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Machine Vision Instrument to Measure Spray Droplet Sizes

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Abstract

A machine vision-based instrument to measure a droplet size spectrum of a spray nozzle was developed and tested to evaluate its accuracy on measuring spray droplet sizes and classifying nozzle sizes. The instrument consisted of a machine vision, light emitting diode (LED) illumination and a desktop computer. The illumination and machine vision were controlled by the computer through a C++ program. The program controlled the machine vision to capture droplet images under controlled illumination, and processed the droplet images to characterize the droplet size distribution of a spray nozzle. An image processing algorithm was developed to improve the accuracy of the system by eliminating random noise and out-of-focus droplets in droplet images while measuring droplet sizes. The instrument measured sizes of the three different balls (254.0, 497.8 and 793.8 μm) and the measurement ranges were 241.2-273.6 μm, 492.9-529.6 μm and 800.8-824.1 μm for 254.0-, 497.84- and 793.75- μm balls, respectively. Error of the measured droplet mean was less than 3.0 %. Droplet statistics, $D_{V0.1}$, $D_{V0.5}$ and $D_{V0.9}$, of a reference nozzle set were measured, and droplet size spectra of five spray nozzles covering from very fine to extremely coarse were measured to classify spray nozzle sizes. Ninety percent of the classification results of the instrument agreed with manufacturer's classification. A comparison study was carried out between developed and commercial instruments, and measurement results of the developed instrument were within 20 % of commercial instrument results.

Keywords : Spray droplet size spectra, LED illumination, Machine vision

1. INTRODUCTION

Knowing comprehensive droplet size distribution of a spray nozzle is an important aspect for the intended use of the spray nozzle in spraying application. Furthermore, a droplet size spectrum of a spray nozzle is a preliminary factor to understand the behavior of spray application pattern (Jeon et al., 2004; Womac et al., 2001). As the concerns on pesticide application grow, selecting proper spray nozzles for different pesticide applications becomes more important because otherwise, improper application or unintended results may occur from the application. Thus, the most agricultural spray nozzles were assigned with specific size classifications over a range of atomization pressures.

Currently, the six classifications, very fine (VF), fine (F), medium (M), coarse (C), very coarse (VC) and extremely coarse (XC), are available for agricultural spray nozzles (ASABE Standards, 2004), and those classifications are mainly relied on three droplet size statistics of spray nozzles.

Research in measuring spray droplet sizes has been actively carried out. For example, Ragucci et al. (1990) investigated possibility of droplet visualization to measure

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droplet sizes using the light scattering technique. Their instrument had two layers, imaging and illumination layers. An atomizer was in-line with the imaging system, and the laser under the imaging system illuminated to an angled mirror through two cylindrical lenses. Thus, the reflected laser was only illuminated to the working distance of the imaging system. They presented an image of well-focused droplets, however, the measurement accuracy and range were unspecified.

Kawaguchi et al. (2002) used a high resolut-ion CCD camera with a laser sheet illumination to measure droplet sizes. The laser location was at the perpendicular to the spray axis. Their imaging system had the resolution of 81 μm^2 with the measurement scope of 2500 mm^2. They used the instrument to measure the size of CO_2 bubbles created from the bottom of a water tank. The range of the bubble size measurement was from 200 μm to 400 μm. They reported the error in average diameter was less than 3%.

Commercial instruments are available to measure spray droplet size. However, due to complexity of the laser illumination source handling and droplet sizing techniques, those droplet sizing instruments require high initial invest-ment (greater than 40,000 USD), which is unattractive to research and industry communities. Therefore, the objective of this study was to develop and test a machine vision-based instrument to measure spray droplet size statistics with reasonable accuracy and cost.

2. MATERIALS AND METHODS

The developed instrument consisted of a monochrome CCD camera (701b, Unibrain SA, Athens, Greece), an array of extra bright light-emitting diode (LED, T18W133196, Ledtech USA Elect-ronics Corp., Northridge, CA, USA), Peripheral Interface Controller (PIC18F258, Microchip Technology Inc. Chandler, Arizona, USA) based LED light controller, and a Pentium 4 based desktop computer (OptiPlex GX400, Dell, Austin, Texas, USA). The schematic of the instrument is in fig. 1.

