Establishing reference nozzles for classification of aerial application spray technologies

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Abstract: Measurement of droplet size from agricultural spray nozzles can be highly variable and heavily influenced by measurement systems, methods and physical difference in measurement facilities. Past efforts have developed a series of nozzles and operational pressure pairings that are used to define relative droplet size classes across the wide range of sizes typical in agrochemical applications. Until recently, the developed classification standards were only application non-aerial spray technologies, as the paired nozzle and pressures used did not account for the secondary breakup resulting from high airspeed typical to agricultural aircraft. A new standard has addressed this issue, with dedicated nozzle/spray pressure pairs designed to generate similar classification boundaries to current standards while operating in high airspeed conditions. To support the application of this standard, multiple sets of dedicated droplet size matched nozzles were developed.

Keywords: Agricultural application, application technology, droplet size, size classification

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1 Introduction

Spray droplet size is recognized as one of the primary factors influence the movement and ultimate fate of applied agrochemical sprays making the ability to measure it critical to understanding the role spray system components (nozzle and solution type) as well as operational conditions (airspeed and spray pressure) play in the atomization process. This understanding allows developing tools that applicators can use when selecting and setting up their spray system. While the measurement and reporting of spray droplet size is conceptually a simple and straightforward process, there is significant potential for varying, and even conflicting, data being reported with numerous laboratories and facilities around the world conducting this type of work and having different measurement systems and methods. Differences in instrumentation and measurement protocols can significantly influence the absolute numerical results reported[1-3]. While a number of standard methods and procedures were developed to standardize these processes to reduce these potential measurement differences, the reality is that different facilities will tend to produce varying results, at least to some degree[4,5].

To address these differences in numerical results between locations, the British Crop Protection Council (BCPC) proposed a system to classify sprays into relative categories of spray quality based on comparison of the numerical data of a candidate spray to that of data from a series of standardized reference nozzles selected to span to wide range of potential spray sizes[6,7]. More recently, the American Society of Agricultural and Biological Engineers (ASABE) adopted the BCPC system and developed it into the ASABE Standard 572.1[8], which is currently being adapted and developed in an International Standards Organization (ISO) standard. These standards were developed for, and intended to be used in, the measurement and classification of all agricultural sprays, with the simple premise that as a nozzle or sprayer of interest is being evaluated for droplet size, the series of reference nozzles are evaluated under the same measurement protocols, with the resulting data reflecting any potential sampling biases and the size classification determined repeatable amongst differing locations. These standards, however, are not applicable to aerial application conditions as the high-speed air results in secondary breakup of the spray resulting in non-sensical reference data. To address the need for a similar system in evaluating aerial sprays, a series of nozzles and pressures were evaluated under high airspeed conditions that returned similar reference curves to the existing standards[9]. Based on these nozzles and operational settings, ASABE Standard S641[10] was developed for use in aerial application droplet size classification efforts

The reference nozzle sets specified by these standards require that new nozzles are flow-rated to tight tolerances to ensure compliance with their designed output characteristics as a means of ensuring that sets of reference nozzles sourced by different groups result in the same atomized sprays. To evaluate the validity of this approach, a number of new nozzles (ranged from 14-49) of each type specified by ASABE S572 were both flowrated and atomization tested[11]. While the results showed little variation in flowrate within each nozzle type, the difference in means for $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$ ranged from 5% to 18%. Womac[11] concluded that maintaining a high tolerance in flowrate within "identical" nozzle types did not guarantee the same droplet size was produced and therefore the use of dedicated sets of droplet-size matched reference nozzles is preferred over precise tolerance flow-rated matched sets. It should be noted that from the groups of nozzles tested, five droplet-sized matched dedicated reference nozzle sets were identified with the resulting droplet sizes typically representing the mean values within the full set of nozzles within each nozzle type.

With a growing number of locations initiating aerial application

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spray nozzle testing, a similar effort to develop dedicated reference nozzles sets based on ASABE S641[10] specified boundaries is needed. The objective of this work was to develop a number droplet-size matched, dedicated aerial reference nozzle sets that can be used in day to day evaluations and multiple laboratory comparisons.

