Recent developments in laser-induced incandescence (LII) for soot diagnostics in high-pressure laminar flames and engine-like Diesel combustion

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The analysis of soot formation and oxidation is essential for Diesel engine development to meet future pollutant emission reduction requirements. In recent years laser-induced incandescence (LII) has developed to a powerful tool for soot diagnostics in flames, even in the challenging environment of Diesel combustion. This work presents some recent applications of LII for soot particle sizing in high pressure combustion environments including premixed laminar ethylene/air flames, diesel combustion in a constant volume spray combustion chamber and in-cylinder engine combustion, with some emphasis on challenges in modeling time-resolved LII signal transients in these environments.

Introduction

For a better understanding of soot formation in high pressure combustion situations, such as gas turbine and Diesel combustion quantitative, in-situ soot particle sizing is a valuable experimental approach. Measurements, either under well-defined conditions (steady laminar flames) or for unsteady, turbulent conditions (spray injections, Diesel engines) create an experimental data base and stimulate further development and validation of modeling codes for soot formation and oxidation in these combustion environments. In addition, two-dimensional optical soot visualization allowed the development of conceptual models for Diesel combustion based on the qualitative understanding of the processes in the Diesel spray flame [1]. Latest developments for direct-injection (DI) Diesel engines tend towards higher injection pressure and smaller nozzle diameters [2].

In the present work we focus on recent development of time-resolved laser-induced incandescence (TiRe-LII) for the determination of mean soot particle size and size distributions in high-pressure combustion environments prevalent either in steady laminar flames, transient Diesel spray combustion in constant volume pressure vessels, or in small-size Diesel engines. Since gas phase and/or soot particle temperatures are essential when evaluating TiRe-LII signal profiles for particle sizing, in the described experiments different techniques were applied in obtaining this parameter.

Laser-induced incandescence has been used successfully in high-pressure combustion environments for measuring soot volume fractions in gas flames [3], spray flames [4], engine combustion [5, 6], and engine exhaust gases [7] both for pointwise measurements and for two-dimensional imaging. Recent reviews state the current situation in LII experiments and modeling [8, 9]. Generally, particle sizes have been deduced from modeling the complete temporal LII signal decay, using theoretical models treating heat, mass and radiative transfer of the laser-heated particle [10, 11]. A numerical tool for simulating TiRe-LII signals (*LII-Sim*) is available online [12].

Experiments and Results

LAMINAR FLAMES – The knowledge of the influence of environmental gas pressure on the LII-signal is important in order to enable the quantitative allocation of soot volume fraction and particle size from LII measurements [13], and can best be investigated in laminar flames. For this purpose, the burner used in our studies was installed inside a high-pressure chamber equipped with four quartz windows for optical access. The burner matrix consists of a stainless steel sinter plate with a diameter of 20 mm. For stabilization, the central sooting ethylene/air flame was surrounded by a non-sooting methane/air flame (diameter 56 mm). The two flames were surrounded by a coflow of air both for further stabilization of the flame and for keeping the windows clean of soot and water. Measurements were carried out for pressures up to 10 bar for an equivalence ratio of ϕ = 2.1, corresponding to a C/O ratio of 0.7. Further details are given in [13, 14].

For the LII experiments the beam of a short-pulsed Nd:YAG laser at 1064 nm was aligned through the burner. A small portion (1.9 mm diameter) of the beam was cut out with an aperture and relay imaged onto the center of the burner in order to obtain a homogeneous energy distribution within the beam. The resulting energy density in the observed volume was tuned in the range of 0.09–0.62 J/cm^2. For simultaneous particle pyrometry applications time-resolved LII signals were detected at right angle at two different wavelengths (550 and 694 nm) with fast photomultipliers.

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Gas phase temperature measurements were accomplished by seeding the fresh gases with 0.5% to 2% of NO and using NO-LIF thermometry [15], where the A-X(0,0) band is probed at 225 nm with a H_2-Raman-shifted KrF excimer laser [16]. Simulated spectra were fitted to the experimental data with absolute temperature, broadband background and total signal intensity as free parameters.

P [bar]	HAB [mm]	T_p^0 [K]	T_g [K]	CMD [nm]	σ_g
1	10	3758	1600	44	1.49
2	10	3854	1710	31	1.54
5	5	3568	1850	10	1.84

Table 1: Results of the measured temperatures and fit parameters of the comparison of the LII signal decay with the model at 1-5 bar.

Measured gas temperatures in the rich ethylene/air flames at total pressures of 1, 2 and 5 bar in the center (region of 10 mm wide × 2 mm high) of the flame are listed in Table 1 with a relative uncertainty of 3%. Spectral broadening of the lines in the excitation spectrum reduces signal intensities and spectral structure at higher pressures. The particle temperatures at the time of laser heat-up deduced from the 2-color pyrometry measurements are also listed.

The time-resolved LII measurements show that the LII decay rate in the heat conduction regime is linearly proportional to pressure, whereas comparison with soot volume fraction measurements by extinction does not show significant pressure dependence. When using prompt detection, calibration of the LII signal at atmospheric pressure should be feasible for high-pressure applications. However, the influence of varying flame conditions on LII must be further addressed.

