IN-CYLINDER MEASUREMENTS OF NO IN A RUNNING DIESEL ENGINE BY MEANS OF LIF DIAGNOSTICS

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ABSTRACT: Two-dimensional NO distributions in a steadily running optically accessible diesel engine are observed by laser-induced-fluorescence using a tunable ArF excimer laser at 193 nm. Simultaneous excitation at 226 nm revealed that no sizeable photo-chemical effects influencing the NO distribution are induced by the excimer laser. The measurements are performed in both a directly injected two-stroke engine and an indirectly injected four-stroke engine. The in-cylinder attenuation of the laser beam due to absorption and scattering by particles as well as the reduced transparency of the quartz windows due to soot deposits are taken into account in the evaluation of the NO distributions. Hereto correction procedures are applied involving the measurement of Mie scattered laser light distributions in the motored and the running engine. Results for the corrected NO-LIF distributions are presented as a function of crank angle and load. The consistency of the obtained results is verified by performing measurements with reversed laser beam direction. The NO-LIF distributions show a reproducible evolution as a function of crank angle. The averaged LIF intensity decreases strongly with increasing crank angle, as expected for an early NO formation followed by an expansion.

INTRODUCTION

In the study of combustion processes, laser induced fluorescence (LIF) has proven to be a powerful technique to extract information about molecular density and temperature distributions. The development of high power tunable excimer lasers in combination with sensitive intensified CCD cameras has enabled the application of LIF in even the most hostile environments such as the combustion chamber of an engine. Whereas the applicability of LIF detection to the study of the combustion process in Otto engines has been widely recognized, there are only few studies involving LIF in diesel engines. To a great deal this is due to the reduction of window transmission by sticky soot deposits and extinction of the laser beam in the cylinder, which reduce the signal strength and complicate the interpretation of the obtained data. In most experiments, therefore, mostly low-sooting fuels or (mixtures of) single component fuels such as n-heptane are used. Moreover, the test engines are usually operated in skip-fired mode (i.e., the combustion in the motored engine only takes place every selectable number of cycles) in order to prolong the optical transparency of the windows of the combustion chamber.

In-cylinder NO distributions have been visualized by means of 2D-LIF as described by Arnold et al. [1], Alataş et al. [2] and Brugman et al. [3]. Alataş et al. [2] using a 50/50 mixture of iso-octane and tetradecane in a square combustion chamber, found evidence that the NO formation ceased at 30 to 40 degrees after top dead center (ATDC). In a previous paper, LIF spectra of NO at 193 nm were reported for a 4-stroke engine operated on both n-heptane and standard diesel fuel [3]. These measurements were performed at low pressures around bottom dead center (BDC). Subsequently, experiments were extended to higher pressures with the objective of exploring 2D-LIF for its capability to obtain relative 2D distributions of NO during the complete combustion cycle.

In this paper, 2D-LIF measurements of NO in a directly injected 2-stroke and an indirectly injected 4-stroke engine are presented. Attention is paid to the effects of attenuation by the soot contaminated windows and the in-cylinder extinction of the laser beam. In order to verify the non-intrusive character of the LIF measurements a two-colour experiment was performed to check the possible occurrence of excimer laser induced photo-chemical processes by which NO is produced or destroyed, which would result in erroneous NO distributions.

EXPERIMENTAL

Measurements are performed on two different single cylinder diesel engines: a directly injected 2-stroke engine (Sachs, swept volume of 412 cc, bore of 81 mm diameter, stroke of 80 mm) and an indirectly injected 4-stroke engine (Hatz-Samofa, swept volume 580 cc, bore 86 mm, stroke 100 mm). Details of the experimental setup including the 4-stroke engine are available in [3]. The NO molecules are excited at 193 nm using a tunable ArF excimer laser (Lambda Physik EMG 150). The laser beam is shaped into a 3 mm x 25 mm sheet and traverses the combustion chamber through an entrance and an exit window. The 4-stroke engine was made optically accessible by mounting three quartz windows in the cylinder wall. In this case, the laser sheet is oriented in a vertical plane (i.e., parallel to the piston axis) and the fluorescence is coupled out in a direction perpendicular to this plane. In the 2-stroke engine, the outcoupling window is mounted in the cylinder head, as shown in Fig. 1, and the laser sheet is in a horizontal plane (i.e. perpendicular to the piston axis). Whereas in the 4-stroke engine the optical access is strongly limited due to the blocking of the windows by the moving piston, this is no longer the case in the 2-stroke engine. Full access is obtained by using a piston with a shallow slot to allow the laser sheet traversing. The experiments described in this paper, however, have been performed by using a flat piston allowing measurements at crank angles larger than 25° ATDC.

