NISTIR 7395

Droplet Size Distributions in the Spray from Commercial 'Fogger' Type Pepper Spray Products

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This report was conducted under the direction of Alim A. Fatah, Program Manager for Chemical Systems and Materials, and Kathleen M. Higgins, Director of OLES.

FOREWORD

The Office of Law Enforcement Standards (OLES) of the National Institute of Standards and Technology (NIST) furnishes technical support to the National Institute of Justice (NIJ) program to strengthen law enforcement and criminal justice in the United States. OLES's function is to develop standards and conduct research that will assist law enforcement and criminal justice agencies in the selection and procurement of quality equipment.

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This document covers research conducted by OLES under the sponsorship of the NIJ. Additional reports as well as other documents are being issued under the OLES program in the areas of protective clothing and equipment, communications systems, emergency equipment, investigative aids, security systems, vehicles, weapons, and analytical techniques and standard reference materials used by the forensic community.

Technical comments and suggestions concerning this report are invited from all interested parties. They may be addressed to the Office of Law Enforcement Standards, National Institute of Standards and Technology, 100 Bureau Drive, Stop 8102, Gaithersburg, MD 20899–8102.

Kathleen M. Higgins, Director
Office of Law Enforcement Standards

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COMMONLY USED SYMBOLS AND ABBREVIATIONS

A	ampere	Hf	high frequency	o.d.	outside diameter
ac	alternating current	Hz	Hertz	Ω	ohm
AM	amplitude modulation	i.d.	inside diameter	p.	page
cd	candela	in	Inch	Pa	pascal
cm	centimeter	IR	infrared	Pe	probable error
CP	chemically pure	J	Joule	pp.	pages
c/s	cycle per second	L	lambert	Ppm	parts per million
d	day	L	Liter	Qt	quart
dB	decibel	lb	Pound	Rad	radian
dc	direct current	lbf	pound-force	Rf	radio frequency
°C	degree Celsius	lbf•in	pound-force inch	Rh	relative humidity
°F	degree Fahrenheit	Lm	Lumen	S	second
dia	diameter	Ln	logarithm (base e)	SD	standard deviation
emf	electromotive force	Log	logarithm (base 10)	sec.	Section
eq	equation	M	Molar	SWR	standing wave ratio
F	farad	m	Meter	uhf	ultrahigh frequency
fc	footcandle	μ	Micron	UV	ultraviolet
fig.	figure	min	Minute	V	volt
FM	frequency modulation	mm	millimeter	vhf	very high frequency
ft	foot	mph	miles per hour	W	watt
ft/s	foot per second	M/s	meter per second	λ	wavelength
g	acceleration	Mo	Month	wk	week
g	gram	N	Newton	wt	weight
gr	grain	N•m	Newton meter	yr	year
H	henry	Nm	nanometer		
h	hour	No.	number		

area=unit^2 (e.g., ft^2, in^2, etc.); volume=unit^3 (e.g., ft^3, m^3, etc.)

PREFIXES

d	deci (10^{-1})	Da	deka (10)
c	centi (10^{-2})	H	hecto (10^{2})
m	milli (10^{-3})	K	kilo (10^{3})
µ	micro (10^{-6})	M	mega (10^{6})
n	nano (10^{-9})	G	giga (10^{9})
p	pico (10^{-12})	T	tera (10^{12})

COMMON CONVERSIONS (See ASTM E380)

0.30480 m =1 ft	4.448222 N = 1 lbf
25.4 mm = 1 in	1.355818 J = 1 ft•lbf
0.4535924 kg = 1 lb	0.1129848 N m = 1 lbf•in
0.06479891 g = 1 gr	14.59390 N/m = 1 lbf/ft
0.9463529 L = 1 qt	6894.757 Pa = 1 lbf/in^2
3600000 J = 1 kW•hr	1.609344 km/h = 1 mph

psi = mm of Hg x (1.9339 x 10^{-2})

mm of Hg = psi x 51.71

Temperature: $T_{°C} = (T_{°F} - 32) \times 5/9$

Temperature: $T_{°F} = (T_{°C} \times 9/5) + 32$

DROPLET SIZE DISTRIBUTIONS IN THE SPRAY FROM COMMERCIAL 'FOGGER' TYPE PEPPER SPRAY PRODUCTS

This report documents a preliminary investigation of the measurement of droplet sizes in the spray from four commercial 'fogger' type pepper spray products. Droplet sizes were measured over the range of 2 μm to 120 μm by phase Doppler interferometry at a distance from the canisters similar to that expected when the spray is used as a defensive weapon.

