Simultaneous air/fuel-phase PIV measurements in a dense fuel spray

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Abstract A new diagnostic has been developed that is capable of obtaining simultaneous two-phase velocity measurements in a gasoline direct-injection fuel spray. This technique utilizes a two-laser (double-pulse) two-camera (double-frame) setup to simultaneously image the injected fuel and entrained air to determine the 2D velocity vector fields of both phases using cross-correlation particle image velocimetry (PIV). The air phase is visualized through fluorescence from seeding particles introduced into the static measurement volume while Mie scattering signals are collected from the fuel droplets. The combination of different laser wavelengths and a spectral signal shift for the air phase allows spectral separation of the signals. Independent timing of the laser pulses permits optimized adaptation of the velocity dynamic range for the two phases to account for the large difference in velocities between air and fuel droplets.

1
Introduction

The breakup of liquid fuel into droplets and the spatial distribution of these droplets depend on several factors, including the momentum exchange between the liquid phase and the surrounding gas phase. In modern fuel injectors the fuel is pressurized to several MPa, which leads to relative velocities between fuel and the surrounding gas on the order of 100 m/s. The rapidly propagating fuel induces a motion in the surrounding gas, adding substantial levels of turbulence to the system (Miles et al. 2001), which in turn can lead to secondary effects on the developing spray itself. An example of this effect is the well-known roll-up vortex in pressure-swirl

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injectors (Zhao et al. 2002). A faithful simulation of sprays will need to predict the surrounding flow field and its impact on the spray evolution. Thus, experimental data for comparison with advanced models need to characterize not only the velocity of the fuel droplets but also (ideally simultaneously) the velocities in the gas phase. Particle image velocimetry (PIV) and related correlation techniques have been widely employed to visualize the velocity vector fields of either air or fuel phases for this purpose (Yamakawa et al. 2001; Hentschel et al. 1999; Krüger and Grünefeld 2000a; 2000b; 2000c; Kozma and Farrell 1997; Rhim and Farrell 2000; Lee et al. 2002). While velocity vector fields from the separate phases are useful, it is helpful to visualize the two phases simultaneously because of cycle-to-cycle variations of the fuel spray. Rottenkolber et al. (1998, 1999) proposed a method to discriminate between phases on a single double-exposure image, but this technique can assign phases incorrectly. Grünefeld et al. (2000) developed a technique based on a gaseous tracer (NO) in the air phase, but the setup is complicated for measurements performed at low temperatures. Khalitov and Longmire (2002) described a phase discrimination algorithm and a combination of particle-tracking and PIV to investigate two-phase flows (in their case, solid–gas). Towers et al. (1999) used a two-color approach whereby Mie scattering at the original, green, laser wavelength marked one phase, and fluorescence from doped particles identified the other phase. The same strategy was used by Lee and Nishida in investigations of DI gasoline sprays (2003). Both investigations have in common that only one double-pulse illumination is performed. In the case of the automotive fuel sprays with a large dynamic range of velocities this can limit the accuracy of the measurement in either phase since a compromise in the time difference of the two laser pulses has to be made. Thus, a new method was developed for the simultaneous measurement of air and fuel velocities in fuel sprays. Not only can it discriminate between phases, but it allows for the velocity resolution to be optimized based on the magnitude of the velocities probed in either phase.

2
Experimental setup

All measurements were performed using a pressure-swirl GDI spray (60° cone angle), which was injected into a static test cell (1000 cm^3 test volume) at room temperature and ambient pressure. The fuel was isooctane pressurized to 8.5 MPa (injection duration 3 ms) for the results presented here using a piston-type accumulator. The cell
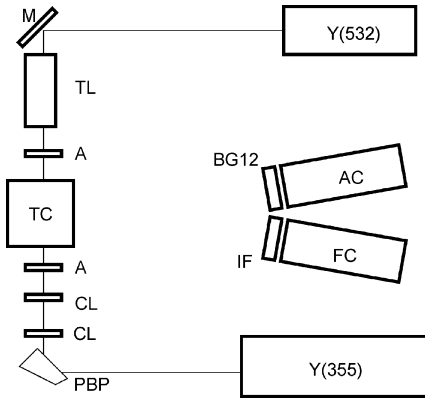
Fig. 1. Experimental setup: *Y(532)*, fuel visualization laser; *M*, dielectric mirror for 532 nm; *TL*, telescopic lens system; *A*, aperture; *TC*, test cell; *BG12*, bandpass filter; *IF*, interference filter; *AC*, air camera; *FC*, fuel camera; *CL*, cylindrical lens; *PBP*, Pellin–Broca prism; *Y(355)*, air visualization laser

Fig. 2. Timing diagram: *AL*, air laser; *FL*, fuel laser; *AC*, air camera; *FC*, fuel camera. Camera gate width of first exposure is 10 µs; second is 125 ms. Timing of the laser pulses is chosen such that the first pulse is fired during the first camera gate and the second pulse is fired during the second camera gate

was optically accessible on five sides through 75 mm diameter quartz windows. After each measurement set (five images per timing) a vacuum system was used to purge the cell.

