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Gas-phase velocity field measurements in dense sprays by laser-based flow tagging

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Abstract. It is demonstrated in this work that gas-phase velocity measurements can be performed in dense sprays by using a new 2D laser-based flow tagging technique. Velocity measurements in *dense* sprays, such as automotive direct injection (DI) Otto and Diesel sprays, are difficult with conventional techniques because of the high number densities of droplets, the optical thickness of the medium, and multiple light scattering effects. The present flow tagging technique is performed by two consecutive laser pulses, i.e., 'write' and 'read' lasers. The write laser creates a grid of tracer molecules (NO) by inducing a photodissociation process. The tracer molecules are convected with the flow and probed by the read laser after a certain delay. The instantaneous velocity field is determined by time-of-flight analysis.

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It is well established that the velocity field of the gas phase is important for secondary break-up and evaporation of sprays [1, 2]. The theory of evaporation in *dense* sprays, where the average spacing of the droplets is only a few droplet diameters, is still incomplete, due to the strong interactions (heat and mass transfer) of the droplets and the gas phase [3]. In addition, the interactions of dispersed and continuous phases in non-evaporating, highly particle-laden gas flows are not fully understood [4]. This makes it difficult to model the flow field of the gas phase in dense sprays. It should be noted that dense sprays are technically important. For example, high-pressure swirl injectors, generating dense hollow-cone sprays, are currently being developed for automotive direct injection spark ignition engines [5, 6].

One reason for the lack of a satisfactory theory of dense spray evaporation is the fact that little experimental data exists of the gas flow field in such two-phase flows. The lack of experimental data is mainly caused by severe difficulties which are encountered when conventional measurement techniques are applied to highly particle-laden flows. In principle, point-wise gas velocity measurements can be performed in sprays by phase doppler anemometry (PDA) based on sufficiently small particles [7]. However, PDA suffers from high number densities of droplets and beam steering, for example, in the dense regions of automotive direct injection sprays [8]. Particle image velocimetry (PIV) based on fluorescent particles can also be employed for gas-phase velocity measurements in sprays [9]. However, PIV is not applicable when the medium is so dense that the detected signal is strongly affected by multiple light scattering [6]. PIV requires that individual particles are resolved, and this becomes impossible when strong multiple scattering results in considerable image blurring. For these reasons we developed a new flow tagging technique, which is based on a molecular tracer. Previous flow tagging experiments are discussed elsewhere [10–16]. Briefly, a 2D tracer distribution (grid) is 'written' in the gas flow by a laser-induced photodissociation process. The tracer molecules are convected with the flow. The read laser is fired after a certain delay Δt, in order to probe the tracer molecules using laser-induced fluorescence (LIF). The present technique works, in principle, similarly to a 2D velocimetry technique (gaseous image velocimetry, GIV), which is based on *random* distributions of a gaseous tracer [15]. The random distributions are generally created by an incomplete, turbulent mixing process. GIV can be applied to *dilute* sprays only because it depends on the absolute LIF signal intensities, which are not reliable in dense sprays. In contrast, the technique proposed in this work can also be applied to dense sprays, because it does not depend on the absolute values of the LIF intensities. The present technique is also hardly affected by multiple light scattering because the tag lines are wide enough, e.g., 0.5–1 mm, so that they can still be resolved. Beam attenuation does not affect the feasibility of the technique as long as the grid is recognized. Laser beam steering is not an important factor because the initial tracer grid is recorded as described in the following section.

1 Experimental

Initial measurements were performed in a hollow-cone gasoline direct injection spray. The prototype swirl injector and

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electronics were supplied by S. Arndt (Robert Bosch GmbH, Stuttgart). It was operated with 50 bar rail pressure in room-temperature air. Ethanol was used as the fuel. Unfortunately, commercial standard fuels like gasoline or diesel cannot be used in this experiment because the ultraviolet (UV) laser light and LIF are strongly absorbed, particularly in the dense spray regions. However, it can be expected that other UV-transparent model fuels like iso-octane could be used as well. The measurements were performed at 1 ms after triggering the injector, i.e., in the fully developed spray pulse (pulse length: 1.5 ms). The maximum droplet density is about 5×10^6 /cm^3 in the probe volume. The Sauter mean diameter of the droplets is $d_{32} \sim 15\,\mu$m [17] (thus, the average droplet spacing at maximum density is $\sim 4d_{32}$). This spray is comparable to previously investigated sprays, in which PIV measurements turned out to be difficult [6].

