Application of Light Extinction Methods for the Investigation of Soot Formation during Combustion in a Model Chamber

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ABSTRACT

Two complementary light extinction methods were developed and successfully applied to the analysis of soot formation and oxidation under diesel engine-like boundary conditions in a model combustion chamber. Compared to other measurement techniques, light extinction methods are characterized by real non-intrusive recording and a high temporal and spatial resolution. Using a suitable experimental setup and evaluation procedure, disturbances due to density gradients, flame radiation and light extinction by liquid fuel can be avoided. 1-dimensional light extinction measurements can supply representative mean values of local and time resolved soot mass concentrations and the temporal behaviour of the total mass of soot in the spray during combustion as well as information about the cyclic variations. These data can be confirmed and completed by qualitative measurements with a 2-dimensional light extinction method for single injection cycles. The results clearly show the two contrary processes of soot formation and oxidation in the spray.

INTRODUCTION

Improvements of the combustion process seem to have great potential to solve the conflict between best thermal efficiency and low pollutant formation in internal combustion engines. Thus, detailed knowledge of the individual, interacting processes during fuel injection, mixture formation, auto-ignition, combustion and pollutant formation is necessary. If we consider the soot emission of diesel engines, the specific distinction between the influence of different parameters on the two contrary processes of soot formation and soot oxidation seems to provide great potential for reducing soot emissions.

A lot of research work concerning engine-internal soot formation and oxidation is done using gas sampling techniques. Such techniques (total-cylinder or local in-cylinder sampling) are characterized by a limited spatial and temporal resolution and affect the investigated processes to a certain degree even before the measuring interval. Besides that, no information about single cycles or cyclic variations can be obtained. Also, some optical measurement techniques (e.g. Laser-Induced Incandescence) can only provide data about one time step for each cycle, because the processes are affected directly after the measurement is done. A combination of a 1-dimensional and a 2-dimensional light extinction method (LEM) can provide real non-intrusive data with high local and temporal resolution for single injection cycles as well as representative mean values of a number of injection cycles.

The processes in DI diesel engines are characterized by very complex boundary conditions (permanently changing geometry, flow field, air temperature and pressure; spray-wall interaction; ...) and an engine only provides restricted optical access. This leads to several restrictions concerning the realization of fundamental research work and the application of optical measurement techniques. Thus, a model combustion chamber, which provides simplified engine-like boundary conditions with the possibility of studying the influence of single parameters on the engine internal processes by using optical measurement techniques, is used as a tool.

MODEL COMBUSTION CHAMBER

All experimental results presented in this paper were obtained in a model combustion chamber (1, 3), which provides excellent optical access for investigations under simplified diesel engine-relevant boundary conditions (Fig. 1). Compressed air continously enters two electrical heaters and passes through straightening blades into the observation section of the chamber. The mean axial velocity of the air-flow is about 0.1 m/s and can thus be considered to be nearly quiescent in comparison with the velocities in the fuel spray. The maximum air pressure is 60 bars and the air temperature is limited to 900 K, so that boundary conditions typical for DI diesel engines between the start of injection and auto-ignition can be realized. In order to minimize heat losses through the walls and to achieve a nearly isothermal temperature field, all walls are equipped with additional electrical heaters and ceramic insulation. The border of the observation section is formed by four quartz glass windows of 100 mm length and 40 mm width in two perpendicular axes. The injection system consists of a single-hole injector in the top section of the chamber (1 * 0.2 mm, hole length 0.8 mm) and a modified commercial BOSCH type MW in-line injection pump.

