Drop-size measurement techniques for sprays: comparison of Malvern laser-diffraction and Aerometrics phase/Doppler

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The purpose of this paper is to compare the drop sizing results of an Aerometrics phase/Doppler particle analyzer with those of a Malvern laser-diffraction instrument. Measurements were performed on a small pressure-swirl atomizer. Since the laser-diffraction instrument measures a line-of-sight average through different regions of the spray while the phase/Doppler instrument characterizes the spray in a small volume, a conversion procedure was necessary prior to comparison. After conversion to equivalent forms, the point-measured average drop sizes exhibited similar trends throughout the spray, but the phase/Doppler values were generally larger. The total volume flow rate measured by the phase/Doppler instrument was inconsistent at different axial locations but significantly larger than the actual value at most locations.

I. Introduction

Over the past twenty years a number of significant advances have been made in drop sizing instrumentation, mostly in the area of optical techniques. Questions have arisen concerning the accuracy and repeatability of various instruments and how well results obtained at one laboratory compare with results for the same spray using a different instrument at another laboratory. Indeed comparisons of this type have been a significant activity of subcommittee E29.04 (Characterization of Liquid Particles) of the American Society for Testing Materials (ASTM). Generally significant differences have been observed between results from different laboratories, but interpretation of these discrepancies has been complicated by the fact that there are numerous possible sources of these differences: (a) actual differences in the spray, even using the same atomizer, due to differences in experimental condition, (b) differences in the type of sampling, e.g., line-of-sight averaging vs point sampling and temporal vs spatial sampling; (c) different size ranges for different instruments; and (d) calibration errors in the instruments.

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Progress in verifying the calibration of different types of drop-sizing instrument has been made but is slowed by the fact that calibration devices are often limited to one type of instrument. Special attention in this paper has been directed to comparing the performance of two types of drop-sizing instrumentation, which represent an important subclass of all available instruments. First, laser-diffraction devices are probably the most widely used drop-sizing instrumentation for testing fuel nozzles, and significant advances have been made in verifying the calibration of these instruments. The most widely used commercial laser-diffraction instrument is manufactured by Malvern Instruments.[1] Thus it was selected to represent laser diffraction devices. Second, modified versions of crossed-beam real fringe laser Doppler anemometers (LDAs) provide spatially resolved measurements of drop size, velocity, and volume flux. This type of data appears invaluable for computer modeling of sprays. These LDA instruments include those based on visibility,[2,3] scattered intensity,[4,5] a combination of visibility and intensity,[5,6] and a phase shift of the scattered light.[7–9] Those LDAs which employ the phase-shift principle seem to possess the largest dynamic range in sizes at a single setting and appear to have the best immunity to optical disturbances. For that reason, a commercially available phase-shift instrument from Aerometrics, Inc.[10] was selected for comparison with the Malvern laser-diffraction instrument.

The Malvern device is inherently calibrated from basic diffraction principles without resorting to a reference standard if certain nonidealities of the detectors are corrected.[11] Hirleman and Dodge[12] have shown that, after correcting detector responsivities, six different Malvern instruments could measure the Sauter mean diameter (SMD) of a distribution of opaque dots on a reference reticle with a maximum error (after averaging over twenty or more repeats) of 2.7% and a total spread of 5.4%. (Larger errors might be expected for multimodal distributions or less ideal distributions.) A Malvern instrument calibrated by this procedure[11] was used for the tests reported here.

The laser-diffraction (LD) instrument measures a line-of-sight average through the complete spray; that is, it samples drops within the volume defined by the intersection of the laser beam and the spray, as shown in Fig. 1. It also registers a signal proportional to the population of drops within the sample volume during the sampling interval, which is referred to as a spatial average.[13] The phase/Doppler (PD), on the other hand, samples in a very small volume rather than through the whole spray, as shown in Fig. 1, and the PD registers a signal proportional to the number of drops passing through the volume, called temporal sampling. Thus, to compare the LD and PD measurements, it is necessary to convert the PD data into line-of-sight spatially averaged data, as performed by Jackson and Samuelsen[9,14] or convert the LD line-of-sight data into point data and the PD results into spatially averaged data. Both approaches have been used to compare results in this paper, but the majority of results are presented in terms of the second approach, a comparison of point measurements throughout the spray. The LD line-of-sight data were converted into spatially resolved data using the deconvolution procedure developed by Hammond.[15]

The paper is organized as follows. First, the experimental apparatus and drop-sizing instruments are discussed. Then the deconvolution procedure for the line-of-sight data is briefly described. Other mathematical procedures necessary to combine point measurements into a line-of-sight equivalent value are discussed. Finally, using these various conversion procedures, drop sizing results from the LD and PD instruments are compared.

II. Experimental Apparatus

The atomizer used for this study was a type which was tested by eleven different laboratories in a recent round robin organized by ASTM subcommittee E29.04. The atomizer was a small pressure-swirl type of peanut style used in gas-turbine combustors and was manufactured by Parker Hannifin Corp. as P/N 3030946. The flow number on aircraft fuel system calibration fluid MIL-C-7024 type II (special-run stoddard solvent) was 2.05×10^{-6} kg/s $\sqrt{\text{Pa}}$ (1.35 lbm/h $\sqrt{\text{psid}}$). The fluid was maintained at 300 K, and measurements were made at pressure differences across the atomizer of 345 kPa (50.0 psid) and 689 kPa (100.0 psid).

The atomizer was mounted horizontally in a rectangular spray chamber of square cross section, 30 cm on a side and 76 cm long. Air was pulled through the chamber by an explosion-proof exhaust fan at a velocity of ~2.26 m/s with an rms turbulence intensity of ~30%. A twisted metal Demister[16] screen ~7.6 cm thick was used to remove the fuel drops before exhausting the air.

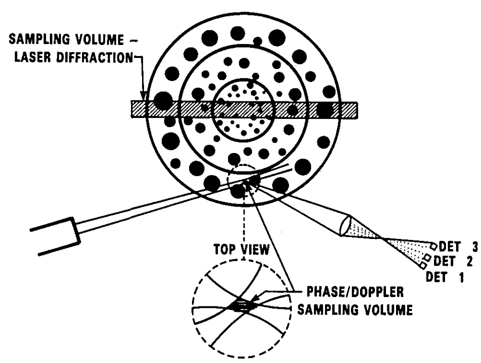

Fig. 1. Comparison of sample volumes of phase/Doppler and laser-diffraction instruments.