Flow tagging is performed in this work by using two consecutive laser pulses, as mentioned in Introduction. The present set-up is outlined in Fig. 1, but the detector is not shown. An image-intensified CCD camera is employed as the detector. A Mie scattering image from the central plane of the spray is included in Fig. 1 to demonstrate the field of view and the orientation of the spray. The field of view (32 mm × 24 mm) has been imaged onto the CCD camera by using a spherical focussing mirror ($f = 35$ cm, $d = 25$ cm, aluminum). A well defined tracer molecule distribution is generated by a 'write' laser grid via photodissociation of parent molecules, which are present throughout the probe volume. The tracer molecules are convected with the flow. The 'read' laser is fired after a certain delay Δt in order to probe the tracer molecules using LIF. The read laser beam is formed into a thick sheet (10 mm × 25 mm) so that all the tracer molecules reside within the probe volume after being convected by the flow. Tert-butyl nitrite, $(CH_3)_3CONO$, is used as the parent molecule in the present experiment [16]. Seeding of gaseous tert-butyl nitrite ($\sim$ 1% mole fraction) is performed by a low velocity coflow of nitrogen as shown in Fig. 1. The tracer gas is predominantly drawn into the spray by the entrainment gas flow (see Sect. 2). The velocity of the coflow is orders of magnitude smaller than the gas velocities in the spray; thus, it does not significantly disturb the gas flow within the spray. A 248-nm KrF excimer laser is used as the write laser, in contrast to previous work where a 193-nm ArF laser was employed [16]. The photodissociation cross-section of tert-butyl nitrite is a factor of ~ 2 smaller at 248 nm compared to 193 nm [18], but the pulse energy of commercial KrF lasers (Lambda Physik) is generally somewhat higher compared to ArF lasers; in addition, the absorption losses in room-temperature air are much smaller at 248 nm. Two sets of write laser lines, each ~ 0.5 mm in diameter (~ 10 mJ/pulse), are created by splitting and focussing the beam of the dissociation laser, basically by using two arrays of 15 cylindrical lenses ($f = 30$ cm) as shown in Fig. 1. The photofragment probed by the read laser is NO, which is excited at about 226 nm via the $R_{21}(17.5)$ line in the $\gamma(0,0)$ band system. A second tunable, narrowband KrF excimer laser is used for this purpose. The detection of NO and discrimination against Mie scattering is described in more detail in a prior paper [16]. It should be noted that the tagging scheme based on tert-butyl nitrite provides the possibility of recording instantaneous 2D velocity fields containing a large number of vectors, in contrast to most other tagging schemes [10–13], because a considerable number of tag lines can be created by a single commercial write laser, and NO can be probed effectively [16]. It is also noteworthy, that the *three* components of the instantaneous velocity in a plane can be measured based on tert-butyl nitrite, as described previously [16].

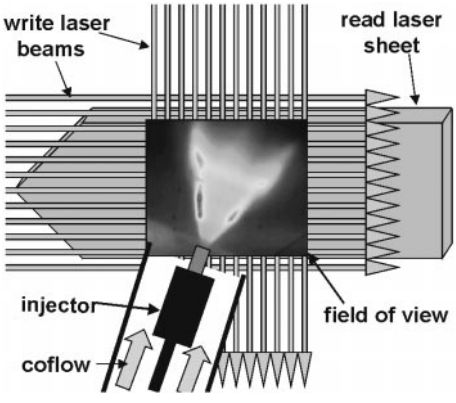

Fig. 1. Experimental set-up. The intensified CCD camera is not shown; instead, a Mie scattering image is included showing the spray at 1 ms after triggering the injector