1. INTRODUCTION

Commercial pepper spray devices are available that deliver a coherent liquid stream or a fine aerosol from the nozzle. These sprays contain, as the active ingredient, oleoresin capsicum (OC), a chemically complex extract from hot peppers, or a synthetic chemical, nonivamide, that is present as a minor component in OC. They may also contain a variety of solvents, carriers, and surfactants. During the use of pepper sprays to assist in subduing violent individuals, it is likely that some of the droplets are inhaled. Therefore, it is potentially useful to determine the size of the droplets since smaller droplets penetrate deeper in to the lung and therefore may present a greater hazard [1][1]. For environmental monitoring purposes droplets are often classified in three size ranges: Droplets larger than 10 μm which do not reach the lungs and are generally not health hazards; droplets with sizes equal to or less than 10 μm (PM_{10}) that reach the upper airways of the lung; and droplets with sizes equal to or less than 2.5 μm ($PM_{2.5}$) that reach the alveoli and are thought to be the most hazardous [2].

This preliminary study examined how the droplet size, the number of particles, and the velocity, changed as successive shots were fired from four commercial 'fogger' type pepper spray products.

2. EXPERIMENTAL

<u>Samples</u>

Four commercially available pepper sprays were tested as listed in Table 1.

[1]See References on page 7.

Table 1. Pepper Spray Canister Properties

Canister Group	Company	Model	Solvent (Propellent)	Solvent Refractive Index	Expiration Date
B	ZARC International, Inc.	Cap-Stun[2] Standard Duty, Z-305, 1 oz	Isopropanol* (Isobutane)	1.378	12/2008
C	Defense Technologies/Federal Laboratories	BodyGuard LE-10, Cone, 3.17 oz	Diethyleneglycol n-butylether** (unknown)	1.431	2008
D	Guardian Personal Security Products, LLC	BodyGuard LE-10, Cone, 1.5 oz	Diethyleneglycol n-butylether** (unknown)	1.431	2006
F	Aerko International, Inc.	PUNCH II M-4, 83 g	Isopropanol* (Isobutane/Propane)	1.378	06/2007

Note: The same model names and numbers, but different company names, for C and D are correct.

* Information on Canister

**Information from Material Safety Data Sheets

Test Apparatus for Firing Canisters

Canisters were mounted on a stand similar to that described in [3]. The apparatus allowed repeated firing for 1 s at 1 min intervals. The canister nozzle was located 1.83 m (6.0 ft) from the point where measurements were made. Since the unconfined canister sprays dispersed quickly, a cylinder of polyvinyl chloride (PVC) pipe, 76 mm (3 in) diameter and 1.52 m (5 ft) in length, served to confine the spray to a narrower cross section in order to obtain sufficient data for droplet diameter measurements. The cylinder was centered between the mounted pepper spray canister and the probe volume of a phase Doppler interferometer (PDI), which was used to measure the spray characteristics. There was significant impingement of the spray on the inside cylinder surface, which resulted in liquid accumulation inside the cylinder. It was assumed that there was no preferential biasing of the measurement (e.g., droplet coalescence) as a result of the confinement. The stand and probe volume were inside a ventilated chamber. The PDI was outside of the ventilated chamber. The arrangement of the experimental apparatus is shown in figure 1.

[2] Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

Phase Doppler Interferometry

Phase Doppler interferometry [4] has been used to characterize sprays in a wide variety of areas including spray combustion, spray coatings, agricultural pesticides, fire suppression, and others. This measurement technique is an extension of laser Doppler velocimetry that measures droplet size as well as velocity [5-7]. Phase Doppler interferometry involves creating an interference pattern in the region where two laser beams intersect, which results in a region of alternating light and dark fringes called the *probe volume*. Due to the interference pattern, a droplet passing through the probe volume scatters light that results in a modulated signal at the detectors (see Fig. 2). This signal is characteristic of the droplet size, refractive index, and velocity. For a droplet with known refractive index, the size and velocity can be determined. Bachalo [8] published a review of PDI and its application to the study of aerosolized flows.

Measurements were done using a two-component phase Doppler interferometer with a 5 W argon ion laser as the illumination source. To accommodate the horizontal orientation of the experimental apparatus, the transmitter and receiver were positioned in a vertical plane as shown in figure 1. The optical arrangement remained unchanged (including the scattering angle of 30°) for all of the experiments. Droplet size and velocity distributions were obtained at one point in the center of the spray. The time interval over which the actual data were collected was 1 s, that is the duration of one canister shot, however, the PDI data acquisition was initiated before the canister valve was opened, and terminated after the pulse of spray was transported past the PDI laser beams. The measurements were corrected for the solvent refractive indices (see Table 1).

3. RESULTS AND DISCUSSION

Measurements of the droplet mean diameter (i.e., Sauter mean diameter [9]), streamwise velocity, and cross-stream velocity were made on successive 1 s bursts separated by 1 min for 15 canisters representing four models (denoted as groups B, C, D, and F) from three manufacturers. Each canister test consisted of depressing the canister nozzle for a 1 s shot, recording the spray characteristics with the PDI system, and repeating the sequence at 1 min intervals until the canister was empty (i.e., no droplets were detected by the PDI). Three canisters from each group were examined using the spray confinement cylinder since the unconfined spray did not reach the required 1.8 m (6.0 ft) distance in a sufficiently predictable direction to produce reliable detection of the droplets without it. One additional canister from each of groups B, C, and D was examined without the spray confinement cylinder.

