Two-line tracer LIF for measurements of instantaneous temperature fields in inhomogeneously mixed systems

Svenja Einecke, Christof Schulz, Jürgen Wolfrum

Physikalisch-Chemisches Institut, University of Heidelberg, Im Neuenheimer Feld 253,
D-69120 Heidelberg, Germany, Phone: +49 6221 548503, Fax: +49 6221 544255,
e-mail: christof.schulz@urz.uni-heidelberg.de

Abstract

Transient two-dimensional temperature distributions in the compression stroke and in the unburned end-gas of an SI engine were measured employing laser-induced fluorescence (LIF) of a fuel marker that possesses strongly temperature-dependent spectroscopic properties. The use of two different excitation wavelengths simplifies the otherwise complicated relation between LIF signal intensity and system parameters. The temperature fields obtained in this manner can be used to correct measured tracer-LIF maps and thus help to determine fuel distributions.

Introduction

Knowledge of the spatial distribution of temperature in the combustion chamber in IC engines prior to ignition is of major interest when modeling engine combustion. Especially in modern engines with stratified load and in systems with exhaust gas recirculation, temperature inhomogeneities must be expected. 2D-temperature distributions between 300 and 1000 K relevant for pre-combustion conditions can hardly be assessed with laser spectroscopic techniques developed for two-dimensional combustion thermometry so far. Rayleigh scattering thermometry is frequently employed for measurements of temperature fields in flames [1]. It was applied to SI engines as well [2] but presents many problems due to background scattering in awkward geometrical environments. The Rayleigh signal intensity is also a function of species-dependent scattering cross-sections and thus this technique is not applicable in inhomogeneously mixed systems. Ketones like 3-pentanone are frequently employed as fuel tracers for quantitative measurements of fuel vapor concentrations as its evaporation properties are similar to those of common model fuels like *iso*-octane [3]. Furthermore, the influence of collisional quenching mainly by molecular oxygen is much reduced compared to aromatic compounds and exciplex systems. 3-pentanone possesses an absorption feature between 220 and 340 nm with the peak near 280 nm at room temperature [4]. This feature exhibits a clearly defined temperature-induced shift towards the red of about 10 nm per increase of 100 K as shown in experiments in static cells with variation of temperature and pressure (Figure 1). This spectral shift of the absorption can be used for measuring temperature, e.g. when 3-pentanone is seeded to non-fluorescing model fuels, as the fluorescence intensity is a function of the absorption coefficient for a given excitation wavelength, and thus, of temperature. This shift in accord with density variations can be used to assess temperature upon excitation with a single wavelength [5]. In systems with inhomogeneous fuel distribution like engines with exhaust gas recirculation, however, fuels and fuel tracers are inhomogeneously distributed in the combustion chamber. Here, after excitation at two different wavelengths the ratio of the fluorescence signal intensities reflects the local temperature independent of the local tracer concentration (Figure 2). This was first described by Grossmann et al. [4] and later applied to temperature measurements using acetone as tracer [5]. With the temperature inferred from this measurement further quantification of the local fuel concentration is feasible by correcting for the temperature influence on the fuel tracer signal obtained for either of the excitation wavelengths. The first detailed application of this technique to measurements of temperature distributions in an SI engine is reported here. Measurements were carried out in an optically accessible two-stroke engine fueled with *iso*-octane/air [6, 7]. Temperature distribution fields were obtained for both the compression stroke and the power stroke. After ignition the temperature could still be measured in the unburned gas region using the same technique.