2 Materials and methods

All droplet size evaluations for this work were conducted at the Pesticide Application Technology Laboratory, which is part of the University of Nebraska – Lincoln, located in North Platte, Nebraska. Established methods for measuring the spray characteristics were used and are briefly discussed below.

2.1 Nozzles tested

Nozzles tested were those defined by ASABE S641 as the thresholds between each droplet size class (DSC) (Table 1). Within each of these nozzle type, 24 new nozzles were obtained. All nozzles were TeeJet® standard flat fan tips in stainless steel (Spraying Systems, Springfield, IL, USA). Based on the work by Womac[11] and previous unpublished work by the authors similar to Womac's, nozzle sets were not screened for flowrate prior to droplet sizing evaluations.

Table 1 Overall mean droplet size data across all nozzles within each nozzle type. Data is presented for current data as well as previous Round Robin test at three locations

Classification Category Threshold	Nozzle spray angle/(°)	Orifice size*	Reference operating pressure/kPa
Very Fine to Fine (VF/F)	110	01	450
Fine to Medium (F/M)	80	03	550
Medium to Coarse (M/C)	80	05	300
Coarse to Very Coarse (C/VC)	65	15	400
Very Coarse to Extra Coarse (VC/XC)	40	15	280
Extra Coarse to Ultra Coarse (XC/UC)	25	08	276

Note: *Orifice size is typically defined by a nominal flow rate at a standard pressure. For nozzles specified by S641, the orifice size is defined at the flow rate in gallons per minute at 40 psi. Therefore, a 01 orifice size corresponds to 1 gallon per minute at 40 psi.

2.2 Droplet sizing

Droplet sizing evaluations were conducted by position the spray nozzles at the outlet section of a high-speed wind tunnel designed to produced airspeed consistent to those representative of aerial application conditions. A detailed description of the test facility and test method is reported by Fritz and Hoffmann[12]. Summarized briefly, a laser diffraction system (Sympatec HELOS, Clausthal-Zellerfeld, Germany) setup with an effective measurement range of 18-3500 µm (Manufacturer denoted R7 lens) was position 45.7 cm downstream of the nozzle outlet. As specified by ASABE S641, all nozzles were tested with water only in an airstream of 51.4 m/s. Spray pressures used for each nozzle type were as specified by the standard (Table 1). Each measurement replication consisted of the spray plume from the nozzle being traversed completely through the measurement zone (traverse rate 6.4 cm/s) with sufficient replications conducted that the standard deviations in $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$ were within 10% of the means.

2.3 Analysis of results

All data analysis was conducted using JMP (Version 13.0, SAS Institute., 2015). Means separation among individual nozzles within each type was done using the Tukey-Kramer HSD method at the Alpha = 0.05 level.

3 Results and discussion

As an initial analysis of the data, means and standard deviations across all individual nozzles within each nozzle type were calculated. In addition to the $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$ data, the percent volume of the total spray contained in droplets of 100 µm or smaller was also included for comparison to previous data (Table 1, labeled as 2018 UNE). As part of a previous round-robin testing efforts made, a droplet size verified set of aerial reference nozzles were evaluated at three aerial spray nozzle testing facilities following the same measurement methods[5]. The three labs involved (denoted in Table 2 as UNE – University of Nebrasksa-Lincoln; ARS – USDA ARS Aerial Application Technology Research Unit; and GAT – University of Queensland, Gatton) each evaluated the same dedicated reference nozzle set in 2013, with the resulting numerical data being very similar (Table 2, labeled as 2013 ARS, 2013 GAT and 2013 UNE). It should be noted that the UNE tunnel involved in the 2013 round robin testing is the same facility at which the current study was conducted. Since the 2013 testing occurred, the UNE facility had an inline spray particulate scrubber installed which results in recirculation of finer spray droplets through the measurement zone. The results of this can be observed in the more recent data set with reduced overall droplet sizes measured, particularly for the coarser spray nozzles (note that the XC/UC category corresponding to the 2508 nozzle was added after the 2013 study). While this potentially has implications in other studies, the data reported still allows for the objective of this work to be completed as measurement biases are the same for each nozzle evaluated allowing for droplet size matched sets to be determined.