Within the 300 cm^{-1} wide tuning range of the laser, NO produced in the cylinder of the running engine can effectively be excited through a series of rotational channels of the $D^2\Sigma^+(v'=0) \leftarrow X^2\Pi(v''=1)$ transition. The 2D-LIF measurements are performed at a fixed laser wavelength (193.588 nm) corresponding to the coinciding $R_1(23.5)/Q_1(29.5)$ transitions of NO. At this wavelength, no disturbance by oxygen absorption is expected [4]. During the measurements, the laser is kept on resonance by monitoring the simultaneously induced fluorescence from NO in an oxy-acetylene flame, produced by a small fraction of the pulse energy. The remaining pulse energy (≈60 mJ/pulse) is directed to the entrance window of the engine. In one experiment on the 4-stroke engine the propagation direction of the laser beam was reversed in order to check the consistency of the obtained NO distribution.

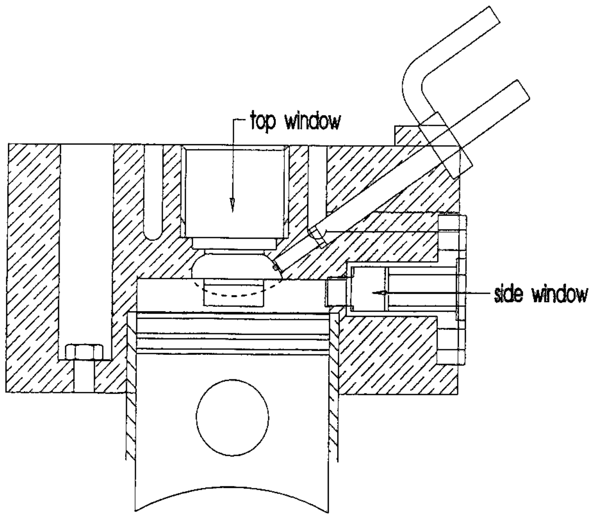

Figure 1. Schematic view of the optically accessible cylinder head of the 2-stroke engine. The entrance and exit windows are out of the plane of the drawing. The laser sheet is oriented perpendicular to the piston axis. The fluorescence radiation is coupled out via the top window. The side window, shown in the figure, is not used in the present measurements.

The imaged in-cylinder area has a diameter of 2.5 cm and 4.0 cm for the 2- and the 4-stroke engine, respectively. The 2D-LIF signal is separated from the resonantly scattered laser radiation by means of a 10 nm bandwidth interference filter (Laser Optik) adjusted to maximum transmission (≈80%) at 208 nm. The 2D-LIF signal is then fed into the 50 ns gated image intensifier of a CCD-camera. The images from the 4-stroke engine are recorded by a video CCD camera (Theta) and digitized by an 8 bit frame grabber (Matrox). In the experiments with the 2-stroke engine, a more sensitive 12-bit slow-scan camera (LaVision) is used. The background of the recorded 2D-LIF signal (if the laser beam is blocked or the laser is tuned off-resonant) is observed to be sufficiently low [3] to make background subtraction procedures redundant. An opto-electronic device continuously measures the crank position of the engine and triggers a delay generator, which in turn synchronizes the laser pulses, the LIF calibration section and the 2D-LIF imaging system. An electric brake mounted on the flywheel of the engine provides adjustable load conditions. Most of the imaging of NO presented in this work is performed while the engine is running steadily (≈1000 rpm for the 4-stroke engine and ≈2000 rpm for the 2-stroke engine) on standard diesel fuel. In the 4-stroke engine, a fixed amount of oxygen (circa 12%) is added to the air-inlet of the running engine in order to raise the combustion temperature, resulting in an increased population of the probed $v''=1$ state of NO. The increased combustion temperature also leads to decreased soot formation and as a consequence a sufficiently high optical transparency of the quartz windows can be maintained over almost unlimited periods of time. The 2-stroke engine is operated without extra oxygen. Nevertheless there are no soot deposits formed on the windows during operation. Probably this is caused by a higher temperature of these windows due to the neighbouring diesel sprays. The pressure in the cylinder of the running engine is monitored by a water-cooled pressure transducer (AVL QC 32) connected to a charge amplifier.

