Quantitative NO LIF measurements in a heavy-duty Diesel engine

QUANTITATIVE NO LIF MEASUREMENTS IN A HEAVY-DUTY DIESEL ENGINE

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Introduction

Quantitative measurements of in-cylinder nitric oxide (NO) concentrations in one of the cylinders of a heavy-duty Diesel engine (DAF, Eindhoven, NL) are performed by means of laser-induced fluorescence (LIF), realising both spatially and crank-angle resolved detection. In order to convert the LIF signal into NO concentration, the pressure and temperature dependence of the fluorescence need to be taken into account. We modelled this dependence with LIFSim [1]. Another prerequisite is a correction for signal loss due to attenuation of both the excitation laser beam (226 nm) and the ensuing fluorescence of NO (237, 248, 259, 270 nm), which can be considerable [2]. We have investigated a number of laser diagnostic techniques to assess this attenuation, enabling a correction for laser intensity and detection efficiency of the NO-LIF data [3].

Bidirectional laser scattering can be used to estimate the local laser beam attenuation (i.e. along the laser beam path) [4]: two exactly counterpropagating laser beams traverse the same probe volume quasi-simultaneously, while the scattered light from each laser pulse is recorded separately. In this case we use the NO LIF signal, detected through one of the side windows of the cylinder, located near the cylinder head (Fig. 1). The local laser intensity can be calculated from the intensity ratio of the two fluorescence distributions.

Detection of NO-LIF through a spectrograph allows quantitative comparison of the intensities of all simultaneously observed fluorescence bands. Any deviations of the relative peak intensities from theoretical (Frank-Condon based) values are presumably caused by wavelength-dependent absorption which can be attributed to hot CO_2 [5], but also to hot O_2 (e.g. ref. [1]). The absorption cross sections of both CO_2 and O_2 increase with increasing temperature, and with decreasing wavelength. Similar to Hildenbrand and Schulz [6], who fitted the CO_2 absorption spectrum to observed deviations between measured and theoretical O_2 LIF spectra, we fit the absorption spectrum of CO_2 and O_2 to deviations in the relative intensities of the NO LIF peaks, using the CO_2 parameters from reference [5]. Thus, transmission curves can be obtained for 237, 248, 259, and 270 nm.

Experimental setup

The research engine is a heavy-duty, six-cylinder truck engine (DAF trucks, NL). A schematic representation of the measurement cylinder is given in Fig. 1. Suprasil windows at various places give optical access. A slot machined into the piston crown prevents complete blocking of one of the side windows even at Top Dead Centre (TDC). The fuel injection takes place through an eight-hole nozzle, located in the centre. The top window can be replaced by a pressure transducer (AVL QHC32), to measure the pressure trace needed for the LIF model. Exhaust NO concentrations are measured by an exhaust gas analyzer (SIGNAL Instruments, NOX analyzer series 4000). For the measurements presented here, the laser beam was directed through a fuel spray, traversing the combustion chamber either top-down or bottom-up. NO molecules are excited at 226.03 nm, with an unfocussed laser beam of 2-5 mJ pulse energy (Lambda Physik ScanMate 3, or Radiant Narrowscan D). NO fluorescence is detected through the nearest side window by an intensified CCD camera (Roper Scientific, ICCD 512T) mounted behind a spectrograph (ARC SpectraPro 500i).

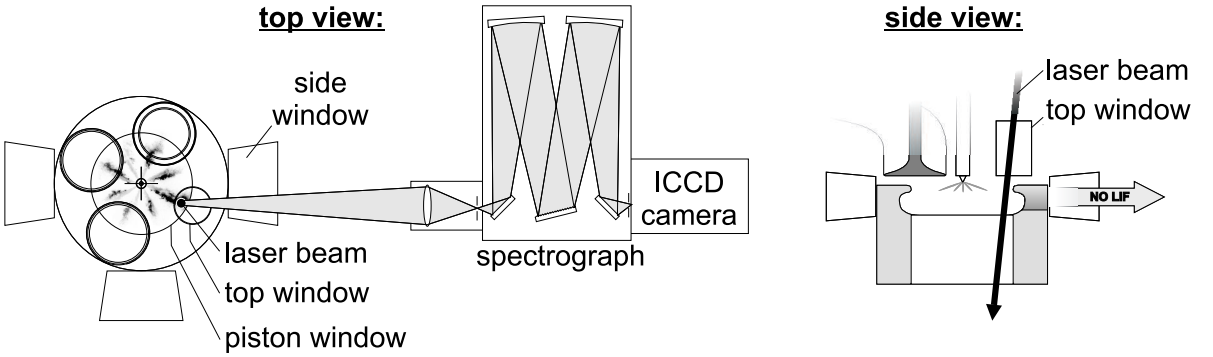

Fig. 1. Schematic representation of the measurement cylinder and the detection system.

Results and discussion

The effect of cylinder pressure and temperature on the NO fluorescence is shown in Fig. 2. The (global) temperature was calculated from the cylinder pressure assuming ideal gas behaviour [7]. Since this may deviate from the probe volume temperature, this introduces a certain error in the fluorescence yield. The effect of quenching causes the LIF signal to strongly decrease with pressure, or increase with crank angle, by a factor of 20. Two additional curves for higher temperatures (T+50% and T+100%) show that the LIF signal does not greatly change with temperature, which partly compensates the temperature inaccuracy.