Table 2 Overall mean droplet size data across all nozzles within each nozzle type. Data is presented for current data as well as previous Round Robin test at three locations

	Nozzle	DV0.1	DV0.5	DV0.9	%Vol<100 µm
2018 UNE	11001	68.5±2.4	154.7±3.7	249.7±6.8	22.1±1.2
	8003	125.2±1.9	262.3±4.3	427.1±14.3	5.7±0.3
	8005	177.1±3.2	347.5±4.5	518.5±16.8	2.2±0.3
	6515	174.5±7	422.4±10.3	672.9±31.5	3.6±0.6
	4015	192.9±14.5	426.5±9.7	648.1±15.9	2.4±1
	2508	265±4.6	492.5±6.9	679.5±7.9	0.7±0.1
2013 ARS	11001	67.3±0.6	150.4±1.6	244.6±0.1	23.0±0.55
	8003	128.6±0.7	268.7±1.7	460.2±6.6	5.4±0.09
	8005	167.3±2.7	342.0±4.3	574.3±13.8	2.8±0.14
	6015	197.8±5.1	441.2±2.8	754.5±3.8	2.0±0.10
	4015	217.7±1.1	472.5±1.9	802.2±8.8	1.6±0.03
2013 GAT	11001	69.0±1.5	149.9±1.5	243.0±3.8	22.6±0.8
	8003	129.4±1.6	267.9±1.3	447.2±2.0	5.1±0.2
	8005	163.5±0.7	333.1±0.4	541.2±7.1	2.8±0.05
	6015	212.5±2.4	460.0±3.4	788.7±14.1	1.6±0.08
	4015	233.8±1.3	503.3±34.0	810.6±18.0	1.1±0.03
2013 UNE	11001	66.9±0.9	148.9±0.9	243±0.6	23.5±0.5
	8003	120.3±1.0	256±1.5	426±1.8	6.5±0.2
	8005	161.2±0.8	339.1±1.0	546.2±1.8	3.2±0.1
	6015	210.2±1.5	466.1±1.0	778.4±3.1	1.9±0.1
	4015	242.6±2.6	519.4±3.5	846.6±6.3	1.2±0.1

To compare the variations in droplet size seen amongst nozzles of the same type, the spread value, as reported[10], was determined (maximum value minus minimum value divided by the mean) (Table 3). The observed spread values were very similar, ranging from 4% up to 30%, though all but the DV0.1 spread data for the 4015 were less than 15%, matching the 5%-18% reported by Womac[10].

Table 3 Maximum, minimum droplet size data observed across the nozzles within each nozzle type. Spread is calculated as (Max. – Min.)/Mean

		Nozzle Type					
		11001	8003	8005	6515	4015	2508
DV0.1	Min. (μm)	64.3	122.6	170.6	163.3	153.8	258.6
	Max. (μm)	74.3	128.3	180.7	188.1	211.5	275.7
	Mean (μm)	68.5	125.2	177.0	174.5	192.9	265.0
	Spread (%)	14.6	4.6	5.8	14.3	30.0	6.5
DV0.5	Min. (μm)	149.0	257.1	339.4	400.5	399.6	483.6
	Max. (μm)	162.8	274.9	354.7	443.8	452.3	507.1
	Mean (μm)	154.6	262.2	347.4	422.3	426.4	492.5
	Spread (%)	9.0	6.9	4.4	10.3	12.4	4.8
DV0.9	Min. (μm)	238.4	406.1	491.7	598.6	621.5	667.9
	Max. (μm)	261.1	462.9	551.7	707.9	694.9	695.0
	Mean (μm)	249.7	427.1	518.5	672.9	648.1	679.4
	Spread (%)	9.1	13.4	11.6	16.3	11.4	4.0