The laser-diffraction instrument was manufactured by Malvern[1] as a model 2200 and was modified for these measurements as follows: The instrument was calibrated by the procedure recommended by Dodge[11] and gave excellent results when checked with a reference reticle developed by Hirleman.[17] To increase the spatial resolution, the laser beam diameter was reduced from 9 to 3 mm. This was accomplished by replacing the output lens of the laser beam expander by one with one-third of the standard focal length. For the receiver, the 300-mm focal length $f/7.3$ lens was used for all tests. The LD drop-size distributions were assumed to be Rosin-Rammler for the line-of-sight data, except where noted otherwise. The size distributions after deconvolution were not assumed to follow any particular function.

The phase/Doppler particle sizer and velocimeter was manufactured by Aerometrics[10] and is referred to as a phase/Doppler particle analyzer (P/DPA). The details of this instrument are described elsewhere,[7] but it can be thought of as a crossed-beam real fringe laser Doppler anemometer with frequency shifting which has been modified for drop sizing. The transmitting unit is similar to a conventional crossed-beam real fringe LDA using a He–Ne laser, except that a rotating grating is used both to split the beam (± 1st order) and for frequency shifting. The grating is a small glass disk with a circular grating pattern, mounted with the shaft of a small dc motor through the center of the disk. Actually three different grating patterns are used in different annuli of the disk, allowing for a range of beam spacings and frequency shifts. The frequency shifting has four advantages: (a) elimination of the velocity ambiguity associated with reverse flow; (b) extension of the dynamic range of the drop velocity measurement; (c) extension of the maximum velocity which can be measured; and (d) improvement in the number of good quality signals due to more fringe crossings within the sample volume.

The receiver and signal processing of the PD instrument are significantly different from a standard LDA.

Table I. Comparison of Temporal and Spatial Sampling

Temporal sampling instruments, such as single-particle counters register signals proportional to temporal frequency (counts/s)

Spatial sampling instruments, such as photographic or laser diffraction register signals proportional (in one dimension) to spatial frequency (counts/m)

	Initial condition	Downstream condition
Atomizer	O O O O O	O O O O O O O
	o o o o o o o o o o	ooooooooooooooooooooooooo

Initial condition

Size	Temporal freq.	Velocity	Spatial freq.
200 μm	10/s	2 m/s	5/m
100 μm	20/s	2 m/s	10/m

Temporal sample

$$D_{10} = \frac{10 \times 200 + 20 \times 100}{30} = 133\ \mu m$$

Spatial sample

$$D_{10} = \frac{5 \times 200 + 10 \times 100}{15} = 133\ \mu m$$

Downstream condition

Size	Temporal freq.	Velocity	Spatial freq.
200 μm	10/s	2 m/s	5/m
100 μm	20/s	1 m/s	20/m

Temporal sample

$$D_{10} = \frac{10 \times 200 + 20 \times 100}{30} = 133\ \mu m$$

Spatial sample

$$D_{10} = \frac{5 \times 200 + 20 \times 100}{25} = 120\ \mu m$$

The velocity measurement is performed in a conventional manner using counter-type electronics. The difference is in the drop sizing, which is based on the phase shift of light refracted through the drop and scattered to different portions of the receiving lens. Each portion of the receiver lens is imaged onto different phototubes, as shown in Fig. 1, and the phase shift of the Doppler signal between the different phototubes can be related to the drop size.[18]

III. Convolution and Deconvolution of Spray Data

From Sec. I and examination of Fig. 1, it is clear that the results from the LD and PD instruments cannot be compared without first treating the results to put them into equivalent sampling formats. The sampling processes of the LD and PD instruments differ in two ways. First, as shown in Fig. 1, the LD device averages results over the line-of-sight intersection between the laser beam and the spray, which includes different zones of the inhomogeneous spray. The sampling volume of the PD instrument is extremely small ($\sim 10^{-5}$ cm^3) and is defined first by the intersection of two focused laser beams but is then further limited by the image into this volume (at 2:1 magnification) of a 50- or 100-μm by 1-mm slit. Thus for comparison the LD data must be spatially resolved, or the PD data must be converted into an equivalent line-of-sight average. Although the second approach is considerably easier, it results in only one overall value for comparison, while the first approach allows comparisons throughout the spray. Both approaches were used here, but the emphasis is on the deconvoluted LD data which allows comparisons throughout the spray.

The second way in which the sampling processes of the LD and PD instruments differ is in the way they are affected by the velocity of the drops. This is illustrated in Table I. The PD instrument measures the number of drops per unit time which pass through the sample volume, and the signal is proportional to this temporal frequency; therefore, the PD instrument measures a temporal average. The LD instrument, on the other hand, responds in proportion to the number of drops within the sample volume, which is proportional to the spatial frequency of the drops (e.g., drops/cm), as shown in Table I. This is referred to as a spatial average. If the velocity of all drops is the same, or if the velocities vary but are not correlated with size, the temporal and spatial averages are identical. However, in many spray systems the velocities are correlated with size due to variations in drag with size, and the temporal and spatial averages are different, as for the downstream condition in Table I. Because the PD instrument correlates velocity and size, it can compute a spatial average as well as the temporal average which it measures directly. For this paper the PD results have been expressed as spatial averages for comparison with the LD results, except where noted otherwise. The conversion from temporal to spatial is performed by dividing the class size by the average velocity for the size class in the averaging summation. For example, the spatially averaged arithmetic mean is computed in a temporally sampling instrument by

$$D_{10} = \left(\sum_i n_i d_i / u_i\right) \Bigg/ \left(\sum_i n_i / u_i\right), \tag{1}$$

where n_i is the counts in size class i, d_i is the diameter of size class i, and u_i is the average velocity of size class i. The Aerometrics phase/Doppler instrument conveniently includes this calculation within the standard software, making it possible to compare temporal and spatial averages. However, there are two shortcomings to this conversion. First, sprays generally have significantly velocity components in two dimensions (three for swirling flows), and this Aerometrics only measures one component of velocity. Therefore, the spatially averaged components are corrected for velocity in only one dimension and are not truly spatial averages. Second, in Eq. (1), the actual velocity for each drop should be used rather than the average for the size class. Since there is usually a considerable spread in drop velocities for a given size class, this could result in a significant error. These criticisms should be conditioned with the fact that the temporal average measured by the Aerometrics is often the preferred quantity, and there is no need to convert to the spatial average. However, for this paper the conversion to spatial averages was necessary for comparison with the Malvern data, and these error sources in the conversion process must be considered.

