Atomization and Sprays, vol. 18, pp. 287–313, 2008

DROPLET SIZE AND VELOCITY MEASUREMENTS FROM COMMERCIAL "FOGGER" TYPE PEPPER SPRAY PRODUCTS

Cary Presser and Edward White V*
National Institute of Standards and Technology, Gaithersburg, MD 20899-8360, USA

Original Manuscript Submitted: 7/25/06; Final Draft Received: 2/27/07

Commercial pepper spray devices are available that deliver either a coherent liquid stream or an aerosol from the canister. Information is unavailable in the literature regarding either the spray characteristics (i.e., the droplet diameter, velocity, and number density) or the canister-to-canister variability of these devices. Consequently, their performance in delivering the active agent to the target is not well characterized and the amount of material delivered as small, potentially harmful, particles is unknown. This investigation used phase Doppler interferometry (PDI) to measure the size and velocity distributions of aerosol-type pepper sprays. This information was used to obtain preliminary information on the amount of smaller diameter droplets present in pepper spray products currently on the market. This preliminary information could then be combined with toxicity information (expected to become available) to determine whether the potential hazard is sufficient to warrant further study. Thus, characterization of the sprays (i.e., both droplet size and velocity) at the target location is important for this purpose. Each canister was fired repeatedly to discharge its contents in 1 s shots at 1 min intervals until the PDI could not detect droplets. Four different sets of commercially available pepper spray canisters were studied to document the variation in the aerosol diameter distribution from shot to shot. The results indicated that there were significant differences in the spray characteristics for the different canister sets. The number of shots per canister varied among the sets of canisters. The droplet mean diameter was fairly constant per shot for three of the four canister sets (averaging 54.0 μm with a standard deviation of 2.4 μm for all shots from these three sets) until nearly all of the canister liquid contents were expelled. At this point, the values of the droplet mean diameter, streamwise velocity, and number of droplets decreased significantly. The droplet diameters detected varied from a few micrometers (at the detection limit of the optical arrangement) to about 120 μm. For some groups, the diameter distributions were bimodal with peaks at about 10 μm and 40 μm.

*Corresponding author; e-mail: cpresser@nist.gov. This work was funded, in part, by the National Institute of Justice through an interagency agreement with the Office of Law Enforcement Standards at NIST. A. A. Fatah was the program manager. Thanks to Y. Dachman for processing of some of the data.

INTRODUCTION

Pepper sprays are gaining acceptance and popularity with law enforcement agencies as a safe and effective method of incapacitating aggressive subjects. Commercial hand-held pepper spray devices are classified by two types: (1) "coherent liquid streams," in which an uninterrupted column of liquid is expelled from the nozzle, and (2) "fog," in which an aerosol is delivered as a cloud of droplets entrained in the airflow [1]. During the use of pepper sprays to assist in subduing violent individuals, it is likely that some of the droplets are inhaled and therefore it is useful to determine the droplet diameters since smaller droplets can penetrate deeper into the lung after inhalation, thereby presenting a greater potential hazard [2]. Particulate matter (e.g., liquid droplets) with aerodynamic diameters equal to or less than 10 μm (PM_{10}) can reach the upper airways of the lung, and particles of diameter equal to or less than 2.5 μm ($PM_{2.5}$) can reach the alveoli and are thought to be the most hazardous [3].

Oleoresin Capsicum (OC) is an extract of naturally grown substances, i.e., the resin of cayenne pepper and different varieties of chili peppers. In addition to its use in food and pharmaceuticals, it is an active ingredient in the aerosol spray used by law enforcement agencies to subdue noncooperative individuals through the production of irritation and pain after contact with the eyes, nose, and throat. The pungent taste and pain associated with OC are the result of a family of compounds known as "capsaicinoids." The major capsaicinoids present in OC are capsaicin and dihydrocapsaicin, with smaller concentrations of related compounds [4, 5]. The effects of spraying these compounds on the skin and eyes are to cause a burning sensation and swelling [4]. Inhalation causes respiratory discomfort by inflammation of the mucous membranes, which stimulate the production of pain [6, 7]. The generation of pain is a temporary phenomenon lasting from 20 min to 90 min and is not the result of tissue damage [8]. The pungency of capsaicinoid compounds and preparations containing them is widely expressed in terms of "Scoville heat units" (SHUs) [4, 8, 9]. Today, high-performance liquid chromatography [10, 11] is used to measure the relative concentrations of capsaicinoids in OC, which correlates with SHU after correction for the relative hotness of the various capsaicinoids.

Oleoresin Capsicum is faster acting, less toxic, and has less "blowback" than mace and tear gas [9]. OC can effectively incapacitate an aggressive individual [7, 12, 13] or animal [9], and reduce injuries to officers and suspects, while reducing the number of complaints due to excessive force [14]. OC has been found to result in effective incapacitation 85–90% of the time without any significant known health effects due to eye or skin irritation, or inhalation of micrometer-sized droplets that can reach the alveoli. At the same time, a number of areas of concern have surfaced, which include legal and policy issues, technical issues such as product specification and performance, medical issues such as the safety and toxicity of OC (especially with regard to long-term use), and operational issues such as training and safety procedures for users [4]. For example, in a recent investigation under controlled conditions [15], corneal erosion was found to develop after an exposure to a pepper spray containing toxic solvents, so it is important to consider the other chemical components. Little is known about the effects and mechanisms by which capsaicinoids interact with airway epithelial cells. No overt respiratory effects have been observed after brief (1–2 s), low-dose exposures to pepper sprays. However, capsaicinoids have been shown to cause acute pulmonary inflammation and respiratory cell injury in laboratory mice and rats, and in human lung epithelial cell cultures [16].