Shot-to-Shot Variations

Shot-to-shot variations are discussed for groups C and F. The total number of shots per canister for each group is given in Table 2. Results for the mean diameter and streamwise velocity with shot number are presented in figure 3 for the four canisters of group C. When the spray was directed through the spray confinement cylinder, the number of droplets transported through the PDI probe

Table 2. Total Number of Shots per Canister with Detected Droplets

Canister Group	Total Number of Shots (Confined Cases)	Total Number of Shots (Unconfined Cases)
B	6	5
C	7	2
D	3 - 5	3
F	59 - 63	-

volume was increased significantly. The mean diameter was fairly constant per shot until when nearly all of the liquid contents were exhausted from the canister (see Fig. 3A). The mean diameter was fairly constant per shot until nearly all of the canister contents were expelled. The value of the mean diameter for the unconfined case (closed symbols) was always lower than for the confined cases, which was attributed to deceleration and dispersion of the droplets with increasing streamwise distance. As shown in figure 3B, the mean streamwise velocity is about 14 m/s for the confined cases and decreases with increasing shot number. For the unconfined case, the initial mean velocity was about 1 m/s, having little momentum to reach the target. Since measurements were carried out only at the center of the spray, it is unknown what the droplet radial spatial profiles may reveal regarding transport of the spray off-axis. Determination of the droplet diameter and velocity distributions at several radial positions would require simultaneous off-axis measurements, which was beyond the scope of this study.

Figure 4 presents the distributions for droplet diameter and streamwise velocity for the first shot of canister *C002* (see Fig. 3), which represents a typical 1 s first shot. Also shown in figure 4 is the last shot that gave measurable results. The distributions initially (see Fig. 4A, shot number 1) included droplets ranging from about 100 µm down to a few micrometers (at the detection limit of the instrument). For the nearly depleted case (see Fig. 4A, shot number 7), all of the detected droplets are smaller than 40 µm. One may speculate that for this shot either the remaining liquid in the canister is well atomized by the gas propellant, or any larger droplets are transported off-axis and were not detected since our measurements were near the center of the spray. Such spray characteristics are typical of certain classes of atomizers [9], for which the smaller diameter droplets are transported essentially along the spray axis, i.e., in the direction along which the canister is pointed, and larger droplets near the spray periphery (boundary). The values of the streamwise velocity decrease, and the distribution becomes narrower, as the canister is emptied.

Figure 5 presents the variation of the mean diameter and streamwise velocity with shot number for group *F*. This group produced more shots with less liquid per shot (about half the number of droplets per shot) than the other groups. The variation in the results for droplet mean diameter (see Fig. 5A) increases significantly as the shots progress. Figure 5A also presents the droplet number count for each shot. As the shots increase, the number count decreases. When the number of detected droplets (counts) is below 200, the variation in the mean increases significantly, making it difficult to discern trends. For example, examination of the size distributions indicates that for shot numbers 57 and 59 (indicated by the two solid arrows) the presence of outliers increases the value of the mean diameter dramatically above what the value would be without the outliers. Low values of the mean diameter are indicative of the lack of data for that shot (see shot numbers 58 and 60, indicated by the dashed arrow).

Differences Between Canister Groups

For each group, the variation of the droplet diameter and velocity from canister to canister was small when the spray was transported through the confinement cylinder. The amount of spray reaching the target from the specified distance was smaller for the unconfined canisters than for the confined canisters. The number of droplets detected for the unconfined sprays of groups *B*, *C*, *D* was 4.4 % to 4.7 %, 1.4 % to 3.2 %, and 51 % to 70 % of that observed for the confined sprays. On a weight basis, this corresponds to 0.0009 % to 0.001 %, 0.0001 % to 0.0025 %, and 9 % to 30 %. Although the number of detected droplets for the unconfined canister *D004* (relative to the confined canisters) is much larger than for groups *B* and *C*, the total number of detected droplets for confined cases of group *D* relative to groups *B* and *C* was much less, i.e., 47 % and 37 %, respectively. Part of the reason why the number of detected droplets was higher for the unconfined canister *D004* was because of the higher mean streamwise velocity of 4.4 m/s, as opposed to 1 m/s for canister *C003*. The velocity distribution is also broader with a maximum value reaching 11 m/s, as opposed to 3 m/s for canister *C003*.

A picture of the general spray characteristics for a canister group is presented by combining the results for the three confined canisters of each group. Figure 6 presents distributions for the droplet diameter and streamwise velocity for the confined cases of each group. The largest droplet diameters detected were about 120 μm and for some groups the distributions were bimodal. The distributions for the individual confined canisters of a particular group are similar to each other, i.e., similar to its group distribution presented in figure 6A. The bimodal nature of the diameter distributions was attributed to changes in the distribution between the initial and final shots. The variation in streamwise velocity between canister groups is presented in figure 6B, with only group *D* having a bimodal distribution to correlate with the bimodal diameter distribution.