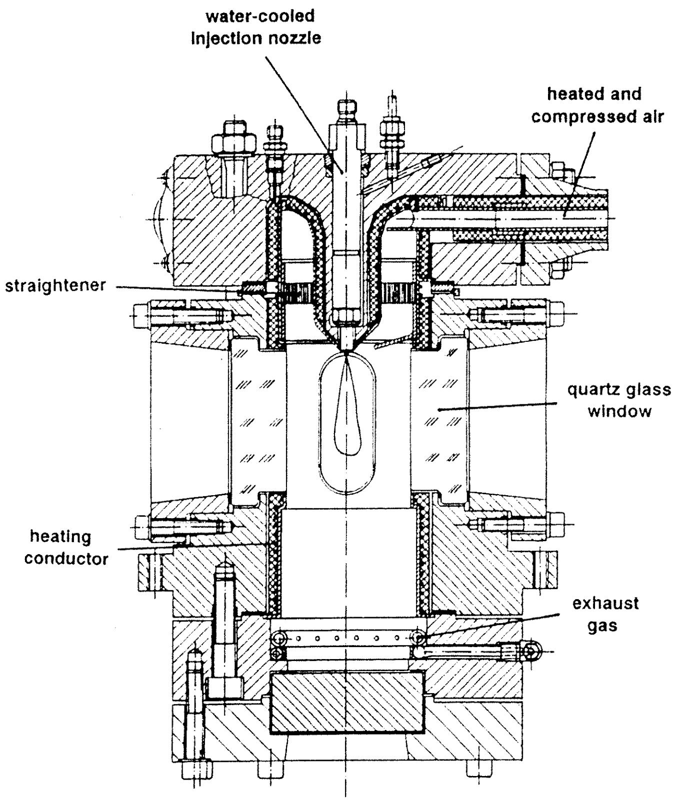

Fig. 1 Longitudinal section of model combustion chamber

The control rack of the injection pump is actuated by a pneumatic cylinder in conjunction with an electromagnetic valve, so that single injections can be realized. Fuel can only be injected each three seconds, because the air in the observation section must be completely changed between two injections. In this configuration, the boundary conditions are characterized as follows:

- The fuel is injected into quiescent air.
- There is no change of geometry during fuel injection and combustion.
- The fuel spray can be considered as a free jet. No spray-wall interaction occurs due to the dimensions of the observation section.
- There is only a slight pressure rise during auto-ignition and combustion due to the large volume in the chamber.

All processes during fuel injection and combustion can be investigated with a large number of non-intrusive optical measurement techniques under well-defined boundary conditions. In contrast to real diesel engines, the influences of single parameters (such as air temperature, air pressure, injection parameters, ...) can be totally separated from each other without any secondary influences. Even the separate influences of air flow parameters (swirl, turbulence) (2) or the spray-wall interaction (3) can be analysed with different modifications which are not dealt with in this paper.

BASICS OF LIGHT EXTINCTION METHODS

The effect of light extinction caused by soot particles can be used for non-intrusive investigations of soot formation and oxidation during combustion. Because the processes are in no way affected by the measurements, data with a high temporal and local resolution can be obtained even for single injection cycles. This distinguishes light extinction methods from other measurement techniques such as in-cylinder gas sampling or Laser-Induced Incandescence. In addition, light extinction methods are characterized by a relatively simple experimental setup, so that such techniques have been successfully applied to engine-like test stands or real diesel engines (4, 5).

Theory of Light Extinction

If a planar electromagnetic wave hits a discontinuity of optical parameters (refractive index m) due to the presence of particles in a gas or liquid, light extinction takes place. For absorbing media, the light extinction is defined as the superposition of light absorption and light scattering in the O° direction. Lambert-Beer's law, which describes the exponential extinction of light transmitted through an aerosol medium, and Mie's light scattering theory for the calculation of the extinction coefficient are applied in order to calculate the relation between the particle concentration and light transmittance (8, 9). The intensity of the transmitted light (I) when passing through a cloud of small particles is described by Lambert-Beer's law as a function of the intensity of the incident light (I_0), the particle number density (n_v), the extinction coefficient (Q_{ext}), the optical path length through the cloud (l) and the particle size distribution (D, N(D)) as follows:

$$I = I_0 \cdot \exp\left(-\frac{\pi}{4} n_v \cdot l \cdot \int_0^\infty Q_{ext}(D) \cdot N(D) \cdot D^2 dD\right) \qquad (1)$$

