

Investigation of Fuel Atomization and Evaporation of a DISI Injector Spray Under Homogeneous Charge Conditions

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ABSTRACT

Understanding the causal loop from injection to combustion in modern direct injection engines is essential to improve combustion and reduce emissions. In this work, the section from injection to fuel-evaporation in this causal loop was investigated using different optical measurement techniques, with a focus on drop size measurements using Phase Doppler Anemometry (PDA). One spray jet of a modern DISI multi-hole injector was investigated using gasoline RON 95 fuel and two single component alkane fuels (n-hexane / n-decane). In a first step the macroscopic spray formation and propagation of this spray jet were studied using a 2D-Mie-scattering technique in an optical injection chamber at homogenous charge DISI conditions. Furthermore, the droplet size distribution and mean diameter were determined spatially and temporally resolved for an ambient pressure of 0.3MPa and different ambient temperature (323K / 423K / 523K) conditions in the optical chamber using Phase Doppler Anemometry. For an ambient temperature of 323K, the influence of the Reynolds number on the atomization process was studied under non-evaporating conditions showing an almost linear decrease in mean diameter versus logarithmic Reynolds number. This work demonstrates that knowledge of the drop size distribution at different positions in a gasoline spray under modern charged conditions is not enough to determine an evaporation ratio, i.e. evaporated mass vs. penetration depth. However, it was possible to determine the influence of the ambient temperature on the drop size and drop size distribution at a fixed measurement position and to estimate an evaporated mass as a function of the ambient gas temperature.

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INTRODUCTION

This work investigates one spray plume of a solenoid driven, multi-hole injector. An advantage of multi-hole injectors for modern direct injection spark ignition (DISI) engines is the fast addition of fuel and the selective spatial distribution of the fuel in the cylinder, which can be adjusted through the targeting of the nozzle holes. The atomization principle is not very effective but comparably robust and therefore injection pressures have been increased to provide a basis for fast and complete evaporation, which is responsible for a good mixture formation. As the combustion process of modern DISI engines is controlled to a significant extent by the mixture formation, the processes mentioned affect the emission of soot and HC and are subsequently of great interest.

With the application of modern regenerative and synthetic fuels, it is increasingly important to gather more information about the influence on atomization and evaporation of the physical properties of the fuel. Therefore, in addition to gasoline, n-hexane and n-decane - which represent a low and

a high boiling point, and a low and high viscosity fraction of gasoline - were also investigated in this work.

The goal was to show how the fuel components influence the drop size distribution, on the one hand by the primary break up, and on the other hand by evaporation. To this end, the ambient temperature as well as the fuel temperature were varied to achieve a change in kinematic viscosity and surface tension. Zigan et al. [1] showed a very small influence of the physical properties on the drop size distribution of single component fuels with a twelve-hole injector for high ambient pressure and comparable low temperatures. However, at high ambient temperatures a strong influence of the boiling temperatures is shown, with different alkane fuels showing a different drop size distribution. In contrast, Lee and Reitz [2] show a considerable influence of viscosity on the spray from a diesel swirl injector. Furthermore, several empirical models of the Sauter mean diameter, which can be found in the literature, include the physical properties of the injected fuel [3,4,5].

EXPERIMENTAL SETUP

The focus of this work was to investigate the influence of increasing ambient and fuel temperature on the spray from a modern DISI injector mainly using results of Phase Doppler Anemometry (PDA) measurements. A Dantec PDA System (Dantec HiDense P80), which was supplied with an Ar⁺ laser (max. power 9W multiline, Coherent Innova 300), was set up to an optically accessible injection chamber (cf Fig. 1). In this chamber a DISI injector was mounted in a thread tempering the injector shaft and the incoming fuel, ensuring that the target values for fuel temperature are met.