VALIDATION OF THE DETECTION METHOD

Laser induced photochemistry

In the two-colour excitation experiment, a setup is used as schematically depicted in Fig. 2. In addition to the ArF excimer laser a frequency doubled Nd:YAG pumped dye laser (Quantel) is applied to excite the NO molecules via the transition $A^2\Sigma^+(v'=0) \leftarrow X^2\Pi(v''=0)$ at 226 nm. A spherical lens (f=30 cm) focuses the dye laser beam at the axis of the cylinder in such a way that both laser pulses have maximum spatial overlap. The dye laser induced fluorescence from the $A^2\Sigma^+(v'=0) \rightarrow X^2\Pi(v''\geq 3)$ bands, observed above 250 nm through a UG 5 filter, is measured both in the presence and in the absence of the excimer laser beam. This way the possible occurrence of photochemical effects on the NO distribution induced by the excimer laser is checked.

In Fig. 3, two NO excitation scans of the 226 nm region measured with the frequency-doubled dye laser in the running engine and in the welding torch are presented. A simulated spectrum, calculated for T=1800 K using data from Reisel et al. [5], is given in the middle row. The three spectra show very good agreement. Evidently, the spectrum obtained from the engine is much weaker than the flame spectrum. The strongest transition ($P_2(22.5)$ at 226.364 nm [5]) was selected to detect any photo-chemical effects of the excimer laser radiation. The effect of the presence of the excimer laser radiation on the dye laser induced LIF signal strength from the running engine (1000 rpm, no load) is depicted in Fig. 4. As can be clearly deduced from this figure, the influence of the excimer laser radiation on the dye laser induced LIF signal strength is negligible, which leads to the conclusion that excimer laser induced photo-chemical processes, if they occur at all, have no observable influence on the population of the $X^2\Pi(v''=0)$ state under the present experimental circumstances. In view of the fast vibrational relaxation of NO [6] this most probably holds for the $X^2\Pi(v''=1)$ state (probed by the excitation at 193 nm) as well. A three-level double resonance experiment is in preparation to directly monitor the depletion of the lower level of the excimer laser transition.

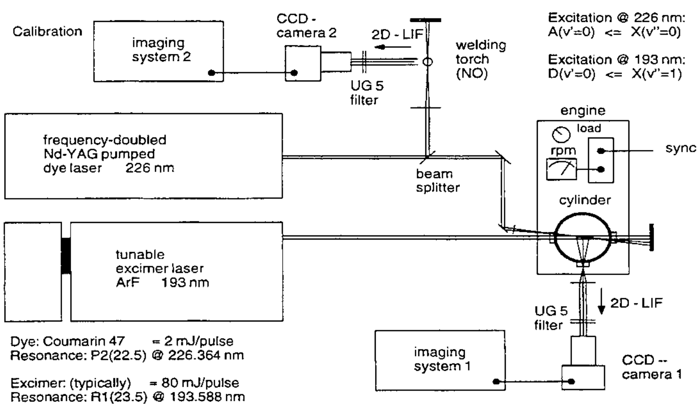

Figure 2. The experimental setup for the two-colour experiment. The NO molecules are probed via the A-X(0, 0) band by a frequency doubled dye laser, operated at Coumarin 47, delivering 2 mJ/pulse at 226 nm. The subsequent fluorescence in the A-X(0, 3) band at 270 nm is measured in the absence and in the presence of the ArF excimer laser beam (80 mJ/pulse), exciting the D-X(0, 1) band of NO.

