Interlaboratory Comparison of Phase Doppler Measurements in a Research Simplex Atomizer Spray

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Phase Doppler interferometry is providing detailed information about the structure of sprays. Such information is attractive to those developing numerical models that predict spray behavior. However, the inherent complexity of sprays and advanced diagnostics warrants the development of a reference point for measurements. Hence, a "standard" spray is evaluated in the current study which can be used to evaluate instrument and operator performance and, once sufficient data sets are generated, can provide a benchmark data set for modeling challenges. A comprehensive set of mean and variation in five sets of measurements is provided. In general, the results reveal reasonable reproducibility, especially in quantities which are dependent solely upon the number of drops (e.g., mean velocities). It is also shown that statistics derived from individual drop sizes reveal less variability than those derived from the entire spray population. Finally, it is observed that quantities which depend upon drop volume and/or sample volume area (e.g., Sauter mean diameter, volume flux) are subject to the greatest variability.

Nomenclature

D_{10} = number mean diameter, μm
D_{32} = Sauter mean diameter, μm
r = distance from centerline, mm
U = mean axial velocity, m/s
u' = rms of axial velocity, m/s
V = mean radial velocity, m/s
v' = rms of radial velocity, m/s
W = mean tangential velocity, m/s
w' = rms of tangential velocity, m/s
Z = axial distance from injector, mm

Introduction

T O facilitate the development of advanced propulsion systems, an understanding of both droplet evaporation and transport in nonreacting and reacting liquid sprays must be established in well-conceived and documented experimental configurations. To provide the needed information, new diagnostics have been established at a variety of institutions, including both the Institute of Aeronautics and Astronautics (IAA), and the UCI Combustion Laboratory (UCICL). These diagnostics portend the opportunity to develop the desired physical insight into the behavior of the liquid breakup and two-phase flows that govern liquid atomizer performance.

Currently, no standard exists for evaluating or comparing the performance of these advanced diagnostics. Hence, given 1) the inherent complexity of sprays and 2) the sensitivity of the advanced instrumentation to operating parameters,[1] interpretation of results obtained in a given laboratory can be challenging. The degree and accuracy to which the results

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need to be interpreted depends upon the application. For example, given the extent to which phase Doppler interferometry (PDI) can provide detailed information, the results obtained are highly attractive for use in model verification. Comparison of PDI results with model predictions can be biased in the absence of detailed assessment of measurement error.

To ensure high-quality spray measurements, the protocol should include at a minimum 1) proper calibration of the measurement device, 2) careful execution of the experiment including repetition of measurements and evaluation of the sensitivity of the results to facility and instrument operation, 3) evaluating the performance of the instrument by testing a standard test article and comparing the results against a data base developed by other laboratories that have utilized the same article, and 4) establishing the reproducibility of the results. Limited resources often preclude the incorporation of any but no. 2 of the above elements. Furthermore, even when the no. 2 element is incorporated, the sensitivity study may be limited.

Given sufficient resources, even the first element cannot always be met. For PDI, for example, the relationship between the phase shift and drop size ("slope") is set at the factory and the user is not required to verify the setting. In early applications of PDI, a monodispersed drop generator was occasionally used to verify calibration, but confidence in PDI performance has increased, reducing the pressure to conduct calibration verification. Furthermore, most users will not have a calibration device available.

Although highly desirable, element nos. 3 and 4 are rarely incorporated. This occurs because the development of an extensive data base on one test article and evaluation of reproducibility require the cooperation of several independent researchers within the same organization or, ideally, among two or more groups.

The objectives of this article are to 1) conduct a test to evaluate the suitability and effectiveness of element 3 and 4, and 2) assess a candidate for a standard spray which can be used to evaluate instrumentation and operator performance.

Background

A good example of a quality control protocol is the study conducted in 1987 by Dodge.[2] In that study, measurements

Table 1 Interlaboratory test matrix

Condition	Fuel ΔP, kPa	Fuel $\dot{m}_l$, g/s	Air ΔP, kPa	Air $\dot{m}_a$, g/s	Diagnostics Diffraction	Diagnostics PDI
1a	68.9	0.62	0.00	0.000	X	
1b			0.62	0.195	X	
1c			1.24	0.309	X	
1d			1.72	0.381	X	
1e			3.45	0.604	X	X
1f			6.89	0.890	X	
1g			10.33	1.097	X	
1h			13.78	1.288	X	
2a	172	0.91	0.00	0.000	X	
2b			0.62	0.195	X	
2c			1.24	0.309	X	
2d			1.72	0.381	X	
2e			3.45	0.604	X	
2f			6.89	0.890	X	
2g			10.33	1.097	X	
2h			13.78	1.288	X	
3a	345	1.26	0.00	0.000	X	X
3b			0.62	0.195	X	
3c			1.24	0.309	X	
3d			1.72	0.381	X	
3e			3.45	0.604	X	X
3f			6.89	0.890	X	
3g			10.33	1.097	X	
3h			13.78	1.288	X	X
4a	689	1.76	0.00	0.000	X	
4b			0.62	0.195	X	
4c			1.24	0.309	X	
4d			1.72	0.381	X	
4e			3.45	0.604	X	
4f			6.89	0.890	X	
4g			10.33	1.097	X	
4h			13.78	1.288	X	

Calibration fluid (Mil-C-7024C Type II). Note that the relationship between mass flow and pressure drop is subject to small variations depending upon the individual atomizers. Parker Hannifin provides a specification sheet with each atomizer. For other fluids (e.g., methanol), this relationship may be different. For the present study, the methanol pressure drop was 375 ± 25 kPa at 1.26 g/s.

