APPLICATION OF GLOBAL SIZING VELOCIMETRY (GSV) TO GASOLINE DIRECT INJECTION (G-DI) SPRAYS

TECHNICAL NOTE (TSI RESEARCH REPORT 10-2006)

Abstract

A spatial technique providing global size and velocity data over a two-dimensional region of a spray is often preferred for rapid optical characterization of sprays. The Generalized Scattering Imaging (GSI) approach for droplet sizing, based on both the Lorenz-Mie theory and the Finely Stratified Sphere Scattering Model can be applied to both homogenous droplets and inhomogeneous and/or absorbing droplets. GSV is based on the GSI approach[1], and it can thus be used to measure the velocity and size of droplets with non-uniform and/or varying refractive index, even in regions of high particle number density. GSV uses a windowed FFT technique to identify the presence and location of droplet oscillation patterns, and an optimized frequency-based algorithm is used to extract the droplet size. GSV uses a two-frame tracking algorithm to measure the velocity of droplets from two consecutive image frames, using only one camera. This research report covers measurements made on two types of atomizers. Results obtained for a swirl type pressure atomizer operating on water and fuel oil depicted well the near-nozzle spray angle and diameter characteristics in various parts of the spray structure. Data was also acquired for a gasoline direct injection (G-DI) system operating at a limited range of conditions, and the resulting droplet size distributions were analyzed.

Test Equipment

Point spray measurement techniques like phase Doppler have good spatial resolution, but measurement over a two-dimensional region requires the spray to remain unchanged for a significant period of time. A spatial technique providing instantaneous global size and velocity over a two-dimensional region of the spray would thus be preferred. GSV has the capability to measure droplets with non-uniform and/or varying refractive index even in regions of high particle number density. The major hardware components for the system are very similar to those of a PIV system, namely a TSI Model YAG50-15 laser, Model 610021S120 Light Sheet Optics, a TSI Model 610035 LaserPulse™ Synchonizer for timing control, a PowerView™ Plus 2MP camera with GSV-1000 extension for GSV. The *Insight*™ 3G software package was used for image capture and analysis. The light sheet thickness was set to about 250 µm using 500 mm and 1000 mm spherical lenses and a single –50 mm cylindrical lens.

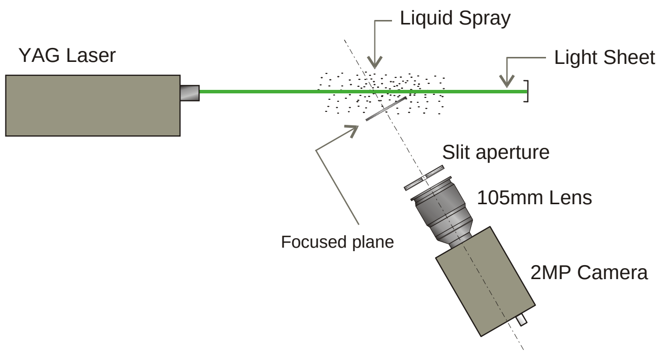

Figure 1. Recording hardware arrangement.

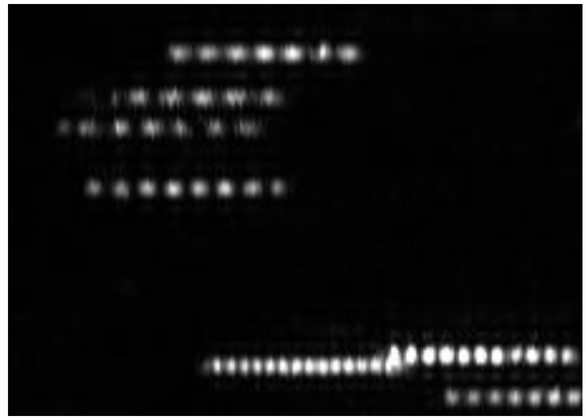

Figure 2. Portion of an out-of-focus spray image (size shown is 228 × 162 pixels).

In order to accommodate droplets in transient conditions such as evaporating or burning sprays, the GSV system records oscillations at a 60° scattering angle to take advantage of GSI, as shown in Figure 1. Image distortion due to 60° imaging is corrected by a geometric correction method. As a result, the calibration required by the system is very simple, and the magnification factor before defocusing is the only calibration required. To allow for measurements in higher number density environments, a slit in front of the camera lens is employed to block all but a narrow string of the original out-of-focus image [2]. A sample of recorded image is shown in Figure 2. This not only reduces the possibility of oscillation pattern overlap, but also improves the quality of recorded oscillations. The system software also incorporates a novel windowed FFT algorithm for fast and fully automated sizing identification. Incorporating the measurement concept of PIV, the GSV system employs a single camera operating in the PIV capture mode to capture two consecutive image frames of the defocused droplets with small time separation between the images. Since the droplets travel a certain distance in the time interval between the two frames, the velocity of the droplets can be measured. Hence the TSI GSV system provides the capability to simultaneously measure the droplet size and velocity in a 2D spatial region of the spray, using a single camera.