The maximum particle count for group *F* (Fig. 6A) is much higher than for the other groups. As mentioned above, the number of shots for group *F* (over 60 shots) was much larger than for the other groups (ranging from 3 shots to 7 shots) although the number of detected droplets per shot was less than half (see Fig. 5A). The total number of droplets detected for group *F* was more than 10 000 droplets per canister, which was at least three times larger per canister than the other groups. Comparing the number of droplets less than 10 µm (i.e., those droplets with a higher probability of inhalation) to the total particle count indicates that 28 % to 35 % of the droplets were smaller than 10 µm on a number basis and 0.03 % to 0.08 % on a mass basis for the confined group *F*. For the other groups, the percentages were 9 % to 15 % on a number basis and 0.001 % to 0.004 % on a mass basis.

4. CONCLUSIONS

Droplet size and velocity measurements were carried out using phase Doppler interferometry in the center of sprays generated from commercial 'fogger' type pepper spray canisters. Four different groups of canisters were fired for which the spray characteristics were obtained under both confined and unconfined conditions. The results indicated that canister-to-canister variations of droplet diameter were small within a particular group. The droplet diameter and velocity distributions were substantially different for each group. The mass fraction of droplets with diameters less than 10 μm, which is the droplet diameter that could carry potentially toxic material to the lungs, was 0.001 % to 0.08 % for the four canister groups measured.

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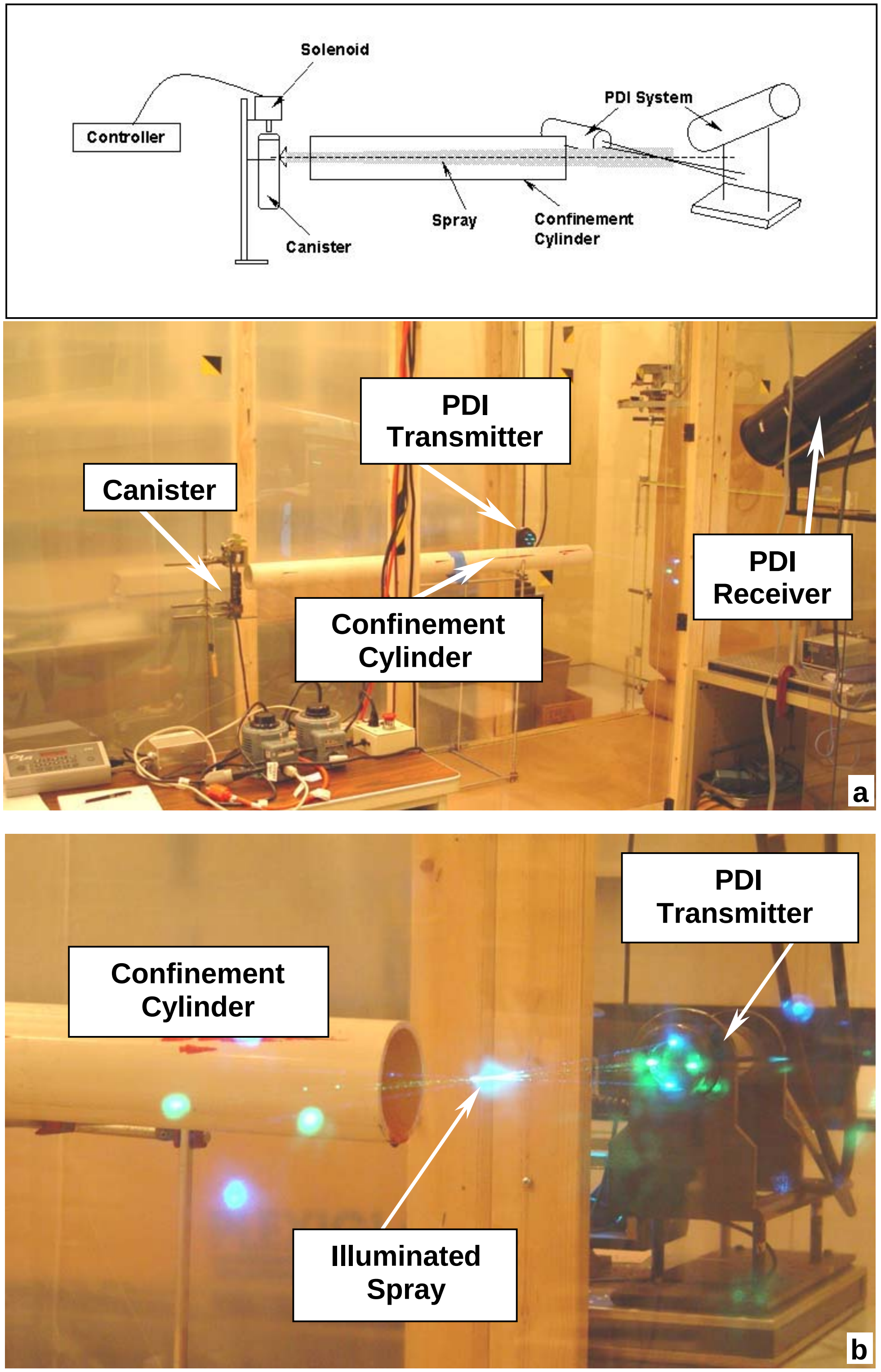