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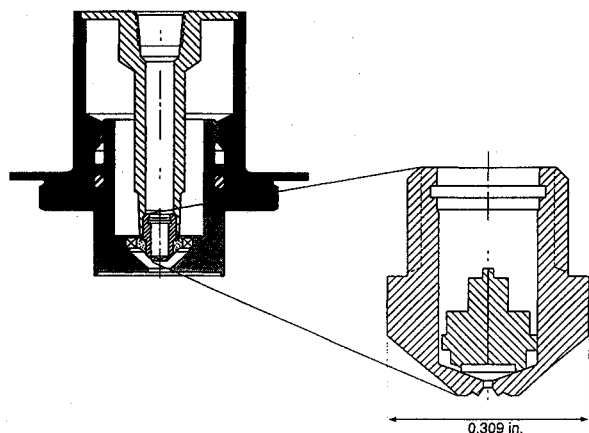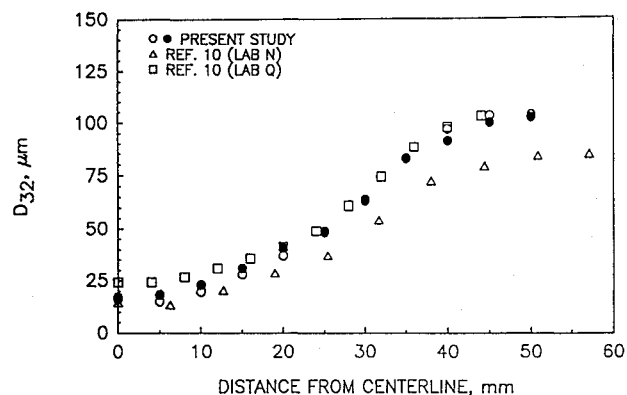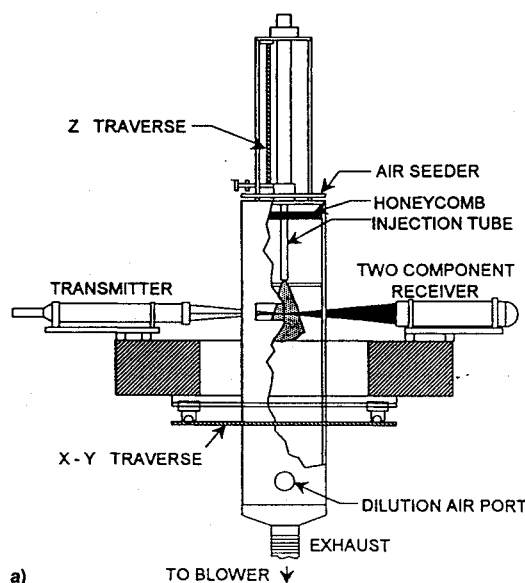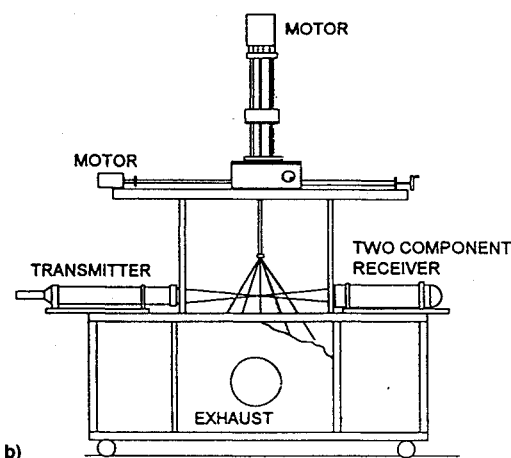

Fig. 1 Research simplex atomizer.

Fig. 2 Comparison of measurements for present study with previous study at $Z = 51$ mm.[10]

Fig. 3 Schematic of facilities utilized: a) UCICL and b) IAA.

from many instruments, including several of the same type, were compared on "round-robin" nozzles with the goal of assessing how well the radial profiles of the size distribution D_{32} compared at a single axial location. Interestingly, a wide variety of results were obtained. Some correlation between results and instrument were observed. At the time that study was carried out, few PDI instruments were available, and the overall agreement between the PDI instruments was worse than was that for calibrated[3] diffraction instruments. A primary advantage that the diffraction instruments had was a standard calibration device[4] which enabled a substantial source

of variability from the diffraction results to be removed.[5] Part of the challenge of comparing results from PDI and diffraction is that the measurement made by each technique is fundamentally different (e.g., line-of-sight vs point measurement, single particle counter vs ensemble measurement). As a result, considerable manipulations (e.g., deconvolution, changing from flux-sensitive to concentration-sensitive basis) and assumptions (e.g., axisymmetry) are imposed upon the results from each instrument to facilitate the comparison made.

Other studies were carried out which focused solely on comparison of measurements from different types of instruments.[6,7] These more focused studies revealed that, despite

general agreement between measurement devices, some inexplicable disparity still existed. From these studies and others, it became apparent that the results obtained via PDI can be quite sensitive to the operation of the instrument, and that, as a result, *interpretation* of results from different sprays and laboratories can be extremely challenging.

Hence, the value of a standard spray for evaluation of instrument and operator performance is apparent. Furthermore, to assist modeling efforts, if enough data sets are obtained on the same test article, an excellent benchmark data set will be established. The objective of the present work is to examine, in detail, the comparison of measurements ob-

Table 2 Instrument setup comparison

Parameter	UCICL	IAA
Transmitter		
Laser power (all lines)	900 mW	400 mW
CH 1		
Waist	223 μm	324 μm
Fringe spacing[a]	9.03 μm	12.20 μm
CH 2		
Waist	212 μm	307 μm
Fringe spacing	9.31 μm	12.58 μm
Receiver		
Focal length	600 mm	500 mm
Lens diameter	105 mm	105 mm
Focusing lens	238 mm	238 mm
Spatial filter	100 μm	100 μm
Collection angle	30 deg off forward	30 deg off forward