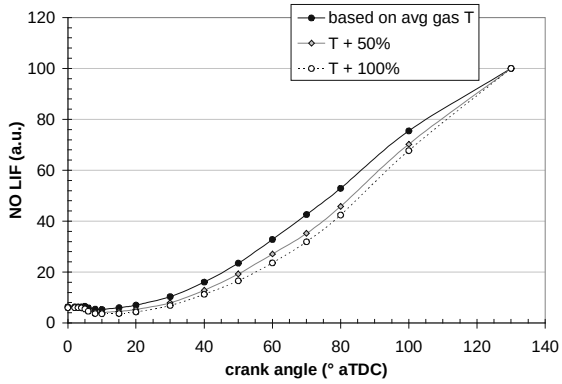

Fig. 2. Fluorescence yield (arbitrary units) *versus* crank angle, using the LIFsim model. Additional curves have been added to show the sensitivity on temperature. For comparison, all curves are scaled to 100 at 130° aTDC.

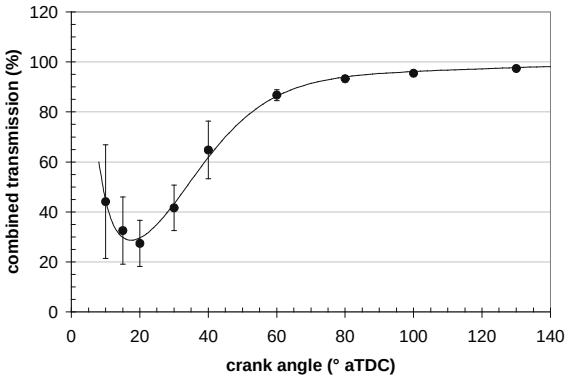

Fig. 3. Product of the laser beam transmission and fluorescence transmission. The estimated error bars are based on the standard error.

Fig. 3 shows the product of the laser beam transmission and fluorescence transmission curves, based on bidirectional laser scattering (laser beam attenuation) and the CO_2 and O_2 absorption spectra (fluorescence attenuation) [3]. Obviously, attenuation affects the LIF intensity considerably: around 20° aTDC, the combined transmission is less than 30%.

Fig. 4 displays the NO signal, integrated over the field of view and over the four observed vibronic bands. NO LIF can be detected as early as 2° aTDC. The strong increase of the LIF signal during the stroke is mainly caused by the decreasing pressure (compare Figs. 2 and 4). In fact, the curves in Figs. 2 and 3 are used to process the data in Fig. 4. Absolute values can be obtained by scaling the resulting curve to the calibration point at 130° aTDC (i.e. exhaust valve opening), by relating the LIF signal to exhaust concentration measurements. The resulting NO curve is shown in Fig. 5. After an initial fast rise between 10 and 20° aTDC, the NO concentration continues to increase very slowly, indicating that the major NO formation takes place during the combustion, and only very little in the "post flame" regions. The curves

for T+50% and T+100% are added to Fig. 7 as solid and dotted lines respectively. The fact that the NO concentration reaches a more or less constant value indicates a reasonably homogeneous NO distribution. In that case, the local measurements are representative of the global NO concentration as measured in the exhaust gas, justifying the calibration of the LIF data with exhaust gas analysis results.

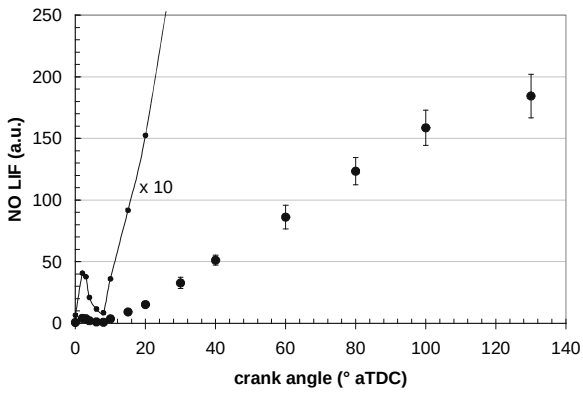

Fig. 4. Total (raw) NO LIF versus crank angle, measured in a fuel spray. The data points correspond to averages of 15 laser shots; the error bars denote the standard error.

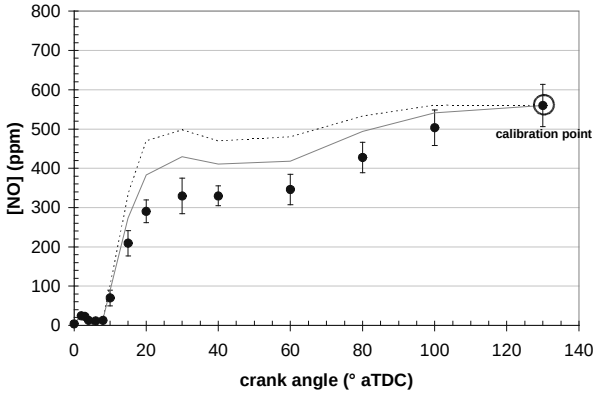

Fig. 5. NO concentration during the combustion stroke, based on the raw data in Fig. 4. The additional lines are based on the T+50% and T+100% curves from Fig. 2.

Conclusions and outlook

We have demonstrated quantitative, in-cylinder NO measurements using laser-induced fluorescence. Conversion of raw NO LIF signals into ppm's requires knowledge of a number of conditions, such as cylinder pressure, the local temperature, and the attenuation of the light involved in the measurement. Of all the processing steps, the pressure dependence of NO LIF is by far the strongest effect, changing by almost a factor of twenty during the combustion stroke. Fortunately, the pressure transducer allows accurate pressure measurements, and quenching rates are relatively well-known. The effects of laser beam and fluorescence transmission are considerable in this engine, despite the minimal path lengths involved. Affecting the fluorescence signal by up to a factor of three, attenuation effects cannot simply be neglected. Reliable methods, such as bidirectional laser scattering and CO_2 and O_2 absorption spectroscopy, are needed to assess this attenuation.

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