Processing Technique

From out-of-focus images like the one shown in Figure 2, the oscillation spacing in pixels can be obtained. The simplest way to convert the spacing in pixels to the angular spacing $\Delta\vartheta$ is by using the equation $\Delta\vartheta = M\delta/\Delta z \cdot n$, where M is the magnification (after defocusing), Δz is the defocusing distance, δ is the pixel size, and n is oscillation spacing in pixels. Since the 60° angle of the camera does not focus at a plane parallel to the light sheet, the defocusing distance and magnification are not uniform across the image, and the geometric correction is performed. The sizing algorithm is composed of two steps: (a) identifying each oscillation pattern to determine the droplet location; and (b) analyzing each pattern to determine the droplet size. A new four-step algorithm based on a windowed FFT technique is used by *INSIGHT*™ 3G software, in order to provide a more robust, user-friendly method of identification of the oscillation patterns [3]. The use of 2D power spectra improves identification of overlapped patterns, and even if two patterns overlap in the spatial domain, they are separated in the frequency domain as long as the oscillation frequencies are different. After pattern identification, individual patterns are extracted from raw images for frequency analysis to obtain the oscillation spacing. This is done in the frequency domain by Fourier transform, which is a better method for its speed, robustness, and sub-pixel accuracy. Moreover, by comparing the highest peak and the second highest peak in the power spectra of each pattern, we can detect oscillations with a dubious frequency, such as those caused by interference of nearby droplets in a dense spray.

The two-frame tracking algorithm developed here is specifically for particles of known size. The input to the algorithm is two sets of particle position and size data. First, a size match between the two images is performed. Then a local motion match is used to help find additional matches. The local flow motion can also be used to detect outliers for both the size match and motion match sub-processes.

Results

Pressure Atomizer

A commercial pressure atomizer (Delavan, type "W") with a nominal angle of 60° and orifice diameter of 0.21 mm was used in tests to generate a spray. The nominal flow rate was 1.89 liter/h at 0.86 MPa. The nozzle was operated with water and fuel oil at 0.6 MPa. The spray was injected into air at ambient pressure. The field of view was about 10 mm by 12 mm. A range of 40 to 75 image pairs were acquired at each location, yielding about 2000 diameter measurements.

As shown in Figure 3, near the nozzle, a dual peaked histogram was observed, with larger drops ($d \approx 45$ µm) being generated in the spray sheet area, and the smaller drops ($d \approx 15$ µm) in the recirculating zone. The sensitivity of our windowed FFT based approach is apparent here, where a population of smaller drops is detected among the more dominant group of larger droplets. Farther downstream in the spray cone edge (±30°) we measured only a single dominant peak at about 45 µm. In the cone center, the peak at about 15um became very dominant[4].

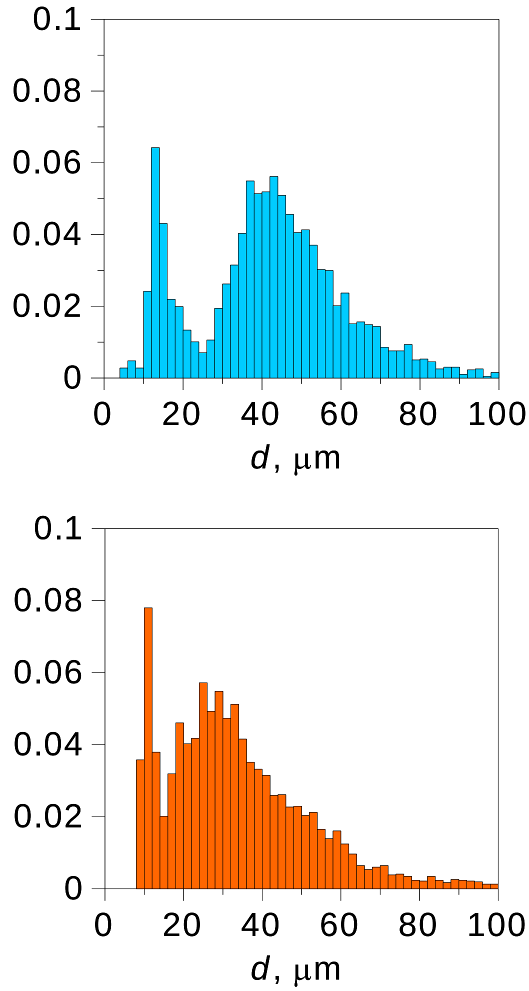

Figure 3. Diameter histogram for water (top) and fuel oil (bottom) sprays near the nozzle.