[a]For 160-mm collimator, grating track 2. Track 2 not used exclusively for all points.
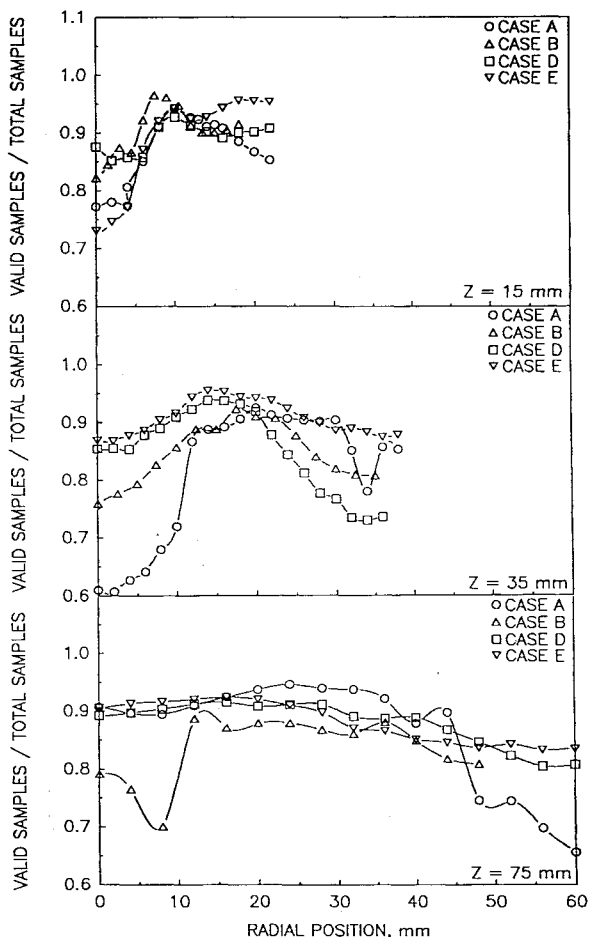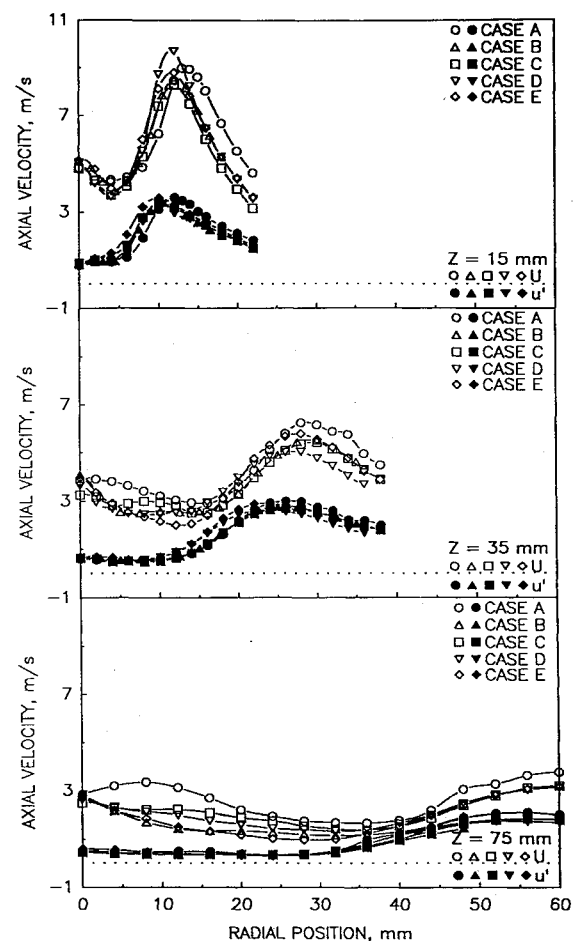

Fig. 4 Comparison of sample validation.

Fig. 5 Comparison of spray axial velocity.

tained with late generation PDPA instrumentation using a standardized research atomizer.

Approach

The approach taken is to 1) utilize the existing test facilities, instrumentation, analysis software, expertise, and protocols developed under spray programs in two independent laboratories, and 2) systematically characterize sprays from a single atomizer design following a standardized test matrix. Two injectors of the same design are characterized at each laboratory. Two-component phase Doppler interferometry (PDI) is utilized in the characterization of the sprays, and measurements are obtained at three axial locations, $Z = 15, 35$, and 75 mm. Each laboratory characterized two injectors of the same design.

Injector

Figure 1 presents the atomizer configuration utilized. Fabricated by Parker Hannifin as the Research Simplex Atomizer (RSA), the injector is designed and manufactured with the goal of producing reproducible performance. Noteworthy is that the simplex tip incorporated into the atomizer is the same as one of those utilized by Dodge[2] in his round-robin study (PH P/N 6780205).[8] Subsequent to this study, a number of investigators have participated in the development of a test matrix for the conduct of intra- and interlaboratory comparisons using the RSA. The conditions selected for the test matrix, listed in Table 1, are chosen so that they can be run without special requirements. The low flow rates and pressures should be able to be accommodated by most laboratories. Although Mil-C-7024C-Type II calibration fluid is used in most cases, it is also suggested that other fluids be considered. In the present case, methanol proved to be an attractive