Commercial products on the market are not well specified. The manufacturers use a wide range of unspecified natural or synthetic formulations. The concentration of OC ingredients may not be identified, and OC may be combined with other active ingredients. OC is either suspended (with the aid of surfactants) or dissolved in carrier liquids, such as water, ethanol, isopropanol, halogenated solvents, and mixtures of these liquids. Ethanol and isopropanol are flammable, and may be part of mixtures that are either flammable or nonflammable. Canisters also include gaseous propellants to expel the liquid content. Commonly used propellants are nitrogen, carbon dioxide, and hydrofluorocarbons, which are nonflammable, while isobutane and isobutane-propane mixtures are flammable. There is a dearth of data that correlates concentration of the different capsaicinoids or carrier liquids with canister performance and effectiveness.

Our objective was to obtain preliminary information on the characteristics of pepper sprays with particular attention to the amount of smaller diameter droplets present in pepper spray products currently on the market. This preliminary information could then be combined with toxicity information, expected to become available, to determine whether the potential hazard was sufficient to warrant further study. To address our objective, we characterized the sprays (i.e., droplet diameter, velocity, and number density) with regard to transport of the sprays to a specified target location. Our focus was on canister performance and not the health issues and inhalation safety since we do not investigate the transport of the aerosol into the lungs. Information on droplet transport can help characterize the performance and effectiveness of pepper spray canisters, which then can aid manufacturers in developing products that meet expectations. This study examined the variation in the droplet diameter and velocity distributions, and droplet number count with successive shots fired from four commercially available aerosol-type pepper spray products. Measurements were carried out under both unconfined and confined conditions. Unconfined conditions provided information on droplet transport under conditions similar to actual use, and the confined case provided a means to characterize the ensemble of droplets generated by the canister at the target location. Shot-to-shot changes are described, as well as differences between canister groups.

EXPERIMENTAL APPARATUS

Facility for Firing Canisters

Canisters were mounted on a stand similar to that described in the National Institute of Justice (NIJ) Standard on hand-held tear gas weapons [1], which establishes minimum performance requirements and test methods for these devices. The canister nozzle was located 1.83 m upstream of the point where the measurements were carried out, as recommended by the above-mentioned NIJ standard. The measurements were made in the probe volume of a phase Doppler interferometry (PDI) system. This recommended distance allowed for some vaporization of the solvent. To obtain sufficient data for the droplet diameter distributions, a cylinder of polyvinyl chloride, 76 mm in diameter and 1.52 m in length, was used to guide the spray to the probe volume, since dispersion of the unconfined spray for the given working distance was significant. The spray full-cone angle was estimated to be about 10^{o} for the different canisters. The confinement cylinder was centered between the mounted pepper spray canister and PDI probe volume, as shown by the overall view of the experimental arrangement in Fig. 1a. 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 central axis of the cylinder was aligned with the probe volume, as shown by the expanded view in Fig. 1b, to ensure detection of a sufficient number of droplets. The stand and probe volume were inside a ventilated plastic-walled chamber with dimensions of 1.2 m (width) $\times$ 2.4 m (height) $\times$ 6.1 m (length). The PDI instrumentation was located outside of the ventilated chamber.