The means and means difference testing results showed significant variation, and thus significant difference between the in DV0.1, DV0.5 and DV0.9 data across the individual nozzles within each nozzle type (Table 4-9). Generally, the data falls as would be expected, based on previous works, and for most nozzle types, the mean falls near the median of the data. There are a few exceptions, most notable the 4015, for which the mean $D_{V0.1}$ and $D_{V0.9}$ values fall to opposite sides of the median. Looking at the numerical data for this nozzle shows spread values that are near the maximum seen across nozzle sets, which results from two nozzles in particular (numbers 21 and 22) that are obvious outliers, with significantly smaller droplet sizes than the remaining nozzles. The 6515 mean data show similar trends, though not to the extent seen in the 4015 data.

In selecting nozzle to fill the dedicated droplet-size matched sets, the desire was to select nozzles whose droplet size data fell near the means of the overall average, which was generally successful (See bolded values in Tables 4-9). The nozzle designation referred to as Number was an arbitrary designation given to each nozzle. As only the $D_{V0.1}$ and $D_{V0.5}$ are used in the classification process, $D_{V0.9}$ values were considered in the selection process, but closer matches in the $D_{V0.1}$ and $D_{V0.5}$ values outweighed variances seen in the $D_{V0.9}$ values. The standard also specifies that the reference curves used in the classification process is set by the mean $D_{V0.1}$ and mean $D_{V0.5}$, each with one standard deviation added. As this variance within each individual nozzle is part of the classification process, summary tables of selected matched nozzles set for each nozzle type are given in Tables 10-15. Generally, standards deviations were very low (<1%-2% of the mean), though a few of the 6515 tips showed standard deviations near 3% of the mean, which were almost certainly measurement induced and not a result of the nozzle.

Table 4 Mean data with means separation for 11001. Means within each column followed by the same letter are not significantly different (alpha=0.05). The two nozzles on either side of the underlined data within each column bracket the mean across all nozzles of this type. Nozzle numbers in bold font are those selected for the droplet-size matched dedicated sets

Number	DV0.1		Number	DV0.5		Number	DV0.9	
5	74.3	a	5	162.8	a	17	261.1	a
7	72.1	ab	7	160.0	ab	24	260.9	a
13	70.9	bc	17	159.8	abc	5	259.7	a
3	**70.3**	**bcd**	13	159.0	bcd	7	258.7	ab
12	70.3	bcde	12	157.9	bcde	13	254.2	abc
17	70.0	bcdef	**20**	**157.2**	**bcdef**	**20**	**254.1**	**abc**
10	**69.3**	**bcdefg**	**10**	**157.0**	**cdef**	**10**	**252.7**	**abcd**
6	69.0	bcdefg	24	156.4	defg	**23**	**252.7**	**abcd**
4	69.0	bcdefg	**3**	**155.7**	**efgh**	12	252.5	abcd
8	68.7	cdefg	**23**	**155.6**	**efghi**	22	250.8	abcd
1	68.7	cdefg	**16**	**155.2**	**efghi**	19	248.6	bcde
11	**68.4**	**cdefgh**	22	155.0	efghi	14	248.2	bcde
9	68.2	cdefgh	**11**	**154.4**	**fghij**	**11**	**248.1**	**bcde**
16	**68.2**	**cdefgh**	19	153.9	ghijk	21	247.7	cde
2	68.0	cdefgh	18	153.1	hijkl	**3**	**247.5**	**cde**
20	**67.7**	**cdefgh**	14	152.7	ijkl	**16**	**247.1**	**cde**
15	67.1	defghi	15	151.6	jklm	18	246.9	cde
22	67.0	defghi	8	151.5	jklm	15	246.0	cde
23	**67.0**	**efghi**	9	151.1	klm	8	244.8	cde
14	66.8	fghi	4	151.0	klm	9	244.0	cde
24	66.6	ghi	21	151.0	klm	6	243.5	cde
19	66.5	ghi	6	150.7	lm	2	242.1	de
21	65.2	hi	2	149.6	m	4	242.1	de
18	64.3	i	1	149.0	m	1	238.4	e