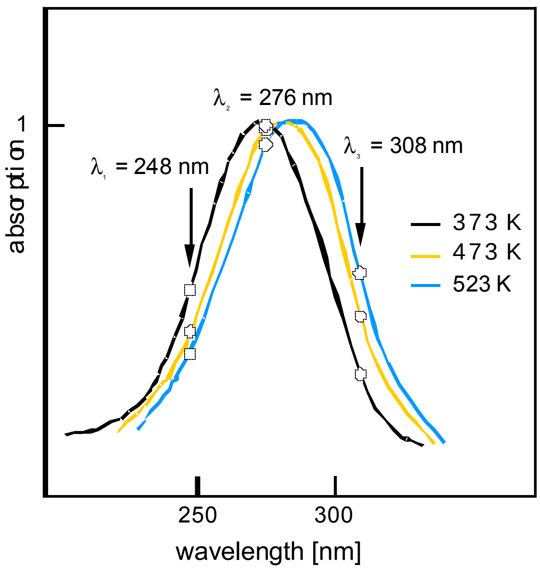

Figure 1: *Shift of the absorption spectra of 3-pentanone with temperature*

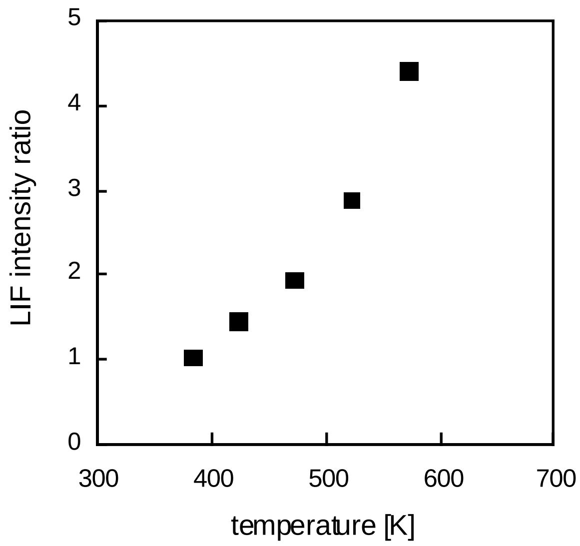

Figure 2: *Temperature dependence of the ratio I_{308} / I_{248} of the LIF signal intensities after excitation at 248 nm and 308 nm, obtained in a static cell [4]*

Experimental

Measurements were conducted in a modified production-line single-cylinder two-stroke engine with a bore of 80 mm and 0.372 l displacement [8] and a compression ratio of 8.6. The original cylinder head was replaced by a quartz ring of 4 mm height to allow for the entrance and exit of the laser sheets, and a cylindrical full-size quartz window on top through which fluorescence could be monitored. The engine was carburetor fueled with *iso*-octane (p.a.) doped with 10% (v/v) 3-pentanone, the mixture composition was kept lean (equivalence ratio ϕ = 0.625). Two excimer lasers were operated with KrF (248 nm) and XeCl (308 nm) gas mixtures, respectively, and fired with a fixed delay of 150 ns to prevent crosstalk of the signals. Measurements were taken for both, motored and fired engine cycles, with ignition at 20° crank angle BTDC, and four motored cycles in between fired cycles to ensure a well-defined gas mixture free of residual exhaust gas. The engine was motored at 1000 rpm. The fluorescence signals from a region of 68 x 52 mm were imaged on two intensified CCD cameras. The 2D-fluorescence information was corrected for background contribution, incidental laser pulse energy as measured on a shot-to-shot basis by two photodiodes, and laser sheet inhomogeneities, using averaged intensity distributions. Finally, pressure effects were taken into account using data previously obtained by Grossmann et al. [4].

Results and discussion

A change in fluorescence intensities as a function of crank angle is clearly discernible: The pressure- and laser-energy-corrected LIF-intensities show an increase of 23 % for excitation at 248 nm and a decrease of 60 % for excitation at 308 nm between top dead center and 402°ca. This behaviour agrees with the shift of the 3-pentanone absorption band. Temperature fields are obtained by calculating the ratio of both LIF intensity distributions pixel-by-pixel (Figure 3) and referencing these results to a calibration measurement at a known temperature.

Single shot temperature distribution images for various timings in the compression and the power stroke of the fired engine are shown in Figure 4. The flame front propagation is depicted by the burned gas region behind the flame front where the tracer has been completely consumed. The temperature distributions appear mostly homogeneous in all single shots for various detection times throughout the engine cycle, as was expected for a skip-fired and carburetted engine. This justifies deriving averaged temperatures for small areas (10 x 7 mm^2) within the unburned gas region for 100 single