It was mentioned in the Introduction that the initial tracer distribution must be recorded in order to correct for laser beam steering. This can done either by probing NO using the read laser at $t \approx 0$, or by recording laser-induced emissions from the write laser grid. The latter can be performed in each individual measurement, so that spatial shot-to-shot fluctuations of the write laser grid could be detected. However, this requires that a second camera image is available to record the write laser beams on a 'single-shot' basis. Actually, the 'progressive scan' CCD camera used in this work is capable of recording two images with a delay down to $\sim 1\,\mu$s. We used this 'double-frame' option to record laser-induced emissions from both the write and the read laser pulses in a number of individual measurements. In this case, the elastic scattering (Mie and Rayleigh) from the write laser beams was exploited to visualize the initial grid. However, such images show strong variations in the spatial distribution of the detected signal along the tag lines, basically due to spatial variations in the droplet density. This makes data evaluation more difficult. Thus, we used the second method mentioned above for visualization of the initial grid, i.e., NO detection by the read laser at $t \approx 0$. This requires that there are no pulse-to-pulse fluctuations in the position of the initial grid because the initial grid and the displaced grid cannot be recorded in a single spray pulse since the read laser can only be fired once. Indeed, we have seen beam steering of the write laser beams, but the beam steering turned out to be reproducible from pulse to pulse. The latter was investigated by evaluating LIF (NO) single-shot images at $t \approx 0$. The shot-to-shot variations in the positions of the tag lines within the spray were found to be insignificant, i.e., smaller than 10% of the tag line width. In addition, the width of temporally averaged tag lines (averaged over ten double pulse measurements) at $t \approx 0$ with and without the spray turned out to be the same (error: $< 5\%$). Both corroborate that shot-to-shot variations in the beam steering were indeed insignificant. Thus, it is sufficient to use a temporally

averaged initial grid for the flow tagging in this particular application.

2 Results and discussion

Figure 2 shows a pair of typical CCD images measured in the spray with a delay of $\Delta t = 40\,\mu$s. Both images show LIF from NO and some residual Mie scattering. Figure 2a was averaged over ten measurements, and Fig. 2b results from a single measurement as described before. It can be seen that there are considerable spatial variations of the NO signal on the grid, basically because of beam attenuation in the dense spray, but the grid is still recognizable in Fig. 2b. The displacement field of the distorted grid in Fig. 2b with regard to the initial grid in Fig. 2a yields the instantaneous gas velocity field. The displacement is found by employing the image correlation velocimetry (ICV) method [15, 19]. The resulting instantaneous velocity field is given in Fig. 3a. The ICV method yields continuous velocity fields. However, the spatial resolution of this measurement technique is, essentially, roughly limited by the spacing of the grid line intersections. The spatial resolution will be discussed in more detail in a forthcoming paper. The accuracy of the instantaneous measurements is limited basically by the displacement of the tag lines, $\Delta x = v\Delta t$, the width of the tag lines (full width at half maximum), ω, and the uncertainty in determining the center of the displaced tag lines, $\sigma_{\Delta x}$. The latter can be estimated to be 10% of ω [11]. In these initial measurements ω equals 1 mm. Thus, the accuracy of a typical velocity measurement with $v = 50\,\mathrm{m/s}$ and $\Delta t = 40\,\mu$s can be estimated, in a first approximation, as $\sigma_v/v \approx \sigma_{\Delta x}/\Delta x \approx 0.1\omega/\Delta x = 100\,\mu\mathrm{m}/2\,\mathrm{mm} = 5\%$. Accordingly, smaller velocities exhibit larger errors. Molecular diffusion does not significantly affect the accuracy in this application because of the short delay $\Delta t = 40\,\mu$s.