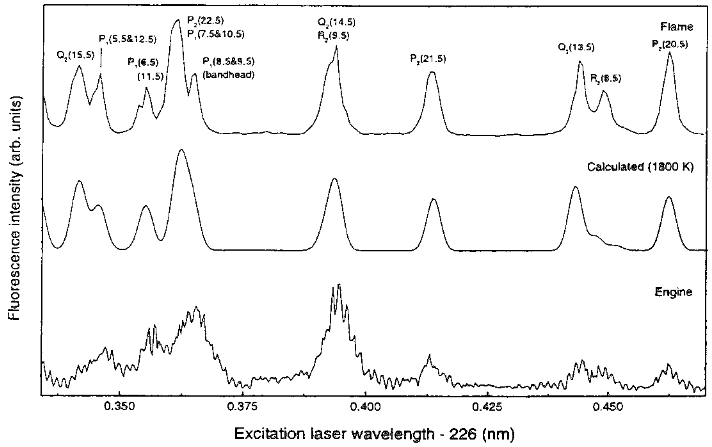

Figure 3. Two excitation scans of NO around 226 nm in the welding torch (top scan) and in the running 4-stroke engine (bottom scan), respectively. In the middle a simulated spectrum is shown, calculated with the data of Reisel et al. [5]. The $P_2(22.5)$ transition is used for the two-colour measurements.

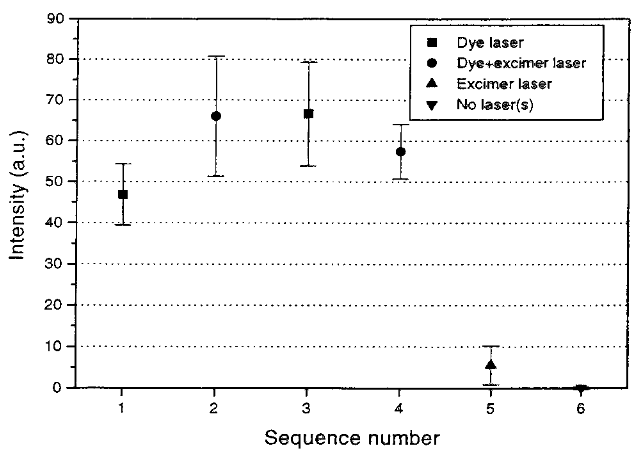

Figure 4. A typical result of the two-colour measurements. Within the experimental accuracy no change in the A-X fluorescence intensity is observed when the excimer laser is switched on or off. It makes no difference whether the excimer laser is set on or off the D-X, $R_1(23.5)/Q_1(29.5)$ transition of NO.

Linearity

In the processing of the NO-LIF signals linearity of the signal strength with the laser pulse energy is a prerequisite. Measurements as a function of the laser intensity showed that within the spread of the experimental results this condition is fulfilled up to the highest energy used in the experiments.

Saturation

The observed linearity of the NO signal strength on the pulse energy does not imply that there are no saturation effects present. An estimate of the degree to which saturation plays a role can be obtained by comparing the actual laser intensity with the calculated saturation intensity, I_S [7]. Since the Einstein coefficient for absorption, B_{12} is not known for the D – X transition only a lower limit can be calculated for I_S by using the known radiative lifetime of the D state. This results in $I_S > 9 \cdot 10^8$ W/m^2 at the present laser bandwidth of 0.5 cm^{-1}. This is about equal to the estimated laser intensity in the imaged area in the combustion chamber. Therefore saturation effects are expected to be of minor importance in the present experiments. It should be noted that even in case of (not too strong) saturation, the LIF signal strength is still linearly proportional to the local NO density.

MEASUREMENT PROCEDURE

A complete measurement, at given crank angle and engine conditions, comprises one NO fluorescence distribution and four Mie scattering images, recorded in a specific order which facilitates post-processing of the NO-LIF distributions [8]. First, with all windows thoroughly clean, a Mie scattering distribution is measured in the motored engine (A in Figs. 5 and 6 below). Then the NO-LIF image is recorded in the running engine (B), immediately followed by a second Mie scattering distribution from the motored engine (C). Finally, a Mie scattering image is recorded in the running engine (E), once again followed by a (third) Mie scattering distribution from the motored engine (F). All individual images are averages over about 300 (4-stroke) or 25 (2-stroke) laser pulses. The Mie scattering images are recorded by bypassing the interference filter in front of the CCD camera. A complete series takes about 15 minutes. The Mie scattering images from the motored engine are used to derive correction factors for locally decreasing window transmission due to soot deposits building up while the engine is running. Local window transmission changes during, for instance, the NO fluorescence measurement, can be detected by a comparison of the two Mie scattering images before and after the 2D-LIF measurement. Since the locations of the soot deposits are observed not to change during the runs, this allows for a correction of the NO-LIF distributions for the attenuation of both the laser beam and the fluorescence radiation due to window fouling.