As a result of several parameter studies and the work presented in reference (10) it can be concluded, that in the probable size range of soot particles formed during diesel combustion, the size distribution can be substituted by a mono-dispersed particle size D_{32} with only insignificant error. For small, spherical particles (size parameter $\alpha < 0.3$, Rayleigh's range), the following approximation for the extinction coefficient can be used:

$$Q_{ext} = -4\alpha\left[\mathrm{Im}\frac{m^2-1}{m^2+2}\right] \qquad (2)$$

Last but not least, a particle concentration c_m can be calculated in the following form from equation (1) and (2):

$$c_m = \rho_s n_v \frac{\pi}{6} D^3 = \frac{\lambda}{6 l \pi \,\mathrm{Im}\left(\frac{m^2-1}{m^2+2}\right)} \ln\left(\frac{I}{I_0}\right) \rho_s \qquad (3)$$

It is obvious, that the particle concentration can be calculated independently from the particle diameter only as a function of the transparency I/I_0 and some physical data. Thus, measurements of the ratio of the intensity of the incident light to the intensity of the transmitted light can be used to determine soot mass concentrations in a diesel spray.

Application to Diesel Combustion

Nearly spherical primary soot particles are formed in the diesel combustion chamber, growing together to agglomerates in the later stage of combustion and chain-like structures in the exhaust system. Besides, in the case of small particles, the extinction coefficient is only weakly dependent on the particle shape. Measurements carried out with different techniques (gas sampling, light scattering, 2-colour LE) show that the mean soot particle size is in the range of up to 40 nm in diesel combustion chambers (11), (12) or in technical flames (13). Thus, the size parameter α is below 0.2 if a He-Ne-Laser ($\lambda = 632.8$ nm) is used as a light source, and the approximation of Rayleigh scattering can be used with only insignificant error.

The refractive index m is complex for absorbing materials, where the real part describes the scattering and the imaginary part the absorption properties of the particles. A lot of data about the refractive index as a function of wavelength (14), C/H-ratio (15) and even temperature (16) are available. Depending on a literature study, the value $m = 1.9 - 0.45i$, which is representative for engine-like conditions, was choosen for the wavelength 632.8 nm.

Due to the problems involved in determining the exact particle volume, the literature gives only very little data about the density of soot particles. The calculations of soot mass concentrations (SMCs) in the following were done with a value of 1.8 g/m^3, which is 10% below the density of dense graphite.

Last but not least, it has to be ensured that the results are not disturbed by effects specific for diesel boundary conditions. Density gradients in the fuel spray or the surrounding gas atmosphere, the light radiation from the combustion process and light extinction caused by liquid fuel must be mentioned here. All these effects can be taken into account by using suitable experimental setups and evaluation procedures.

1-DIMENSIONAL LIGHT EXTINCTION METHOD

A 1-dimensional LEM (Fig. 2) is used to obtain representative mean values for spatial and time-resolved soot mass concentrations and the temporal behaviour of the total mass of soot in the spray during combustion. Because a lot of single injection cycles have to be analysed in order to calculate reliable mean values, these data can also be used for an analysis of the cyclic variations at single locations.

Measurement Setup

The fuel spray is lighted by a laser beam (He-Ne-laser, wavelength 632.8 nm, beam diameter 1 mm). A focussing lens is placed at a distance of twice its focal length between the spray axis and the photodiode, which is used to convert the light intensities into voltage signals. Before entering the photodiode inlet, the light is filtered by a narrow bandpass filter (center wavelength 632.8 nm, half-width value FWHM = 1.0 nm). The output signals of the photodiode are recorded by a signal memory recorder before being transferred to a computer system for evaluation. Thus, extinction signals with high temporal resolution (10 μs) are available. The whole experimental setup is built up in such a way that different locations in the fuel spray can easily be measured without readjustment. It must be kept in mind, that only the transparency I/I_0 and not 'real' light intensities are used for the calculation of SMCs.