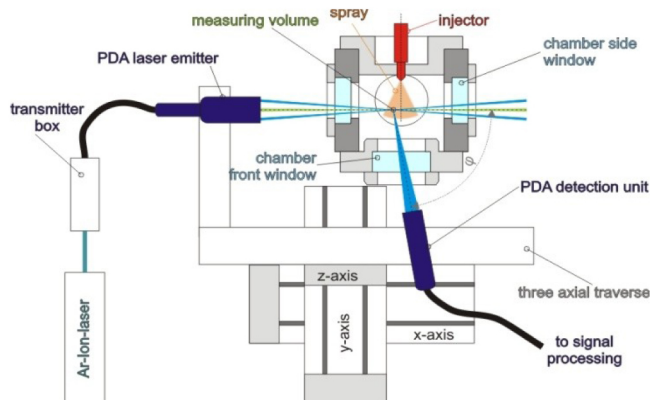


Fig. 1. Setup of the PDA measurement system and the injection chamber

In Table 1 the configurations and setting of the PDA system are listed.

Table 1. Optical configuration and settings of Phase Doppler Anemometry System: Dantec HiDense P80

Transmitting optics:	
Laser beam power	Each: 170mW
Beam wavelength	514.5nm
Beam Spacing	60mm
Focal length	310mm
Receiving optics:	
Collecting angle	Brewster angle: ~69°C
Focal length	300mm
High Voltage Amplification	1000V
Processor Parameter:	
S/N validation ratio	-2dB
Spherical validation	10%
signal bandwidth	100MHz
Detection time span	0-5ms after electrical signal
Validation:	
Spherical validation	~80% of accepted droplets
Data rate	100-300 droplets per injection
High Voltage Amplification	1000V

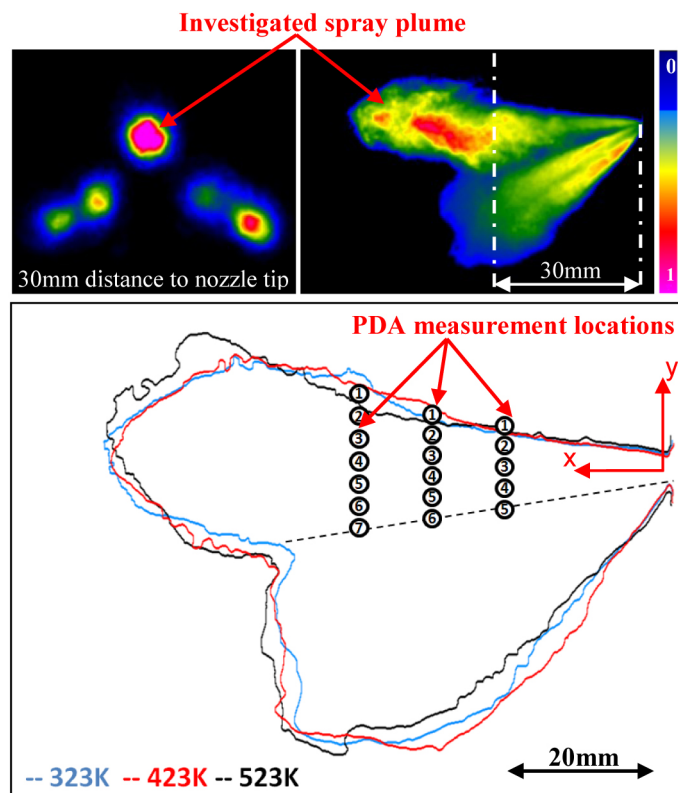


Fig. 2. **Top:** Average MIE-2D-lightsheet image (direction: radial and axial spray propagation) of the whole spray of the injector (investigated spray plume marked with arrows); **Bottom:** Contour plots of the average MIE-2D-lightsheet images for three different temperatures with PDA measurement places marked; Operating conditions: $p_{amb} = 0.3\text{MPa}$, $p_f = 20\text{MPa}$, $v_f = 298\text{K}$;

To gain an overview of the global spray structure and to find adequate measurement positions for the PDA measurement technique, the axial spray structure of the top spray plume of injector was first investigated with lightsheet illumination. To do this the beam of a pulsed frequency double Nd:YAG laser (532 nm; pulse duration: about 10ns) is formed by telescope lenses to a lightsheet. In Figure 2 (Top) the spray from the DISI injector and the investigated plume especially is shown in average images (axial and radial spray direction) calculated from 32 single images and represented in a false color style. In the bottom part of Figure 2 the locations for the PDA measurements are marked in contour plots at three different distances to the nozzle tip (20mm / 30mm / 40mm), each with five to seven measurement positions located perpendicular to the spray axis equally distributed across the spray plume. These contour plots represent the spray shape of the injector for the three different ambient temperatures and show only a small influence of ambient temperature on the global spray shape, especially in the region next to the nozzle tip. Therefore, the main parts of investigation were carried out at a distance of 30mm, as a

good compromise to produce a constant spray shape in the measurement plane and signal quality for the PDA measurements.

