Development and application of a high-speed planar laser induced fluorescence imaging system to evaluate liquid and vapor phases of sprays from a multi-hole Diesel fuel injector

S. E. Parrish* and R. J. Zink
General Motors Global R&D
30500 Mound Road
Warren, MI 48090-9055 USA

Abstract
A high-speed imaging system capable of acquiring Planar Laser Induced Fluorescence (PLIF) images and Mie scattering images in a near-simultaneous fashion has been developed. Acquiring both LIF and Mie images enables the liquid phase to be discriminated from the vapor phase. High-speed imaging allows the temporal evolution of flow structures to be evaluated. Images of sprays from a multi-hole Diesel fuel injector operating under engine-like conditions were acquired. The vapor phase images reveal intricate fluid dynamic structures that exhibit a high degree of variability.

*Corresponding author
Introduction

It is well known that the fuel economy and emissions of Diesel engines are significantly influenced by the fuel injection process and in particular the characteristics of the fuel spray. As a result an extensive amount of work has been performed in the area of fuel injector spray characterization. While extensive, the large majority of the work has been confined to characterization of the liquid phase. Far less has been reported regarding characterization of the vapor phase.

Planar Laser Induced Fluorescence (PLIF) imaging has been used for decades to image a myriad of fluid flow phenomena. A significant body of work related to fuel spray characterization utilizing laser-induced fluorescence exists [1-3]. The vast majority, however, pertains to single-shot acquisition where, for each injection event, a single image is acquired at a discrete point in time referenced from the start of the event. Repeating at various points in time allows a time sequence of images to be collated. While this method has great utility, it does not allow the temporal evolution of a single event to be evaluated. This is particularly of interest when event-to-event repeatability varies considerably. Some have shown single-shot Diesel vapor phase images, for example, that illustrate interesting and complicated structures [4] leaving one to ponder about their formation and subsequent development.

In contrast, high-speed imaging allows continuous temporal evolutions to be evaluated. The motivation for this work was to develop an imaging system sensitive to both the liquid and the vapor phases of Diesel sprays at high-speed. Such a system allows systematic studies to be performed to improve understanding of spray characteristics under various operating conditions. The data generated should be of interest to computational modelers, particularly those interested in Large Eddy Simulation (LES), for model validation and to combustion system engineers to assist in combustion system development.

In the case of a multiphase flow, such as a fuel spray, both the liquid and vapor phases contribute to the LIF signature. This makes it impossible to definitively distinguish one phase from another without an accompanying measurement. The work presented here describes a high-speed imaging system capable of acquiring Mie scattering and LIF images in a near-simultaneous fashion. Acquiring both types of images allows the Mie scattering images, which are sensitive only to the liquid phase, to be compared to the LIF images to discriminate liquid from vapor.

In recent years there has been a limited amount of high-speed PLIF work reported. Some have used multiple low repetition rate lasers and cameras to acquire images in rapid succession of fuel LIF and OH in a direct-injection spark-ignited engine [5,6]. While their system provided good temporal resolution it was complicated and limited to acquiring a maximum of eight images. More recently, Cundy and Sick [7] used a commercially available high-speed 355 nm Nd:YAG laser along with biacetyl as a fuel tracer in a direct-injection spark-ignited engine. Phan et al. [8] reported on the use of a custom-built, burst-mode 355 nm Nd:YAG laser system [9,10] to acquire Diesel PLIF images at 10 kHz. While their work was similar in nature to that presented here, there are several differences. Their system was exclusively a PLIF system and did not allow for a complimentary liquid only measurement. Additionally, due to the ambient pressure and temperature utilized in their work (35 bar and 600 K) it is likely that their LIF images are predominantly liquid phase where as the results presented here are predominantly vapor phase. Finally, the work presented here is believed to be the first use of a high-speed Nd:YAG laser operating at a 266 nm for Diesel PLIF imaging.

The process of LIF is well understood and treated in detail elsewhere [11]. For this work common Diesel fuel was utilized along with ultra-violet excitation, therefore a fluorescent dopant was not required. With 266 nm excitation, Diesel fuel LIF emission generally peaks between 350-375 nm and exhibits a long wavelength tail extending well into the visible range [12]. LIF emission is primarily due to the presence of polycyclic aromatic hydrocarbons (PAHs) [12]. In particular it is believed that the primary contributors include alkylated naphthalenes and phenanthrenes, with fluorenthenes and anthracenes contributing at longer wavelengths [12].

Imaging System

Figure 1 shows the imaging system that was developed. The primary components of the system included two 532 nm Nd:YAG lasers with custom external frequency doubling and beam combining optics, conventional beam steering and sheet forming optics, and a high-speed camera.