Table 3 Summary of results

Radial position, mm	% Valid,[a] mean	% Valid,[a] rms	U, mean, m/s	U, rms, m/s	V,[b] mean, m/s	V,[b] rms, m/s	u', mean, m/s	u', rms, m/s	v,[b] mean, m/s	v,[b] rms, m/s	D$_{10}$, mean, μm	D$_{10}$, rms, μm	D$_{32}$, mean, μm	D$_{32}$, rms, μm	Vol flux,[a] mean, cc/cm² s	Vol flux,[a] rms, cc/cm² s	Density[a] mean, #/cc	Density[a] rms, #/cc
Mean and variation table at Z = 15 mm																		
0.0	0.800	0.063	4.985	0.168	−0.087	0.574	0.856	0.062	0.836	0.105	5.614	1.784	9.621	1.788	5.61E-04	2.46E-04	5110	2102
2.0	0.808	0.054	4.441	0.251	−0.055	0.401	0.978	0.061	0.743	0.235	5.947	1.603	9.905	1.621	7.09E-04	3.17E-04	5984	1535
4.0	0.826	0.046	3.901	0.239	0.001	0.141	1.058	0.147	0.649	0.243	7.672	1.919	12.128	1.836	1.41E-03	6.50E-04	6620	1344
6.0	0.876	0.032	4.261	0.134	0.144	0.384	1.530	0.350	0.688	0.084	10.134	2.181	16.933	2.263	3.53E-03	1.46E-03	6965	1621
8.0	0.926	0.025	5.418	0.419	0.523	1.299	2.593	0.464	1.152	0.218	16.101	3.044	27.268	3.426	1.51E-02	7.16E-03	6463	2107
10.0	0.941	0.010	7.545	0.932	3.237	0.706	3.334	0.182	2.115	0.273	27.033	4.569	43.141	4.250	7.43E-02	2.94E-02	5055	1065
12.0	0.919	0.007	8.730	0.564	5.289	0.474	3.220	0.234	2.609	0.109	38.263	4.641	58.992	4.536	1.88E-01	4.55E-02	4053	1283
14.0	0.910	0.012	8.060	0.552	6.137	0.428	2.887	0.246	2.827	0.032	44.369	2.676	64.208	8.176	1.85E-01	1.22E-01	2663	1198
16.0	0.911	0.022	6.703	0.772	5.992	0.711	2.504	0.173	2.867	0.190	45.342	3.753	61.368	8.462	7.08E-02	7.09E-02	1085	640
18.0	0.914	0.031	5.457	0.710	5.552	0.714	2.151	0.149	2.823	0.263	44.997	3.600	57.437	7.195	1.59E-02	1.72E-02	336	230
Mean and variation table at Z = 35 mm																		
0.0	0.773	0.119	3.763	0.323	−0.128	0.295	0.638	0.037	0.439	0.022	7.432	1.977	11.614	1.415	9.33E-04	3.93E-04	5028	1835
2.0	0.776	0.120	3.360	0.357	−0.080	0.279	0.610	0.059	0.421	0.063	7.881	2.321	12.160	2.026	1.11E-03	5.31E-04	5374	1308
4.0	0.786	0.113	3.017	0.456	−0.072	0.240	0.548	0.077	0.393	0.078	9.157	2.665	13.821	2.406	1.52E-03	7.60E-04	5363	1222
6.0	0.803	0.114	2.829	0.492	−0.035	0.233	0.533	0.032	0.378	0.081	10.607	3.390	15.554	2.900	2.05E-03	1.02E-03	5265	913
8.0	0.826	0.103	2.753	0.448	0.022	0.188	0.543	0.051	0.360	0.070	12.381	3.500	17.555	2.986	2.76E-03	1.18E-03	4943	628
10.0	0.850	0.091	2.675	0.416	0.099	0.161	0.584	0.081	0.354	0.059	14.440	3.706	19.848	2.904	3.72E-03	1.25E-03	4708	706
12.0	0.903	0.036	2.586	0.387	0.189	0.115	0.745	0.126	0.378	0.038	16.713	3.845	23.151	2.728	5.23E-03	1.40E-03	4692	1198
14.0	0.916	0.034	2.530	0.311	0.269	0.110	0.994	0.197	0.453	0.027	19.985	3.844	26.899	3.103	7.48E-03	2.10E-03	4276	1325
16.0	0.920	0.029	2.684	0.242	0.442	0.118	1.397	0.269	0.630	0.068	23.578	3.711	31.624	3.212	1.05E-02	3.38E-03	3654	1194
18.0	0.925	0.016	3.055	0.228	0.718	0.132	1.882	0.298	0.911	0.079	28.244	3.483	37.505	3.357	1.61E-02	4.50E-03	3253	1238
20.0	0.923	0.013	3.590	0.304	1.153	0.145	2.312	0.231	1.262	0.046	33.355	3.482	43.699	3.700	2.37E-02	6.03E-03	2658	989
22.0	0.908	0.025	4.304	0.337	1.823	0.198	2.624	0.160	1.644	0.069	38.959	3.619	50.652	4.293	3.39E-02	1.21E-02	2047	893
24.0	0.890	0.034	4.899	0.307	2.502	0.127	2.757	0.144	1.897	0.026	44.471	3.470	57.732	5.323	4.60E-02	1.84E-02	1572	638
26.0	0.871	0.045	5.331	0.363	3.137	0.119	2.761	0.164	2.075	0.040	49.714	4.074	65.486	8.545	5.78E-02	3.21E-02	1174	471
28.0	0.852	0.059	5.565	0.464	3.679	0.233	2.702	0.188	2.196	0.071	55.291	5.073	71.330	10.059	5.87E-02	3.73E-02	802	310
30.0	0.843	0.063	5.467	0.495	3.994	0.323	2.534	0.167	2.218	0.073	59.181	5.529	73.976	10.373	4.53E-02	3.09E-02	520	199
32.0	0.820	0.066	5.168	0.507	4.041	0.353	2.338	0.200	2.169	0.106	60.640	4.840	74.732	10.768	2.01E-02	1.69E-02	263	112
34.0	0.799	0.064	4.822	0.608	4.091	0.543	2.109	0.148	2.096	0.100	62.034	5.392	74.225	10.508	8.28E-03	9.63E-03	129	54
Mean and variation table at Z = 75 mm																		
0.0	0.874	0.056	2.708	0.153	−0.041	0.203	0.522	0.071	0.326	0.015	9.850	2.329	16.862	1.191	1.67E-03	4.36E-04	5218	2130
4.0	0.868	0.069	2.435	0.433	−0.016	0.196	0.472	0.078	0.313	0.036	11.378	3.522	18.755	3.747	2.05E-03	8.40E-04	4760	2066
8.0	0.853	0.103	2.254	0.652	0.011	0.224	0.439	0.047	0.305	0.046	13.320	5.062	21.387	5.765	2.52E-03	1.37E-03	4273	2151
12.0	0.907	0.015	2.054	0.685	0.016	0.207	0.426	0.058	0.264	0.067	16.283	6.463	24.533	6.081	3.09E-03	1.47E-03	3670	1981
16.0	0.906	0.026	1.848	0.573	0.035	0.185	0.403	0.063	0.239	0.076	19.693	7.314	28.082	5.585	3.75E-03	1.34E-03	3060	1583
20.0	0.911	0.024	1.646	0.411	0.057	0.136	0.358	0.023	0.217	0.065	23.453	6.757	31.591	4.751	4.46E-03	1.65E-03	2440	1028
24.0	0.912	0.027	1.494	0.371	0.085	0.118	0.327	0.025	0.195	0.051	27.703	6.702	35.439	4.751	5.32E-03	2.16E-03	2080	961
28.0	0.904	0.030	1.377	0.307	0.112	0.095	0.355	0.016	0.196	0.036	32.590	6.195	39.865	4.356	6.21E-03	2.85E-03	1736	799
32.0	0.889	0.034	1.321	0.265	0.145	0.081	0.483	0.040	0.240	0.028	37.867	5.490	45.112	3.875	7.38E-03	4.03E-03	1444	777
36.0	0.888	0.024	1.378	0.190	0.211	0.081	0.770	0.122	0.367	0.027	43.765	4.919	51.207	3.872	8.12E-03	4.15E-03	1066	553
40.0	0.866	0.020	1.572	0.175	0.363	0.075	1.066	0.128	0.560	0.040	50.317	3.917	57.425	3.702	9.56E-03	4.85E-03	835	470
44.0	0.857	0.034	1.929	0.231	0.641	0.102	1.386	0.122	0.794	0.055	56.783	3.404	64.495	3.543	1.14E-02	5.70E-03	641	386
48.0	0.809	0.045	2.460	0.397	1.096	0.236	1.664	0.151	1.051	0.087	64.574	3.560	74.661	7.281	1.38E-02	7.03E-03	398	217