A Mie scattering image, similar to the one given in Fig. 1, is shown in the background of Fig. 3a to indicate the spray contour. It can be seen that there are large eddies (up to $\sim 60\,\mathrm{m/s}$) formed at the edge of the spray cone, and strong air entrainment is observed closer to the nozzle. Obviously,

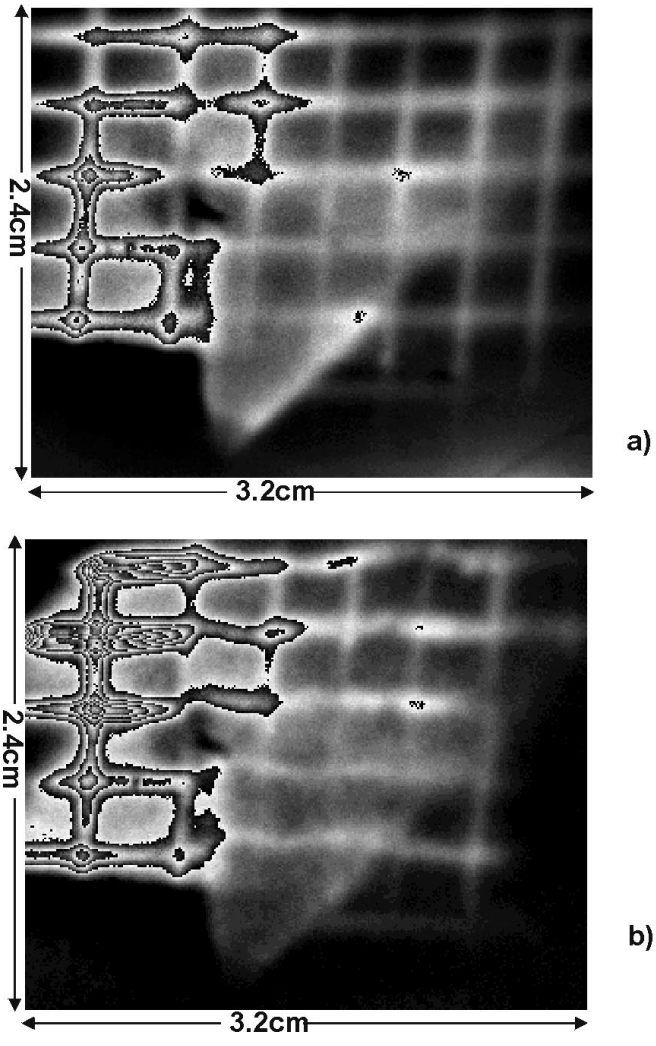

Fig. 2a,b. Pair of LIF (NO) images measured in the spray with a delay of $\Delta t = 40\,\mu$s. **a** Measurement at $t = 0$ averaged over ten double pulses. **b** Instantaneous measurement at $t = 40\,\mu$s