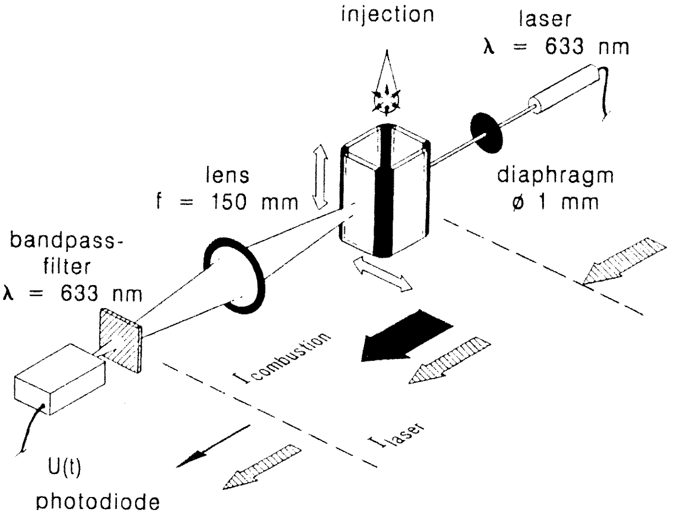

Fig. 2 Experimental Setup of the 1-dimensional LEM

The bandpass filter in front of the photodiode is used to suppress the influence of flame radiation on the measured light intensities. Using such a filter, only the light emission in the wave range of the filter, which is in the order of 0.1% of the laser light intensity and thus insignificant, affects the measured light extinction signal. Light scattering by local density gradients in the fuel spray is eliminated to a large extent by a large detection area and the focussing lens, which collimates the scattered light onto the photodiode. Otherwise, light deflected by density gradients would also be interpreted as light extinction. The accuracy of this action has in the past been proved by comparing a methanol injection with and without combustion.

Evaluation Procedure

For the calculation of local soot mass concentrations and the total mass of soot in the spray from LE measurements, the measured light intensities are corrected with a calibration curve for the data acquisition process, and the time-resolved geometrical mean values are calculated for each measuring location from 64 single cycles in a first step. Because light extinction is also caused by fuel droplets in the early injection phase, this influence must be eliminated. Therefore, additional measurements were carried out in a nitrogen atmosphere (to suppress auto-ignition and soot formation), leading to LE-signals, which are only caused by fuel droplets

(Fig. 3). It is obvious that the first peak of the LE signal is almost exactly reproduced by the injection into a nitrogen atmosphere. On the basis of a large number of LE measurements, the correction of the influence of fuel droplets is now carried out numerically with negligible error, so that the time-consuming and expensive measurements in a nitrogen atmosphere are no longer necessary. It must be remarked, that the influence of fuel droplets and thus errors due to the numerical correction are limited to the very early phase of soot formation.

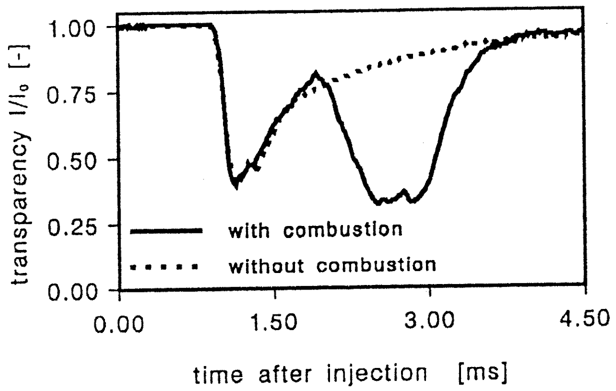

Fig. 3 Typical LE signals with / without combustion

After that, the transparency I/I_0 is calculated for each cycle by relating the light intensities of each time step to the intensity before the start of injection, thus taking fluctuations of the laser intensity or light weakening caused by dirty windows into account. The integral SMCs, averaged over the dimension of the soot area at the measurement location, are calculated as a function of time after injection according to equation (3). In this, the optical path length l is determined from the measurements themselves as the distance from the spray axis, where light extinction is no longer detected.

