ and $g(\omega)$ of the lasers.

The accuracy of the determination depends obviously on the quality of the theoretical N_2 and CO_2 spectra. The model for CO_2 has been developed in our laboratory in collaboration with ONERA and the University of Besançon. Essentially it is based on the energy gap model. It is described in detail in [7].

Figure 3 gives examples of the good agreement found between the model and experimental spectra recorded in a cell containing 50% of CO_2 in nitrogen.
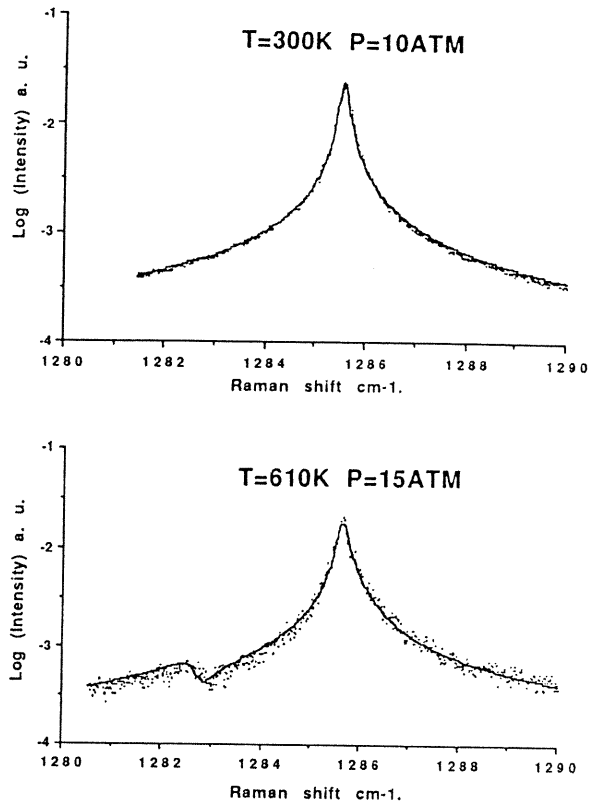

Fig. 3 -Comparison between theoritical
(solid line) and experimental data
(dots). $2\nu_2$ branch of CO_2 .
50% of CO_2 in nitrogen.

RESULTS AND DISCUSSION

Preliminary measurements have been made in a cell, at room temperature, to test the accuracy of the method. A mixture of 88.5% N_2, 4.5% CO and 7% CO_2 under a pressure of 4 Bar was used. The standard deviation of 100 measurements of ratio R was found to be 10%. As the concentration of CO_2 appears squared in relation (5) a standard deviation of only 70% affects this value.

These measurements could also be used to determine constant K. It appeared however that K depends notably on the particular optical aligment and laser adjusting and could vary from one day to the other.

Therefore constant K was determined in performing the measurements in filling the engine chamber with a flow of the CO_2, CO, N_2 mixture just before runing the engine.

Temperature and CO_2 concentration have been measured at various crank angles. In the burnt gas at 660 crank angle degrees the pressure is 1 Bar and the temperature was found to be 1200K $(\sigma_T = 50K)$. Due to high temperature and low pressure, the CO_2 signal was weak and only a rough approximation of the CO_2 concentration could be deduced. The value was found close to the 12.5% value measured in the exhaust gases by classical analysis. No attempt was made so far to perform measurements in the burnt gas earlier in the cycle.

During the compression stroke the temperature is lower and good signal-to-noise ratios are obtained despite the weaker amount of CO_2 (present in the residual). Table 1 gives the mean temperature, pressure and CO_2 concentration as well as their respective σ. Measurements have been averaged over about 100 shots.

C.A.D.	330	300	240	180
Temperature (K)	515	490	400	385
σ_T	45	50	40	40
N_{CO_2}/ N_{N_2}	0.021	0.018	0.012	0.014
σ	0.005	0.005	0.005	0.005
Pressure (Bar)	6.3	3.25	1.25	1.0
σ_P	0.15	0.20	0.25	0.30