To study the influence of a raised ambient temperature, which is determined as the average out of the incoming and out streaming gas, on the drop size of different fuels it is helpful to study the influence of the other relevant injection parameters first. This produced the following table for different injection and ambient parameters:

Table 2. List of parameter varied for ambient and injection conditions

Fuel temperature v_f :	298K / 363K
Injection pressure p_f :	6.5MPa / 20MPa
Ambient pressure p_{amb} :	0.3MPa
Ambient temperature v_{amb} :	323K / 423K / 523K

Gasoline and two single component fuels n-hexane and n-decane were used to study the influence of the physical properties.

RESULTS AND DISCUSSIONS

In a first step the influence of the physical properties on the atomization process is shown by a variation of both injected fuel and fuel temperature. The influence of the raised temperature on the spray - especially the drop size and drop size distributions - are shown as a function of penetration depth and as a function of raised ambient temperature in a second and third step.

Evaluation of the Atomization Process as a Function of Reynolds Number

According to Lefebvre [6] the spray break-up is described by the dimensionless numbers of Ohnesorge (Oh), liquid Weber (We_L) and Reynolds (Re_L), which are described by Equ.1, Equ. 2, Equ. 3. Whereas the primary break-up is described by Reynolds and Ohnesorge number in the Ohnesorge diagram, and the wind induced secondary break-up by Weber number. For gasoline injection typically small Weber numbers occur resulting from small ambient gas densities. Furthermore the relative velocities between fuel droplets and surrounding air are limited by strong air induction into the spray leading to a quite small influence of the secondary atomization for gasoline spray under moderate ambient conditions.

$$Re_L = \frac{D \cdot u}{\nu}$$

Equ.1

$$Oh = \frac{\nu}{\sqrt{\rho_g \cdot \sigma \cdot D}}$$

Equ.2

$$We = \frac{\rho_g \cdot D \cdot u_{rel}^2}{\sigma}$$

Equ.3

The physical properties necessary for the calculation of the dimensionless numbers - density, kinematic viscosity and surface tension - are listed in Table 3. Initial investigations without the influence of evaporation were conducted in order to obtain a reference for the quantification of evaporation.

Table 3. Physical properties of the used fuels at 0.3MPa ambient pressure

	density [kg/m ³]	surface tension ² [mN/m]	kinematic viscosity [m/s ²]
n-hexane 298K	655	17,92	0,45 x 10 ⁻⁶
n-hexane 363K	591	11,27	0,28 x 10 ⁻⁶
n-decane 298K	727	23,37	1,17 x 10 ⁻⁶
n-decane 363K	676	17,39	0,59 x 10 ⁻⁶

¹: data base of National Institute of Standards and Technology (NIST; www.nist.gov)

²: surface tension at 0.1MPa atmospheric pressure

A variation in the fuel temperature and the influence on the drop size distribution of the different fuels is shown in Figure 3.

Due to the reduction of the kinematic viscosity (n-hexane: 38%, n-decane: 50%) the droplet size distribution was shifted to smaller droplets (cf Fig. 2: left / right) when the fuel temperature was increased.

To work out the influence in a more detailed manner, a correlation between the mean drop sizes and the Reynolds numbers was conducted (Fig. 1).

Plotting the results of the average drop size logarithmically, one can observe a linear dependency of the mean drop size on the logarithm of the Reynolds number. This is, therefore, an indicator of the quality of the primary break-up. The velocity u , necessary to calculate the Reynolds number was calculated using Bernoulli's law.

The difference in the drop size for the two different injection pressures is also thought to be influenced by the secondary break-up, where the Weber number (cf Equ. 3) and, consequently, the velocity of the droplets play the decisive role. Additionally, there is an influence from enhanced cavitation in the nozzle due to higher mass flow.