It is important to note that the temporal averages are conserved quantities for steady spray processes with no recirculation, evaporation, or coalescence, while the spatial averages are not, as shown in Table I. That is, if a temporally averaged quantity is computed for a complete cross section of a nonrecirculating spray with no evaporation or coalescence, that quantity is the same at any axial location.

After converting the PD data into spatial averages, the PD data were then summed for an equivalent line-of-sight average, or the LD data were deconvoluted into narrow annular rings. The deconvolution procedure is briefly described below, followed by a discussion of the summation of PD data into line-of-sight equivalent values. Then the procedures to compute overall averages for the complete spray cross section at any axial location for both the LD and PD data are described.

A. Deconvolution of Laser Diffraction Data

The purpose of the deconvolution procedure is to convert line-of-sight averaged LD drop size data into spatially resolved drop size information. This procedure is considerably simplified for sprays which are axially symmetric, a good assumption for the atomizer examined here. Assuming axial symmetry, the spray may be divided into annular rings which exhibit radial but not angular variations, as shown in Fig. 2. Line-of-sight averaged data were taken through various chords of the spray, and then size distributions and number densities were computed for each annulus using the procedure described by Hammond.[15] Other deconvolution procedures are also available.[19]

The spatial resolution of the deconvolution procedure is determined by the number of measurement locations chosen radially outward from the center line, as can be inferred from Fig. 2, and by the diameter of the laser beam (3 mm). For this work, nine to sixteen measurements were performed at even radial increments from the center line to each edge of the spray. Basically the procedure assumes a homogeneous outermost ring (ring 1 in Fig. 2), which is sampled at the outermost radial location (location 1 in Fig. 2). The angular scattering data are used to compute the drop size distribution, and the attenuation of the unscattered light, combined with the drop size data is used to compute the number distributions. At the next radially inward sampling location (location 2 in Fig. 2) the beam passes through both the outer ring (1) and the next ring (2). The effect of ring 1 on the measured value may be subtracted out mathematically and the drop size distribution of ring 2 solved for. This procedure is repeated to the center line of the spray. Errors tend to increase toward the center line, which can be seen in some of the data presented later.

Hammond[15] has examined the problem of propagation of errors in the deconvolution procedure resulting from noise in the experimental data and pointed out the need to smooth the data to provide mathematical stability. However, the cubic spline smoothing used by Hammond to smooth the radial variation of the line-of-sight drop-size distributions can result in negative populations at some radii. To avoid that possibility, an alternative scheme was used to smooth drop-size distributions, which adds a contribution from all the other measurement locations with the contribution being damped out exponentially for further removed measurement locations. More precisely, the fractional number density of drops in the kth size category for the ith measurement radius $n'_{k,i'}$ was smoothed by adding in contributions from the other measurement radii:

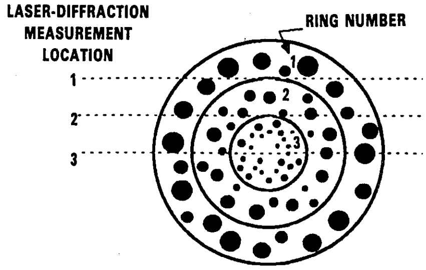

Fig. 2. Line-of-sight measurement locations for deconvolution procedure.

$$C_{k,i'} = \sum_{i} n'_{k,i} \exp\{-[(i - i')/N_R]^2 \times F\} \qquad i = 1,2,\ldots,N_R, \qquad (2)$$

where $n'_{k,i}$ is the numerical fraction of drops in the kth size class for the ith measurement radius, N_R is the total number of measurement radii, and F is an adjustable damping factor. After $C_{k,i'}$ was added to $n'_{k,i'}$ for all values of k, the $n'_{k,i'}$ values were renormalized.

Large values of F imply minor smoothing and vice versa. Values of F of ~100 were initially used, and the resulting deconvoluted Sauter mean diameters (SMDs), number densities, etc. were examined for stability (smooth variation with radius). If the procedure was unstable, F was gradually reduced until stability was obtained. If the procedure still exhibited instability for an F value of 25, the data were considered unsuitable for deconvolution.

The data were also smoothed between size classes at a given measurement location by assuming a Rosin-Rammler distribution. After deconvolution the drop-size data for each ring did not necessarily follow a Rosin-Rammler distribution, and the SMDs and other averages in each ring were computed by their defining summations.

The transmitted (unscattered) laser beam intensity was also smoothed. These values were smoothed by fitting a third-degree polynomial through the five nearest data points (two on each side and the actual value) describing transmission as a function of radial location.[20]

B. Computation of Line-of-Sight Equivalent and Overall SMDs

The SMD or D_{32} is defined for a spray consisting of N_c size classes by

$$D_{32} = \frac{\sum_i N_i D_i^3}{\sum_i N_i D_i^2} \qquad i = 1,2,\ldots,N_c, \tag{3}$$

where N_i is the number or fractional number of drops in the ith size class, and D_i is the average diameter of the ith size class. If the spray is assumed to consist of zones as shown in Figs. 1 and 2 and the number of drops are known for the distribution within the jth zone as N_{ij}, D_{32} becomes

$$D_{32} = \frac{\sum_j \sum_i D_{ij}^3 N_{ij}}{\sum_j \sum_i D_{ij}^3 N_{ij}} \qquad \begin{array}{l} i = 1,2,\ldots,N_c, \\ j = 1,2,\ldots,N_R, \end{array} \tag{4}$$

where N_R is the number of rings or points where the distribution is known. However, there are some practical problems in applying Eq. (4) to the PD data to compute an equivalent line-of-sight average D_{32} (SMD) for the spray. Typically it required about twenty-five PD measurement points at a given axial location to define the radial variation along a diameter across the whole spray, and the distribution at each point was described by a drop count in sixty-eight channels. Furthermore, since the object was to compute a spatial line-of-sight equivalent D_{32}, each channel would have to be corrected for its average velocity. Furthermore, to compute a line-of-sight average through chords other than the diameter, these complex summations would have to be repeated with a factor for the path length through each ring of the spray, such as those shown in Fig. 2.