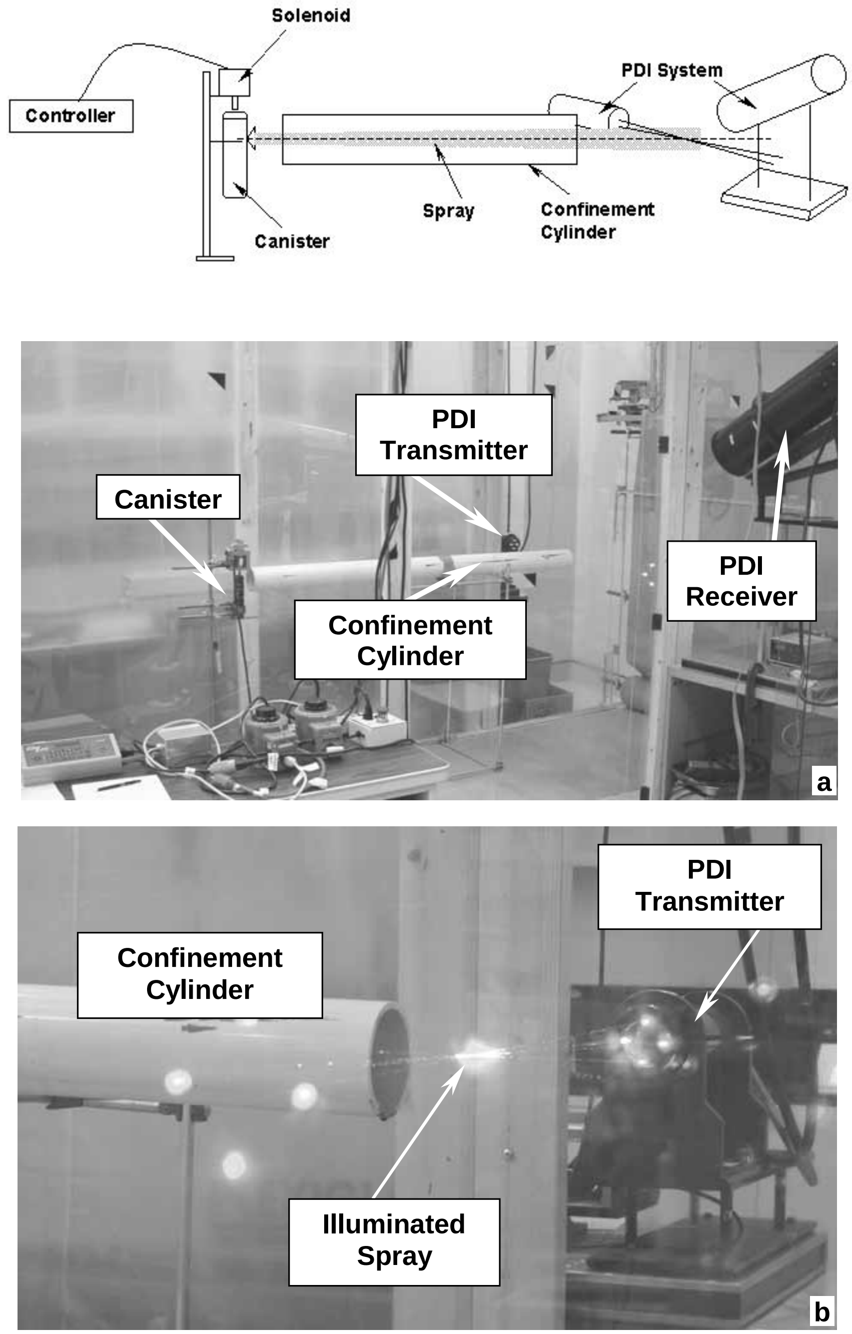

Fig. 1 (a) Schematic and photograph of the overall experimental arrangement. (b) An expanded view of the pepper spray exiting the confinement cylinder and illuminated by the laser beams of the phase Doppler interferometry (PDI) system.

Pepper Spray Canisters

Fifteen pepper spray canisters were evaluated, which included four models from three different manufacturers, and are denoted as groups *A*, *B*, *C*, and *D*. All canisters examined for a group were the same model and from the same manufacturer. The net canister weight and solvent for each group is presented in Table 1. The manufacturers did not provide either the nozzle design or canister pressures. The propellant was not specified in two cases, and was isobutane and an isobutane-propane mixture in the others. Each group included three canisters, the contents of which were expelled through the cylinder (i.e., confined case). For groups *B*, *C*, and *D* the contents of one canister were also expelled directly into the environment without the spray confinement cylinder (i.e., unconfined case). Each canister test consisted of depressing the canister nozzle with a solenoid for 1 s [1], recording the spray characteristics with the PDI system, and repeating the sequence at 1 min intervals until no droplets were detected by the PDI.

Table 1 Characteristics of the Different Canister Groups

Canister	Canister net weight* (g)	Solvent*	Total number of 1 s shots (confined cases)			Total number of detected droplets (confined cases)			Total number of 1 s shots (unconfined cases)	Total number of detected droplets (unconfined cases)
Group \ No.			*001*	*002*	*003*	*001*	*002*	*003*	*004*	*004*
A	83	isopropanol	61	63	59	11,916	10,153	10,806	–	–
B	28	isopropanol	6	6	6	4428	4248	4625	5	201
C	90	2-(2-butoxy-ethoxy) ethanol	7	7	7	3228	6336	7484	2	104
D	44	2-(2-butoxy-ethoxy) ethanol	5	3	3	1700	2245	2322	3	1185

*Provided by the manufacturer.

Phase Doppler Interferometry

Phase Doppler interferometry [17] 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 in that it measures droplet diameter as well as velocity [18–20]. 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 each of three detectors. The three modulated signals are out of phase with one another, allowing determination of the droplet diameter if the refractive index is known. The droplet velocity is determined from the number of fringes and droplet transit time through the probe volume. Bachalo [21] has published a review of PDI and its application to the study of aerosolized flows.