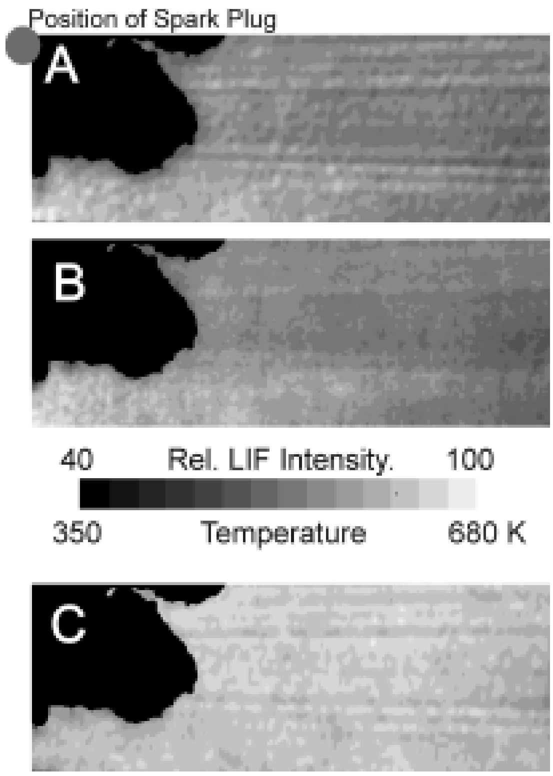

Figure 3: *Instantaneous tracer-LIF distributions obtained from 3-pentanone after excitation at a) 308 nm and b) 248. c) shows the instantaneous temperature field for a single engine cycle at 360°ca inferred from a) and b). Displayed is a region of 1.9 x 5.4 cm^2.*

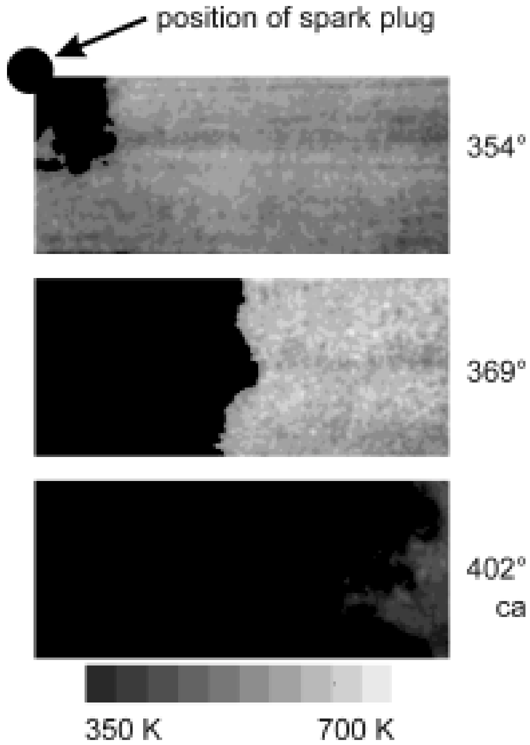

Figure 4: *Single-shot temperature fields for three different crank angle timings (360°ca is top dead center in the power stroke). The dark area represents burned fuel.*

temperature measurements per detection timing. These averaged temperatures were compared to the results of the adiabatic compression temperature calculated from measured pressure traces for an empirical temperature-independent ratio of heat capacities of $\kappa = 1.33$ (Figure 5). The temperatures calculated for motored engine cycles fit the experimental data remarkably well. The standard deviations of these data sets, which include engine cycle-to-cycle variations as well as the statistical error of the method, demonstrate that the temperature measurements can be obtained with an accuracy of better than ± 25 K.

The instantaneous temperature fields obtained in the manner described above can be used to correct the corresponding tracer-LIF images of either excitation line for temperature effects by applying the appropriate factor for temperature dependence on a per pixel basis. The resulting images contain relative fuel concentration distributions. These can be calibrated to yield absolute fuel concentrations by referencing the values to a single measurement of known fuel concentration, e.g. with a calibration gas mixture in the stopped engine, or, in the case of close to homogeneous fuel distributions, by assuming the known global fuel concentration in the combustion chamber to be representative of the average fuel concentration within the volume illuminated by the laser sheet. In this case, each pixel can be assigned a local fuel concentration by referencing its value to the integral sum of pixel values across the entire laser sheet.