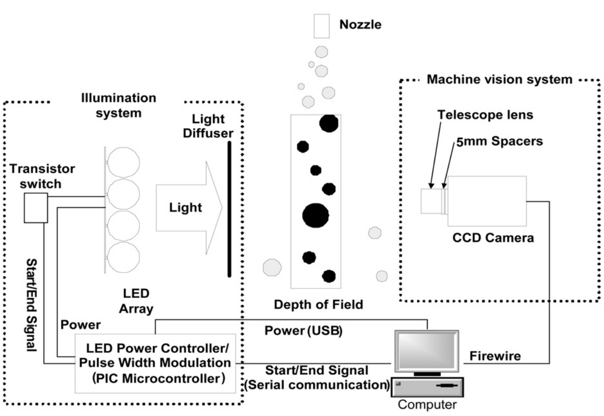


Fig. 1 Schacmatic of developed instrument.

A. MACHINE VISION

The machine vision had a Firewire (IEEE 1394 interface) port to transfers captured digital images to a computer, and aslo had gain and shutter speed controls (Maximum shutter speed: 1 μs). A variable focal length telescope lens (focal length range: 12.5 - 75 mm, Navitar TV Zoom Lens, F 1.8, Japan) was used on the camera to increase magnification of the camera view. In addition, four 5-mm spacers (Edmund optics, Barrington, NJ, USA) were installed between the camera and telescope lens. The working distance of the machine vision system was approximately 298 mm, and the depth of the field of the camera was approximately ± 1.3 mm from the working distance. The field of view (FOV) of the machine vision system was approximately 10.6 mm × 7.9 mm at the working distance. The camera was approxi-mately 340 mm down from the nozzle orifice to capture droplet images. The pixel resolution (16.5 μm/pixel) of the machine vision was estimated from a 0.5- mm spacing grid printed on clear film.

B. ILLUMINATION

An LED array with a transistor switch was used as illumination. The LED array was powered by Universal Serial Bus (USB) of the computer. A 4-by-6 array of LEDs were used as the illumination source. The LEDs were installed side by side to obtain uniform illumination. The LED array was installed on the opposite side of the machine vision system, thus, it directly illuminated FOV. A diffusing film was placed in front of the array to provide uniform illumination.

C. SYSTEM CONTROL AND DROPLET IMAGE PROCESSING ALGORITHMS

A control application program for the instrument was developed with Microsoft Visual C++ 2005 (Microsoft Co., Redmond, WA, USA) and Fire-I API (Applic-ation Programming Interface, Unibrain Co LTD, Greece). After starting the application, the computer sent a signal to turn on the LED array, and the instrument captured and stored a blank background image. While the LED was illuminating FOV, the camera captured droplet images.

Image subtraction between the background and droplet images was performed, and droplets were identified and converted to a binary image by a predetermined threshold value. After the image threshold, a median filter was applied to eliminate the noise. The mixture of focus and out-of-focus droplets was observed in the image because countless spray droplets were traveling through the viewing axis of the machine vision system. As the out-of-focus droplets reflected inaccurate droplet size, the mean pixel valves of the droplet and the background were computed within pixel intensity measure range (PIMR), four pixels from the droplet left edge to eliminate the out-of-focus droplets at the vertical center of the droplet image. The range was empirically determined to identify pixel value changes between focused and out-of-focus droplets. Within the PIMR of each droplet, the mean pixel values of a droplet image and background were computed, and the difference between them was calculated. The difference was normalized by the minimum pixel value on the vertical center line of the droplet, therefore, the difference in the mean values was expressed as a ratio to the minimum. The empirically determined threshold was applied to eliminate the out-of-focus droplets in the image. Thus, the droplet size distribution only includes the size data of well-focused droplets to minimize measurement error (Hardalupas et al., 1994; Kashdan et al., 2007). An example processing image set for detecting droplets is in fig. 2.

Total image pixels of each droplet image were counted, and the droplet diameter was computed by following equation (Kashdan et al., 2007).