Measurements were carried out using a two-component phase Doppler interferometer (PDI) with a real-time signal analyzer (RSA), both manufactured by TSI, Inc.[1] [20, 21]. This PDI system is composed of the following: (1) transmitter (model XMT204-4.3), (2) fiber drive (model FBD240-X), (3) receiver (model RCV216-X), (4) real-time signal processors (models RSA3200-P and RSA3200-L), (5) photomultiplier tube box (model RCM200P), and (6) RSA IO card v.3.0 (model RSA3CB2DV3). The PDI was controlled using TSI DataVIEW software version 2.02 run on a personal computer using the Windows NT operating system. The RSA has the ability to optimize the number of samples acquired from the Doppler signal in real time. A 5 W argon ion laser operating in multiline mode was used as the illumination source. The green (wavelength of 514.5 nm) and blue (wavelength of 488 nm) lines of the argon ion laser were separated by beam conditioning optics, and focused by the transmitting optics to intersect and form the probe volume. The transmitting optics were coupled to the beam conditioning optics using fiber-optic cables to permit the transmitter to be located near the experiment. The front lens on the transmitter has a focal length of 500 mm. The green and blue beams have a beam separation distance of 39.9 mm and 40.2 mm, fringe spacing of 6.45 μm and 6.07 μm, and beam waist of 164 μm and 155 μm, respectively. The beam diameter

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

was 2 mm for both beams. Frequency shifting was set at 40 MHz. To accommodate the horizontal orientation of the experimental apparatus, the transmitter and receiver were positioned in a vertical plane, as shown in Fig. 1. The receiver was located at a scattering angle of 30^o measured from the direction of propagation of the laser beams. The size of the ventilated chamber and the desire to avoid contaminating the optics with pepper spray required the use of long focal length optics, which limited the detection of particles with sizes below 2.1 μm. The front and back lenses on the receiver had focal lengths of 1000 mm and 532 mm, respectively. The spacing for the three photomultiplier tube detectors used to carry out the sizing measurements was 34.8 mm between the first and second, and 101 mm between the first and third. A 150 μm slit aperture is located within the receiver to limit the length of the probe volume. The detectable droplet diameter range was 2.1–263 μm with the current optical arrangement. Further information describing the optical arrangement is provided elsewhere [22].

The setup procedure and normal systems tests for the optical arrangement were carried out as specified by the manufacturer [23]. The transmitted beams were checked for changes in their polarization, beam coincidence with each other inside the chamber, and proper focusing of the collected light on the receiver slit. Measurements of the water droplet diameters from a humidifier that was placed inside the chamber were used to check the quality and repeatability of the Doppler signal output and size measurements by comparison with previously recorded data. The droplet mean size and velocity were reproduced within 5% of the prior humidifier results. The optical arrangement remained unchanged (including the scattering angle) for all of the experiments. The signal processor was operated with a sample frequency of 40 MHz (the rate at which the Doppler signal is sampled), mixer frequency of 36 MHz (mixers are used to reduce the signal frequency prior to analog-to-digital conversion), and low-pass filter setting of 20 MHz (low-pass filters are used to remove the summed components from the down-mixed signal, so that only the difference is used). The settings were chosen to optimize the processor operation for the expected Doppler frequency, which is governed by the droplet velocity and fringe spacing. Hardware coincidence, which requires that droplets be detected on both PDI channels to be validated (with a maximum gate time of 200 μs), was used as an additional validation criterion for all measurements. The probe volume correction (to account for droplets of varying size traveling through different sections of the Gaussian beam profile) was carried out to optimize the quality of the measurements, but the intensity validation correction (to remove particles whose scattered light intensities are too low and high, and result in erroneous phase shifts and particle sizes) was not, because of the limited data rate and number of detected droplets per canister shot.

Droplet diameter and velocity distributions were obtained at one point in the center of the spray. Thus, knowledge of the droplet spatial distribution, i.e., transport of droplets off axis is beyond the scope of this work. The time interval over which the actual data were collected was 1 s, which is the duration of the 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. A refractive index of 1.378 (nondimensional slope value of 0.723) was used for isopropanol, and 1.431 (nondimensional slope value of 0.685) for 2-(2-butoxyethoxy)ethanol. Estimation of the measurement uncertainty is determined from statistical analysis of a series of replicated measurements (referred to as Type A evaluation of uncertainty) and from means other than statistical analysis (e.g., manufacturer estimates, referred to as Type B evaluation of uncertainty) [24]. The combined standard uncertainty for the PDI measurements is estimated from an earlier study [25] to be 8% for droplet diameter and 10% for droplet velocity. Note that the uncertainty associated with repeated measurements (Type A) was much smaller than the Type B uncertainties.

RESULTS AND DISCUSSION

The droplet Sauter mean diameter [26], mean streamwise velocity, and mean cross-stream velocity are compared for shot-to-shot variations in each canister group, and variations between groups. This information is used to characterize the droplets that reach the target location, and to determine whether droplets less than 10 μm are present in the diameter distribution. Sauter mean diameter is used for this study because the focus of the work is on the characterization of sprays (i.e., droplet transport). However, knowing the diameter distribution, one can obtain the representations commonly used in health effects studies. As a gauge of the number of droplets less than 10 μm at the target location, we provide the percentage of these droplets to the total number detected per shot knowing that the lower limit in size is 2.1 μm.

