

High-speed non-intrusive measurements of fuel velocity fields at high-pressure injectors

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ABSTRACT

Using a single high-speed camera and a frequency modulated laser, a novel approach is presented for fast velocity field measurements in unsteady spray flows. The velocity range is from zero up to several 100 m/s, which requires a high measurement rate and a large dynamic. Typically, flow measurements require to seed tracer particles to the fluid. A paradigm shift to seeding-free measurements is presented. The light scattered at the phase boundaries of the fluid droplets is evaluated. In order to validate the high-speed measurement system, a detailed uncertainty analysis is performed by means of measurements as well as simulations. Thereby, variations of the scattered light intensity, which are based on the high temporal velocity gradients, are found to be the main contribution to the uncertainty. The eventually measurement results, obtained at a measurement rate of 500 kHz, exhibit spray velocities ranging from 0 m/s up to 400 m/s in less than 1 ms, and the detection of unsteady and irregular flow phenomena with a characteristic time of several μ s is achieved. This demonstrates the high measurement rate, the high temporal resolution and the large measurement range of the proposed high-speed measurement system.

1. Introduction

The reduction of noise and pollutant emissions is a demanding task concerning the development of Diesel engines. Since these emissions are influenced significantly by the injection of the fuel into the combustion chamber, a deeper understanding of the unsteady fuel spray distribution is necessary. Hence, time-resolved velocity measurements of entire injection cycles are indispensable in order to resolve the unsteady flow behavior of the fuel droplets and, thus, to optimize the injection process in modern Diesel engines. The fast injection process in such engines is operated at injection pressures over 2000 bar, which typically leads to fuel velocities from zero to several hundred m/s and back to zero within 1 ms [1,2].

For this reason, the used measurement system has to fulfill several requirements such as a high measurement range and a high dynamic range. In order to allow fast, dynamic and non-invasive measurements, an optical measurement system without additional seeding particles shall be used. A high-power light source is thereby necessary for the illumination due to the dense fuel concentration. In addition, a high-speed camera system is required, which provides field measurements with more than 100 kHz. The imaging capability and the high measurement rate are necessary for analyzing the complex, unsteady behavior of single fuel injections. With respect to the distance to the

nozzle outlet, the distribution of the injected fuel is classified into four areas [3]. These four regions are from upstream to downstream.

- (i) the internal nozzle flow region, where a liquid flow is present and cavitation occurs,
- (ii) the near-nozzle (near-field) spray formation region, which includes a liquid sheet that breaks up into non-spherical droplets and further into smaller spherical droplets,
- (iii) the far-field developed-spray region, where the smallest droplet sizes occur, and
- (iv) the spray-wall interaction region, where often a liquid film is formed onto the surface.

Here we focus on the spray formation in the near-nozzle region (ii) and how it is influenced by different nozzle geometries.

Planar measurements of the fuel penetration depth and the velocity of the spray front were performed with 500 kHz using flash lights and a high-speed camera [4]. However, no velocity information from inside the spray was obtained. The in-spray velocity field can be measured with particle image velocimetry (PIV). PIV is a well-known standard technique, which provides flow field measurements with a high temporal resolution in the μ s range or better. Various measurements of the fuel velocity were performed using PIV in the far-field spray

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region (iii), where correlatable spray structures are detectable [1,2] or particles are added to the spray [5]. Furthermore, simultaneous measurements of the air velocity and the fuel velocity distribution using fluorescent seeding particles in the air and correlatable structures in the spray were shown for the far-field region (iii) [6,7]. Since such correlatable structures are not present in the near-nozzle region (ii), it is not possible to perform PIV measurements in this area without adding seeding particles [8]. Either the fuel droplets are too small and, thus, not resolved by the imaging system or no droplets occur. This problem is solved by optical measurement techniques which evaluate the light scattered at the phase boundaries between air and fuel. By detecting the velocity-dependent change of the scattered light frequency (Doppler frequency), these measurement techniques are not limited by the resolution of the imaging system. As a result, velocity measurements inside sprays were performed with laser Doppler anemometry (LDA) or phase Doppler anemometry (PDA) [9,10]. However, both techniques typically offer no instantaneous field measurement and the measurement rates are in the low kHz range. Field measurements of spray velocities were presented using Doppler global velocimetry (DGV) with pulsed lasers at low repetition rates of 10 Hz [11,12] and at a higher measurement rate of 250 kHz using planar Doppler velocimetry (PDV) [13]. Furthermore, field measurements and high measurement rates up to 200 kHz were demonstrated with Doppler global velocimetry with laser frequency modulation (FM-DGV) [8]. Using a power-amplified laser with fast sinusoidal frequency modulation and a high-speed camera, FM-DGV measurements of high-pressure fuel injections have been presented for the first time, whereat unsteady flow phenomena in the range of several μs were detected [8]. As a result, the measurement rate and the respective temporal resolution of the high-speed camera-based FM-DGV approach has to be increased further in order to improve the detection of the fast unsteady injection phenomena. The measurement rate equals the modulation frequency of the laser, which results in a modulated intensity signal that has to be detected with the high-speed camera [8]. Hence, the measurement rate is limited by the frame rate of the camera and, thus, the number of frames required for one velocity value has to be minimized in order to increase the measurement rate. The latter can be achieved in principle with frequency shift keying Doppler global velocimetry (FSK-DGV) [14]. However, FSK-DGV was only tested with slow cameras for time-averaged flow measurements with

temporal resolutions in the range of one second. In addition, FSK-DGV was only applied for slow seeded flows. The possibility of fast FSK-DGV measurements with a high-speed camera in the near-nozzle region of a high-pressure injection remains to be investigated.