Figure 1. a) Schematic and photograph of the overall experimental arrangement. b) An expanded view of the pepper spray exiting the confinement cylinder and illuminated by the laser beams of the phase Doppler interferometry (PDI) system.

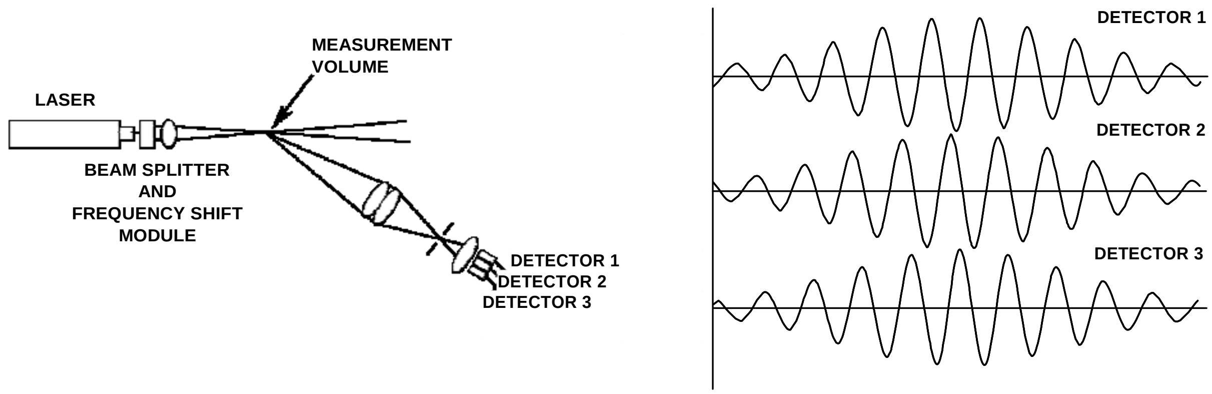

Figure 2. Schematic of the principle of operation of the phase Doppler interferometry system.

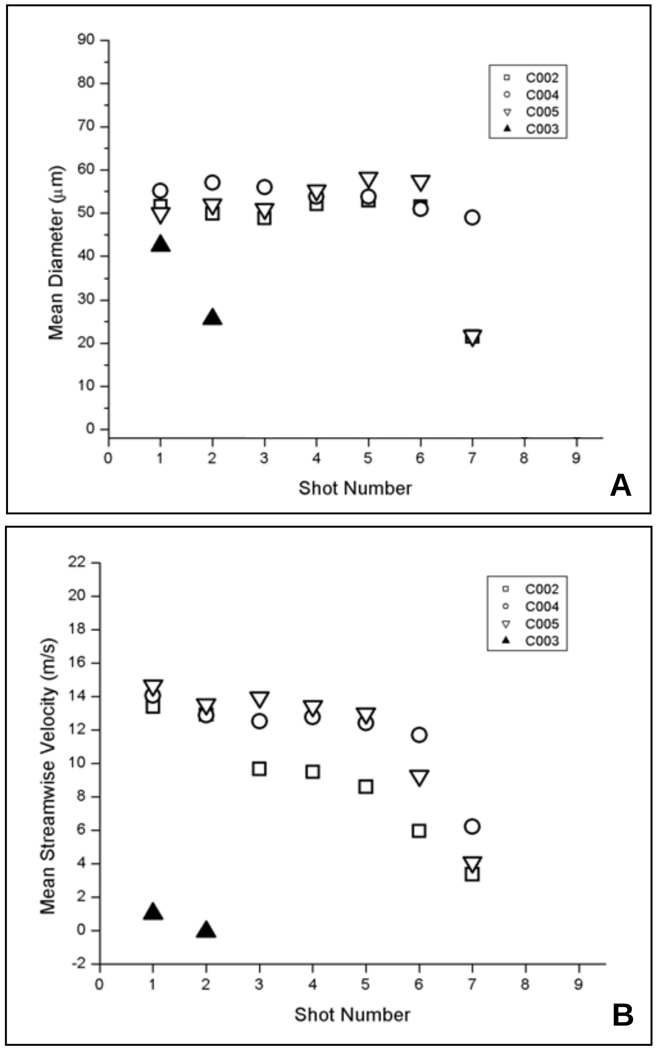

Figure 3. Variation of (A) droplet mean diameter and (B) streamwise velocity (*U*) with shot number for the four canisters of group *C*. The open symbols referred to confined cases and the closed symbols refer to the unconfined case.