$$D_M = \sqrt{\frac{4A}{\pi}} \times \mathrm{Re}$$

Where,

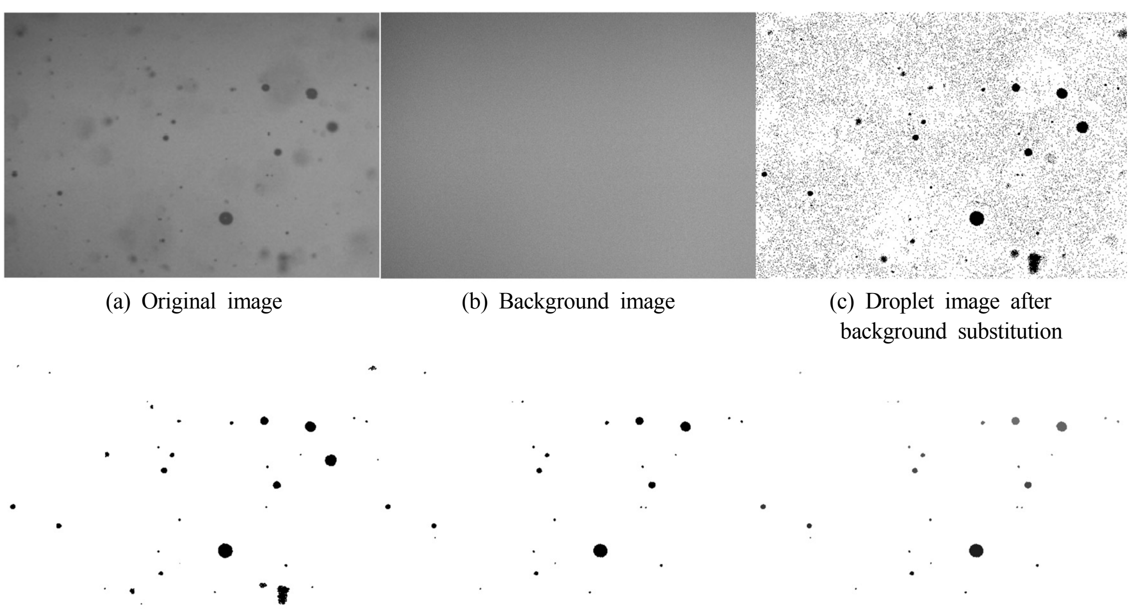
D_M = Droplet diameter in μm

A = Droplet area in pixel

Re = Machine vision resolution (μm/pixel)

π = Circumference ratio

Droplet diameters were accumulated to an array, and the instrument automatically stopped when the predetermine number of droplets was captured. Droplet statistics such as $D_{V0.1}$, $D_{V0.9}$, volume median diameter (VMD, $D_{V0.5}$), number median diameter (NMD), and relative span, were computed after collecting the droplet cumulative distribution. $D_{V0.1}$, and $D_{V0.9}$ defines droplet diameters that 10% ($D_{V0.1}$) and



(a) Original image (b) Background image (c) Droplet image after background substitution

(d) Droplet image after median filters (e) Droplet image after the gradient filter (f) Droplet image after the identification

Fig. 2 An example set of image processing results for droplet size measurement.

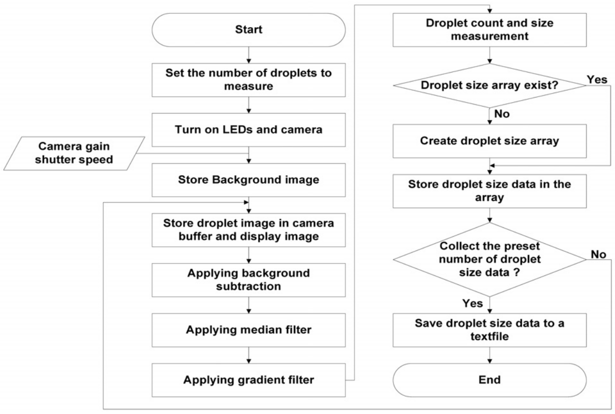


Fig. 3 Flowchart for the droplet size spectrum measurement program.

90% ($D_{V0.9}$) of the nozzle droplet spectrum liquid volume is occupied in less than each diameter (ASABE Standards, 2007). The flowchart for the control program for measuring droplet size is shown in fig. 3.

D. INSTRUMENT ACCURACY AND MEASUREMENT VARIATION

To examine the accuracy of the instrument, the images of 254.0-, 497.8- (Bal-tec Inc., Los Angeles, CA, USA, Grade: 24 (Tolerance: 2.5 μm) and 25 (2.5 μm)), and 793.8- μm balls (McMaster Co., Santa Fe Springs, CA, USA, Grade: 200 (25 μm)) (Fig. 4) were captured, and processed by the instrument. The average measurement, errors, and variations were computed.