G-DI Spray: n-heptane Substitute

Further measurements were performed on a gasoline direct injection (G-DI) system operating on a gasoline substitute at a pressure of 0.9 MPa, spraying into the ambient atmosphere. This spray developed as a hollow cone with a separate cluster of droplets exiting mainly along the centerline at the start of injection, likely due to residual fuel in the orifice region. The cone part of the spray developed a leading edge roll-up vortex. Shown in Figure 4 is a bubble plot indicating droplet size and location for the G-DI spray. The top of this plot is 13 mm downstream from the nozzle, and the left edge of this plot is at the injector centerline. What is most striking about this figure is the detail present, including the spray angle, since the technique was actually able to detect and measure droplets all the way up the spray nozzle.

Figures 5, 6, and 7 show diameter distributions for a plane through the nozzle centerline, 2 mm away from the centerline, and 4mm from the centerline, respectively. Comparing these histograms, one can see that the peak and maximum diameters are increasing as we move away from the nozzle centerline. Overall, however, smaller droplet sizes are indicated here compared to the pressure atomizer (above), even though the applied pressure is at an engine start-up level. Very few droplets have diameters above 100 µm. This is shown by the trend in SMD with distance from the centerline, shown in Figure 8.

The important trends of this atomizer were detected very well by the GSV system, in spite of the highly dense spray plume. Being a global technique, GSV has the advantage of being able to make a measurement whenever (40 to 75 frames captured) and wherever (10 mm x 12 mm field of view) there is an identifiable oscillation pattern in the image. Point measurement techniques, on the other hand, are not able to gather data except from the interrogation point.

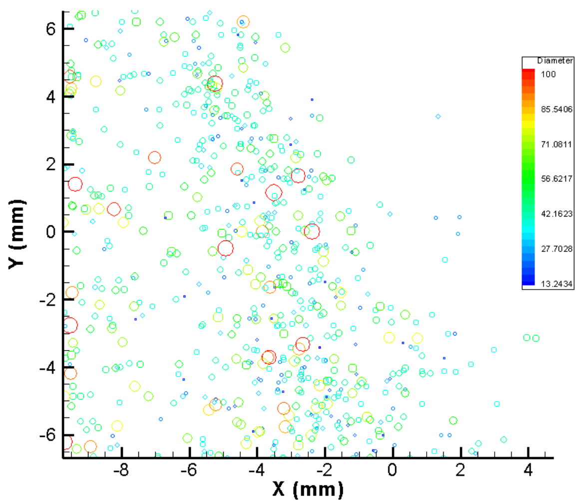

Figure 4. Droplet size and location for G-DI spray.

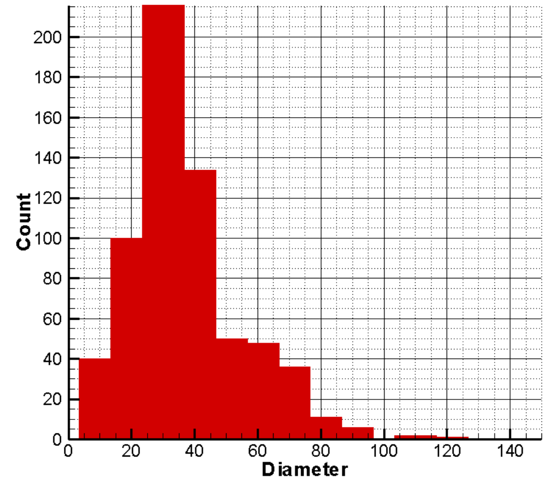

Figure 5. Diameter distribution for G-DI spray at location x=8.7 mm, y = 13 mm, and z= 0 (on-axis).

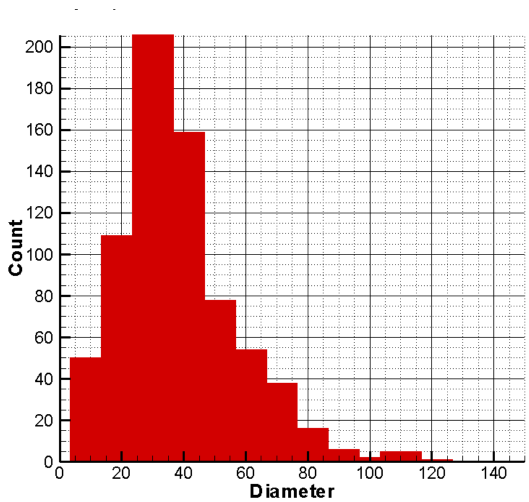

Figure 6. Diameter distribution for G-DI spray at location x=8.7 mm, y=13 mm, and z=2 mm (off-axis).

