

Optical Investigations of the Ignition-Relevant Spray Characteristics from a Piezo-Injector for Spray-Guided Spark-Ignited Engines

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ABSTRACT

The spray-guided combustion process offers a high potential for fuel savings in gasoline engines in the part load range. In this connection, the injector and spark plug are arranged in close proximity to one another, as a result of which mixture formation is primarily shaped by the dynamics of the fuel spray. The mixture formation time is very short, so that at the time of ignition the velocity of flow is high and the fuel is still largely present in liquid form. The quality of mixture formation thus constitutes a key aspect of reliable ignition.

In this article, the spray characteristics of an outward-opening piezo injector are examined using optical testing methods under pressure chamber conditions and the results obtained are correlated with ignition behaviour in-engine. The global spray formation is examined using high-speed visualisation methods, particularly with regard to cyclical fluctuations. In order to characterise the recirculation zone of the hollow cone spray that is relevant to the ignition behaviour, laser-optical measuring methods were used. It was possible to achieve a significant increase in knowledge, in particular by combining different methods. Both droplet diameter and velocity were determined with a high degree of temporal and spatial resolution using Phase Doppler Anemometry (PDA). Furthermore, an extinction measurement method was used with which the liquid part of the fuel in the recirculation zone of the outward-opening piezo injector could be quantitatively determined under experimental conditions for the first time. To do this, a new approach was developed for calculating the mean extinction coefficients. In conjunction with the results of the PDA measurements it was thus possible to determine the air/fuel equivalence ratio achieved with the liquid fuel phase. The tests were carried out for a typical partial load range point whilst varying the number of injections, the chamber pressure and the injector control parameters. By comparing the spray sizes with the misfire rates determined in-engine, it was possible to assess the spray status with regard to ignition behaviour.

CITATION: Breuninger, T., Schmidt, J., Tschoeke, H., Hese, M. et al., "Optical Investigations of the Ignition-Relevant Spray Characteristics from a Piezo-Injector for Spray-Guided Spark-Ignited Engines," *SAE Int. J. Engines* 8(1):2015, doi:10.4271/2014-01-9053.

INTRODUCTION

Reducing fuel consumption and the associated CO₂ emissions is currently one of the dominant topics in the development of combustion engines. In gasoline engines, the spray-guided combustion process offers the possibility of significantly

reducing fuel consumption in the partial load range in comparison with homogeneous operation. The arrangement of the spark plug in close proximity to the injector and the close chronology of injection and ignition are characteristic of this combustion process. Reliable ignition is dependent on there being an ignitable mixture present in the ignition volume and

sufficient ignition energy being transmitted to the mixture by the ignition system. The interaction of the mixture and ignition parameters is thus decisive for reliable ignition. Methods employed so far in the series use an outward-opening piezo injector. In stratified charge mode the spray from this nozzle forms a characteristic recirculation zone, which is used as the ignition zone. The mixture formation process is thus dominated by the dynamics of the fuel spray. Ignition is typically initiated during the injection process, with high demands on the ignition of the mixture resulting from the short mixture formation time. Consequently high flow velocities occur in the ignition location at the moment of ignition, as well as strong temporal and spatial gradients in the air/fuel equivalence ratio λ . Furthermore, the fuel is still present in liquid form to a significant extent.

In [1, 2, 3] initial results of optical examinations of a piezo injector with an A-nozzle were presented. The focal point of this article is an analysis of the spray characteristics in the ignition-relevant recirculation zone. The results of the optical examinations are correlated with those of in-engine ignition tests, thus contributing to a better understanding of ignition in the spray-guided combustion process.

EXPERIMENTAL METHODS

Pressure Chamber, Injector and Single-Cylinder Engine

The optical examinations took place in a heated pressure chamber. The chamber conditions were aligned with the combustion conditions of the single-cylinder engine used for the in-engine tests. The chamber temperature was a constant 200°C, the air density ρ_A was adjusted via the chamber pressure p_{Ch} of the in-engine density to the crank angle of the end of injection (EOI) (in the case of triple injection, the end of injection is defined as the end of the activation of the 2nd partial injection). The tests were based on a chamber pressure of $p_{Ch} = 8.1$ bar, which corresponds to the conditions at the end of injection of 25 °CA BTDC ($\rho_A = 5.9$ kg/m³). In order to prevent fuel from building up inside the chamber, a constant stream of air was passed through it. An outward-opening piezo injector (HDEV 4) manufactured by Robert Bosch GmbH was used to form the mixture. The temperature of the injector cooling circuit was 70°C. The fuel pressure was 196 bar, as a result of which, in comparison with the engine used, the same differential pressure was achieved at the nozzle at the moment when injection ended. EuroSuper RON 95 was used for the fuel.

The ignition tests in charged gasoline injection mode (CGI) were carried out in a single cylinder engine (Daimler AG). A standard transistorised coil ignition system (TCI) was used as

the ignition system. To record the ignition signals of the ignition system, a digital storage oscilloscope was used. The engine testing bench is described in [4, 5].