Table 5 Mean data with means separation for 8003. Means within each column followed by the same letter are not significantly different (alpha=0.05). The two nozzles on either side of the underlined data within each column bracket the mean across all nozzles of this type. Nozzle numbers in bold font are those selected for the droplet-size matched dedicated sets

Number	DV0.1		Number	DV0.5		Number	DV0.9	
23	128.3	a	23	274.9	a	23	462.9	a
10	127.2	ab	4	267.2	b	21	441.6	ab
24	127.0	abc	10	266.5	bc	24	441.4	ab
18	126.9	abcd	24	266.0	bcd	15	440.6	ab
4	126.9	abcd	8	265.4	bcd	20	436.6	bc
5	**126.9**	**abcd**	18	265.1	bcd	18	434.6	bc
8	126.8	abcd	15	264.8	bcd	17	433.7	bc
16	126.2	abcde	21	263.9	bcd	1	432.2	bcd
21	125.8	abcdef	16	263.6	bcde	4	430.9	bcde
17	125.6	abcdef	17	263.4	cdef	10	430.0	bcde
13	**125.5**	**abcdef**	**5**	**263.2**	**cdef**	**11**	**429.5**	**bcde**
15	125.5	abcdef	**13**	**262.5**	**defg**	16	427.1	bcde
6	125.2	abcdef	**11**	**260.2**	**efgh**	**13**	**426.5**	**bcde**
3	**125.0**	**abcdef**	**19**	**260.2**	**efgh**	**22**	**425.5**	**bcde**
9	124.3	bcdef	**3**	**260.0**	**fgh**	8	424.9	bcde
11	**124.1**	**bcdef**	1	259.5	gh	**19**	**421.0**	**bcde**
22	**123.9**	**bcdef**	**22**	**259.4**	**gh**	12	418.3	bcde
19	**123.7**	**cdef**	9	259.2	gh	9	417.6	bcde
14	123.7	cdef	12	259.1	gh	**5**	**416.9**	**bcde**
7	123.6	def	20	258.8	h	14	416.4	bcde
12	123.6	def	6	258.2	h	2	414.2	cde
2	123.2	ef	14	257.7	h	**3**	**413.8**	**cde**
20	122.7	f	2	257.3	h	6	407.2	de
1	122.6	f	7	257.1	h	7	406.1	e

Table 6 Mean data with means separation for 8005. Means within each column followed by the same letter are not significantly different (alpha=0.05). The two nozzles on either side of the underlined data within each column bracket the mean across all nozzles of this type. Nozzle numbers in bold font are those selected for the droplet-size matched dedicated sets

Number	DV0.1		Number	DV0.5		Number	DV0.9	
13	180.7	a	1	354.7	a	1	551.7	a
6	180.2	ab	14	351.7	ab	15	534.7	ab
14	180.0	ab	10	351.0	abc	10	534.1	ab
2	179.7	ab	15	351.0	abc	18	532.5	abc
15	179.4	ab	18	350.6	abc	14	532.1	abc
1	179.3	ab	13	350.6	abc	20	530.5	abc
18	179.2	ab	16	350.2	abc	13	528.4	abcd
10	179.0	ab	19	350.0	abc	21	528.0	abcd
12	178.4	abc	6	349.9	abc	12	525.7	abcd
11	**178.3**	**abc**	2	349.7	abc	2	524.0	bcde
16	177.7	abc	21	349.6	abc	16	522.7	bcde
19	177.7	abc	20	349.3	abc	**11**	**522.6**	**bcde**
9	**177.4**	**abc**	12	349.0	abc	6	522.2	bcde
20	177.2	abcd	**11**	**348.8**	**abc**	19	520.3	bcdef
21	177.1	abcd	**9**	**347.5**	**bcd**	**9**	**516.1**	**bcdefg**
4	**176.7**	**abcd**	**7**	**346.1**	**bcde**	**7**	**514.5**	**bcdefg**
7	**176.6**	**abcd**	**17**	**345.4**	**bcde**	**5**	**513.8**	**bcdefg**
17	**175.9**	**abcde**	**5**	**345.0**	**bcde**	**17**	**506.8**	**cdefg**
5	**175.7**	**abcde**	**4**	**344.4**	**cde**	**4**	**502.8**	**defg**
3	174.8	bcde	3	341.4	de	22	498.5	efg
8	172.9	cde	23	341.4	de	3	498.1	efg
23	171.8	de	8	341.0	de	8	497.5	efg
22	171.6	de	22	340.4	e	23	493.9	fg
24	170.6	e	24	339.4	e	24	491.7	g