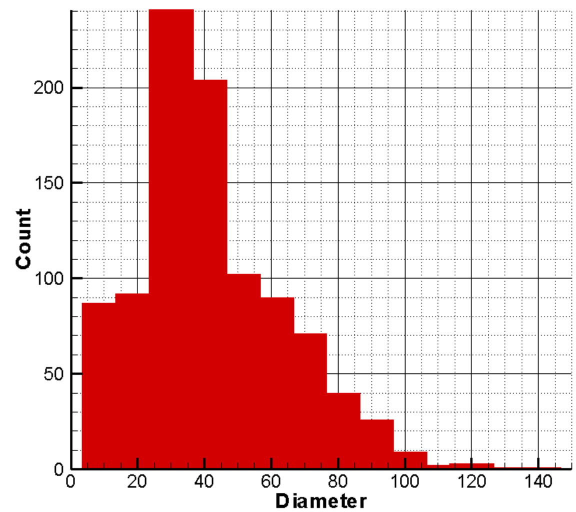

Figure 7. Diameter distribution for G-DI spray at location x=8.7 mm, y=13 mm, and z=4 mm (off-axis).

Conclusions

A new global droplet size and velocity measurement system has been developed using the GSI approach, with the capability to measure the velocity and size of droplets with non-uniform and/or varying refractive index. The windowed FFT based approach together with the optimized frequency-based algorithm was shown to extract the droplet size accurately and robustly. Sizing accuracy was verified using monodisperse droplets and a graded index optical fiber.

A two-frame tracking algorithm was employed to measure the velocity of droplets from the two consecutive image frames. The size range and droplet concentration limits were investigated using simulated out-of-focus images. The measurable diameter range for the system was verified to be from 10 µm to 600 µm for the range of magnification and defocus recommended here. The maximum droplet concentration was expected to be about 3000 #/cc.

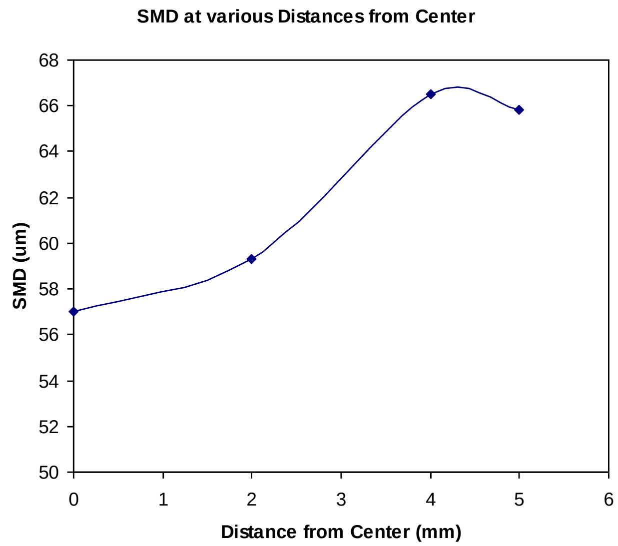

Figure 8. Sauter Mean Diameter as a function of distance from the nozzle centerline.

Data were obtained for a swirl type pressure atomizer operating on water and fuel oil. Results depicted well the near-nozzle spray angle and diameter characteristics in various parts of the spray structure. The water spray had generally larger droplet sizes compared to the fuel oil spray. Variation in fluid pressure from 0.6 MPa to 0.8 MPa caused a dramatic variation in spray angle and spray structure. Recirculation and spray sheet zones could easily be identified in the data, by the relative population of small and large droplets.

Measurements of a G-DI spray were possible with the GSV system. These measurements revealed several interesting trends, including an increasing SMD as the measurement plane was traversed away from the centerline.

References

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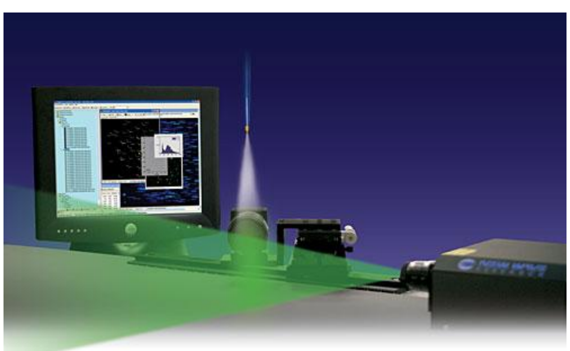

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