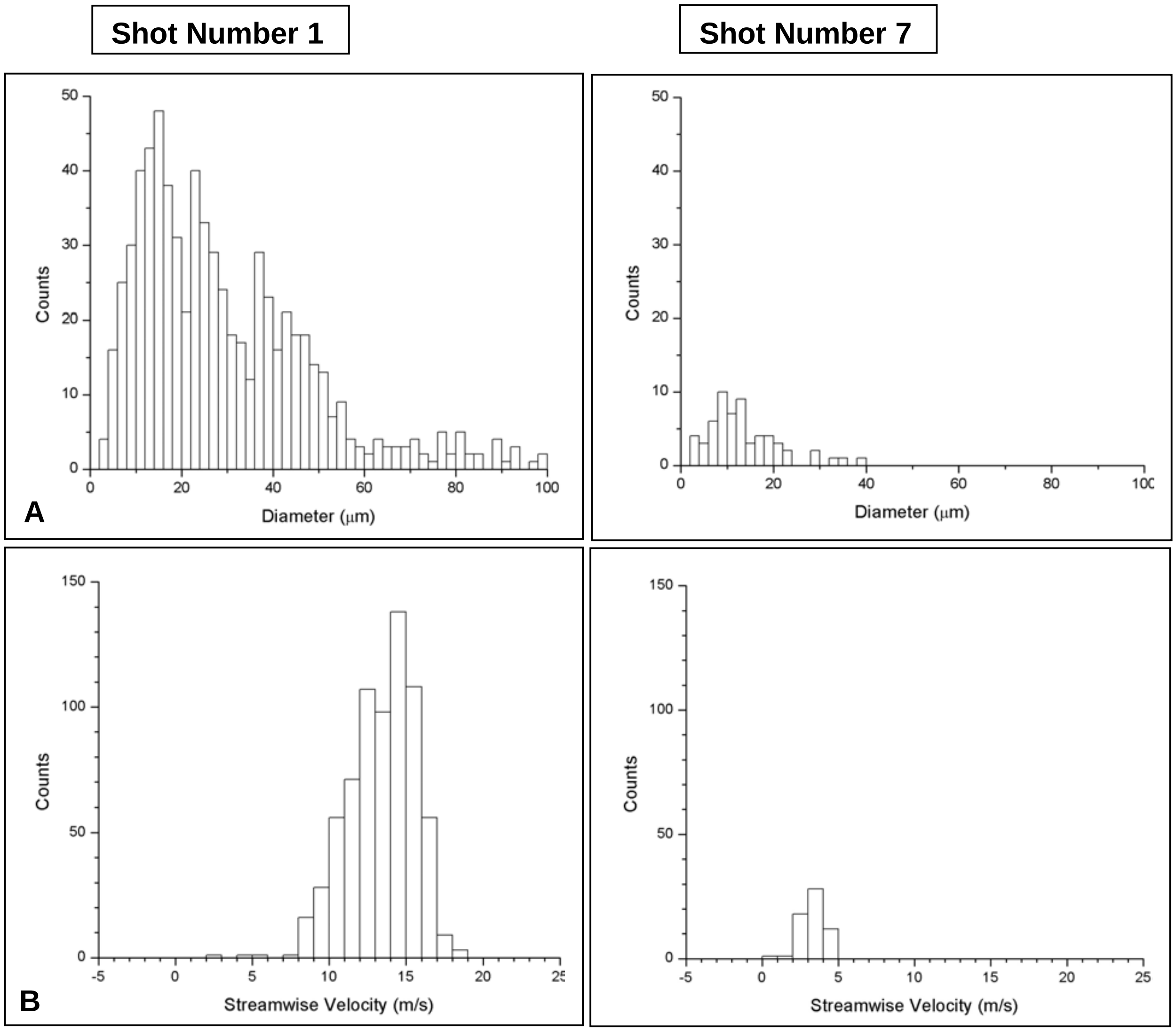

Figure 4. Distributions for droplet A) size and B) streamwise velocity determined for shot numbers 1 (initial shot) and 7 (final shot) of canister *C002*.