A schematic of the experimental setup is given in Fig. 1. Mie scattering images were recorded from the spray, while air motion was tracked using fluorescent tracer particles seeded into the cell. The fuel phase measurement system consisted of a frequency-doubled double-pulse Nd:YAG laser (New Wave Mini-Lase, 30 mJ/pulse), sheet forming optics that focused a vertical light sheet through the center of the spray ($\approx$1-mm sheet thickness, matched to the desired spatial resolution for the vector fields), and a double-frame nonintensified CCD camera (LaVision Flowmaster3, 1280×1024 pixels per frame). A separation time of 8 µs between laser pulses was chosen based on the desired resolution of the velocity vectors ($\approx$1 mm) and the expected velocity range ($\approx$100 m/s). An interference filter was placed in front of the fuel-designated camera to filter out any interference from the air-phase signal.

The test cell was equipped with a droplet seeding system (Laskin-type nozzle), which introduced small seeding particles of ethylene glycol doped with Lambdachrome Stilbene 3 (428-nm peak fluorescence, 415–439-nm range, 15% fluorescence efficiency) into the test chamber prior to the experiment. PIV measurements of these tracer droplets taken before fuel injection confirm that the air in the cell was quiescent. The dye was excited with a frequency-tripled double-pulse Nd:YAG laser (Continuum Surelite 355 nm, 100-mJ/pulse; the double-pulse operation with this laser was achieved with a second Marx bank to fire the Q-switch twice during one flashlamp event), and the resulting fluorescence was recorded on a second nonintensified CCD camera, identical to the one used for recording Mie scattering images. A BG-12 band-pass filter (407 nm, FWHM 104 nm) was used to separate the LIF signal from Mie scattering from the spray occurring at 355 nm and also to suppress Mie scattering from the 532 nm lasers. A delay time of 80 µs between pulses was chosen based on the magnitude of air velocities and desired resolution. The laser pulses for the fuel measurement were triggered inside the timing pulses for the air phase as
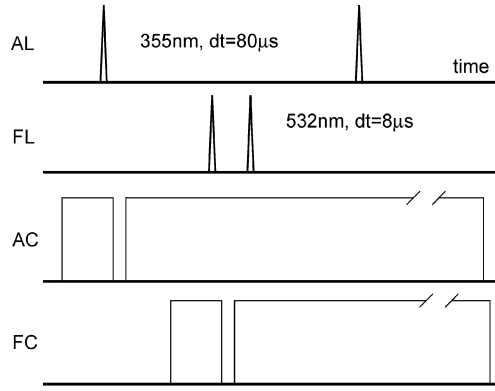
illustrated in Fig. 2 for a simultaneous measurement of the two phases. The two laser systems, two cameras, and injector were synchronized using two programmable timing units that were part of the camera systems.

The air-phase droplets are smaller, and their number density is substantially less than that of the fuel droplets. Thus, the fuel images did not show measurable signals from the air phase. Furthermore, the air-phase droplets will have been displaced only a small amount in the time between the spray phase pulses, and any vector processed with this inadequately short pulse separation for the air velocity would result in near-zero displacement. Given the intense Mie scattering signal from the fuel, a reduced level of signal from the droplet phase is, however, present in the images for the air phase. Correlation for these droplet images is poor since the pulse separation (80 µs for the air phase) is too long to ensure that both droplet images from the fuel are within the correlation window. Attempts to analyze the fuel images with particle tracking algorithms did not result in satisfactory results. Particle tracking is most appropriate where individual particle images are distinctly resolved from their neighbors by distances that are at least as large as the particle displacements. This condition is far from satisfied in the dense GDI spray being examined here.

Image processing involved the correction of images from each phase for distortion because of the slight inclination of the optical axis with respect to the normal to the laser light sheets (Fig. 1) and also matching of the spatial coordinates. The exact overlap of images from the two cameras is not critical for the success of the technique since velocities of a given phase are determined using a cross-correlation algorithm that is applied to the double-frame image recorded with a single camera. The images from each camera were remapped to exactly coincide with each other as if both cameras were viewing the field of view from exactly the same perspective. This was achieved by calibrating each camera to a target grid of crosses positioned at the plane of the light sheet in the cell. The crosses are measured to within 0.05–0.1 pixels, being based on the same cross-correlation algorithm as the measured particle displacements, and these positions combined with the

precisely known grid spacing to generate a polynomial mapping function using a least squares fit to the data. The final registration of the remapped images is better than the uncertainty of the individually measured crosses and so therefore conservatively better than 0.1×1 mm/32=3 μm. The double-frame images from both cameras were processed separately to determine the corresponding vector fields. A sliding background (minimum) with a 5-pixel filter size was subtracted from the raw images to increase accuracy and reliability of the velocity results. A multipass cross-correlation strategy with a final interrogation window size of 32×32 pixels and 50% overlap was chosen to evaluate the velocities. Images were also post-processed restricting the allowed velocity range to remove erroneous vectors and to mask noise from outside the measurement area.