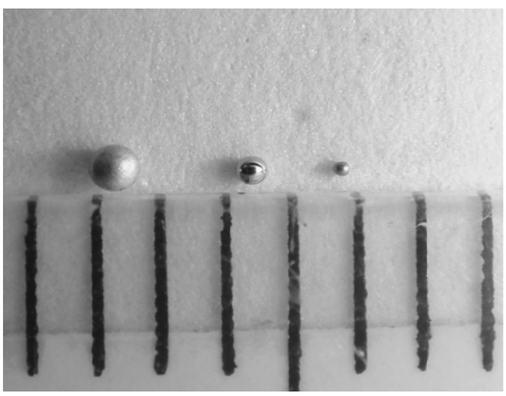


Fig. 4 Size comparison between three size balls in order of 793.8-, 497.8- and 254.0- μm ball: The space between vertical lines is 1 mm.

E. DROPLET SIZE MEASUREMENT AND NOZZLE CLASSIFICATION

A reference nozzle set (Womac, 1999) was used to create a reference curve for the spray nozzle classification of the instrument. The nozzles were atomized by air-pressurized liquid tank to create steady system pressure. While the nozzles were spraying, the system pressure was monitored through an analog gauge.

Recommended operation conditions of the nozzles were followed to atomization (Womac, 1999). The flow rates of the nozzles were measured before measuring droplet sizes by collecting timed volumetric changes. The measurement results of flow rates and mean are in table 1. Each nozzle in the reference nozzle set operated until the system captured more than 5000 droplets at three horizontal locations, the nozzle center, 150 mm (100 mm for the very/extremely coarse nozzle due to the narrow spray angle) to the left and right sides from the center with three replications for each measurement. An average cumulative volume statistics were identified for each nozzle: VMD, $D_{V0.1}$ and $D_{V0.9}$. The distance between the nozzle outlet and the center of the camera was approximately 340 mm.

Table 1 Flow rates of reference nozzles tested following the ASABE Standard S572.1

	VF/F* (110)**	F/M (110)	M/C (110)	C/VC (80)	VC/XC (65)
Flow rate***	496	1256	1950	2880	3240
	479	1260	1950	2940	3240
	480	1260	1920	2940	3180
Mean	485	1259	1940	2920	3220

*VF: Very Fine, F: Fine, M: Medium, C: Coarse, VC: Very Coarse, XC: Extremely Coarse
**Nozzle spray angle
***Unit of flow rate is mL/min

Four extended range(XR) and one air induction(AI) flat spray nozzles were selected for the classification test (Table 2). The nozzles were operated under manufacturer's guide-line to create a specific size range of droplets. The instrument measured spray droplet sizes of the five nozzles to examine the droplet size classification capability. The droplet size classification of the spray tips was ranged from very fine to extremely course (Catalog 50, Teejet, Wheaton, IL, USA). Droplet size spectra for the selected nozzles were measured under equivalent nozzle height and liquid flow source to droplet size data collection for reference nozzle droplet size. Tested spray nozzles were classified by $D_{V0.1}$, $D_{V0.5}$ and $D_{V0.9}$ means of the tested nozzles and the reference nozzles.

In addition, the results of spray droplet size measurement of the developed instrument were compared with a commercially available system (VisiSizer and PIV, Oxford Lasers Ltd., Oxford Shire, UK) for further examination on the accuracy of the developed instrument. Two ellipse nozzles, XR8004 and XR8005 (Teejet, Wheaton, IL, USA), were selected, and operated them under identical conditions:

1) Tested nozzles were located approximately 50 cm above from the measurement axis, and
2) Operating pressures of XR8004 and XR8005 were 290 and 138 kPa, respectively.

Table 2 Nozzle operating conditions for the classification by the instrument and their classification from the manufacturer

Nozzle	Nozzle operating condition (kPa)	Nozzle classification*
XR**11001	344.74 (435)***	VF****
XR11001	206.84 (338)	F
XR8002	275.79 (730)	F
XR8002	137.90 (504)	M
XR8004	275.79 (1504)	M
XR8004	137.90 (1020)	C
XR8008	275.79 (2807)	C
XR8008	137.90 (1914)	VC
AI11004	413.69 (1807)	VC
AI11004	206.84 (1243)	XC

*Teejet Catalog 50.
**XR refers extended range flat fan spray nozzle, and AI refers air induction flat fan spray nozzle.
***Flow rate of the nozzle in mL/min
****VF: Very Fine, F: Fine, M: Medium, C: Coarse, VC: Very Coarse, XC: Extremely Coarse