The laser was designed to enable a variety of modes of operation. Two mirrors mounted on flip mounts dictate whether or not the beams from the lasers are directed through Deep Ultra-Violet (DUV) frequency doubling crystals. When these mirrors are in position the DUVs are bypassed. Alternatively when these mirrors are flipped out of position, the beams pass through the DUVs resulting in the formation of beams with wavelengths of 266 nm. Two sets of beam combining optics located ahead of and behind the DUVs are utilized to combine beams of the same wavelength. A final configuration is achieved when one flip mounted mirror is in position while the other is out of position, resulting in one 532 nm beam and one 266 nm beam. This was the configuration employed for the work presented here. The 532 nm beam was used to produce
Mie scattering and the 266 nm beam was used for LIF excitation.

In the case of the 266 nm beam, a Pellin-Broca prism was used to remove any residual 532 nm and turn the beam 90 degrees. A final mirror directed the beam through a spherical and cylindrical lens combination and into the vessel. This lens combination produced a gradually divergent sheet of light with dimensions, at the region of interest, of approximately 60 mm in height and 0.5 mm in thickness.

In the case of the 532 nm beam, an uncoated fused silica flat was used to turn the beam 90 degrees. This resulted in a dramatic ($\approx 96\%$) reduction in beam intensity. This was necessary because the beam intensity, when operating the laser at the minimum power to ensure stable operation, was orders of magnitude greater than that required for Mie scattering purposes. By using a sufficiently thick flat, the primary reflection was easily isolated from the secondary reflection with the use of an aperture. A neutral density filter set was used to further attenuate the beam to the desired intensity. A final turning mirror directed the beam through the lens combination and into the vessel. Careful alignment ensured that both light sheets were coplanar.

The final turning mirrors along with the spherical lens were mounted on a translation stage to allow the resulting light sheets to be translated in the vessel. This enabled the light sheets to be located on the center of a spray plume.

Although a faster repetition rate would have been ideal, the laser was operated at 10 kHz because power output diminished at rates beyond 6 kHz. At 10 kHz the average 266 nm laser power was approximately 2.5 Watts, which translates to 0.25 mJ per pulse. This excitation energy was found to produce adequate LIF emission and did not require the use of an image intensifier.

Images were captured with a high-speed digital camera equipped with a 60 mm lens. Mie scattering and LIF images were captured in a nearly simultaneous fashion utilizing frame straddling. Frame straddling, most commonly used in high-speed PIV, results in image pairs that are slightly temporally separated. Previously we reported work utilizing the same strategy to acquire Mie scattering and schlieren images with a single high-speed camera [13].

The primary advantage of utilizing a common camera along with frame straddling, compared to utilizing two cameras, is that it eliminates the need to spatially register independent images. One apparent disadvantage is that the images cannot be acquired simulta-

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**Figure 1.** High-Speed Planar Mie/LIF imaging system. A 20 kHz camera framing rate translates to image pairs at 10 kHz. Mie scattering exposures occurred at the end of the even numbered frames while LIF exposures occurred at the beginning of the odd numbered frames.
neously. The degree to which this becomes an issue depends on the speed of the event being captured in comparison to the overall time required to capture the images.

A timing diagram depicting the image acquisition process is illustrated in Figure 1. To acquire image pairs at a rate of 10 kHz, a 20 kHz camera framing rate was required. The camera exposure time was set to be nearly equal to the frame interval. The Mie exposure occurred at the end of even numbered frames while LIF excitation and resulting emission occurred at the beginning of the odd numbered frames. Laser pulse durations were approximately 100 ns. The total amount of time from the beginning of the Mie exposure to the end of the LIF exposure was approximately 3 µs. This translates to 1.8 mm of displacement for objects traveling at 600 m/s. This magnitude of velocity is not uncommon for diesel engine fuel sprays but it is usually associated with the early stages of injection and dissipates quickly. Therefore for most conditions of interest the time delay between images was adequately small.

**Experiment Details**

A high temperature pressure vessel was used to allow measurements to be performed at elevated pressures and temperatures. A continuous flow of nitrogen gas passed through the vessel to provide evacuation of the injected mass. Although other conditions were evaluated, for the work presented here the pressure and temperature within the vessel were fixed at 60 Bar and 900° K, respectively.

Fuel was injected into the vessel by a production style Diesel injector with a 7-hole, micro-sac tip with a nominal included spray angle of 158 degrees. A coolant jacket surrounding the injector mount was used to control the injector temperature. The fuel temperature was assumed to be equal to the coolant temperature and was set to 90º C to mimic fully warmed up conditions. Injection pressure was set at 1500 Bar and maintained using a PID controlled production style fuel pump.

Injection quantity was fixed at 3.5 mg, resulting in approximately 0.5 mg per spray plume. Independent injection rate measurements were performed to determine the required injection duration. This relatively small injection quantity was of interest for a couple of reasons. First, the injection of small quantities is of great importance to modern day Diesel engines. Often, multiple injection is employed in the form of a small pilot injection followed by a larger main injection. Secondly, a small quantity was of interest to ascertain the sensitivity and utility of the imaging system under development.