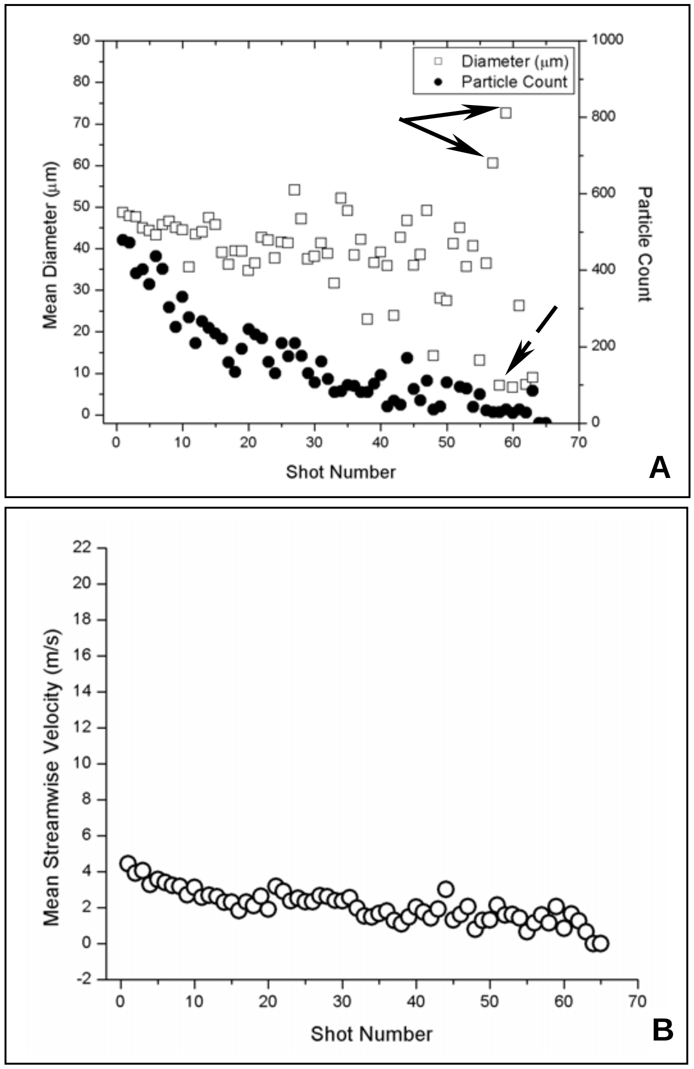

Figure 5. Variation of (A) droplet mean diameter and particle count and (B) streamwise velocity with shot number for canister *F005* (confined).