In addition to the correction for the reduced window transmissions, the measured NO LIF distributions have to be corrected for in-cylinder attenuation of the laser beam. At the pressures considered (< 10 bar) the attenuation is mainly due to Mie scattering and absorption by particles. The scattered signal is linearly proportional to both the laser intensity and the local particle density. If it is assumed that the particles are more or less uniformly distributed in the imaged area, the Mie scattering image reflects the laser intensity distribution, which then can be used to obtain more realistic NO-LIF distributions[8].

Presently, it is not yet possible to correct for the effects of collisional quenching on the measured NO fluorescence distributions. Inelastic collisions induce a considerable decrease of the number of excited NO molecules and as a consequence the intensity of the induced fluorescence is reduced (quenched). This will affect the total signal strength of the observed NO-LIF distributions, thus making the determination of absolute NO densities difficult. Therefore the present experiments are aimed at the study of relative NO density distributions as a function of crank angle and load.

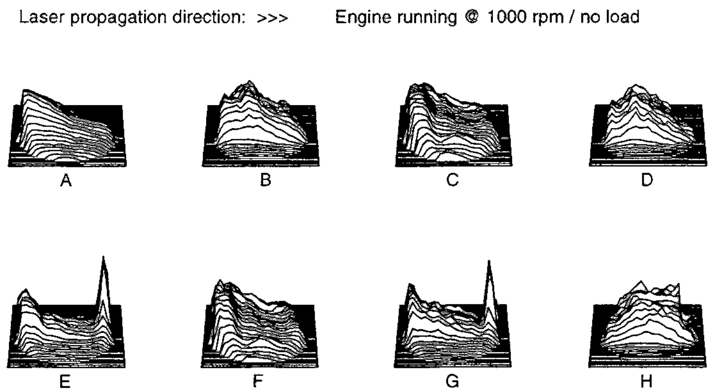

Figure 5. Measured 2D images of Mie scattered laser light and of NO fluorescence in the 4-stroke engine at 135° ATDC. The laser sheet enters the imaged area from the left hand side. In picture A, a Mie scattering image is shown, measured in the motored engine with clean windows; picture B shows a NO-LIF image, recorded in the running engine; pictures C and F show images of Mie scattered distributions in the motored engine after running, i.e. with dirty windows; in picture E, a Mie scattering image is shown, measured in the running engine. Pictures D and G represent images of NO-LIF and Mie scattering distributions after correction for the soot deposits on the windows. The final result for the NO-LIF distribution corrected for both window fouling and in-cylinder laser extinction is given in picture H. All individual images are averages over about 300 laser pulses.

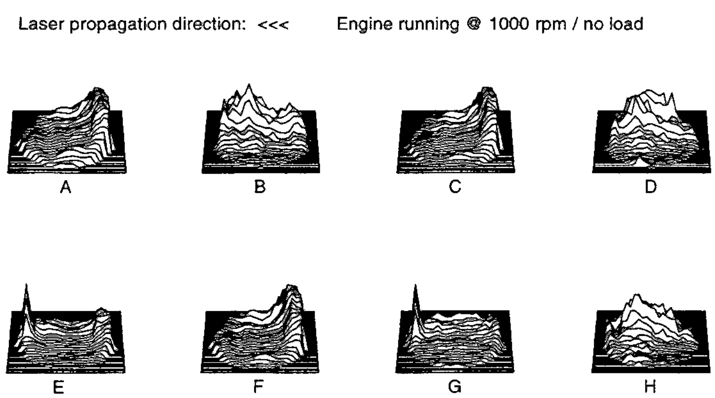

Figure 6. The same as in Fig. 5, but with the opposite laser sheet direction. The laser beam enters the imaged area from the right hand side.

The correction procedures are described in detail in [8]. Their application is based on the assumption that the sampled 2D-LIF signal strength depends linearly on both the laser pulse energy as well as on the NO population density in the imaged area. As discussed above, the in-cylinder laser intensity is low enough to preclude any observable photochemical processes. Within the experimental accuracy, the NO-LIF signal is linearly dependent on the laser intensity at the considered engine operating conditions and saturation is not expected to play an important role.