The injector was oriented so that one spray plume was directed in the downward direction as shown in Figure 2. The co-planer laser sheets were translated to intersect the center of the plume. It should be noted that with this orientation another spray plume was located between the camera and the plume of interest. In some cases the shadow of this intermediate plume could be seen in the Mie scattering images. This was particularly apparent at lower ambient temperatures when there was an abundance of liquid phase present. Additionally it is likely that this intermediate plume (and the plume behind the plume of interest) could have contributed to the Mie scattering image in the form of secondary scattering. In any event, the viewing of the leading portion of the plume of interest was not obstructed and therefore this portion of the Mie scattering image is considered reliable.

**Figure 2.** Injector and laser sheet orientation. Field of view is represented by the rectangle.

**Mie Scattering images**

Mie scattering images from three individual injection events along with the ensemble average and probability envelopes of 25 injection events are shown in Figure 3. Each row corresponds to a different point in time referenced from the start of injection. The images were false colored to accentuate the lower intensities which presumably represent minute amounts of liquid (surface area).

The probability envelopes were generated by binarizing and summing the images at each time increment. A pixel value just above the background count was chosen as a threshold for the binarizing operation. Ten contours are shown representing the probability (in 10% increments) that liquid occupied the space within each contour. The inner most contour indicates that 100% of images contained liquid within the contour area.

Due to the small injected quantity and the highly evaporative conditions, Mie scattering (liquid phase fuel) is only exhibited in the 0.1 ms and 0.2 ms frames. The images for each injection event appear similar when compared to one another suggesting a high degree of repeatability. The similarity of the ensemble average to each individual injection event along with tightly concentrated probability contours provides further evidence of strong injection-to-injection repeatability.
Figure 3. High-speed Mie scattering images. Three injection events are shown along with the ensemble average and probability envelope of 25 injections. Injection pressure: 1500 Bar, Vessel pressure: 60 bar, Vessel temperature 900 K.

PLIF images

The corresponding PLIF images for the same three individual injection events shown in Figure 3 are shown in Figures 4 and 5. The ensemble average and probability envelopes of 25 injections are also shown. Each row corresponds to a different point in time referenced from the start of injection. The probability envelopes were generated in the same manner described previously. The false color scale was intentionally saturated for the early time frames to provide better range at later times.

While, in general, the PLIF intensity is proportional to fuel concentration, no attempt was made here to quantify concentrations. This would require careful examination and measurement of many variables [14] and was considered out of scope for this initial demonstration. Therefore the intensity variations shown should be considered only as a qualitative measure of fuel concentration.

One major benefit of acquiring Mie scattering images nearly simultaneously with PLIF images is that it allows for the determination of when the PLIF images represent only the vapor. As indicated by the Mie scattering images shown in Figure 3, liquid phase does not persist beyond 0.2 ms and therefore beyond 0.2 ms the PLIF images represent only vapor.

In contrast to the Mie scattering images, the PLIF images do not appear similar when compared to one another indicating a high degree of injection-to-injection variability. This is particularly true as time progresses. The images exhibit intricate fluid dynamic structures that evolve in time. For example in the case of injection event 1, at around 1.5 ms the vapor structure begins to narrow (annotated by the arrow) on the far right side of the image. This is accompanied by a locally high concentration in the same region. This structure persists for the remainder of the sequence.

Another interesting observation, related to injection event 3, is the propensity for the vapor to follow along the wall of the injector mount. This is annotated by the arrow on the 1.0 ms image.

The dramatic differences between the ensemble averages and each of the individual injection events clearly indicate large injection-to-injection vapor phase variability. The widely spaced probability contours provide further supporting evidence of large variability.

Summary and Conclusions

A novel high-speed imaging system capable of acquiring PLIF and Mie scattering images in a near-simultaneous fashion has been developed. A custom high-speed laser provided a 532 nm beam that was used for Mie scattering and a 266 nm beam that was used for LIF excitation. The use of frame straddling allowed both the Mie and PLIF images to be captured with a single camera nearly simultaneously. Acquiring both types of images allows the Mie scattering images, which are sensitive only to the liquid phase, to be utilized, among other things, to determine when the PLIF images represent only vapor phase.

While the Mie scattering images indicated good event-to-event repeatability of the liquid phase, the PLIF images indicated substantial variability of the vapor phase. Not surprisingly, the vapor phase PLIF images exhibited intricate fluid dynamic structures that evolved as time progressed. Acquiring images at high-speed allowed their formation and subsequent development to be observed.
References
Figure 4. High-speed PLIF images. Three injection events are shown along with the ensemble average and probability envelope of 25 injections. Injection pressure: 1500 Bar, Vessel pressure: 60 bar, Vessel temperature: 900 K.
Figure 5. High-speed PLIF images. Three injection events are shown along with the ensemble average and probability envelope of 25 injections. Injection pressure: 1500 Bar, Vessel pressure: 60 bar, Vessel temperature: 900 K.