Shot-to-Shot Variations

Shot-to-shot variations are discussed for groups *A*, *C*, and *D*. Group *B* behaved similarly to groups *C* and *D*. The total number of shots detected by the PDI per canister for each group is given in Table 1. Droplets were detected by the PDI for all of the shots of the confined cases until the liquid content of each canister was nearly expelled. Only the first few shots with expelled liquid were detected at the probe volume location for the unconfined cases (except that, for canister group *A*, unconfined results were not recorded), which was attributed in part to the canister or spray orientation and droplet dispersion. Thus, the number of shots with detected droplets was less than the number of shots that produced significant visible spray. The total number of shots available per canister with significant visible spray was therefore approximated by the confined results (note that gas was still expelled from the canisters after the liquid was depleted). Results for the mean diameter and streamwise and cross-stream velocities with shot number are presented in Fig. 2 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 volume was increased significantly. The mean diameter was fairly constant per shot (average of 53.2 μm with a standard deviation of approximately 2.8 μm for shot numbers 1–6 of the three canisters) until nearly all of the liquid was exhausted (see Fig. 2a). Similarly, the average of mean diameters for the confined cases of group *B* was 55.0 μm with a standard deviation of 2.6 μm, and of group *D* was 54.1 μm with a standard deviation of 2.3 μm. The values of the mean diameter for the unconfined cases (closed symbols) were always lower than for the confined cases. This is attributed to droplet deceleration and dispersion with increasing streamwise distance, which also explains why the number of shots for the unconfined cases listed in Table 1 is lower than for the confined cases. Note also the difficulty in aligning and directing the unconfined spray since transport of the spray along the line of sight between the canister and probe volume is not assured. As shown in Fig. 2b, the mean streamwise velocity is initially about 14 m/s for the confined cases and decreases with increasing shot number (the average was 11.9 m/s with a standard deviation of 2.3 m/s for shots 1–6 of the three confined cases). For the unconfined case, the initial mean velocity was about 1 m/s, thus the spray had little momentum to reach the target. Figure 2c presents the mean cross-stream velocity (for which positive values are the component of velocity in the upward direction from the orientation of the PDI laser beams) and indicates little off-axis transport of droplets for the unconfined case (the average was –0.44 m/s with a standard deviation of 0.08 m/s for shot numbers 1–6 of the three confined cases). 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.

Figure 3 presents the distributions for droplet diameter and two compo-

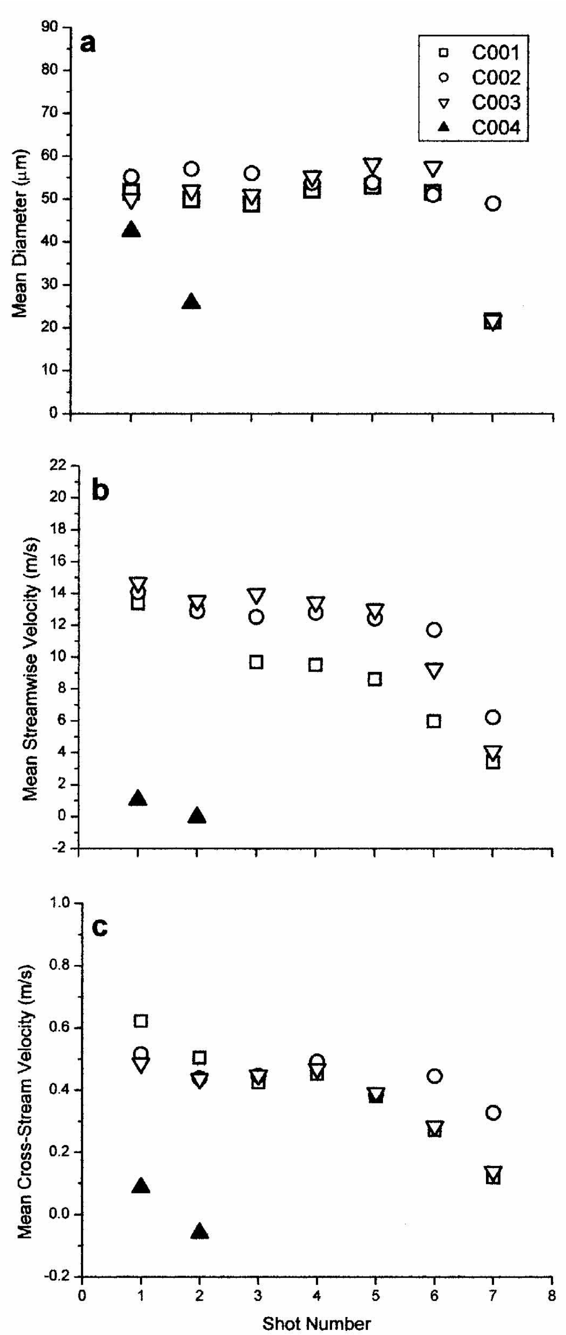

Fig. 2 Variation of the droplet (a) Sauter mean diameter, (b) mean streamwise velocity, and (c) mean cross-stream velocity with shot number for the four canisters of group *C*. The open symbols refer to confined cases and the closed symbols refer to the unconfined case.