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Results and discussion

The resolution of the velocity measurements is determined by the size of the interrogation region chosen. A resolution of 1 mm was desirable for both air and fuel since it provides enough detail for study and comparison against modeling results without exceeding the limitations of the equipment and technique. Since the velocities of the entrained air were an order of magnitude lower than those of the injected fuel, the delay between laser pulses needed to be adjusted for each phase so the 1-mm resolution could be attained in both phases. These delay times were chosen by limiting displacement of either phase to approximately one quarter of the interrogation region. The results presented below use a delay time of 8 μs for fuel and 80 μs for air, based on estimated maximum velocities of fuel (50–100 m/s) and air (5–10 m/s). Since there is a large range of fuel velocities in the spray, the fuel delay may also be optimized in this manner to study specific regions in the spray with increased accuracy.

An example of the velocity fields that were obtained simultaneously from both phases is shown in Fig. 3. The air entrainment results (shown at 8.5 MPa injection pressure, 0.54 ms after start of injection) adequately capture the air movement as it is pushed outward by the prespray and recirculated at the edge of the main spray. The fuel velocity data illustrate the predominantly downward direction of the fuel droplet flow. The most significant problem associated with measuring the velocity of the fuel phase using PIV is due to the dense nature of the GDI spray. For PIV ideally one requires clearly resolved images of the droplets whose velocities are being measured. In the fuel spray the number density of droplets is such that images of droplets overlap to some degree, creating partial speckle at the image plane. The speckle component of the image will decorrelate between laser pulses especially if there is out-of-plane motion (Adrian 1984). The subtraction of a sliding minimum improves the correlation of the fuel Mie scattering images. We also tried to eliminate speckle by doping the fuel with 1% 3-pentanone and excited with a frequency-quadrupled Nd:YAG laser (3 mJ/ pulse). Fluorescence signals were too weak to be detected with the nonintensified camera, and an intensified camera was not desirable since it would further blur results). Thus,
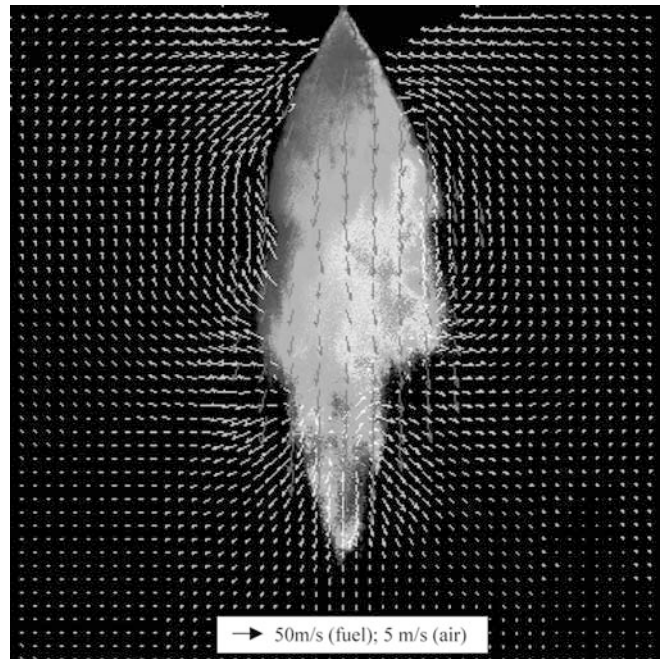

Fig. 3. Simultaneously measured air velocities (*white arrows*) and fuel velocities (*blue vectors*) in a single spray event (8.5 MPa injection pressure, 0.54 ms after start of injection). Fuel velocities are 10 times larger than air velocities for a given vector length. Also note that for clarity only every second fuel velocity vector in each direction is displayed. The background image is Mie scattering from the liquid fuel droplets Note that Fig. appears in grayscale format

Mie scattering was used to visualize the fuel spray in all experiments.

4
Summary and conclusions

A new technique was demonstrated for the simultaneous determination of entrained air velocities and fuel velocities in a dense spray. This method allows for unambiguous phase separation and optimal adaptation to best velocity resolution through the adjustment of laser delay times. The ability to achieve simultaneous velocity measurements with 1-mm resolution will assist efforts to model atomization and mixing in dense sprays.

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