Various different injection strategies were examined in the pressure chamber. Based on the in-engine operating point of engine speed $n = 2000$ l/min and the indicated mean effective pressure (IMEP) = 3 bar, a single injection and a triple injection were examined. The corresponding injection durations are shown in figure 1. Furthermore, examinations were carried out whilst varying the injection durations t_i (with single injection) and the chamber pressure p_{Ch} . The measurements in the pressure chamber were carried out without a spark plug.

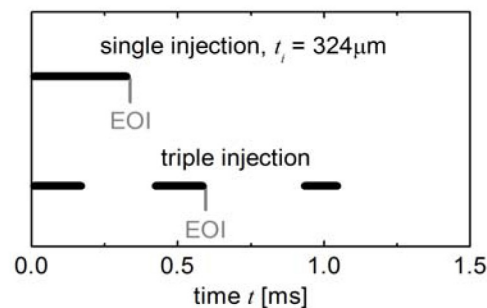


Figure 1. Injection durations for the in-engine operating point $n = 2000$ l/min and IMEP = 3 bar

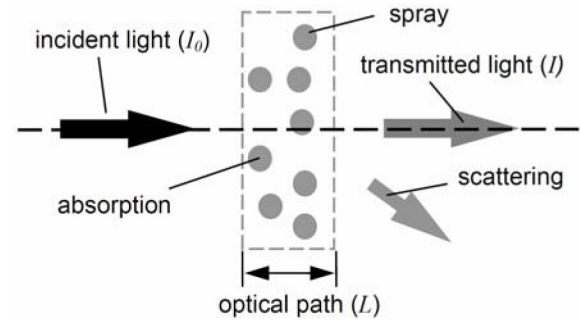
High Speed Visualisation

The shadow method was used to assess the spray dispersion. In this connection, the camera, spray and lighting were on the same optical axis; the experimental set-up is described in [6]. The high speed camera used (HighSpeedStar 6, LaVision) enables an image domain of 768 × 768 pixels with the selected frame rate of 10 kHz. The NanoLite flash lamp (High-Speed Photo-Systeme) was used as a light source; this is characterised by a very short exposure time of approx. 20 ns.

Phase Doppler Anemometry

Phase Doppler Anemometry is a measuring technique based on scattered light for contactlessly determining droplet diameters and velocities. The measuring volume is formed by two intersecting laser beams. If a droplet moves through the measuring volume, then the scattered light is detected by the receiving optics and then processed by the electronic evaluation system. Please refer to the relevant literature [7] for the principles of the PDA measuring method.

The experimental setup is shown in figure 2. A PDA system that is specifically designed for use in dense sprays is used (HiDense, Dantec). The scattering angle is 70°, as a result of which the measurement is largely independent of changes in the refractive index. Further system parameters are shown in table 1.



The extinction cross section C_{ext} required for this is composed from the portions of the scattering C_{sca} and absorption C_{abs} (equation (2)), whereby the absorption of visible light in fuels can be disregarded [9]:

For the individual droplets, the extinction cross section is calculated with the droplet diameter d and the extinction coefficients Q_{ext} from:

The extinction coefficient Q_{ext} is dependent on the wave length λ of the light, the relative refraction index m and the droplet diameter d , which is known from the PDA measurements. In polydisperse spray it is furthermore necessary to average the extinction cross section C_{ext} from the particles present in the optical path, see equation (4):

For sufficiently large particles ($d > 5 \mu\text{m}$), $Q_{\text{ext},i} = Q_{\text{ext}}^* = 2$ applies as a good approximation for the extinction coefficient, whereby equation (4) simplifies to:

For the A-nozzle used, $Q_{ext}^* = 2$ cannot be assumed as a consequence of the small diameter of the droplets. The extinction cross section can be calculated according to equation (4), however the dependence on the diameter distribution and the relative refraction index is detrimental. For this reason, a new method is presented, that enables the calculation of the extinction cross section in polydisperse fine sprays, which only requires the average diameter d_v as an

Table 1. Configuration of the PDA system

	channel 1	channel 2
laser power	55 mW	30 mW
wave length	514.5 nm	488 nm
focal length	310 mm	310 mm
scattering angle	70°	
probe volume diameter	47 μm	
slit width	50 μm	
scattering mode	refraction first order	
polarisation	parallel	
relative refractive index gasoline / air, $m = n_F / n_A$	1,398	

Theory

The extinction measuring process is used to quantify the liquid portion present in the ignition zone. When light passes through the spray, the intensity of light is attenuated as a consequence of scattering and absorption, see [figure 3](#). The droplet density c_N can be determined using this attenuation (extinction) on the basis of Lambert-Beer's law. Disregarding multiple scattering, Lambert-Beer's law is as follows [8]:

$$T = \frac{I}{I_0} = e^{-c_N \cdot c_{ext} \cdot L} \quad (1)$$

input parameter alongside the wave length of the light λ used ([10], for derivation see appendix). The following regression equation is used to determine the extinction coefficients:

$$\bar{Q}_{ext,reg} = 2.02 + 3.256 \cdot \left(\frac{\pi \cdot d_{20}}{\lambda} \right)^{-0.8362} \quad (6)$$

$$\text{valid for } 7 \leq \frac{\pi \cdot d_{20}}{\lambda} \leq 250 \quad (7)$$

The extinction cross section sought $\bar{C}_{ext,reg}$, can now be determined analogously to equation (5) from:

$$\bar{C}_{ext,reg} = \frac{\pi}{4} \cdot d_{20}^2 \cdot \bar{Q}_{ext,reg} \quad (8)$$

Comparative calculations in accordance with equation (8) and the general method in accordance with equation (4) using typical diameter distributions of gasoline high pressure sprays (d_{20} approx. 5 - 10 μm) produce a typical deviation of approx. 1% (cf. [6]).