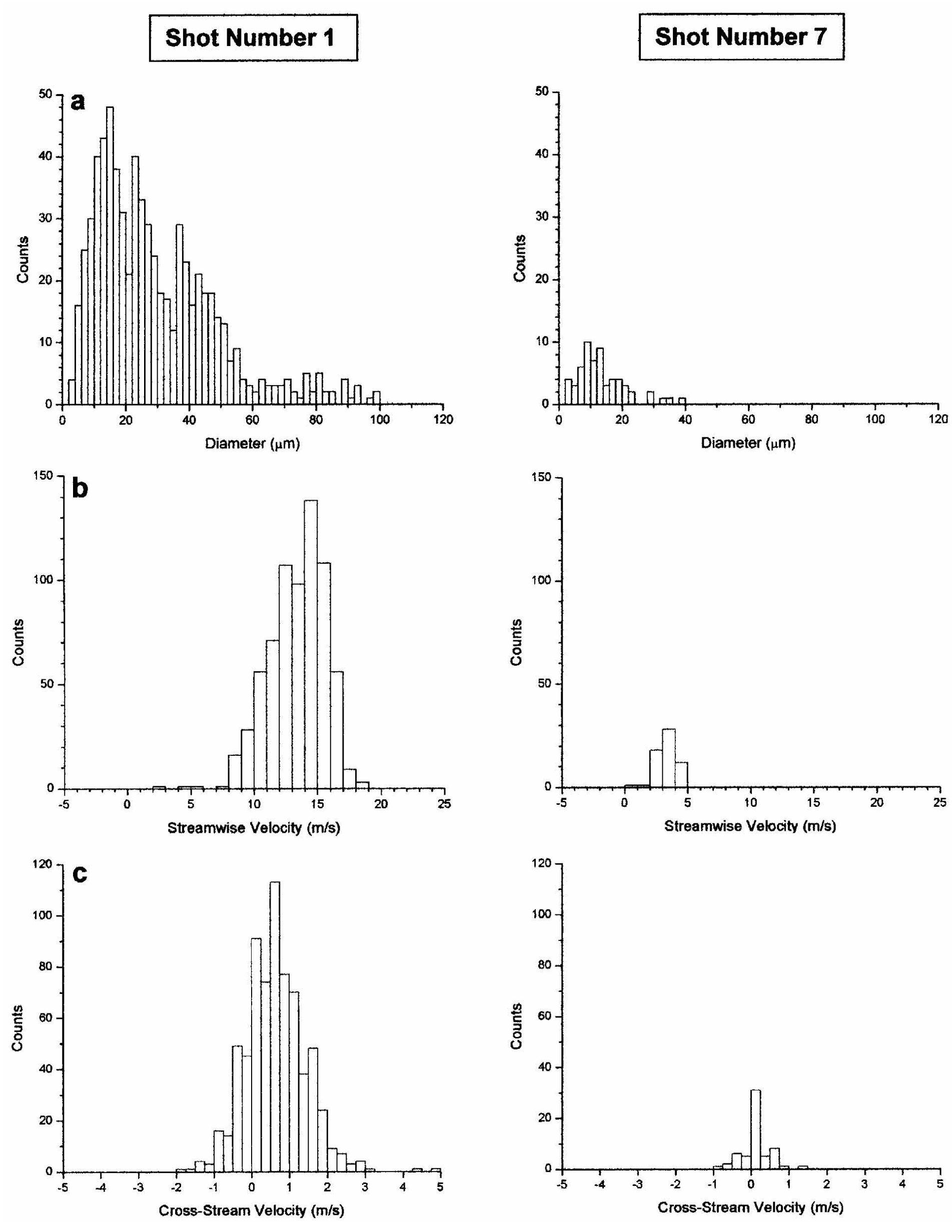

Fig. 3 Distributions for the droplet (a) diameter, (b) streamwise velocity, and (c) cross-stream velocity for shot numbers 1 (initial shot) and 7 (final shot) of canister *C001* (confined).

nents of velocity for the first shot of canister *C001* (where an arbitrary numerical designation was given for each canister of each group), which represents a typical 1 s first shot (i.e., similar to shot numbers 2–6). Also shown in Fig. 3 is the last shot (shot number 7) that gave measurable results. The distribution initially (see Fig. 3a, 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. 3a, 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 was well atomized by the gas propellant, or any larger droplets were transported off axis and were not detected since our measurements were near the center of the spray. Such spray characteristics are typical of hollow-cone sprays [26], 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 are near the spray periphery (boundary). The values of the streamwise and cross-stream velocity decrease, and the distributions become narrower as the canister is emptied (i.e., when comparing shot number 7 to number 1 in Figs. 3b and 3c, respectively). Note that the value of the cross-stream velocity for some droplets is as large as 5 m/s (see Fig. 3c, shot number 1). However, the corresponding streamwise velocities are as large as 17 m/s and indicate that the flow is still essentially in the axial direction. In the confined cases, the cylinder diameter (76 mm), along with droplet dispersion, allows for some droplet nonaxial transport. As the spray exits the cylinder, the unconfined droplets can further disperse before traversing the probe volume, resulting in a small radial component.