RESULTS AND DISCUSSION

A. INSTRUMENT ACCURACY AND MEASUREMENT VARIATIONS

Sizes of three balls measured and their populations were 484, 747 and 793 for 254.0- μm, 497.8- μm and 793.8- μm balls, respectively (table 3). The measurement means were 261. 6 μm with measurement range (MR) from 241.2-273.6 μm, 508.5 μm with MR from 492.2-529.6 μm and 811.6 μm with MR from 800.8-821.1 μm for the 254-, 497.8- and 793.8- μm balls, respectively. The range of measurement errors was from 7.6 μm to 31.8 μm. A major error source was image segmentation at the ball edge.

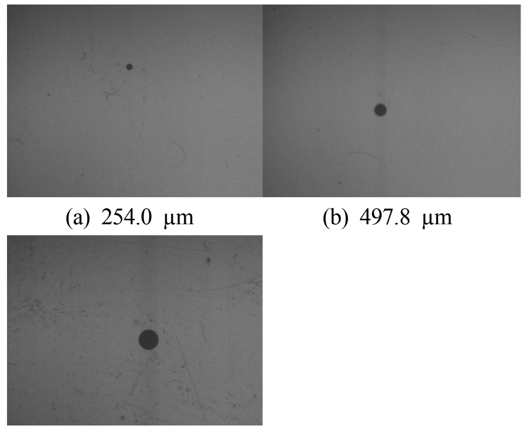

(a) 254.0 μm (b) 497.8 μm (c) 793.8 μm

Fig. 6 Captured ball images by the instrument for size measurement.

Table 3 Size measurement results for 254, 497.84, and 793.75- μm balls

size (μm)	Measurement Population	Min. (μm)	Max. (μm)	Ave. (μm)
254.00	484	241.3	273.6	261.6
497.84	747	492.9	529.6	508.5
793.75	793	800.8	824.1	811.6

B. DROPLET SIZE MEASUREMENT AND NOZZLE CLASSIFICATION

The means of $D_{V0.1}$, $D_{V0.5}$ and $D_{V0.9}$ for reference nozzles are tabulated (table 4). In general $D_{V0.9}$ had relatively large variations mainly because occasionally captured large spray droplets contributed to the variations due to their relatively large volume. The coefficients of variations (CV) of the overall Dv0.1, $D_{V0.5}$ and $D_{V0.9}$ means were ranged from 2.3 to 12%.

The means of $D_{V0.1}$, $D_{V0.5}$ and $D_{V0.9}$ and the droplet size classifications for testing nozzles are tabulated (table 5). Operating pressure changes for the XR nozzles had relatively more influences in relatively smaller statistics, $D_{V0.1}$ and $D_{V0.5}$, however, the large droplet statistic, $D_{V0.9}$, had relatively less changes in fine, medium and coarse sizes by the changes. The result implies that the large droplet statistic, $D_{V0.9}$, should consider as a least significance aspect to determine the spray droplet size classification of the XR nozzles because the size variations by operating condition

Table 4 $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ means over three different locations and overall Dv0.1, Dv0.5 and Dv0.9 means of a reference nozzle set

Nozzles type	Size (μm)	Left side	Center	Right side	Mean
VF/F*	$D_{v0.1}$	84.7	75.3	79.7	79.9
	$D_{v0.5}$	119.4	109.2	118.4	115.6
	$D_{v0.9}$	167.3	158.7	171.3	165.8
F/M	$D_{v0.1}$	93.3	87.7	91.3	90.8
	$D_{v0.5}$	165.4	197.1	183.9	182.1
	$D_{v0.9}$	374.7	402.7	384.7	387.3
M/C	$D_{v0.1}$	110.5	110.0	106.0	108.8
	$D_{v0.5}$	222.6	256.8	232.9	237.4
	$D_{v0.9}$	454.3	514.0	469.8	479.3
C/VC	$D_{v0.1}$	154.7	175.7	148.0	159.4
	$D_{v0.5}$	404.0	456.3	401.6	420.6
	$D_{v0.9}$	660.3	746.7	683.3	696.8
VC/XC	$D_{v0.1}$	179.5	227.8	214.3	207.2
	$D_{v0.5}$	449.0	539.1	512.9	500.3
	$D_{v0.9}$	768.8	854.0	834.3	819.0