The parameters of the liquid fuel phase sought can now be determined using equations (1), (6) and (8). The density of the number of droplets $c_{N,F,liq}$ follows from:

$$c_{N,F,liq} = \frac{-4 \cdot \ln(T)}{\pi \cdot d_{20}^2 \cdot \bar{Q}_{ext,reg} \cdot L} \quad (9)$$

The mass concentration $c_{M,F,liq}$ can be indicated with

$$c_{M,F,liq} = \pi \cdot d_{30}^3 \cdot c_{N,F,liq} \cdot \rho_{F,liq} / 6 \text{ from}$$

$$c_{M,F,liq} = -\frac{2}{3} \cdot \frac{\ln(T) \cdot d_{32} \cdot \rho_{F,liq}}{\bar{Q}_{ext,reg} \cdot L} \quad (10)$$

The air/fuel equivalence ratio formed with the liquid fuel phase can now be calculated from:

$$\lambda_{F,liq} = \frac{\rho_A}{c_{M,F,liq} \cdot AFR_{stoich}}$$

$$= -\frac{3}{2} \cdot \frac{\rho_A \cdot \bar{Q}_{ext,reg} \cdot L}{\ln(T) \cdot d_{32} \cdot \rho_{F,liq} \cdot AFR_{stoich}} \quad (11)$$

As the vaporous fuel portions cannot be recorded here, the air/fuel equivalence ratio λ formed with the liquid and vaporous fuel always exhibits smaller values. For the stoichiometric air/fuel ratio of the super fuel, the value $AFR_{stoich} = 14.26 \text{ kg}_A/\text{kg}_F$

is used; the fuel density is assumed to be $\rho_{F,liq} = 700 \text{ kg/m}^3$ due to the unknown fuel temperature and composition during the ignition process.

Set-Up and Experimental Procedure

The experimental set-up for measuring the extinction is shown in figure 4. A helium neon laser (output less than 1 mW, $\lambda = 633 \text{ nm}$) is used as the light source. In order to be able to carry out the measurement in close proximity to the ignition zone, a special measuring probe is used. This consists of two coaxially aligned capillary tubes whose gap defines the measuring volume (optical path: $L = 3.6 \text{ mm}$). An aperture on the light path of the measuring probe reduces the beam diameter to 0.8 mm (aperture A). The aperture positioned before the receiver (diameter 3.6 mm, aperture B) has the objective of fading out the light scattered at small angles. A high speed camera is used as a receiver. Using a neutral density filter, the intensity of the laser beam is adjusted to the dynamic range of the CMOS chip. The measurement rate of the camera system used is 50 kHz with an exposure of 2 μs . Per measuring point, 50 injection cycles are carried out.

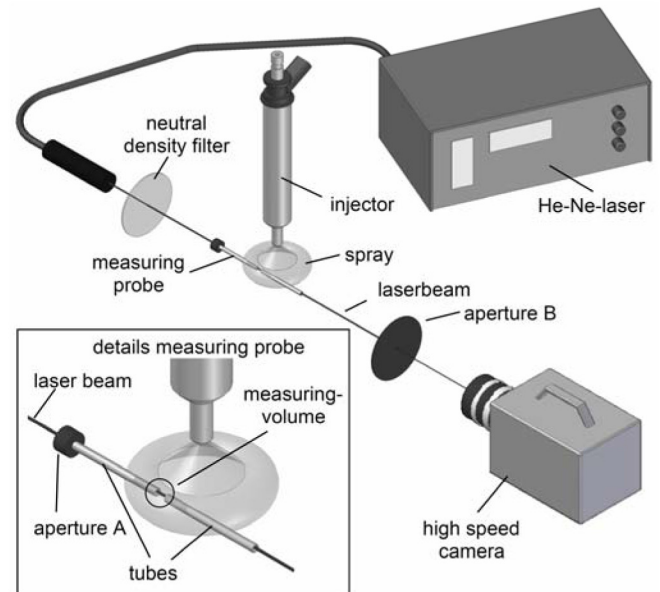


Figure 4. Experimental set-up for extinction measurement

The intensity of the incident light I_0 was determined for each injection cycle within the first 200 μs after the start of injection. In this time domain, there was still no spray in the measuring section so that it was possible to determine the intensity I_0 very reliably for each cycle using the high speed camera. The air density at the moment of ignition $\rho_{A,IT}$ was used to calculate the air/fuel equivalence ratio $\lambda_{F,liq}$. The resulting values for an interval from the end of injection and ignition timing of EOI - IT = 3°CA are shown in table 2 for the respective chamber pressures.