[a]Does not include CASE C.   [b]Does not include CASE E.

candidate since it was available at both laboratories at low cost.

Although the results of Dodge[2] were available at the time of the current tests, they were not provided to the instrument operators at either facility at the time of the tests, thus removing bias from the setup. For the current study, one condition (3a) from Table 1 was selected for detailed comparison, and PDI results from one of the two injectors are presented. Additional results and comparisons are available elsewhere.[9]

To provide continuity to the PDI results (flux sensitive) from the program conducted by Dodge, Fig. 2 presents results obtained on the current test article at the same axial location and operating conditions [Calibration Fluid run at a ΔP of 345 kPa (1.26 g/s)]. The results obtained are quite similar to those obtained at Lab Q, and tend to fall between the results obtained at the two labs considered.[10] Considering the advances made in the instruments used in the present study, these results reflect the consistency in measurements from even early PDPA systems.

Test Facilities

The test facilities used are presented schematically in Fig. 3. Basically, the spray is injected downwards, and has modest coflowing air surrounding it (less than 1.0 m/s). In each case, an Aerometrics two-component PDPA system is utilized. Both PDI systems are similar in setup and optical configurations, although subtle differences are present which, though not extraordinary, may play a role in any differences observed in measurements. Details are provided in Table 2. Although provided for in the software settings in the systems used, the automatic high voltage and associated intensity validation features were not used for these tests. This decision was made due to some unreliable behavior observed with the second component settings and the apparent immaturity of the algorithm utilized for setting voltages at the time of these tests.

Results

Results from five sets of data are included, and are labeled as CASES A – E. In each case, condition 3a was used as indicated in Table 1. CASES A and B were obtained in one lab and CASES C – E were obtained in the other. These data sets were obtained between Nov. 1989 (CASE A) and February 1992 (CASE B). CASES D and E were obtained within the same two-week period by the same operator. CASE C was obtained approximately 6 months prior to CASES D and E. CASES A – C were obtained by different operators than D and E. For some results, not all five cases are compared. This occurs for the following reasons: 1) CASE E: measured U and W, hence V is not available; and 2) CASE C: software bug invalidated flux, number density, and validation.
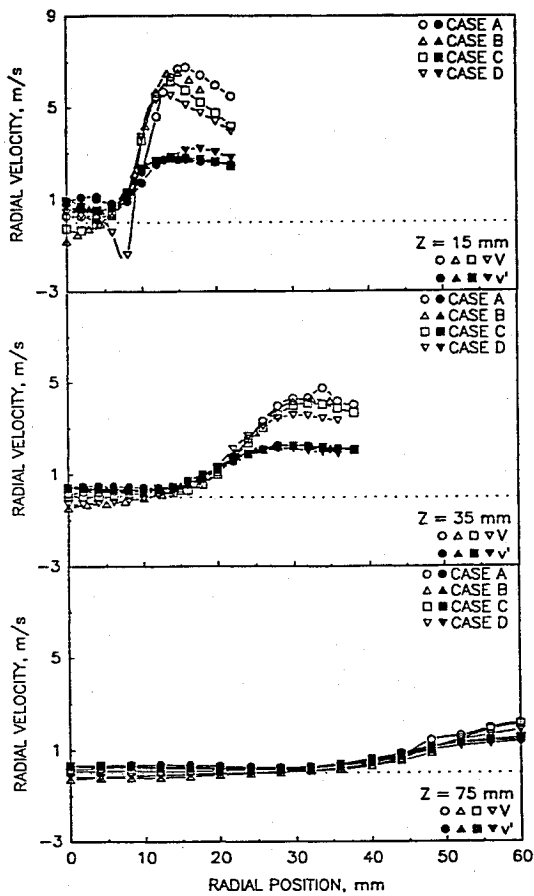
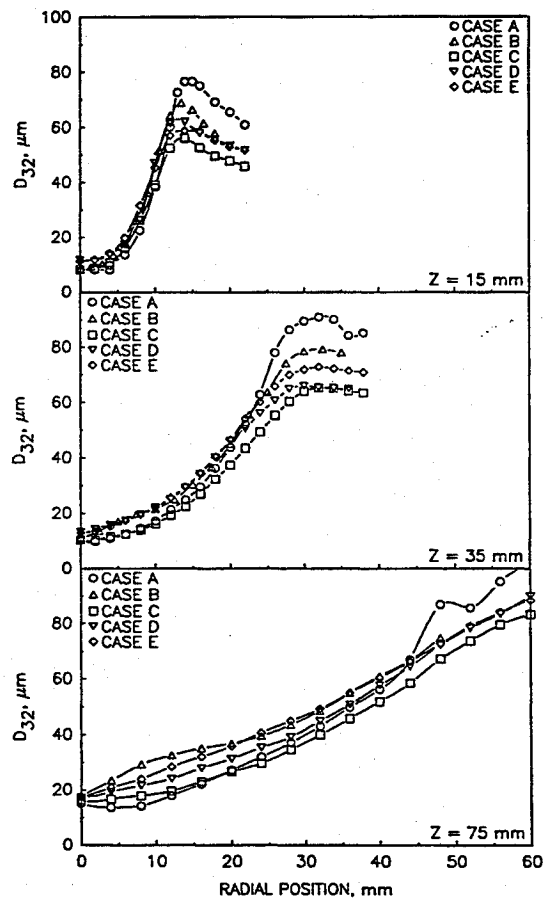Fig. 6   Comparison of spray radial velocity.