Table 7 Mean data with means separation for 6515. Means within each column followed by the same letter are not significantly different (alpha=0.05). The two nozzles on either side of the underlined data within each column bracket the mean across all nozzles of this type. Nozzle numbers in bold font are those selected for the droplet-size matched dedicated sets

Number	DV0.1		Number	DV0.5		Number	DV0.9	
2	188.1	a	21	443.8	a	21	707.9	a
1	186.1	ab	17	430.1	b	19	698.4	ab
3	184.5	abc	19	429.9	b	23	697.3	ab
4	183.7	abc	23	429.6	b	24	696.8	ab
21	183.5	abc	24	429.4	b	**16**	**695.9**	**ab**
8	176.6	bcd	**9**	**429.4**	**b**	**20**	**695.9**	**ab**
17	176.3	cd	8	429.2	b	17	695.6	ab
22	**176.0**	**cd**	**13**	**428.7**	**b**	**13**	**694.3**	**abc**
9	**175.5**	**cd**	**16**	**428.4**	**bc**	**9**	**693.7**	**abcd**
13	**175.2**	**cd**	**20**	**428.3**	**bc**	8	692.7	abcde
7	**175.1**	**cd**	**22**	**427.1**	**bc**	**22**	**691.4**	**bcde**
11	173.0	de	**7**	**426.8**	**bc**	**7**	**690.4**	**bcde**
16	**172.5**	**def**	18	424.7	bcd	18	685.2	bcdef
20	**172.4**	**def**	14	422.7	cde	11	678.8	cdef
23	171.7	def	11	422.6	cde	14	677.7	def
24	171.6	def	15	420.1	de	15	676.9	ef
19	171.5	def	2	419.2	de	12	673.8	f
18	170.4	def	12	418.6	e	6	670.5	f
6	170.4	def	6	418.6	e	2	644.5	g
14	169.9	def	3	408.8	f	3	625.6	h
12	168.1	def	1	408.5	f	4	624.7	h
15	167.8	def	4	407.7	f	1	624.6	h
5	164.0	ef	5	403.3	fg	5	617.6	h
10	163.3	f	10	400.5	g	10	598.6	i

Table 8 Mean data with means separation for 4015. Means within each column followed by the same letter are not significantly different (alpha=0.05). The two nozzles on either side of the underlined data within each column bracket the mean across all nozzles of this type. Nozzle numbers in bold font are those selected for the droplet-size matched dedicated sets