CONSTANT VOLUME CELL – For the comparison with model simulations, and for the development of optical diagnostics techniques, measurements in cells where the fuel is injected into air at high pressure and temperature and with no moving pistons, such as in engines, often are more helpful. For this purpose measurements at the high-temperature, high-pressure spray combustion chamber at PSI (Switzerland) were performed. The cell is equipped with pneumatically actuated inlet and outlet valves, four sapphire optical windows (40 mm clear aperture) and a water cooled electromagnetically actuated single-hole injection nozzle. To simulate conditions close to top-dead center during Diesel combustion the cell is heated with four heating cartridges (2 kW power consumption each) and is loaded with preheated, pressurized air prior to fuel injection. The cell can be operated with pressures up to 80 bar and wall temperatures up to 800 K, respectively.

TiRe-LII experiments were performed with a similar excitation / detection setup as described above (with only a single-color detection channel active), acquiring LII decay profiles during predetermined temporal delays after start of injection (SOI). Soot temperatures prior to particle laser heat-up were determined from spectrally resolved soot pyrometry using a spectrometer / camera detection channel. A more detailed description of the complete experiment and measurement techniques can be found in [17, 18].

Measurements were performed for initial gas pressures between 1 and 3 MPa, injection pressures between 50 and 130 MPa, and laser probe timings between 5 and 16 ms after SOI. It is shown, that evaluated count mean particle diameters (*CMD*) and standard deviations σ_g are only slightly biased by the choice of typically assumed size distribution widths and gas temperatures. For a fixed combustion phase mean particle diameters are not much affected by gas pressure, however they become smaller at high fuel injection pressure. At a mean chamber pressure of 1.39 MPa evaluated mean particle diameters increased by a factor of two for probe delays between 5 and 16 ms after start of injection, irrespective of the choices of first-guess fitting variables, indicating a certain robustness of the least-squares fitting algorithm applied for TiRe-LII profile analysis.

ENGINE SOOT DIAGNOSTICS – The engine used for in-cylinder LII was a single-cylinder, two-stroke Diesel engine with a displacement volume of 250 cm^3 with optical access through a custom designed temperature-controlled (80°C) cylinder head. The laser beam axis passed the center of the combustion chamber through two silica glass windows, while the already described 2-color detection system has access to the combustion chamber by a third window at the top of the cylinder head. To keep windows clean and the thermal load on the cylinder head low the engine was motored by an electrical asynchronous motor at a constant speed of 1500 rpm and was fired for some individual cycles only. Further details of the experiment are provided in [19]. All experiments were performed at an injection crank angle of 23°CA before TDC and an equivalence ratio of ϕ = 0.26. Soot particles were heated with a laser beam fluence at 1064 nm of 0.10 J/cm^2. Finally, a thermophoretic particle sampler was located in the exhaust gas manifold to get particle probes for further analysis by transmission electron microscopy (TEM).

For the evaluation of the particle radiation signals in terms of particle size, it is important to know the respective mean combustion chamber pressure p_g and temperature T_g. For the present engine conditions, the pressure varied from nearly 80 bar at 0°CA to close to 1 bar at 100°CA. Gas temperatures changed in this region from 2000 K to 1500

K, as was deduced both from two-color pyrometry without laser heat-up and by calculating an individual combustion cycle. With these two parameters it was possible to evaluate the TiRe-LII signals.

Results are shown in Fig. 1. The *CMD* is in the range of 30 to 75 nm, increases up to a crank angle of about 10°CA and then decreases again towards a value of about 30 nm at 100°CA after TDC. This behavior can be explained by particle formation and subsequent particle oxidation. σ_g is constant at a value of 1.1 up to a crank angle of 70°CA and then increases to about 1.32. The two circled values of *CMD* and σ_g, which are shown at the right edge of the diagram, are results of the TEM analysis of the exhaust gas primary particles. It is observed that the TiRe-LII measured sizes at 100°CA after TDC approach the TEM determined primary particle sizes in the exhaust gas quite well.

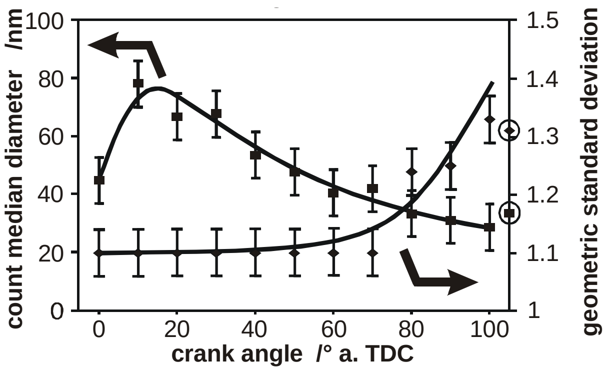

Fig. 1: CMD and σ_g evaluated from the LII signals taken in the engine combustion chamber; symbols on the right axis are the respective values from the exhaust gas TEM sampling

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