Fig. 8   Comparison of size distribution D_{32}.

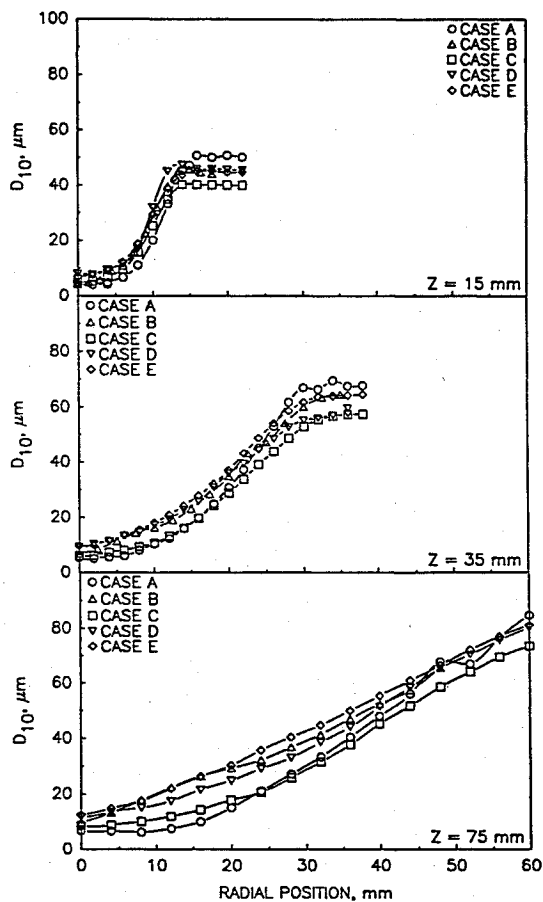Fig. 7   Comparison of size distribution D_{10}.
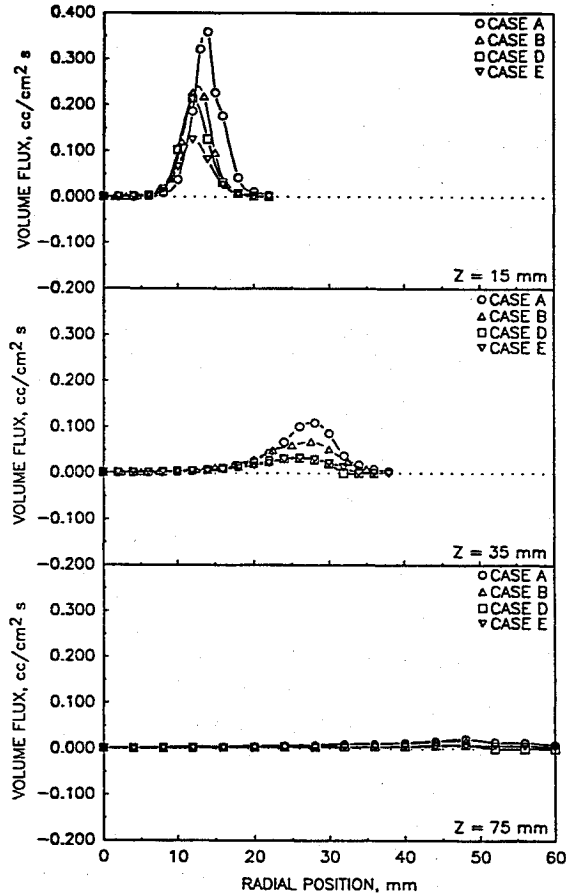

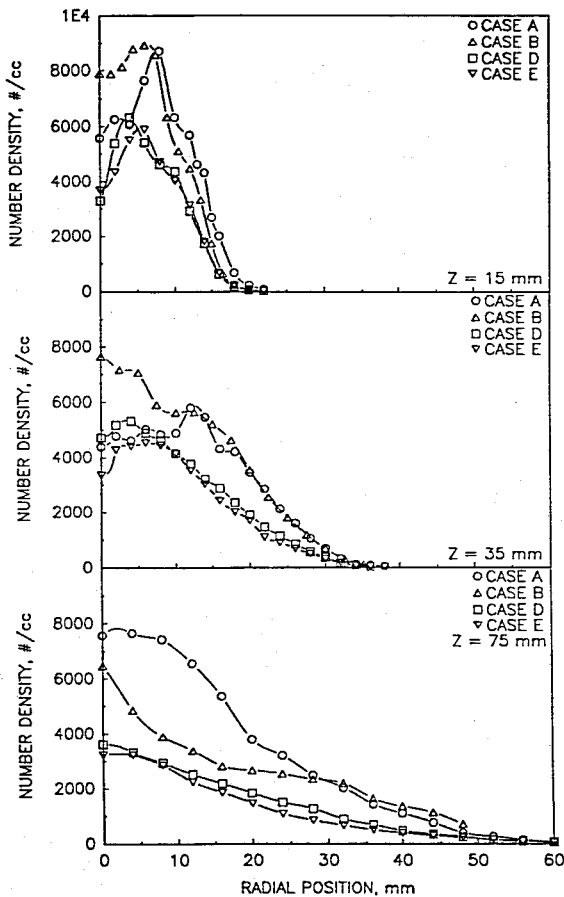Fig. 9   Comparison of volume flux.

Fig. 10   Comparison of number density.

In each comparison, at least one result from each lab is included. The comparisons presented are broken down into 1) distribution means and 2) cross correlations. Noteworthy is that CASES B and D were taken with the atomizer in the same orientation with respect to the diagnostic so that the same physical part of the spray was characterized. Also note that CASES D and E were obtained during a relatively short time period and provide information along two orthogonal profiles in the same spray. As a result, comparison of CASES D and E provides an indication of the symmetry of the spray.

Distribution Means

Figures 4 – 10 present the individual distribution means for the spray for each case at the three axial locations. Table 3 summarizes the mean and standard deviation of the measurements made at each point. In one of the cases (B), measurements were not obtained at the same radial locations as the other cases. As a result, linear interpolation was used to determine the value at the specified radial location. Since the points were obtained at closely spaced increments, this will not incur any significant error.