A new approach for measuring the velocity inside the spray in the near-nozzle region is presented using a high-speed camera-based FSK-DGV. Note that no additional seeding particles are used. The system is capable of measuring velocities up to 450 m/s at measurement rates up to 500 kHz, i.e. one half of the maximum camera framerate, which is found to be the physical limit when using a single camera. The system is operated at the edge of the Nyquist–Shannon sampling theorem. The measurement principle, the resulting measurement system as well as the experimental setup for the injection measurements are presented in Section 2. Note that the measurements are performed at ambient pressure and temperature due to the easier optical accessibility. Nonetheless, in principle the measurement system is capable of in-process measurements in combustion chambers at typical chamber pressures of several hundred bar, if the chamber exhibits an optical access. A validation of the new FSK-DGV approach by means of comparison with FM-DGV and a discussion of the influence of certain flow characteristics on the measurement uncertainty as one important error contribution is given in Section 3. The measurement results are shown in Section 4 as a comparison of two different injection nozzles. Finally, a summary and an outlook are given in Section 5.

2. Setup

2.1. Measurement principle

The measurement principles of FSK-DGV and the similar FM-DGV are described in detail in [14–16], respectively. Both techniques are based on the evaluation of the Doppler shift

$$f_D = \frac{f_c \cdot |\vec{\sigma} - \vec{i}|}{c} \cdot v, \quad \text{with} \quad v = \frac{(\vec{\sigma} - \vec{i})}{|\vec{\sigma} - \vec{i}|} \cdot \vec{v}_f, \quad (1)$$

of the laser light center frequency f_c due to the light scattering at particles or the phase boundaries between liquid (fuel) and gas (air) moving with the fuel velocity $\vec{v}_f$. Note that the detectable frequency shift of the scattered light depends on the observation direction $\vec{\sigma}$ of

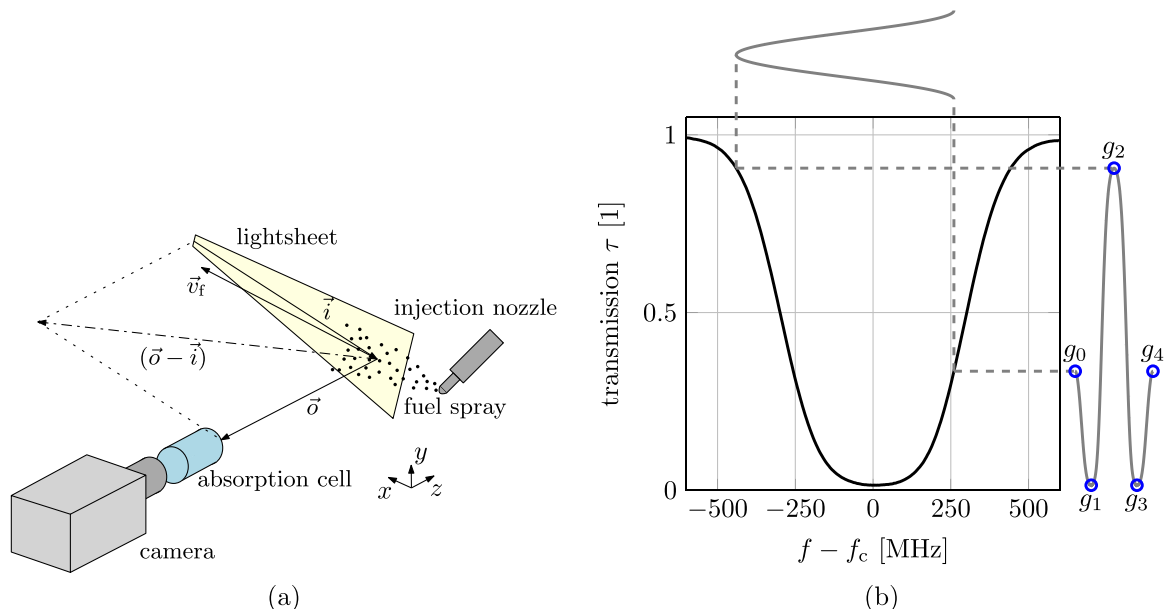


Fig. 1. (a) Principle setup of the FM/FSK-DGV. The particles moving with the velocity $\vec{v}_f$ are illuminated from the direction $\vec{i}$ and the scattered light is observed through a cesium absorption cell at the direction $\vec{\sigma}$. (b) The laser frequency is modulated cosinusoidally with the modulation amplitude f_h around the laser center frequency f_c . Due to the transmission curve, the Doppler frequency shift f_D leads to a change of the transmitted light intensity. The shown transmission curve is a measurement result.

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