Number	DV0.1		Number	DV0.5		Number	DV0.9	
2	211.5	a	2	452.3	a	23	694.9	a
4	205.6	b	4	435.9	b	2	694.1	a
5	202.9	bc	5	431.4	c	4	649.7	b
8	201.4	cd	8	431.2	c	5	648.1	b
3	201.3	cd	10	431.0	c	8	647.6	b
7	199.7	cde	3	430.2	cd	3	647.5	b
10	199.7	cde	7	429.5	cde	7	647.3	b
9	199.3	de	13	429.0	cdef	10	647.1	b
13	198.6	def	9	428.9	cdef	15	646.8	b
1	197.4	efg	15	428.1	cdefg	9	646.5	b
6	197.0	efgh	6	426.8	defgh	13	646.4	b
15	196.6	efghi	23	426.6	defgh	6	645.2	b
14	**195.7**	**fghij**	**19**	**426.5**	**defgh**	**19**	**645.2**	**b**
16	**194.9**	**ghij**	**14**	**426.5**	**defgh**	**14**	**645.0**	**bc**
19	**194.9**	**ghij**	**16**	**425.8**	**efgh**	**16**	**644.8**	**bc**
17	**193.8**	**hij**	1	425.6	efgh	**18**	**644.8**	**bc**
18	**193.8**	**hij**	**18**	**425.3**	**fgh**	1	644.7	bc
11	**193.7**	**ij**	**17**	**425.0**	**fgh**	**11**	**644.0**	**bc**
12	192.7	j	**11**	**424.5**	**gh**	**17**	**643.9**	**bc**
20	192.6	j	20	423.7	h	20	643.4	bc
23	162.6	k	12	419.1	i	12	636.3	cd
21	156.9	l	21	405.4	j	21	631.0	d
22	153.8	l	22	399.6	k	22	621.5	e

Table 9 Mean data with means separation for 2508. Means within each column followed by the same letter are not significantly different (alpha=0.05). The two nozzles on either side of the underlined data within each column bracket the mean across all nozzles of this type. Nozzle numbers in bold font are those selected for the droplet-size matched dedicated sets

Numberb	DV0.1		Number	DV0.5		Number	DV0.9	
19	275.7	a	19	507.1	a	24	695.0	a
24	271.9	ab	24	503.8	ab	19	694.6	a
20	271.0	abc	20	501.8	abc	20	690.8	ab
12	268.6	bcd	12	499.1	bcd	12	685.9	bc
23	267.7	bcde	23	498.8	bcd	22	685.2	bcd
18	267.6	bcde	6	496.4	cde	23	684.5	bcd
14	267.4	bcde	18	496.2	cde	14	683.7	bcde
22	267.4	bcde	22	496.2	cde	18	683.6	bcde
6	267.1	bcde	14	496.1	cde	6	682.9	bcde
15	**266.2**	**bcde**	**16**	**493.5**	**def**	**16**	**681.9**	**cde**
16	**265.9**	**cde**	**13**	**492.9**	**def**	**13**	**680.2**	**cdef**
13	**264.6**	**def**	**15**	**492.6**	**def**	**15**	**679.0**	**cdefg**
11	**264.1**	**defg**	10	490.7	efg	**11**	**678.1**	**cdefgh**
17	263.3	defg	**11**	**490.6**	**efgh**	**2**	**677.7**	**cdefgh**
21	**263.2**	**defg**	**2**	**490.1**	**efgh**	**21**	**676.8**	**defgh**
2	**263.1**	**defg**	**21**	**489.7**	**efgh**	17	675.6	efghi
1	263.0	defg	17	489.4	efgh	10	675.4	efghi
10	262.8	defg	5	487.7	fgh	5	673.3	fghi
5	262.3	efg	1	486.5	fgh	1	672.4	fghi
8	259.9	fg	9	484.7	gh	9	671.4	ghi
3	259.6	fg	8	484.1	gh	8	670.3	hi
4	259.5	fg	3	483.8	gh	3	670.1	hi
9	258.9	fg	4	483.7	gh	7	669.7	hi
7	258.6	g	7	483.6	h	4	667.9	i

Table 10 Means and standard deviations for nozzles selected to be included as part of the droplet sized matched set for the 11001 nozzles setting the Very Fine to Fine threshold

Number	$D_{V0.1}$	$D_{V0.5}$	$D_{V0.9}$
3	70.3±0.9	155.7±1.2	247.5±1.6
10	69.3±0.3	157.0±0.8	252.7±1.5
11	68.4±0.6	154.4±0.9	248.1±1.1
16	68.2±1.0	155.2±0.7	247.1±1.9
20	67.7±0.5	157.2±0.9	254.1±3.0
23	67.0±0.5	155.6±0.8	252.7±3.8