Two-line planar LIF-imaging of 3-pentanone provides a technique for measuring the temperature distribution and development in the unburned gas region. The technique can be applied to highly turbulent systems with inhomogeneous species distribution under transient conditions and was applied successfully in SI engine combustion for the first time. Temperature distributions obtained from the two-line measurement can subsequently be used to further quantify the fuel distribution as obtained from either single-wavelength measurement. Thus, the temperature influence on tracer LIF-imaging as reported in several applications can be accounted for.

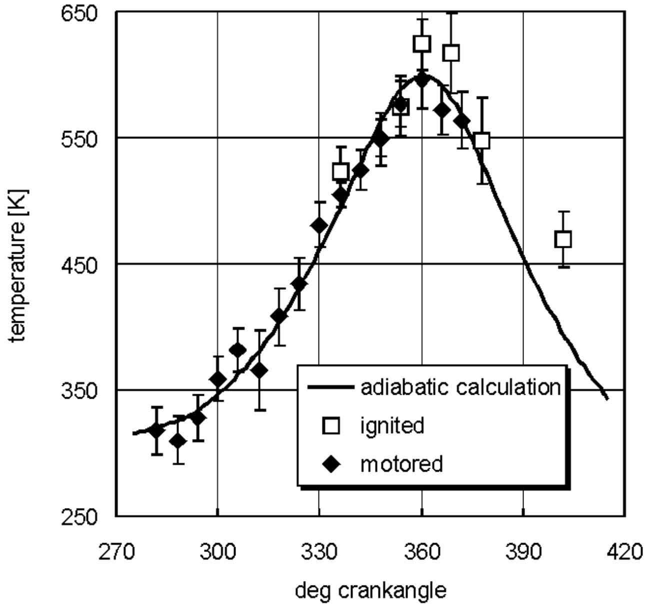

Figure 5: *Averaged measured temperatures in motored and fired engine cycles, compared to the adiabatic temperature in the motored engine derived from the measured pressure trace with* $\kappa = 1.33$

References

1. A. Buschmann, F. Dinkelacker, T. Schäfer, M. Schäfer, J. Wolfrum, "Measurement of the instantaneous detailed flame structure in turbulent premixed combustion", *26th Symp. (Int.) on Combustion*, The Combustion Institute, Pittsburgh, 437 (1996)
2. C. Schulz, V. Sick, J. Wolfrum, V. Drewes, M. Zahn, R. Maly, "Quantitative 2D single-shot imaging of NO concentrations and temperatures in a transparent SI engine", *26th Symp. (Int.) on Combustion*, The Combustion Institute, Pittsburgh, 2597 (1996)
3. A. Arnold, A. Buschmann, B. Cousyn, M. Decker, F. Vannobel, V. Sick, J. Wolfrum, "Simultaneous imaging of fuel and hydroxyl radicals in an in-line four cylinder engine", *SAE Paper* 932696 (1996)
4. F. Großmann, P. Monkhouse, M. Ridder, V. Sick, J. Wolfrum, "Temperature and pressure dependences of the laser-induced fluorescence of gas-phase acetone and 3-pentanone" *Appl. Phys.* B **62,** 249 (1996)
5. M.C. Thurber, F. Grisch, R.K. Hanson, "Temperature imaging with single- and dual-wavelength acetone planar laser-induced fluorescence", *Opt. Lett.* **22**, 251 (1997)
6. S. Einecke, C. Schulz, V. Sick, "Dual wavelength temperature measurements in an IC engine using 3-pentanone laser-induced fluorescence", in: *"Laser Application to Chemical and Environmental Analysis"*, Technical Digest (Opt. Soc. of America; Washington DC), 84 (1998)
7. S. Einecke, C. Schulz, V. Sick, A. Dreizler, R. Schießl, U. Maas, "Two-dimensional temperature measurements in an SI engine using two-line tracer LIF", *SAE paper No. 982468* (1998)
8. F. Hoffmann, B. Bäuerle, F. Behrendt, J. Warnatz, "2D-LIF investigation of hot spots in the unburnt end gas of I.C. engines using formaldehyde as a tracer", *3rd Internat. Symp. COMODIA 94*, 517 (1994)