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Soot particle sizing during high-pressure Diesel spray combustion via time-resolved laser-induced incandescence

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Single-pulse time-resolved laser-induced incandescence (TiRe-LII) signal transients from soot particulates were acquired during unsteady high pressure Diesel combustion in a constant volume cell for typical top dead center conditions during a Diesel engine cycle. 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 start of fuel injection. In separate experiments and for the same cell operating conditions gas temperatures were deduced from spectrally resolved soot pyrometry measurements. Implementing the LII model of Kock et al. [Combust. Flame 147 (2006) 79–92] ensemble mean soot particle diameters were evaluated from least-squares fitting of theoretical cooling curves to experimental TiRe-LII signal transients. Since in the experiments the environmental gas temperature and the width of an assumed particle size distribution were not known, the effects of the initial choice of these parameters on retrieved particle diameters were investigated. It is shown that evaluated mean particle diameters are only slightly biased by the choice of typical 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 data analysis procedure.

1. Introduction

Worldwide air pollution, e.g., by transportation systems in urban areas is a major environmental threat. Diesel engine powered vehicles are known for their fuel efficiency but suffer due to the nature of the combustion process from high carcinogenic soot emissions. Consequently, over time emission regulations are increasingly tightened. Apart from exhaust gas after-treatment by Diesel particulate filters a reduction of soot tailpipe emissions is desirable by engine-internal measures. This requires a better basic understanding of engine based soot formation and oxidation processes to create optimized combustion strategies within a wide range of engine operating conditions.

Non-intrusive, *in-situ* optical diagnostics can provide detailed information on soot particle size and volume fraction. Such measurements may help in the validation of kinetic mechanisms for numerical simulation of engine in-cylinder soot formation and oxidation. Specifically, laser-induced incandescence (LII) [1,2] has emerged as a powerful tool for quantitative measurement of soot volume fraction and particle size with high spatial and temporal resolution. LII is based on the detection of soot incandescence radiation induced by energy absorption of a pulsed laser beam in the sample, which raises particulate temperature to 3000–4000 K, far above typical flame temperatures. In time-resolved LII (TiRe-LII) this incandescence radiation is recorded with a fast photo-detector, reflecting the heat-up and subsequent cooling of particulate matter. Size information is then obtained from least-squares fitting of calculated LII intensity decay curves to experimental signal profiles, with particle diameter as a free parameter. Many aspects concerning theoretical modeling and practical developments of LII were recently discussed on two successive workshops at the Universities of Duisburg-Essen [3] and Karlsruhe [4], respectively, with scientific results being published in a topical issue of Appl. Phys. B [5] and in [6].

Laser-induced incandescence diagnostics in high pressure steady and unsteady combustion environments is a challenging task. Nevertheless, several research groups have employed LII previously for soot diagnostics in steady high pressure flames [7–9] and in engine-like combustion environments such as optically accessible constant volume cells [10], rapid compression machines [11], as well as in light- [12] and heavy-duty [13–16] Diesel engines. In

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Nomenclature

c_t	mean thermal speed of evaporating molecules (m/s)
d_p	particle diameter (m)
d^0_{pg}	first-guess value of fitted geometric mean particle diameter of assumed particle ensemble (m)
d_{pg}	fitted geometric mean particle diameter of assumed particle size distribution (m)
$E(m)$	absorption function (dependent on refractive index m)
Kn	Knudsen number
m	complex refractive index (–)
m_v	molecular mass of vapor (kg)
$p_{0,chamber}$	pressure in combustion chamber before combustion (MPa)
$p_{LII,chamber}$	pressure in combustion chamber at LII probe time (MPa)
p_{fuel}	pressure in fuel line (MPa)
$\Delta p_{LII,chamber}$	pressure difference between maximum and minimum pressure value recorded for a series of measurement cycles
PSD	particle size distribution
q_{int}	rate of internal energy change (W)
q_{abs}	rate of absorbed laser energy (W)
q_{rad}	radiative heat flux (W)
q_{subl}	heat flux due to evaporation (W)
q_{cond}	conductive heat flux (W)
r_p	particle radius (m)
r_{p0}	particle radius before heating laser pulse hits the sample (m)
r_{pg}	geometric mean particle radius of assumed particle size distribution (m)
SDF	particle size distribution function
SOI	start of injection
S_{LII}	detected laser-induced incandescence signal intensity
Δt_{LII}	temporal delay between start of fuel injection and LII probe time (ms)
$T_{0,chamber}$	temperature in combustion chamber before combustion (K)
T^0_g	first-guess value of fit parameter *gas temperature* (K)
T_g	fitted/measured value of gas temperature (K)
T^0_p	soot particle temperature right after laser heat-up (K)
T_p	soot particle temperature (K)
T_v	temperature of vapor phase soot (K)