Figure 4 presents the comparison of the percentage of valid samples for each case. This is determined from the ratio of the valid samples to the number of droplets detected. Many reasons for invalidation exist such as 1) measured drop size out of selected range; 2) measured drop velocity (either component) out of selected range; 3) noncoincident signals for channels 1 and 2; 4) measured phase shift between two sets of detectors inconsistent (multiple drops, noisy signal); and 5) overflow in fringe count register (multiple drops, more than 256 fringe crossings detected).

All five cases show similar trends, namely poorest validation at the center and edge of the spray. The highest validation occurs somewhere between these two regions, and is not correlated to any particular spray feature (e.g., region of highest velocity, lowest concentration, etc.). The variability in the

validation is modest, and the most extreme variability occurs for CASE A at $Z = 35$ mm, and CASE B at $Z = 75$ mm. In general, the validation is greater than 75% at most locations. The comparison of CASES D and E reveal only small differences which reflects the symmetry and similar operator protocol used. CASES D and B, being obtained from the same physical locations in the spray by two operators reveal fairly significant variation, suggesting that user protocol rather than symmetry is primarily responsible for the variability shown.

Figure 5 presents the comparison of the spray mean and fluctuating axial velocity profiles for all five cases. Near the centerline, little variation is observed. Case A reveals the greatest variation, and shows, in particular, greater values of both mean and fluctuating velocities at the edge of the spray. In general, the agreement in the fluctuating values are better than for the mean values. Note that the *shape* of the profile for CASE A exhibits behavior which is different from the rest of the cases. This is especially evident at $Z = 75$ mm. This may be attributed to a mismatch between the geometric and aerodynamic centerline in this case. The comparison of CASES D and E and CASES B and D reveal no especially small variation, indicating that both symmetry and user protocol are important for the velocity measured.

Figure 6 presents the comparison of the spray mean and fluctuating radial velocities. In this case, no one case appears to be highly different from the others in a consistent fashion. CASE D appears to have some outliers in the region of $r = 10$ mm, but overall, the variation between the cases shown is small, especially compared to the axial velocity. Comparison of CASES B and D indicate that no significant improvement in the variation is reached by measuring within the same physical location of the spray.

In the comparison of the spray velocity distribution means, several points need to be raised. The PDI instruments used account for variation of the sample volume with drop size. As a result, the droplet size distribution is "corrected." However, the velocity distributions are not corrected. Hence, in a spray where significant dependency between size and velocity exist (such as the current one), the size range sampled dictates the velocity. If more small drops are sampled (e.g., higher photo multiplier tube gain), the velocity statistics will reflect this. Since it is impractical (and unrealistic) to maintain identical instrument settings between all cases, the results shown reflect this type of variability. Note that both mean and fluctuating quantities are affected by this. As a result, a more "fair" comparison of velocity is presented in the next section. Considering the potential impact this effect can have, the comparison of velocity is remarkably good.

Figure 7 presents the comparison of the distribution D_{10}. In this case, the distribution mean is based upon the corrected distribution which accounts for dependency of the sample volume and drop size. Again, all five cases show similar trends at each of the axial locations considered. The greatest variability appears at the edge of the spray. Comparison of CASES B, D, and E indicates that some reduction in variability is realized by using the same user protocol and sampling in the same region of the spray.

Figure 8 presents the comparison of the distribution D_{32}. Similar trends are observed as for D_{10}. Again, CASES B, D, and E show slightly less variability when compared to all five cases. Noteworthy is that the general variability in D_{32} is no more extreme than that in D_{10}. However, the *largest* variability occurs in D_{32} rather than in D_{10}. This is due to the high sensitivity of D_{32} to few numbers of large drops. Hence, if one user sets the maximum size limit to a significantly larger value than another, and detects one or two exceptionally large drops, D_{32} can be greatly affected. Whether these drops are "real" or are a manifestation of the instruments ability to discern between reflected and refracted light for certain particle trajectories and sizes is subject of considerable debate. Armed with cross correlations, it is sometimes possible to deduce if these drops are real. For example, if small drops
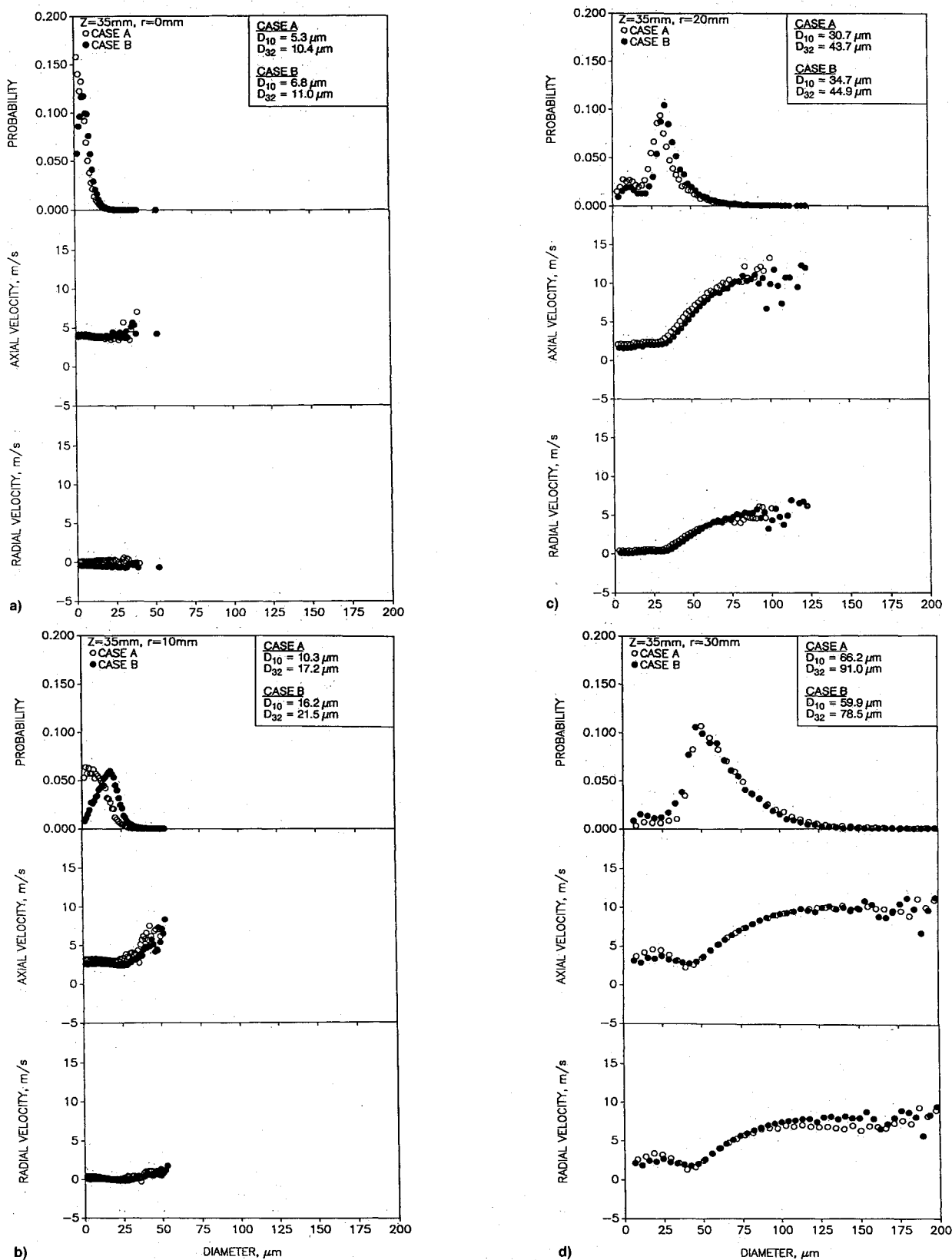
Fig. 11   Comparison of corrected size distribution and size-velocity correlations, $Z = 35$ m: a) $r = 0$ m, b) $r = 10$ mm, c) $r = 20$ mm, and d) $r = 30$ mm.