Table 1

Figure 4 shows the mean value of $[CO_2]$ as function of the crank angle. Within the uncertainties ($\pm \sigma$), $[CO_2]$ is constant and would correspondant to a residual fraction of 15%. However a variation of the concentration with the crank angle can be seen, which would correspond to inhomogeneity of the gases. The measurements are performed at the top of the combustion chamber and, at the begining of the compression stroke, it is possible that a larger amount of exhaust gas exists in the bottom of the cylinder than in the top, near the valves.
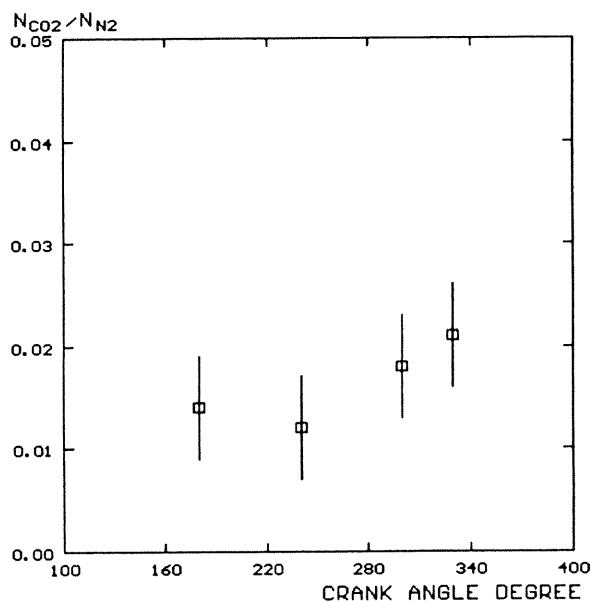
Fig.4 - CO_2 concentration vs crank angle

The likely inhomogeineity of the charge can also be shown in analyzing Fig.5 where the single-shot determinations of $[CO_2]$ are plotted versus the corresponding measured temperatures. A clear correlation between $[CO_2]$ and $[T]$ can be seen : the larger the temperature, the larger the concentration of CO_2 (measurements performed at the other crank angles give the same results). It can be thought that measurements are performed in pockets containing more or less exhaust gases.
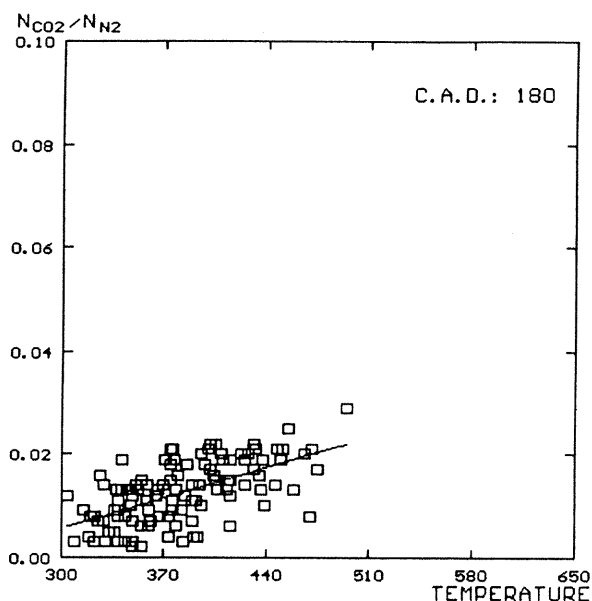
Fig. 5 - Correlation between $[CO_2]$ and temperature at 180 crank angle degrees

The size of the probe volume (1cm in length) is probably larger than the size of pockets and the value found are averaged over the content of the probe volume. Of course, one would like to have a better spatial resolution. It should be clearly understood that such correlations can be done thanks to single-shot determination of T and $[CO_2]$ and that, so far, can be performed only with a poor spatial resolution.

REFERENCES

[1] STENHOUSE I.A., WILLIAMS J.R., COLE J.B. and SWORDS M.D., Appl. Opt.18, 3819 (1979).

[2] RAHN L.A., JOHNSTON S.C., FARROW R.L. and MATTERN P.L., in "Temperature Its Measurement and Control in Sciences and Industry", vol.5, American Institute of Physics, New-York, p.609 (1982).

[3] ALESSANDRETTI G.C. and VIOLINO P., Journal of Physics D : Appl. Phys. 16, 1583 (1983).

[4] KLICK D., MARKO D.A. and RIMAI L., Appl. Opt.23, 1346 (1984).

[5] LUCHT R.P. et al., Combust. Sci. and Techn.55, p. 41 (1987).

[6] PEALAT M., BOUCHARDY P., LEFEBVRE M. and TARAN J.P., Appl. Opt.24 (1985).

[7] GRISCH F., ROBLIN A., PAPINEAU N., PEALAT M. and LEFEBVRE M. "Influence of the motional narrowing on the $2\nu_2$ Q branch of CO_2 . Comparison between experimental and computed CARS spectra" (In preparation).