If measurements are carried out in a matrix of locations in the fuel spray, a linear progress between two locations and rotational symmetry to the spray axis are assumed for the *integral* SMCs , *local* SMCs can be calculated from these data. Besides that, the mass of soot at a certain distance from the nozzle as well as the total mass of soot in the spray can be calculated as a function of time by means of two integrations.

2-DIMENSIONAL LIGHT EXTINCTION METHOD

A 2-dimensional LEM is used to obtain complementary information about soot formation and soot oxidation in the whole spray even for single injection cycles. It must be remarked that only qualitative results can be obtained with this technique, because some of the assumptions necessary for the application of Mie's light scattering theory are not fulfilled (e.g. illumination with parallel light). Similar techniques have been applied to the analysis of spray propagation or soot formation in the literature (4, 6, 7, 15), but the results are often affected by density gradients to some degree.

Measurement Setup

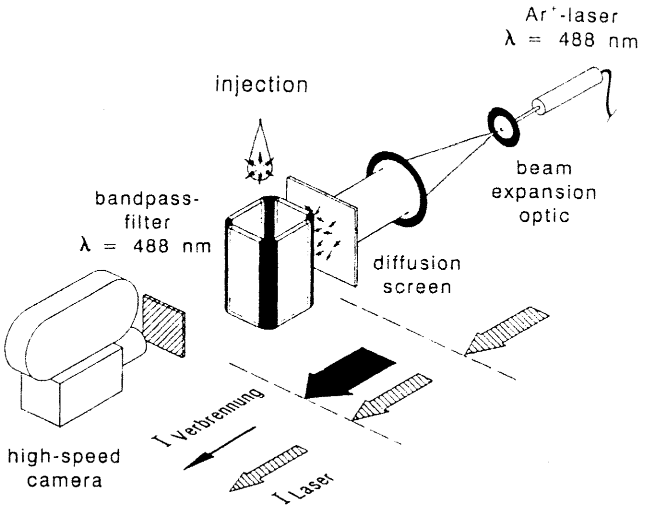

Fig. 4 Experimental Setup of 2-dimensional LEM

The fuel spray is lighted by an expanded Ar^+-laser beam (wavelength 488 nm, power 2 W). In contrast to the laser shadowgraphy technique, a diffusing screen is placed in front of the combustion chamber in order to suppress LE caused by density gradients (4). After passing through the combustion chamber, the transmitted light is filtered by a bandpass filter to suppress the influence of flame radiation on the measured light intensity, and recorded with a high-speed film camera (NAC E-10).

Evaluation Procedure

The high-speed films are evaluated with regard to their optical density using a digital image processing system. Therefore, the films are digitized with a video camera and the transparency I/I_0 is calculated for each pixel by relating the intensity after the start of injection to the intensity directly before the start of injection. Thus, errors due to unequal illumination during filming or digitalization are taken into account. After that, the images are filtered with a low-pass filter in order to minimize signal noise, and the transparencies are converted into grey values from black ($I/I_0 = 0$) to white ($I/I_0 = 1$). For the interpretation of the obtained results it must be kept in mind that, comparable to 1-dimensional measurements, light extinction is also caused by liquid fuel. This can be corrected to a large extent by additional measurements in a nitrogen atmosphere.

EXPERIMENTAL RESULTS

The potential of the LEM is pointed out by means of some exemplary results for a temperature of 550°C, a pressure of 50 bars and an injected fuel quantity of 14 mm^3/cycle, which corresponds to full load conditions in larger DI engines. These boundary conditions lead to an injection duration of 1.89 ms, a maximum injection pressure of 680 bar and an ignition delay of 1.19 ms.

Measurements were carried out in a matrix of locations in the fuel spray. The distance from the injection nozzle was varied in 10 mm steps from 30 mm (closer to the nozzle, no soot signals could be separated from the fuel signals) to 80 mm from the nozzle; the distance from the spray axis was varied in 2 mm steps until no light extinction could be detected any more. The data of 64 single injection cycles were averaged for each location.