RESULTS AND DISCUSSION

Demonstrations of the measurement procedure applied to two NO fluorescence distributions recorded in the running 4-stroke engine (no load, 135° ATDC) are given in Fig. 5 and Fig. 6 for the two directions in which the laser beam can traverse the combustion chamber. Both figures consist of 8 three-dimensional representations of the measured and corrected images. The plots labelled A were measured first, and they display the laser intensity distributions in the motored engine with previously cleaned windows as imaged by Mie scattering. The plots labelled B are depictions of the (unprocessed) measured NO fluorescence distributions. The plots labelled C show the in-cylinder laser intensity distributions measured immediately after the NO fluorescence measurement in the running engine. Plots 5D and 6D display the results of applying the correction procedure for window fouling to the measured NO fluorescence distribution. Comparing Fig. 6B with Fig. 6D, one observes a shift of the corrected NO distribution towards the centre of the imaged area, whereas in this particular case (with apparently little window fouling) this first correction hardly affects the initially imaged NO fluorescence distribution for the other direction (Fig. 5B). The plots labelled E are the (uncorrected) results of the Mie scattering measurements of the laser intensity distribution in the cylinder of the running engine. The high intensities at the laser exit sides are most probably artefacts caused by reflections of the laser sheet at the laser exit window. The plots labelled F are Mie scattered images from the motored engine measured immediately after the measurements which produced the plots E. The plots A and F are used to apply the same correction procedure for window fouling, mentioned above, to the plots E and the results are shown in Fig. 5G and Fig. 6G. The latter, in combination with the corrected NO fluorescence distributions (plots D), form the ingredients of the second correction procedure, which accounts for the decreasing laser intensity [8]. Finally, the plots labelled H are depictions of the fully corrected NO fluorescence distributions. It should be noted here that the NO distributions of Fig. 5H and Fig. 6H are very similar in contrast to the original, uncorrected, NO fluorescence distributions Fig. 5A and Fig. 6A. Thus, after two corrections, an in-cylinder NO fluorescence distribution is found which, at least qualitatively, is independent of the propagation direction of the laser sheet. This is a strong indication for the reliability of the correction procedures and the resulting in-cylinder NO distributions.

Comparing Fig. 5E with Fig. 5A and Fig. 6E with Fig. 6A, one might conclude that the decay of the laser intensity in the motored engine is much larger than the decay observed in the running engine. In order to verify this, the overall transmission of the laser through both windows and the cylinder was measured. It turned out that the transmission of the laser is about two times better if the engine is running ($\approx$20%) instead of being motored ($\approx$10%). An explanation is most likely to be found in the higher in-cylinder temperature of the running engine, causing vaporization of the lubricant and other scattering particles. This will reduce the scattering losses in the cylinder of the running engine. At high pressures, absorption by oxygen is expected [9], due to broadening of the individual lines in the Schumann-Runge band. For the pressure range in the present experiments ($<$ 10 bar) no line broadening larger than the 0.5 cm^{-1} bandwidth of the laser is expected and no indication of absorption by oxygen is found.

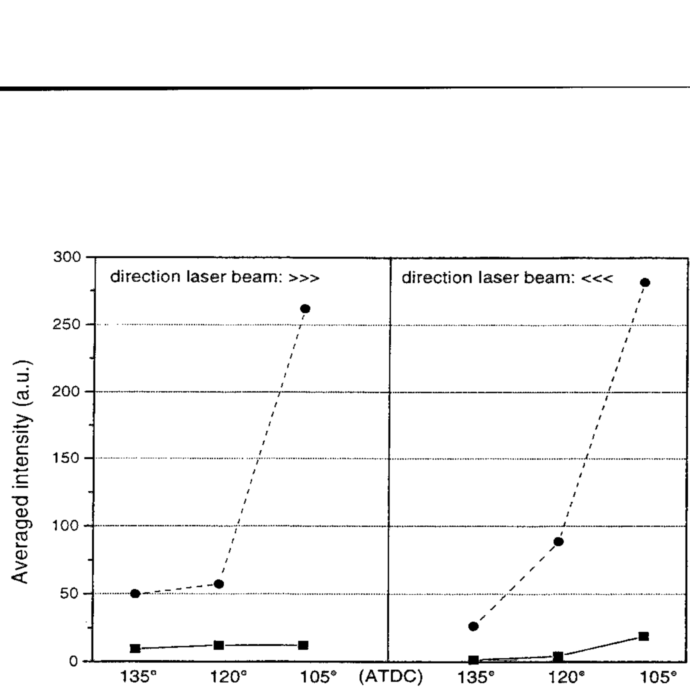

Figure 7. The averaged NO LIF densities for the two opposite laser sheet directions as a function of crank angle in the 4-stroke engine, before (●) and after (■) correction for window fouling and laser beam extinction.