Rather than attempting to reprocess the raw data in the form of Eq. (4), it is possible to compute the spatial line-of-sight equivalent D_{32} from the spatially averaged quantities calculated for a point by the Aerometrics PD instrument. It can be readily derived that the line-of-sight D_{32} value is given by

$$D_{32} = \frac{\sum_j D_{30,j}^3 (N_j/V_j) L_j}{D_{20,j}^2 (N_j/V_j) L_j} \qquad j = 1,2,\ldots,N_R, \tag{5}$$

where $D_{30,j}$ and $D_{20,j}$ are the volume mean and area mean diameters of the jth ring, (N_j/V_j) is the number density of the jth ring (or number flux for temporal measurements), and L_j is the path length through the jth ring. All quantities except L_j are calculated by the Aerometrics PD instrument. For equally spaced points and a calculation through a diameter, the L_j values are all equal and may be ignored, but for calculations through chords other than the diameter (which are reported here) the L_j values must be included and are calculated geometrically. Both spatially and temporally averaged values of D_{30} and D_{20} are computed by the Aerometrics PD instrument. Thus spatially or temporally averaged D_{32} terms may be computed by Eq. (5). For comparison with the LD instrument the spatial average is required.

To compute the average Sauter mean diameter or D_{32} over the whole cross section of a spray at a given axial location, Eq. (5) was used with the path length L_j replaced by the area of the ring represented by the measurement location. Thus, for the LD instrument, the ring dimensions were defined as in Fig. 2 from the center of the laser beam. For the PD measurements, the ring boundaries were assumed to be midway between the measurement locations.

These conversions for spatially averaged quantities as computed by the Aerometrics phase/Doppler instrument are subject to the error as discussed for Eq. (1); that is, this instrument only measures one component of the velocity. Thus the spatial values are not corrected for the other velocity components and are not truly (in general) spatial averages.

It is interesting to note that, although the deconvoluted LD data and the PD data both give local or point values of D_{32}, a number weighted or volume weighted average of these local (point) values does not yield the correct overall D_{32} for the spray cross section.

Spray densities were computed as both number densities and volume fractions, where volume fractions represent the fraction of space actually occupied by the liquid at a point. The volume fraction for the jth ring was computed from the number density (N_j/V_j) by

$$\text{vol. frac.}_j = \pi/6 D_{30,j}^3 (N_j/V_j), \tag{6}$$

and the volume fraction for the complete cross section was computed by summing Eq. (6) over all the rings including a factor for ring area. This total volume fraction is of questionable value because it clearly depends on where the outside edge of the spray is assumed to be, but it was useful as a relative number between the LD and PD instruments using the same assumption for the edge of the spray.

IV. Results and Discussion

A. Sources of Errors and Differences in Laser Diffraction and Phase/Doppler Measurements

Before presenting the results of the comparison of the two instruments, it is worthwhile reviewing some of the possible sources of errors in the instruments and in the comparison procedures. There are at least twelve possible sources of differences.

(1) The imaging system for the receiver unit of the Aerometrics instrument introduces aberrations which result in the counting of some drops, particularly larger drops, which are outside the proper sample volume. This problem is exacerbated by using the smaller of the two collection slits, which was used in this experiment due to the very high number densities. This results in a large overestimate of the volume flux and a small overestimate of the average drop sizes. The manufacturer identified this problem and is working on correcting it.

(2) The spatial SMDs shown for the Aerometrics PD instrument are corrected for axial velocity only, and a correction for the radial velocity would systematically lower the SMDs in the outer radial half of the

spray, with no effect on the inner half of the spray. This is a very small correction for this atomizer but would be more significant for higher capacity nozzles which produce larger drops. Also, as discussed for Eq. (1), the individual drop velocities rather than the average velocity for the size class should be used (if feasible) to convert from a temporal to a spatial average. These are not faults in the Aerometrics PD instrument which measures temporally but are a limitation in the conversion to a spatial distribution.

(3) The PD instruments are very sensitive to optical alignment, and misalignment seems to cause a loss of the smallest drops and, in some conditions, the false appearance of larger drops.

(4) Another source of difference could be the loss of some of the smaller drops by the Aerometrics PD instrument near the center of the spray where number densities were high and there were significant overlaps in the raw data signals. It might be possible in these circumstances to count preferentially the larger drops whose signals are up to 1200 times as large as the smallest drops and completely miss smaller drops passing through the sample volume at the same time. To minimize this problem the smaller of two detector slits was selected to decrease the sample volume, but this increases problems associated with error source (1).

(5) The sampling locations of the LD and PD instruments are as comparable as possible but still not identical. The radial resolution of the PD instrument is much finer than the deconvoluted LD data. The LD instrument also averages over much larger parts of the spray than the PD instruments. All this also assumes an axially symmetric spray, which appears to be a good approximation for this spray.

(6) A significant source of error in the LD instrument is the nonuniform response of the thirty detectors which are used to measure the diffracted light energy distribution. A procedure has been developed to correct for this by measuring the detector responsivities and then using these values in the software for the data reduction.[11] This calibration procedure has been applied to the LD instrument used for these tests, and agreement with reference reticles was obtained to within 3%.

(7) The deconvolution of the LD data requires extensive computations which can lead to errors, as evidenced by poor convergence at the center line for some cases. Adjustment of smoothing factors is sometimes necessary to stabilize the procedure while still minimizing the smoothing effect. Deconvoluting data which were obtained close to the nozzle (10- and 20-mm locations) seemed most subject to instability. However, there is no evidence of systematic errors associated with the deconvolution procedure.

(8) The Malvern is limited toward its upper size range by extremely large size bins, which for this case were 160–262 and 262–563 μm for the two largest size bins. This poor size resolution can lead to errors in some sprays but was probably not significant for this fine-spray atomizer.

(9) Jackson and Samuelson[14] pointed out significant differences in the Malvern LD data depending on whether the Rosin-Rammler or model-independent analyses were used to process the data. They favored the model-independent analysis. Limited analysis in this work suggests some differences between the two distribution forms but no particular advantage for the model-independent approach.