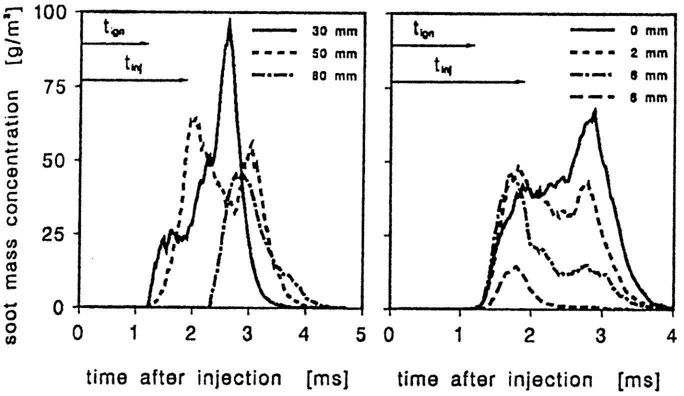

Fig. 5 Integral soot mass concentrations

Fig. 5 shows the integral SMCs in relation to time after injection for different distances from the nozzle (left) and different distances from the spray axis 40 mm below the nozzle (right). Two significant peaks of high SMC occur in the spray. The second peak, which appears approximately 1 ms after the first peak, is limited to a region close to the injection nozzle and close to the spray axis. This results from the significant overlapping of injection and combustion for the present boundary conditions, so that fuel, which is only insufficiently evaporated and mixed, is burnt close to the nozzle. This effect does not occur for smaller injected fuel quantities (part load). The maximum integral SMCs decrease for increasing distances from the nozzle and increasing distances from the spray axis. At the same time, the maxima of the SMC signals are shifted to later times, due to transportation processes along the spray axis and the spreading of the flame from the ignition kernel to encompass the whole spray.

As no information about the radial dimensions of the soot area can be derived from these data and the integral SMCs only provide insufficient information about the distribution of soot in the spray, local SMCs were calculated for all measuring locations and combined in graphical figures (Fig. 6). In these presentations, different local SMCs are represented by different grey scales from white (low SMC) to black (high SMC). Whereas, directly after the start of combustion, the mass of soot rapidly increases, a significant decrease of the mass of soot is obvious for later times due to a predomination of soot oxidation in the spray. These processes are superimposed by transportation along the spray axis. But the maximum SMCs are always found on the spray axis in the region of rich fuel/air-mixtures. In this presentation, the occurence of two regions of high SMC becomes more clearly. The same results are obtained from measurements with the 2-dimensional LEM for single injection cycles (Fig. 7).