Table 11 Means and standard deviations for nozzles selected to be included as part of the droplet sized matched set for the 8003 nozzles setting the Fine to Medium threshold

Number	$D_{V0.1}$	$D_{V0.1}$	$D_{V0.1}$
3	125.0±0.2	260.0±0.5	413.8±1.6
5	126.9±0.5	263.2±0.7	416.9±2.1
11	124.1±1.3	260.2±2.0	429.5±13.2
13	125.5±1.1	262.5±1.2	426.5±10.5
19	123.7±1.7	260.2±1.2	421.0±9.5
22	123.9±1.1	259.4±1.1	425.5±3.7

Table 12 Means and standard deviations for nozzles selected to be included as part of the droplet sized matched set for the 8005 nozzles setting the Medium to Coarse threshold

Number	$D_{V0.1}$	$D_{V0.1}$	$D_{V0.1}$
4	176.7±1.1	344.4±0.9	502.8±5.7
5	175.7±2.1	345.0±0.9	513.8±1.5
7	176.6±0.8	346.1±0.8	514.5±2.9
9	177.4±1.9	347.5±0.6	516.1±1.5
11	178.3±1.5	348.8±0.8	522.6±3.6
17	175.9±2.2	345.4±1.3	506.8±10.0

Table 13 Means and standard deviations for nozzles selected to be included as part of the droplet sized matched set for the 6515 nozzles setting the Coarse to Very Coarse threshold

Number	$D_{V0.1}$	$D_{V0.1}$	$D_{V0.1}$
7	175.1±1.3	426.8±1.7	690.4±2.6
9	175.5±4.7	429.4±1.6	693.7±0.7
13	175.2±2.7	422.7±0.8	694.3±1.8
16	172.5±1.3	430.1±1.2	695.9±1.5
20	172.4±3.1	443.8±1.6	695.9±3.3
22	176.0±6.8	429.6±2.7	691.4±4.9

Table 14 Means and standard deviations for nozzles selected to be included as part of the droplet sized matched set for the 4015 nozzles setting the Very Coarse to Extra Coarse threshold

Number	$D_{V0.1}$	$D_{V0.1}$	$D_{V0.1}$
11	193.7±1.2	424.5±1.0	644.0±0.9
14	195.7±0.4	426.5±1.3	645.0±1.6
16	194.9±0.6	425.8±0.7	644.8±0.4
17	193.8±0.5	425.0±0.6	643.9±0.6
18	193.8±0.3	425.3±0.2	644.8±0.5
19	194.9±0.6	426.5±0.3	645.2±0.2

Table 15 Means and standard deviations for nozzles selected to be included as part of the droplet sized matched set for the 2508 nozzles setting the Extra Coarse to Ultra Coarse threshold

Number	$D_{V0.1}$	$D_{V0.1}$	$D_{V0.1}$
2	263.1±3.2	490.1±3.0	677.7±2.8
11	264.1±2.7	490.6±3.9	678.1±5.2
13	264.6±2.8	492.9±3.2	680.2±3.0
15	266.2±1.0	492.6±2.1	679.0±2.2
16	265.9±0.3	493.5±0.9	681.9±2.6
21	263.2±1.5	489.7±0.8	676.8±1.2

4 Conclusions

To support future collaborative and independent research amongst groups conducting aerial application nozzle atomization studies, six droplet-sized matched, dedicated reference nozzles sets were developed. Six nozzles from within each nozzle type that define the different droplet size classification levels were selected based on droplet sizing results from large population of nozzles within each type. These matched sets will serve as references when evaluating and classifying aerial application nozzles, allowing independent data sets from multiple research locations to agree on the relative droplet size class of tested spray technologies, regardless of differences in instrumentation and methods used. While absolute droplet size numerical data will still vary with differences in methods and systems, the reference nozzles will further provide a standard metric to determine the magnitude of these differences. Ultimately, use of a size classification standard, aids in avoiding confusion or misinterpretation of absolute data that may vary by location. The developed aerial reference nozzle data sets will be distributed to key research facilities around the world to be used as part of their research efforts.

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