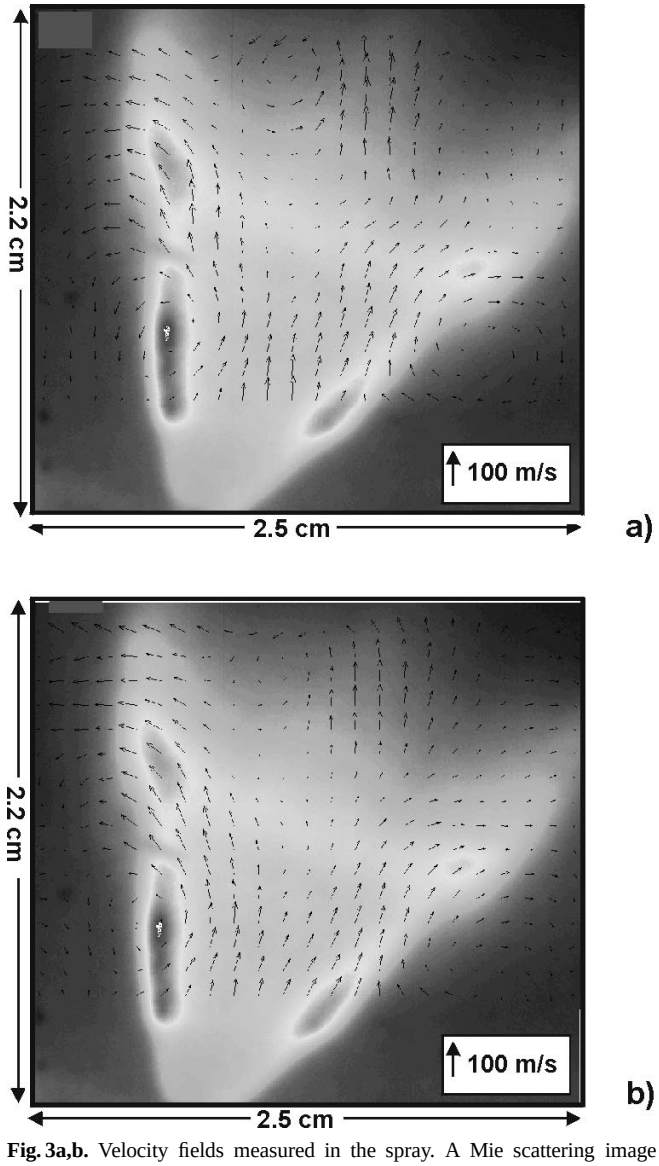

Fig. 3a,b. Velocity fields measured in the spray. A Mie scattering image is given in the background to show the distribution of the liquid phase. **a** Instantaneous velocity field. **b** Mean velocity field averaged over ten instantaneous measurements

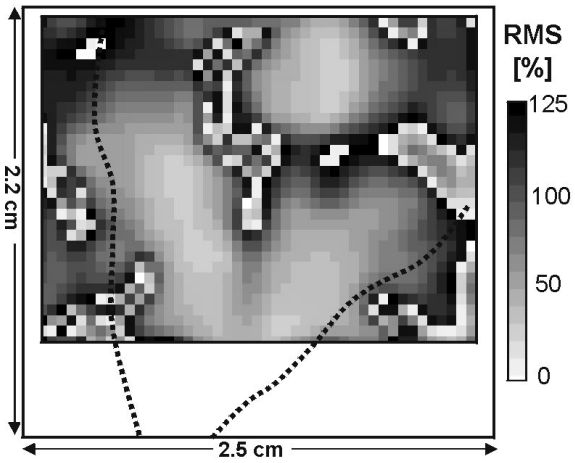

Fig. 4. Relative standard deviation of ten instantaneous measurements corresponding to the data given in Fig. 3. The edge of the spray cone is indicated by a *dotted line*

these eddies deform the shape of the spray cone, although the droplets travel at high velocity (of the order of 50 m/s [17]). This can be explained by the small size of the droplets, since $d_{32} \sim 15\ \mu$m as mentioned above.

A mean velocity field, that has been averaged over ten instantaneous measurements, is given in Fig. 3b. It can be seen that it is qualitatively very similar to the instantaneous measurement in Fig. 3a (thus, ten instantaneous measurements are sufficient to determine the mean velocity field at least within the spray). One might think that the high-pressure spray generates a highly turbulent flow field of the gas phase. However, this is not necessarily true since small particles tend to reduce the turbulent intensity [4]. Small particles follow the gas flow, and thereby turbulent energy is transformed into the kinetic energy of the particles. This is indeed seen in the data: The relative standard deviation of the velocity magnitudes of the ten instantaneous measurements is given in Fig. 4. The spray cone is outlined by dotted lines. Obviously, the pulse-to-pulse fluctuations of the gas flow are small (20%–30%) in most regions of the spray cone, where the droplet density is high. The fluctuations are much larger inside the hollow-cone and in the ambient air. In conclusion, the spray tends to generate high turbulence only in regions where the droplet density is relatively low.

3 Conclusions and outlook

It is demonstrated that instantaneous velocity fields of the gas phase can be measured in dense sprays by the present flow tagging method. In comparison to well established techniques, such as PDA and PIV, the present technique is much less affected by multiple light scattering, beam steering and beam attenuation in optically thick two-phase flows. To our knowledge, this is also the first application of a laser-based flow tagging technique to a spray.

The present technique provides the possibility of studying the interactions of dispersed and continuous phase in highly particle-laden, evaporating and non-evaporating gas flows, in particular when it is combined with a suitable method of measuring the corresponding particle velocity field. Work is underway in our lab to develop a similar tagging technique based on the liquid phase in order to obtain the droplet velocity field in dense sprays with the same measurement system.

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