(10) High spray densities cause errors in the LD instrument due to the multiple-scattering effect, resulting in a systematic bias toward smaller average drop sizes for the LD instrument.[21] For this relatively low capacity atomizer, the highest attenuation level recorded for the laser beam was 47%, below the ~60% level where corrections for multiple-scattering become necessary.[21] Thus in these tests multiple-scattering errors for the PD instrument were not significant.

(11) The size ranges of both the LD and PD instruments are limited. In the configuration used, the LD instrument has a range of 5.7–563 μm. However, using the Rosin-Rammler distribution function effectively extends the range beyond these limits. The PD instrument has a broader overall range than the LD instrument but a more limited dynamic range of 35:1. These range limitations for both instruments are presumed to have had only a minor effect on the results.

(12) Since the measurements with the two instruments were not performed simultaneously, some variation in the actual spray was present, contributing to the other differences.

B. Comparison of Laser-Diffraction and Phase/Doppler Spray Measurements

A detailed comparison of the SMDs measured by the LD and PD instruments was conducted in small radial steps across the whole spray at seven different axial locations—10, 20, 30, 40, 50, 75, and 100 mm downstream of the nozzle tip at two different fuel pressures for each condition, 344.7 kPa (50.0 psid) and 689.5 kPa (100.0 psid). Because of space limitations, results presented here are limited to four axial locations for the 689.5-kPa case, although results for the other axial locations and the 344.7-kPa case are available elsewhere.[22] This comparison required the deconvolution of the Malvern LD data to convert the line-of-sight average values to point measurements. The 50-mm axial location was chosen as typical, and the effect of the deconvolution is shown in Fig. 3. Note that the deconvoluted values must approximately converge to the measured values of the edge of the spray. Each radial half of the spray was deconvoluted separately, and for this case (Fig. 3) they converge nicely in the center. This was not true in all cases, with the center points for several cases showing a discontinuity due to the accumulation of errors in the deconvolution procedure as it marched toward the center line. Figure 3 indicates good axial symmetry, which is fortunate since symmetry is a requirement for the deconvolution procedure used.

The general shape of the spray and the variation of SMD with radial and axial distance may be seen in Fig.

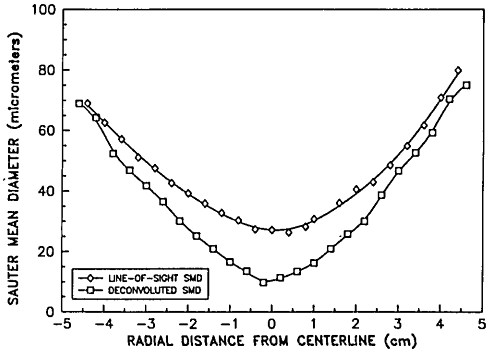

Fig. 3. Laser-diffraction line-of-sight and deconvoluted SMDs at an axial distance of 50 mm.

4. The trends in SMD as a function of radial location were as expected for a pressure-swirl atomizer. The majority of the spray leaves the nozzle in the outer cone of the spray, and then air entrained by the spray pulls the smaller drops toward the center while the larger drops maintain their momentum along the periphery of the spray. There is little coalescence or evaporation at these conditions. Thus the spray changes only slightly in traveling downstream. Drop distributions along the edge of the spray cone become narrower in distribution width and larger in average size in traveling downstream due to the entrainment into the center of the spray of the smaller drops.

The deconvoluted SMDs from the Malvern LD instrument are compared with the spatial SMDs from the Aerometrics PD instrument in Fig. 5. Considering the completely distinct measurement methods and sampling effects as well as the range in drop sizes and spray densities, the agreement shown in Fig. 5 is rather remarkable. The agreement shown in Fig. 5(a) where the radial step sizes were smaller than the LD beam diameter and the spray densities were quite high is much better than anticipated. Overall, the SMDs measured by the PD instrument were slightly larger than the LD data, possibly due to error sources (1) and (3).

An alternative way to compare SMDs from the LD and PD instruments is to convert the PD data into line-of-sight equivalent data using Eq. (5). These line-of-sight equivalent data can then be compared directly to the LD measurements. The PD measurements on opposite sides of the spray at the same radial distance from the center line were averaged together and multiplied by the appropriate path length. Results for the 50-mm axial location are shown in Fig. 6. The datum for a radial distance of zero represents a line-of-sight through the center line, while the other points are for chords progressively closer to the edge. This approach avoids the use of the deconvolution procedure but seems to be harder to evaluate and certainly does not describe the spray structure as well. The differences in the LD and PD data in Fig. 6 seem to be larger than the comparable comparisons in Fig. 5(c). The reason for this is uncertain, although it may have to do with the fact that Fig. 6 results from Eq. (5), which uses the values of D_{30} and D_{20}, while Fig. 5(c) is based on D_{32}. Perhaps differences in drop-size distribution shapes result in better agreement of D_{32} than in D_{30} and D_{20}.

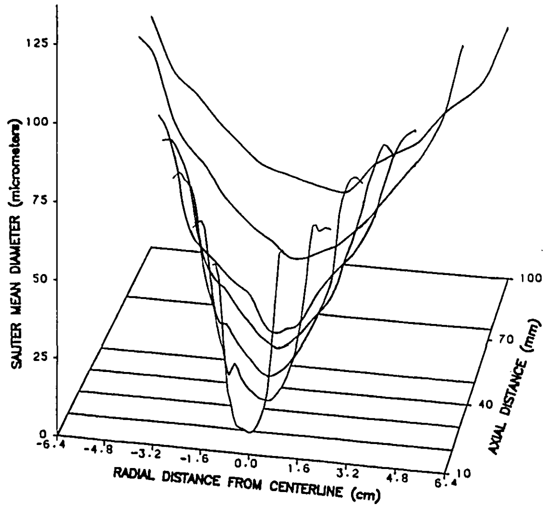

Fig. 4. SMD as a function of radial and axial distance, 689-kPa pressure differential case (measured by Aerometrics phase/Doppler as a spatial average).