Constants

c_0	speed of light (2.998×10^8 m s^{-1})
k_B	Boltzmann constant (1.381×10^{-23} J K^{-1})
σ	Stefan–Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4})

Greek symbols

α_T	thermal accommodation coefficient (–)
α_v	mass accommodation coefficient (–)
$\varepsilon(\lambda)$	wavelength dependent emissivity
$\lambda_{MFP,vap}$	mean free path of vapor molecules (m)
λ_s	(a) detection wavelength of LII signal (m); (b) soot emission wavelength (m)
λ_{cond}	thermal conductivity of the gas (W m^{-1} K^{-1})
ρ_s	density of soot vapor (kg m^{-3})
σ_g	geometric width of particle size distribution (–)

Subscripts

cont	continuum regime
fm	free molecular regime
g	gas, geometric
p	particle
v	vapor

Superscripts

0	(a) first-guess value (parameter in fitting routine); (b) fixed value in fitting run

some of this work mean soot particle diameters were determined from TiRe-LII measurements.

In studies of steady high pressure non-premixed flames Thomson et al. [8] found that mean particle size as well as soot volume fraction increase with ambient gas pressure. Applying spatially resolved TiRe-LII and laser extinction in a variable pressure co-annular flow laminar methane/air-flame, Thomson found the mean particle diameter in the soot formation zone to increase from 20 nm at 0.5 MPa to 120 nm at 4 MPa, whereas the soot volume fraction, f_v, correspondingly increased from 3 to 60 ppm [8]. A power-law scaling with pressure ($\sim p^n$) of path-integrated f_v gave an exponent of $n = 1.4$, somewhat larger than the value of 1 determined by McCrain et al. for a similar flame [17].

For evaluating particle size information from TiRe-LII experiments during transient combustion events, some thermo-physical parameters involved in the precise modeling of the LII signal decay, such as local gas temperature and the particle size distribution (PSD), often are not easily accessible and need to be estimated. In the present work TiRe-LII is applied for soot particle sizing during high pressure transient Diesel spray combustion events initiated in a constant volume cell operated in a mode to simulate top dead center conditions in real engines. In the described experiments the transient combustion process necessitates single pulse measurements, which causes a low signal-to-noise ratio and large statistical variability in the acquired LII transients. Moreover, several model parameters required in precise least-squares fitting theoretical cooling curves to experimental data were not known and needed to be estimated or separately measured, which in turn may lead to biased results. Our results show that, despite these unfavorable prerequisites in the data evaluation, the analysis of TiRe-LII profiles still can provide trend information of evaluated particle size development as a function of gas pressure, fuel injection pressure and probe time after the fuel injection event.

2. Theoretical approach

2.1. General approach

The principle of TiRe-LII, including the derivation of the governing equations and data evaluation procedures, is outlined in a number of publications, i.e., Refs. [1,12,18–21], and will therefore only briefly be discussed here. In the present work the time-dependent particle temperature and mass are calculated using the approach of Kock et al. [12,18], which has been developed and applied for particle sizing during high pressure Diesel combustion.

The energy conservation equation for an individual spherical soot particle imposed to the absorption of light is written as

$$\dot{q}_{int} = \dot{q}_{abs} - \dot{q}_{rad} - \dot{q}_{subl} - \dot{q}_{cond}, \quad (1)$$

where the terms from left to right represent, respectively, the particle's rate of change of total internal energy, light absorption, particle radiation, soot evaporation and heat conduction to the