have a low velocity and large drops a high velocity, and an exceptionally large drop shows a low velocity, chances are it might be a signal from reflected light rather than refracted light and should be rejected. It is noteworthy that the intensity validation feature not used in the present comparison was developed specifically to provide a basis for rejection of such drops and could lead to lower variation.

Figure 9 presents the comparison of the volume flux. In this case, the trends are quite similar for the four cases considered. However, CASE A shows significantly more flux than the other three cases. CASES B and D reveal similar results at $Z = 15$ mm, but the differences are greater at $Z = 35$ mm. The degree to which symmetry is responsible for the large values of CASE A is not known. However, the drop

sizes measured for CASE A are greater, suggesting that this is the reason for the greater flux.

Figure 10 presents the comparison of the spray number density. Here, extremely large variation exists (approaching 50%). Furthermore, no systematic trend is apparent other than that the effect of user protocol seems large (CASES B, D, and E). Obviously, the number density is very sensitive to instrument operation. This is not surprising given that the formulation used requires accurate determination of 1) the total number of drops sampled per unit time, 2) the drop size, 3) the drop velocity, and 4) the correlation between drop size and sample cross section. Given the combination of errors associated with each of these measurements, a large variance may be expected. As an example, if 80% of the drops detected are validated, the number density determination will be at least 20% too low. If the sample area determined varies by 20%, this will lead to a 20% variation in measured number density.

Cross Correlations

Figure 11 presents a direct comparison of the size distribution and cross correlations between size and the axial and radial velocity components from two of the CASES at four radial locations at $Z = 35$ mm. Additional comparisons are provided in Reference 9. In each part of Fig. 11, the top portion presents the probability distribution function of drop size which accounts for variation in bin width and total sample number between the two cases. Note that the corrected size distribution is presented which accounts for variation in sample volume as a function of drop size. The middle portion provides the mean axial velocity for each drop size. The lower portion presents the mean radial velocity for each drop size.

At $r = 0$ mm (Fig. 11a), the size distributions appear different for CASES A and B. Case B shows a local maximum, whereas CASE A shows a monotonic increase in population with a decrease in size. However, despite the variation in size distribution, the variation between the velocity measurements for a given drop size is small.

Figure 11b presents the comparison at $r = 10$ mm. At this location, the corrected size distributions are quite different. Case A shows significantly more small drops. However, once again, the velocities measured for a given drop size are very similar. Case A reveals modestly higher axial velocities for the larger drops sizes.

Figure 11c presents the comparison at $r = 20$ mm. In this case, the corrected size distributions reveal identical characteristics, including a modest bimodal feature. The trends in the drop velocities are also identical, although CASE A reveals values which are systematically slightly higher than CASE B.

Figure 11d presents the comparison at $r = 30$ mm. At this location, which corresponds to the location of most large drops, the comparison is outstanding. Despite the remarkably good comparison of individual drop measurements, the distributions means are considerably different. This is due to slightly more larger drops detected for CASE A (which are not readily observed in the pdf of drop size).

Conclusions

Some conclusions drawn from the study are as follows:

1) Based on extent of reproducibility, the current spray makes an excellent standard spray. The validation is reasonably high, and tests conducted over a period of time greater than 2 yr in duration reveal similar results.

2) Statistics based solely on the number of drops show the least variability (e.g., mean velocities, rms velocities, D_{10}).

3) Statistics based upon drop volume and/or sample area show the greatest variability (e.g., D_{32}, volume flux, number density).

4) Large variation in D_{32} is not a good indicator of general disparity in two measurements.

5) Since size and velocity moments are determined on different samples (one from corrected counts, one from uncorrected counts), comparison of variability between the two is biased. Variation in velocity is more likely to be impacted by instrument operation since no correction for correlation of sample volume size and drop size is made in the velocity calculation.

6) Comparison on the basis of individual drop sizes is a better gauge of variability than is comparison of statistics generated based on the entire spray.

7) The variation observed could possibly be reduced with the use of relatively new features such as intensity validation which were not incorporated in the present study. However, the present effort represents an important benchmark for data sets obtained with or without such features.

Acknowledgments

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