Figure 4 presents the variation of the droplet mean diameter and two components of velocity with shot number for group *A*. This group produced more shots (over 60 shots) with less liquid per shot (about half the number of droplets per shot) than the other groups, as shown in Table 1. The total number of droplets per canister detected for group *A* was more than 10,000, significantly larger than for the other groups. The variation in the results for droplet mean diameter (see Fig. 4a) increases significantly as the shots progress. The average of all mean diameters was 41.1 μm with a standard deviation of 10.2 μm. Figure 4a 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 diameter distributions indicated that for shot numbers 57 and 59 (see the two solid arrows), the presence of outliers and a small number count increased the value of the mean diameter dramatically above what

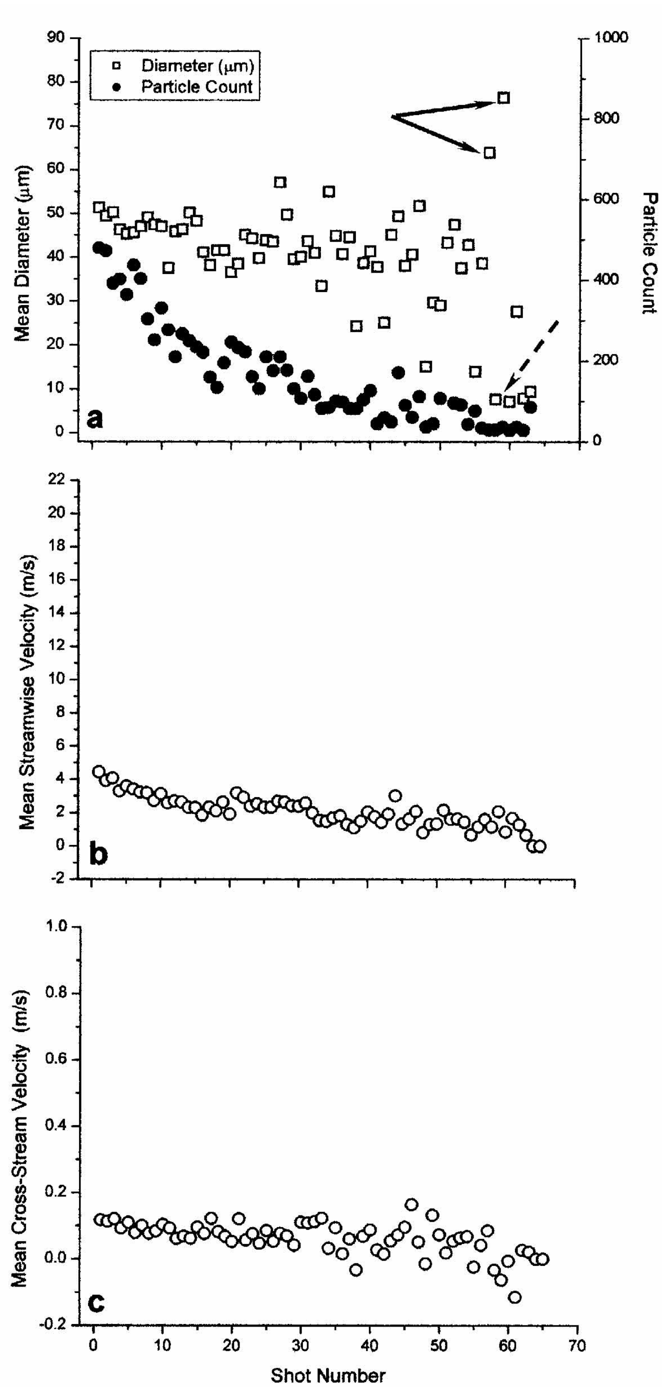

Fig. 4 Variation of the (a) droplet Sauter mean diameter and number count, (b) mean streamwise velocity, and (c) mean cross-stream velocity with shot number for canister *A002* (confined).

the value would be without the outliers. This is attributed to the greater weighting that an outlier has for a small population of droplets, as opposed to when the number count is large. Low values of the mean diameter are indicative of the limited amount of data (small number count and the absence of detected larger droplets, as statistically expected) for that shot (e.g., see shot numbers 58 and 60, pointed out by the dashed arrow). This variability is also present in both components of velocity (see Figs. 4b and 4c).