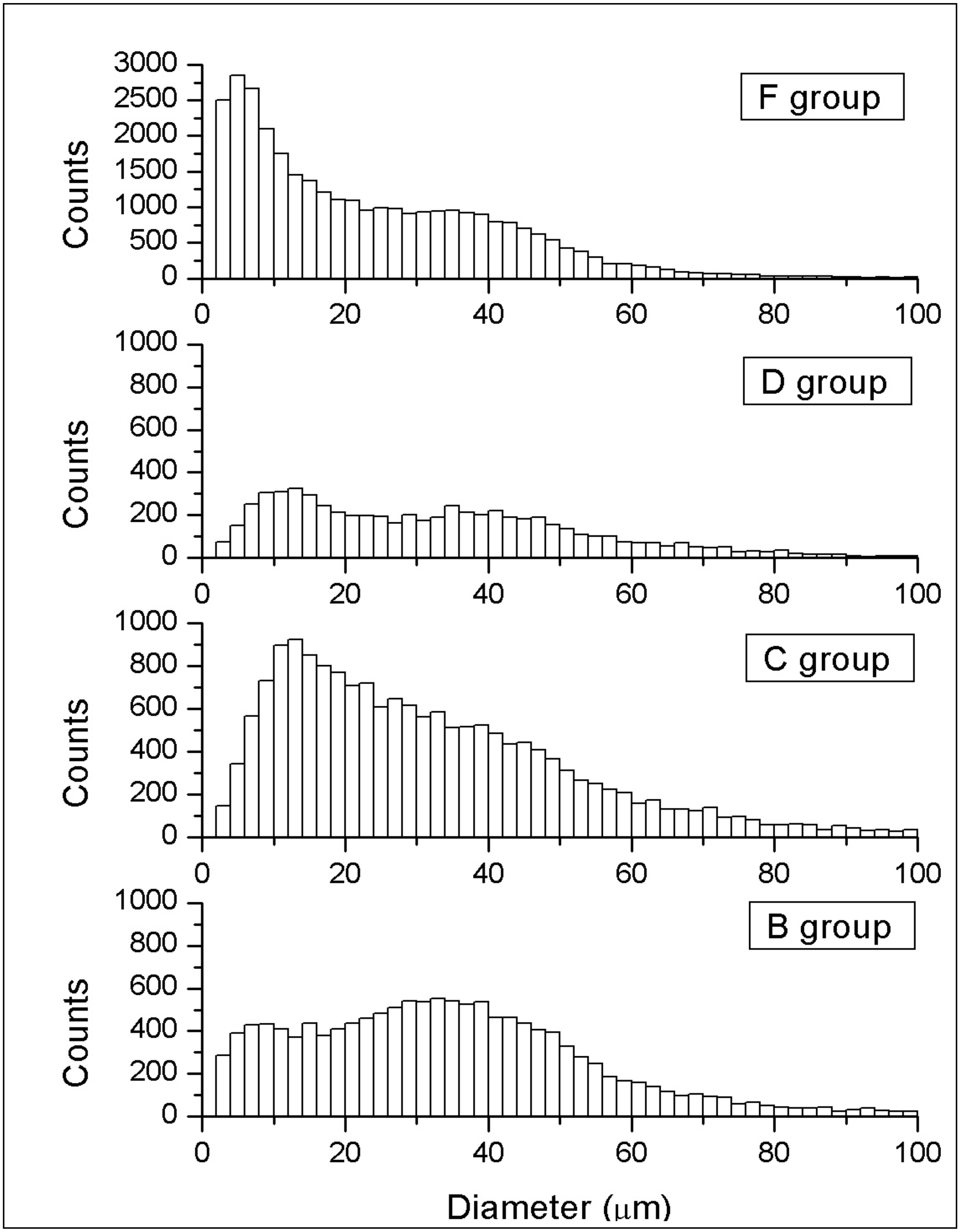

Figure 6A. Size distributions determined for all confined canisters in each group.

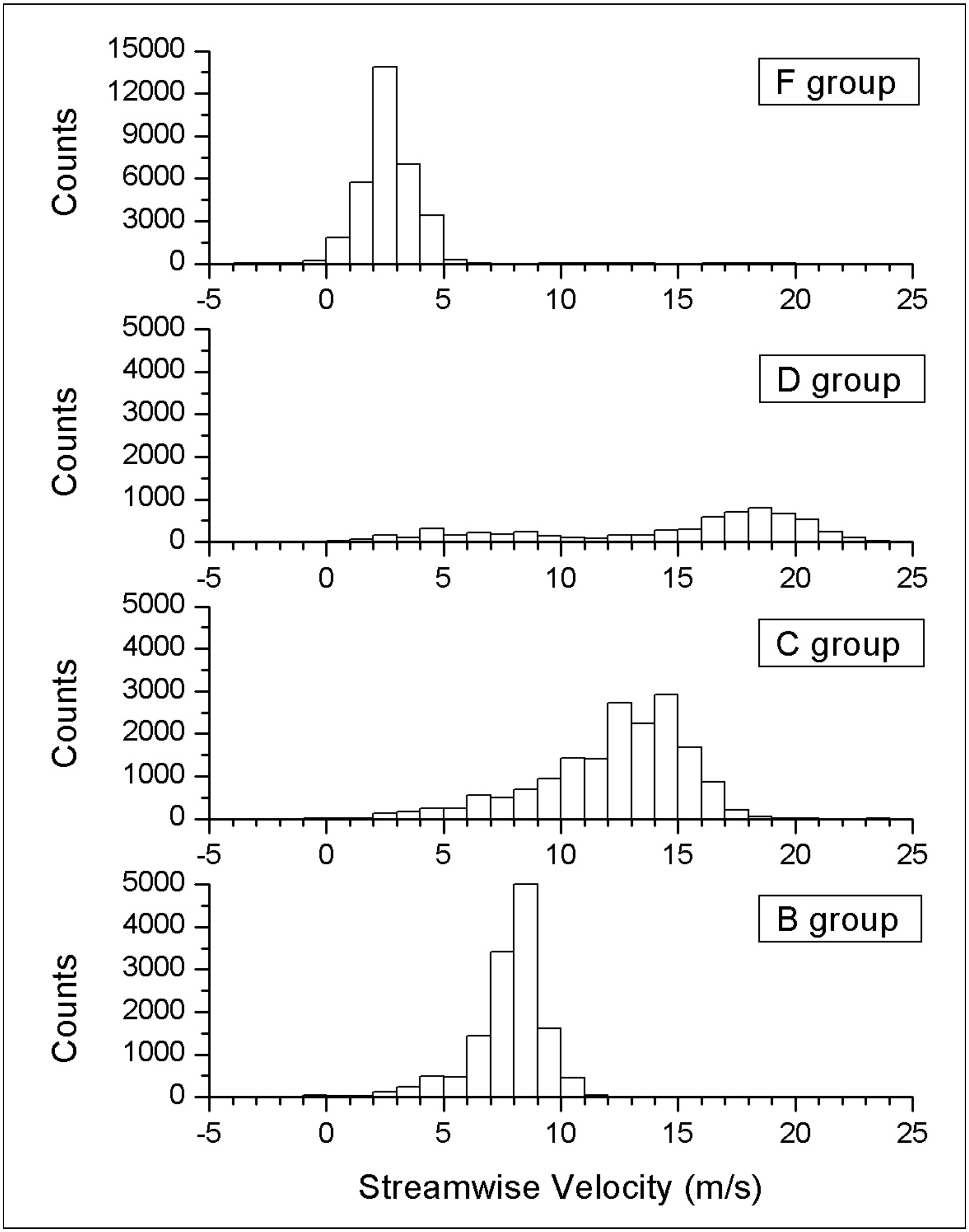

Figure 6B. Streamwise velocity distributions determined for all confined canisters in each group.