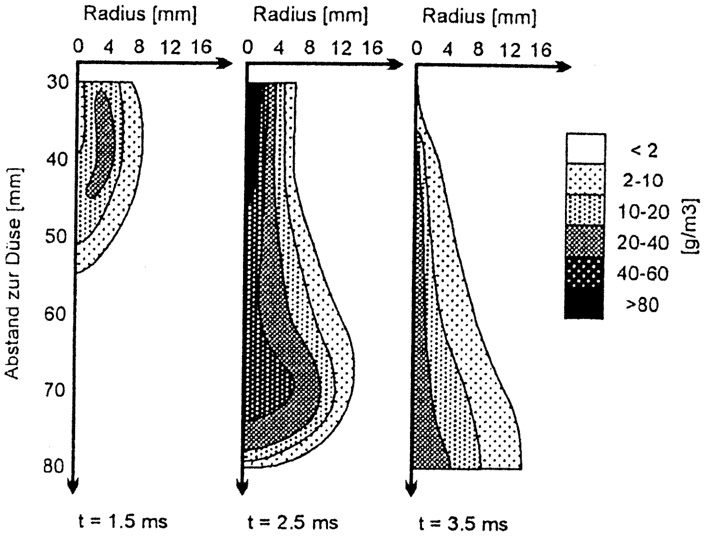

Fig. 6 Distribution of soot mass concentration,·1-D LEM

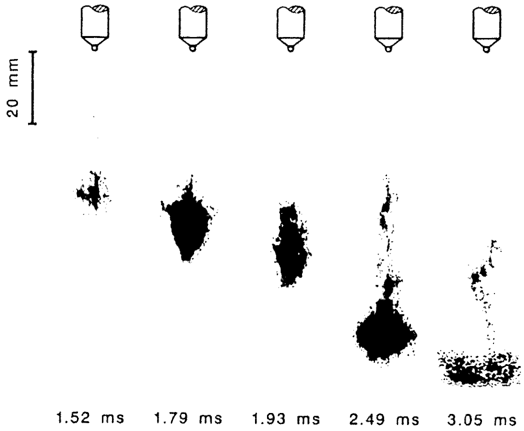

Fig. 7 Distribution of soot, 2-dimensional LEM

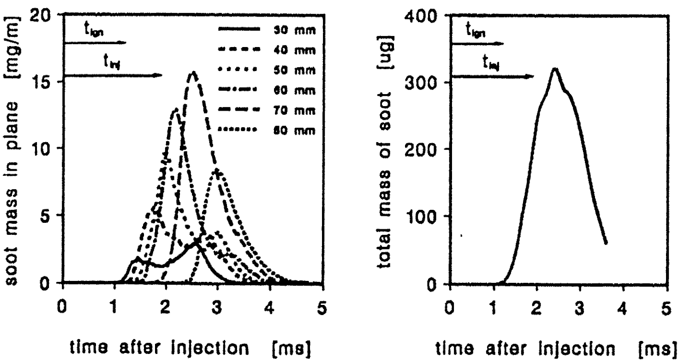

Fig. 8 Mass of soot for definite planes below the nozzle (left) and in the whole spray (right)

If we consider the mass of soot at certain distances from the nozzle and the total mass of soot in the spray, calculated from the local SMCs, we again notice a rapid increase in the mass of soot during the injection duration up to a maximum value of about 325 µg 2.37 ms after the start of injection and a strong decrease in the mass of soot later on (Fig. 8). A maximum rate of soot formation in the whole spray (defined by the gradient of total mass of soot in the range 1.5 to 2.0 ms) is calculated to be 430 mg/s. Although the maximum SMCs are found close to the nozzle, the largest amount of soot is found in a plane 70 mm below the nozzle, due to the large dimensions of the soot area here. Close to the nozzle (30 mm), most of the mass of soot is caused by the high SMCs during the combustion of recently injected fuel in the second peak.

SUMMARY

Two different light extinction methods proved to be a suitable tool for investigating soot formation and oxidation during diesel combustion with a high temporal and local resolution. The results show that the SMC in the spray decreases for increasing distances from the nozzle with a maximum on the spray axis, depending on the mixture stratification. The local and temporal behaviour of SMC in the spray is dominated by soot formation in the early phase and soot oxidation in the later phase of combustion, both processes being superimposed by transportation processes in the spray and the spreading of the flame. An analysis of the total mass of soot shows that the main part of the soot formed during combustion is oxidized later on. A significant overlapping of injection and combustion for a large injected fuel quantity leads to a second peak of high SMC close to the nozzle. The cycle-averaged results obtained with the 1-dimensional LEM are completed and confirmed by the 2-dimensional LEM for single injection cycles.

NOMENCLATURE

c_s = mass concentration of soot particles
D = soot particle diameter
D_{32} = Sauter mean diameter of soot particles
I = intensity of the transmitted light
I_0 = intensity of the incident light
k = imaginary part of the complex refractive index
l = opticle path length through the soot cloud
LEM = Light Extinction Method
m = complex refractive index of soot particles ($\hat{=} n + ik$)
n = real part of the complex refractive index
$N(D)$ = soot particle size distribution
n_v = volumetric number density of soot particles
Q_{ext} = extinction coefficient
SMC = Soot Mass Concentration
α = size parameter ($= \pi D/\lambda$)
λ = wavelength of the incident light
ρ_s = density of soot particles

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