The effect of the correction procedures is shown in Fig. 7, where the averaged NO-LIF densities are plotted as a function of the crank angle before and after the signal processing. The two parts of the figure correspond to the two opposite directions of the laser beam through the combustion chamber. The largest effect is seen at 80° ATDC (not shown in the figure), the smallest angle where measurements are possible in the 4-stroke engine. The corrected signal is here more than 20 times stronger as compared to the unprocessed signal. The increase of the NO density towards higher pressures (i.e. earlier in the expansion stroke) is in agreement with the expectation that the NO is formed early in the combustion and expands with the volume during the stroke. The results for both laser beam directions are in qualitative agreement to each other. The quantitative differences might be due partly to the spread of the experimental data and partly to a larger concentration of scattering particles at the exhaust valve, which is situated close to one of the windows, as explained in more detail in [8].

In Fig. 8, three series of two-dimensional NO-LIF distributions are shown in false colours, measured in the 2-stroke engine as a function of the crank angle. The series were measured at the same engine conditions, a few minutes after each other. All images are averaged distributions measured during 1.25 seconds (25 strokes). In all these images, the laser beam travelled from top to bottom; the position of the fuel injector is at the right hand side of each image. Because the scaling factors are different for each image, only the distributions and not the absolute values of these pictures should be compared among themselves. Although the series differ from each other, due to the highly turbulent character of the combustion process, some reproducible pattern is observed: the NO seems to move from the top (at 62° ATDC) to the bottom in the image (at 105° ATDC). Possibly this effect is caused by a specific gas flow circulation in the cylinder during the stroke. If the different scaling factors are taken into account the average NO LIF densities are obtained as given in Fig. 9. In this figure, the results are also shown for another diesel fuel with a different cetane number. A behaviour similar to the result obtained for the 4-stroke engine is obtained: the amount of NO is almost zero at the point where the exhaust and inlet port are both open and increases strongly at higher pressures, corresponding to an expanding amount of NO at increasing crank angle.

The averaged NO LIF densities in Figs. 7 and 9 are not corrected for the change in fluorescence quenching and temperature during the stroke. The effect of the temperature is expected to be small as explained above. The fluorescence quenching will be stronger at higher pressure, which would result in steeper curves in Figs. 7 and 9 after correction.

In the 4-stroke engine, measurements were also performed at different loads, yielding an increase of the in-cylinder NO amount with load, as expected. Measurements are in progress to follow the NO-LIF distribution towards higher pressures.

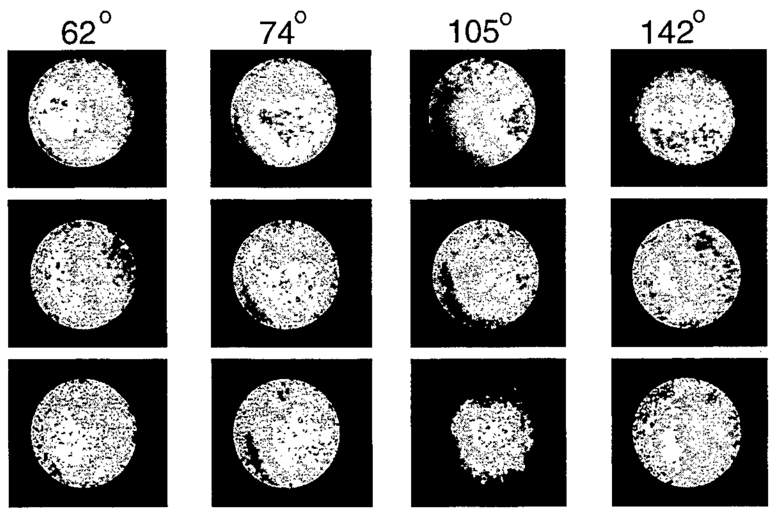

Figure 8. Three series of corrected NO-LIF density distributions in the 2-stroke engine at four crank angles. The series were measured immediately after each other at the same fuel and engine conditions. The laser beam traverses the imaged area from top to bottom. The fuel injector is at the right hand side of each image.