This difference in distribution shape may be seen by comparing the (spatial) D_{10} values (arithmetic average diameter) of the LD and PD instruments at the 50-mm axial location in Fig. 7 with the D_{32} values in Fig. 5(c). The D_{32} values compare more favorably than the D_{10} values, confirming a difference in the width of the size distribution. Experience with both instruments suggest that both measure D_{32} values with better repeatability (and probably accuracy) than D_{10} values. Fortunately, for combustion work, the D_{32} values are of much greater significance than the D_{10} values.[23] The comparisons reported here suggest that the PD instrument is missing some of the smaller drops, or the LD instrument is overemphasizing them. Limited experience with the PD instrument suggests that the D_{10} values are very sensitive to optical alignment and filter settings.

Jackson and Samuelson[9] also reported a difference in drop-size distribution shape in their comparison of LD and PD instruments with differences qualitatively similar to those observed here. They reported that changing from the Rosin-Rammler distribution to the model-independent distribution within the Malvern data reduction procedure resulted in substantially different Malvern results and better agreement with the PD data. For those reasons, and the assumption that the model-independent distribution must provide a more accurate fit of the data, they recommended the model-independent procedure.

Because of these conclusions by Jackson and Samuelson,[9] the model-independent analysis was compared with the Rosin-Rammler distribution for Malvern LD measurements performed through the spray center line at an axial distance of 50 mm with results as shown in Fig. 8. The drop size distribution for the model-independent case is not significantly different

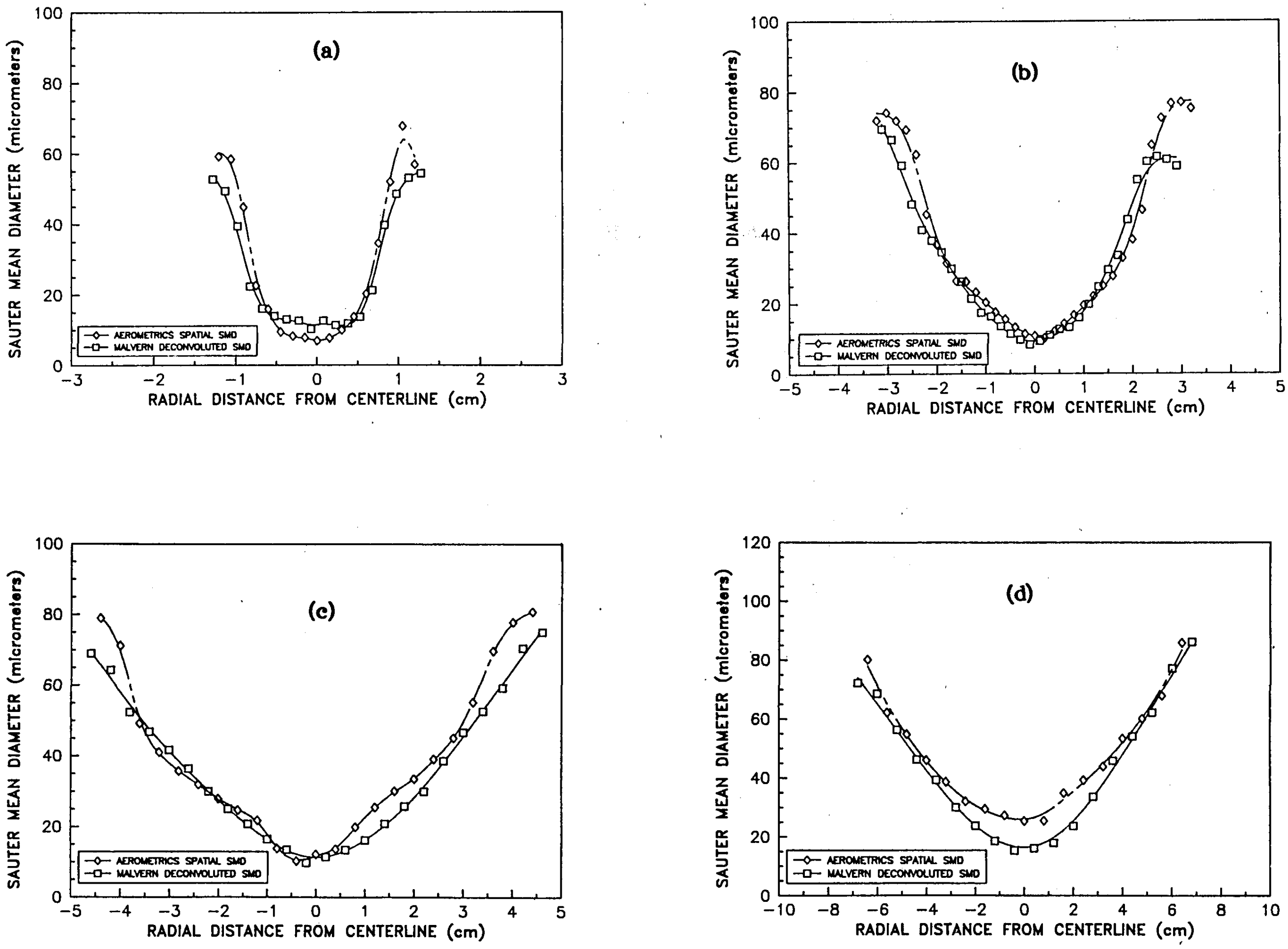

Fig. 5. Comparison of SMDs measured at a point by Aerometrics phase/Doppler instrument and by Malvern laser-diffraction instrument (after deconvolution) for an axial distance of (a) 10 mm, (b) 30 mm, (c) 50 mm, and (d) 100 mm.

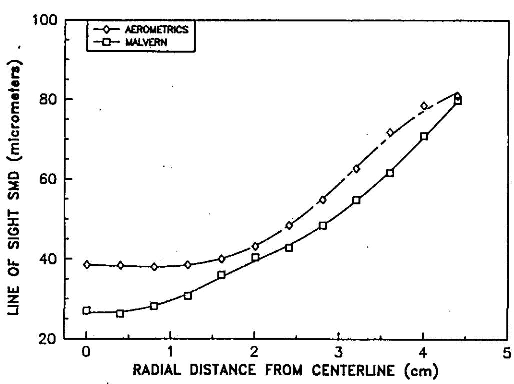

Fig. 6. Comparison of line-of-sight SMDs measured by the Malvern laser-diffraction instrument and computed from the Aerometrics phase/Doppler measurements at an axial distance of 50 mm.