*VF: Very Fine, F: Fine, M: Medium, C: Coarse, VC: Very Coarse, XC: Extremely Coarse

Table 5 Means of Dv0.1, Dv0.5 and Dv0.9 and the nozzle classification based on their size statistics using the reference nozzle statistics

Nozzles	Size (μm)			Classification	
	$D_{v0.1}$	$D_{v0.5}$	$D_{v0.9}$	I*	M*
XR11001	79.7 (2.3)**	112.0 (2.0)	170.6 (1.0)	VF	VF***
XR11001	84.7 (2.8)	118.6 (3.0)	185.4 (5.2)	F	F
XR8002	95.4 (7.5)	169.3 (7.5)	347.0 (5.4)	F	F
XR8002	111.0 (15.1)	212.4 (17.1)	360.2 (8.5)	F	M
XR8004	105.7 (0.8)	252.6 (5.4)	482.4 (0.8)	M	M
XR8004	119.3 (5.3)	293.2 (3.5)	505.1 (2.8)	C	C
XR8008	143.1 (9.6)	385.9 (11.2)	662.1 (9.1)	C	C
XR8008	164.0 (5.0)	426.1 (4.6)	717.9 (3.5)	VC	VC
AI11004	176.6 (2.7)	471.7 (2.7)	773.2 (3.5)	VC	VC
AI11004	254.8 (3.2)	612.6 (2.2)	985.3 (2.9)	XC	XC

*Results in 'I' column was classified by developed instrument, and 'M' column was suggested by the manufacturer.
**C.V. of means of measurements at three different locations within nozzle's spraying fan
***VF: Very Fine, F: Fine, M: Medium, C: Coarse, VC: Very Coarse, XC: Extremely Coarse

changes were relatively smaller than the other statistics.

The nozzle classifications from droplet size measurement results of the instrument were well matched with the manufacture's classification. One disagreement was found with the medium size nozzle, and the incorrect classification was caused by the $D_{V0.9}$ statistic of the spray droplet spectrum: the $D_{V0.9}$-nozzle classification disagreement in our test was likely a casual result due to randomly captured big droplets rather than an issue in the instrument's size measurement.

In the comparion study, measurement results had disagreement approximately 18.7 - 68.8 micron(10.9 - 19.3%) from commercially available instrument (table 6). One of the reasons for the disagreement could be that the instrument measured droplet size of stationary nozzles at three locations, and the means of all measurement are presented here. However, the results from the VisiSizer and PIV were obtained from transversely scanning spray droplets. In addition, although measurement conditions were controlled for both instruments, the potential of dissimilarity in the measurement conditions cannot be overlooked, as well.

Table 6 Droplet size statistic measurement results of selected nozzles under the specific operating conditions

Size (μm)	XR8004		XR8005	
	Developed instrument	VisiSizer	Developed instrument	VisiSizer
Dv0.1	103.1 (15.3)*	121.8	116.5 (19.3)	144.3
Dv0.5	275.4 (14.3)	321.3	334.7 (12.9)	384.4
Dv0.9	487.4 (11.3)	549.4	562.7 (10.9)	631.5

*Measurement difference between two instruments in % of VisiSizer measurements.

SUMMARY AND CONCLUSION

The instrument to measure the droplet size spectrum of a spray nozzle was developed and tested. The instrument consisted of a machine vision to capture droplet images, an LED array for illumination within FOV and a desktop computer to control the LED array and machine vision. The computer controlled instrument's components through a C++ based program, and the program processed droplet images and computed the droplet sizes and their statistics. While processing droplet images, out-of-focused droplets and random noise were eliminated to increase the accuracy of the instrument.

The accuracy and measurement variation of the instrument were examined by measuring the sizes of accurately manufactured balls. The balls have three different sizes, 254, 497.84 and 793.75 μm, and the range of measurement was 241.2-273.6 μm, 492.9-529.6 μm and 800.8-824.1 μm for 254.0-, 497.84- and 793.75- μm balls, respectively, and the measurement error range was from 7.6 to 31.8 μm. The droplet size spectra of the spray nozzles with the droplet size range from very fine to extremely coarse were measured and the nozzle classifications were made with the nozzle's means of $D_{V0.1}$, $D_{V0.5}$ and $D_{V0.9}$. As a result, the instrument's classification results of 90% agreed with the manufacturer's classification. In addition, measurement results of developed instrument were compared with the results from a commercially available droplet imaging system, and the differences were within 20%.

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