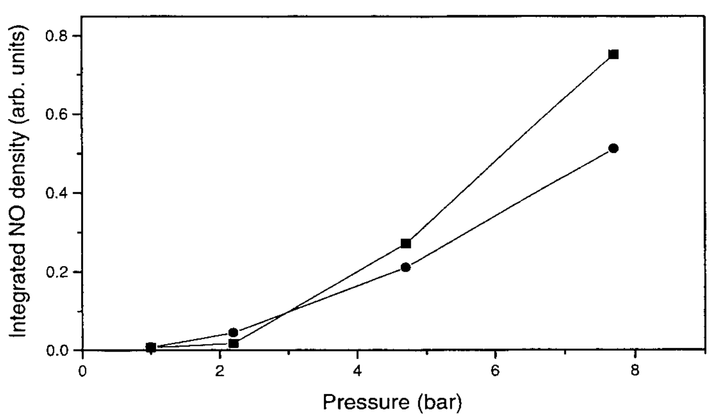

Figure 9. Averaged NO-LIF densities as a function of pressure in the 2-stroke engine for two fuels with different cetane number.

CONCLUSIONS

Nitric oxide distributions inside the cylinder of a running diesel engine operated on standard diesel fuel can be visualized by 2D-LIF detection at 193 nm. This is demonstrated for both a directly injected and an indirectly injected engine. Despite the high energy of the excimer laser pulse, the measured NO LIF distribution is not influenced by possible photochemical effects. After correction for window fouling and in-cylinder laser beam extinction, relative NO distributions are obtained, showing the expected behaviour of an expanding gas in the expansion stroke. Qualitatively, the results are independent of the direction of the laser beam. Future experiments will, amongst others, address the dependence of the NO distribution on engine load and fuel composition during as large a part of the combustion cycle as possible.

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REFERENCES

1. **Arnold, A., Dinkelacker, F., Heitzmann, T., Monkhouse, P., Schäfer, M., Sick, V., Wolfrum, J., Hentschell, W., and Schindler, K.P.,** DI Diesel engine combustion visualized by combined laser techniques, *Twentyfourth Symposium (International) on Combustion*, The Combustion Institute, 1605-1612, 1992.
2. **Alataş, B., Pinson, J.A., Litzinger, T.A., and Santavicca, D.A.,** A study of NO and soot evolution in a DI Diesel engine via planar imaging, SAE Paper 930973, 1993.
3. **Brugman, Th.M., Klein-Douwel, R., Huigen, G., van Walwijk, E., and ter Meulen, J.J.,** Laser-induced-fluorescence imaging of NO in an n-heptane and diesel-fuel-driven Diesel engine, *Appl. Phys.* B57, 405-410, 1993.
4. **Lee, M.P., and Hanson, R.K.,** Calculation of O_2 absorption and fluorescence at elevated temperatures for a broad band argon-fluoride laser source, *J. Quant. Spectrosc. Radiat. Transfer* 36, 425, 1986.
5. **Reisel, J.R., Carter, C.D., and Laurendeau, N.M.,** Einstein coefficients for rotational lines of the (0,0) band of the NO $A^2\Sigma^+$ - $X^2\Pi$ system, *J. Quant. Spectrosc. Radiat. Transfer* 47, 43-54, 1992.
6. **Frost, M.J., Islam, M., Smith, I.W.M.,** Infrared-ultraviolet double resonance measurements on the temperature dependence of rotational and vibrational self-relaxation of NO($X^2\Pi$, v=2, j), *Can. J. Chem.* 72, 606-611, 1994.
7. **Demtröder, W.,** *Laser Spectroscopy*, Springer, Berlijn, 104, 1981.
8. **Brugman, Th.M., Stoffels, G.G.M., Dam, N., Meerts, W.L., and ter Meulen, J.J.,** to be published in *Appl. Phys.*
9. **Schulz, C., Yip, B., Sick, V., and Wolfrum, J.,** A laser-induced fluorescence scheme for imaging nitric oxide in engines, *Chem. Phys. Letters*, 242, 259-264, 1995.