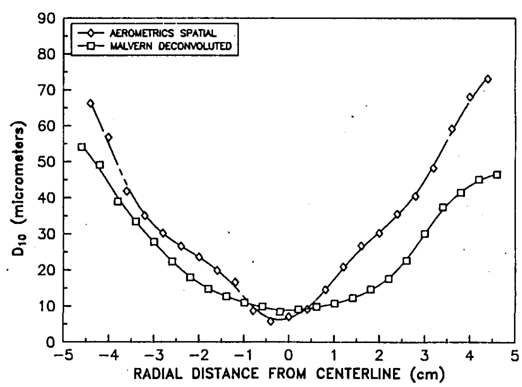

Fig. 7. Comparison of arithmetic average drop diameter D_{10} measured at a point by the Aerometrics phase/Doppler instrument and Malvern laser-diffraction instrument (after deconvolution) at an axial distance of 50 mm.

from the Rosin-Rammler case except in the largest size classes. The effect of substituting the model-independent LD results for the Rosin-Rammler data was evaluated for the deconvolution procedure, as shown in Fig. 9. (These data are for a pressure differential of 345 kPa and an axial distance of 50 mm.) The choice of distribution form for reducing exactly the same experimentally measured light distribution introduces some difference in the results for the LD instrument, but there does not appear to be a systematic bias or better agreement with the PD data using one or the other of the distributions.

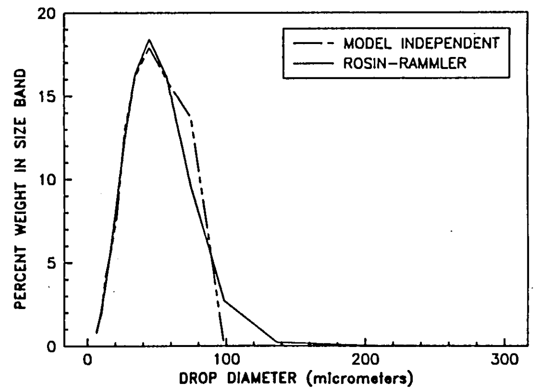

Fig. 8. Comparison of weight distributions for Rosin-Rammler and model-independent size distribution functions at an axial distance of 50 mm.

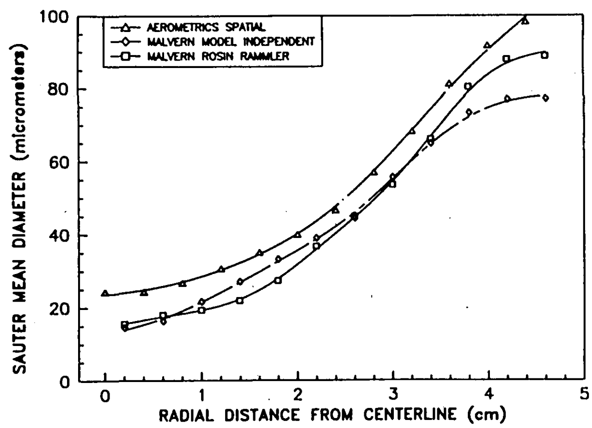

Fig. 9. Effect of laser-diffraction drop-size distribution function on deconvolution procedure and comparison with phase/Doppler results.

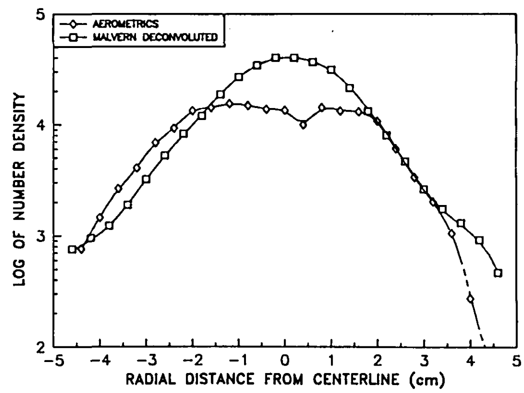

Fig. 10. Comparison of number densities measured at a point by the Aerometrics phase/Doppler instrument and Malvern laser-diffraction instrument (after deconvolution) at an axial distance of 50 mm.

The LD deconvolution procedure can be used with input data in the form of Rosin-Rammler or model-independent distributions, but the input requirements in the first case are only two values at each radial location, while the latter case requires fifteen values at each radial location. Thus the second approach is more tedious. A second advantage of the Rosin-Rammler approach is that the deconvolution procedure requires a number distribution, but the Malvern LD instrument produces a weight (volume) distribution requiring a conversion before processing. The Rosin-Rammler continuous weight distribution function can be integrated to get a number distribution, but for the model-independent distribution discrete summations are used for the fifteen size classes, resulting in errors from the broad width of size classes with unknown information about distributions within a size class. A third problem with the model-independent analysis is that there is apparently an error in the model-independent analysis, or a premature termination of the convergence procedure, as it often has a larger error between the predicted and actual light distribution than the Rosin-Rammler analysis. Since the model-independent analysis has the freedom to adjust the populations of fifteen size classes, while the Rosin-Rammler is forced to compute the same populations by varying only two parameters, an optimum model-independent procedure should always achieve a lower error in comparing predicted and actual light distributions. For forty-four data recorded at the 50-mm location, the fitting error was higher for the model-independent analysis in fourteen cases, suggesting an error in the model-independent analysis. A fourth problem with the model-independent analysis is that the optical alignment is much more critical for repeatable results. For the above reasons, the Rosin-Rammler analysis of LD data which are to be deconvoluted is often the preferred choice for monomodal light distributions.

In addition to comparing drop size measurements, the drop number densities, volume fractions, and volume fluxes of the LD and PD instruments were compared. Again choosing the 50-mm axial location for comparison, the number densities are compared in Fig. 10. The reasonably good agreement shown, considering the order-of-magnitude ranges, is somewhat puzzling in consideration of the apparent differences in sensitivities to the smaller drops as discussed above. The PD number densities are systematically higher than they should be due to the single-component-of-velocity limitation discussed previously. The number densities are computed by dividing the number flux through the sampling volume by the particle velocities averaged for each size bin. However, the actual velocities are larger than the measured ones due to the second (and in some cases third) component of velocity. It is possible that this systematic error toward increased number densities might be offsetting some missed small drops, resulting in reasonably good agreement with the LD data.

The corresponding volume fractions at the same axial location and nozzle conditions are shown in Fig. 11. Considering the order-of-magnitude ranges involved, the agreement is not terribly bad, but it is not terribly good either, with the PD data being a factor of 2 or 3 larger in some cases. The volume fractions are

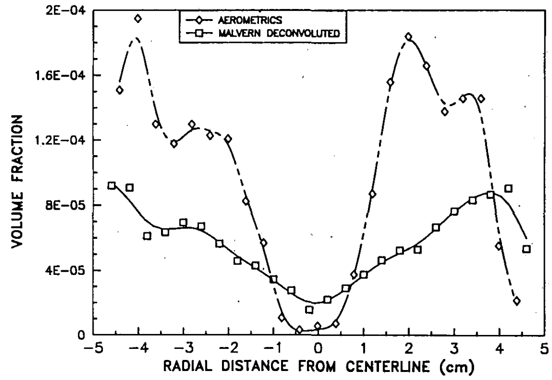

Fig. 11. Comparison of volume fractions measured at a point by the Aerometrics phase/Doppler instrument and Malvern laser-diffraction instrument (after deconvolution) at an axial distance of 50 mm.

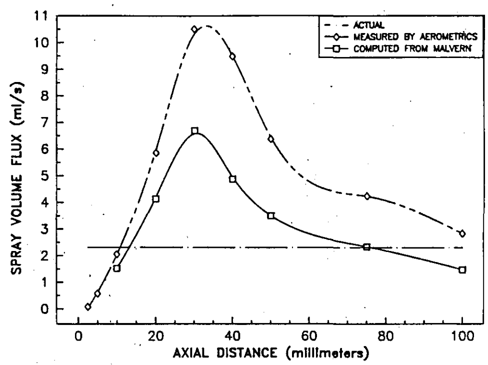

Fig. 12. Comparison of integrated volume flux measured by the Aerometrics phase/Doppler instrument with the atomizer fuel delivery rate as a function of axial distance. Also shown is volume flux measured by Aerometrics and multiplied by the ratio of volume fractions, Malvern/Aerometrics, from Fig. 11.

computed from the number fractions by multiplying by the appropriate D_{30} terms. Thus the volume fractions of the PD instrument would be significantly reduced by including the other velocity component(s) in calculating the number fractions. The manufacturer of the Aerometrics instrument has recently suggested another error source—the imperfect imaging of drops onto the slit in the receiver. This results in drops outside the computed sample volume being counted. The manufacturer suggests that a larger slit would reduce this error and that better alignment of the receiver optics will be used for future instruments.

Although the volume fractions are difficult to compare to any other standard, the volume fluxes may be compared to the known delivery rate of the nozzle. Assuming no recirculation and no evaporation, the integrated volume flux across the spray cross section should be a constant as a function of axial distance in spite of the deceleration of the spray. The volume flux measured at a point by the Aerometrics PD instrument was integrated for the whole spray cross section and is compared with the known delivery rate in Fig. 12 as a function of axial distance. Included in these figures is the flux as measured by the PD instrument and then multiplied by the ratio of the volume fractions of the LD to the PD instruments after integration over the spray cross sections. The data in Fig. 12 are somewhat troubling in that the PD instrument always rejects some of the drops as unsuitable, and its volume flux should always be less than the actual value, rather than several times higher. Again, the imperfect imaging of the drops onto the slit in the receiver may be responsible for the abnormally high volume flux. The low values measured close to the atomizer are probably due to the very high rejection rate of the PD instrument due to incomplete spray formation and extremely high drop intensities. The reduction in measured volume flux at 75 and 100 mm might be partially due to a failure to include the complete spray cross section due to the spray diluteness and some drop evaporation. No particular significance is attached to the better agreement for the LD modified PD volume fluxes shown in Fig. 12.

Since the preparation of this manuscript, several modifications have been made to the PD instrument which apparently improve the volume flux measurements. These modifications include a new set of more accurately aligned lenses for the receiver system, a new set of phototubes more closely matched in response than the original set, and the use of a 100-μm slit in place of the 50-μm one. Preliminary measurements of the integrated volume flux at the 30- and 50-mm axial locations resulted in values of 1.88 and 2.08 mliter/s, respectively, compared with the previous values of 10.50 and 6.37, respectively, and the actual flow rate of 2.21 mliter/s. Thus the values measured recently are close to the actual flow rate and may be within the circumferential variation of the spray. The volume flux measurements will be examined more closely and the subject of another paper.

V. Conclusions

The Aerometrics phase/Doppler and Malvern laser-diffraction instruments are different types of instrument and are ideally suited for different types of job. The Aerometrics PD device is ideally suited to detailed spray modeling where drop velocities as well as sizes are required and to applications requiring high spatial resolution. The Malvern LD instrument is very repeatable and fast for examining overall spray behavior and is ideally suited for determining fuel effects on atomization, nozzle-to-nozzle variations, and some process control applications. Combined with deconvolution technique, the LD instrument may be used to examine spray structure and provide data suitable to compute an average over a spray cross section. In spite of these differences, a comparison of performance of the LD and PD instruments offers a critical check of both the instruments and the mathematical procedures for deconvolution and averaging of data. The following conclusions are made concerning this comparison.

(1) The agreement in point-measured SMDs between the deconvoluted LD data and PD data is excellent. This simultaneously confirms the operation of

the PD instrument and the deconvolution procedure for the LD data for measurements of SMD.

(2) The agreement in line-of-sight averaged SMDs, which were calculated from point-measured D_{20} and D_{30} terms, is not as good as the agreement for point-measured SMDs. Although the agreement is still reasonably good, it raises questions about the drop-size distribution shapes measured by both instruments.

(3) The volume fractions measured by the LD and PD instruments show only fair agreement. The fact that the PD instrument measures only one component of velocity has been shown to cause a systematic overestimate of the number density and volume fraction by the PD instrument.

(4) The volume fluxes measured by the Aerometrics PD instrument are significantly higher than the actual values. This is probably due (at least in part) to imperfect imaging of drops onto the slit of the receiver. More recent measurements indicate significant improvements in this area (see text).

(5) The model-independent data reduction procedure for the Malvern LD instrument does not work as well as expected. The Rosin-Rammler distribution function offers some advantages for simple monomodal sprays, especially when the results are processed by a deconvolution procedure.

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