Differences between Canister Groups

As noted above, the variation of the droplet diameter and velocity from canister to canister within each group was relatively small when the spray was transported through the confinement cylinder. The variation between canister groups indicated that the amount of spray (i.e., number of droplets and total liquid mass) reaching the target from the specified distance was smaller for the unconfined canisters than for the confined canisters. For example, the ratio of the amount of liquid detected for the unconfined sprays to the confined sprays (R) for groups B, C, and D (i.e., for all shots and canisters per group) was 4.7%, 3.2%, and 70% (largest value for each group) on a number basis (n) and 1.4%, 1.8%, and 66.0% on a mass basis (m), respectively. The variable R_{iN} is defined as N_{iu}/N_{ic} where the subscripts u and c refer to the unconfined and confined cases, respectively, $N = n$, m, and $i = B$, C, D. The mass was determined by summing the cube of each droplet diameter (the ratio results in the density and constant associated with the droplet volume canceling out). Given these results, the value of R for group D was much larger than the other groups (i.e., $R_{DN} >> R_{BN}$, R_{CN}). It was noted that the total number of detected droplets for the unconfined canister of group D (*D004*) was much larger than for groups B and C (i.e., $N_{DU} >> N_{BU}$, N_{CU}). Also, the total number of detected droplets for the confined cases of group D relative to groups B and C was much less, i.e., by 47% and 37%, respectively (i.e., $N_{DC} << N_{BC}$, N_{CC}), and thus resulted in a larger value for the ratio of R_{DN}. Part of the reason for the larger number of detected droplets for the unconfined canister *D004* was the higher mean streamwise velocity of 4.4 m/s, as opposed to the other unconfined cases, e.g., 1 m/s reported above for the unconfined canister *C004*. As a result, more droplets reached the probe volume for canister *D004*. The streamwise velocity distribution was also broader for canister *D004* (as compared to the other unconfined cases) with a maximum value reaching 11 m/s, as opposed to, e.g., 3 m/s for canister *C004*.

Figure 5 presents distributions for the droplet diameter, streamwise ve-

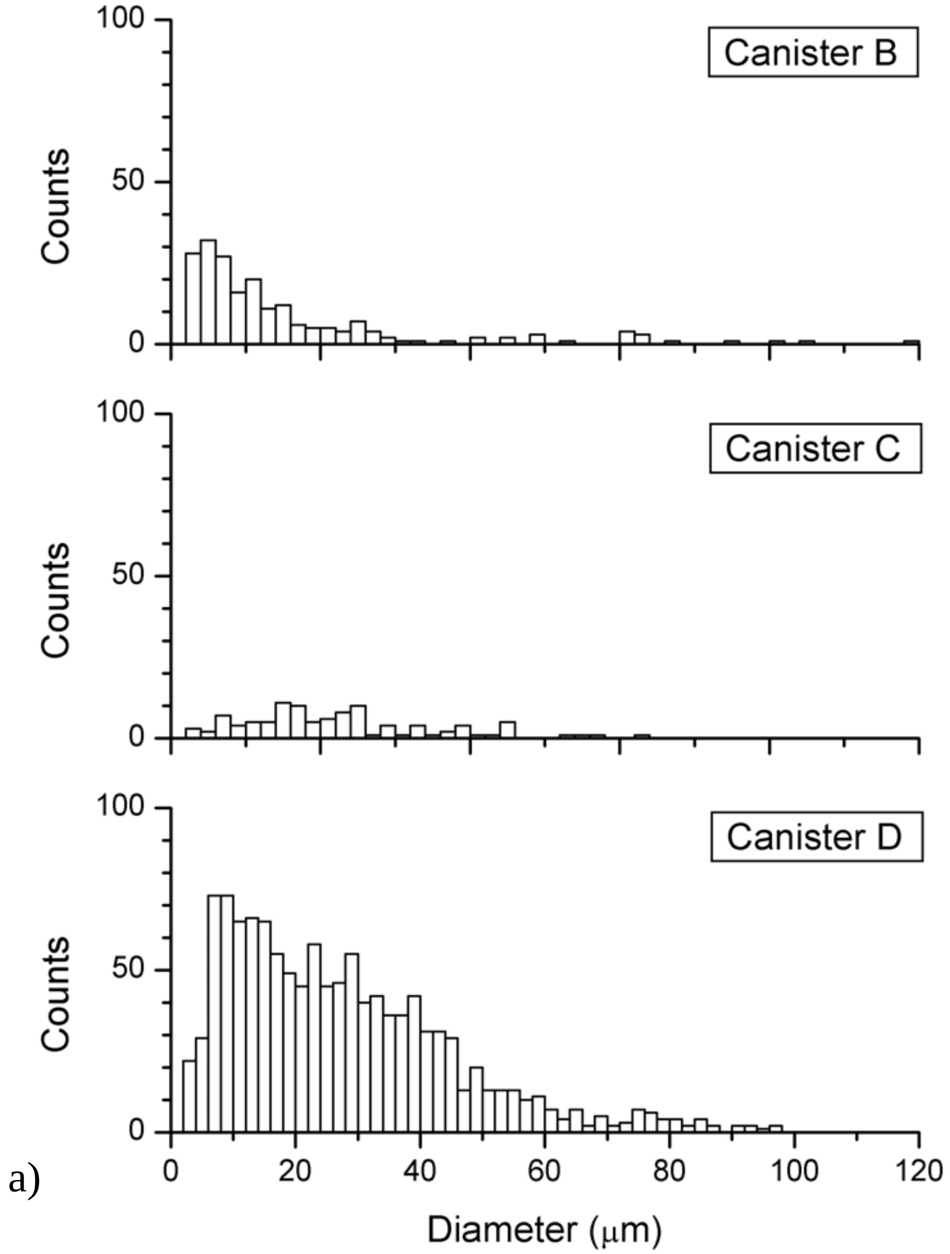

Fig. 5 (a) Droplet diameter distribution for three unconfined canisters (*B004* from canister group *B*, *C004* from canister group *C*, and *D004* from canister group *D*).

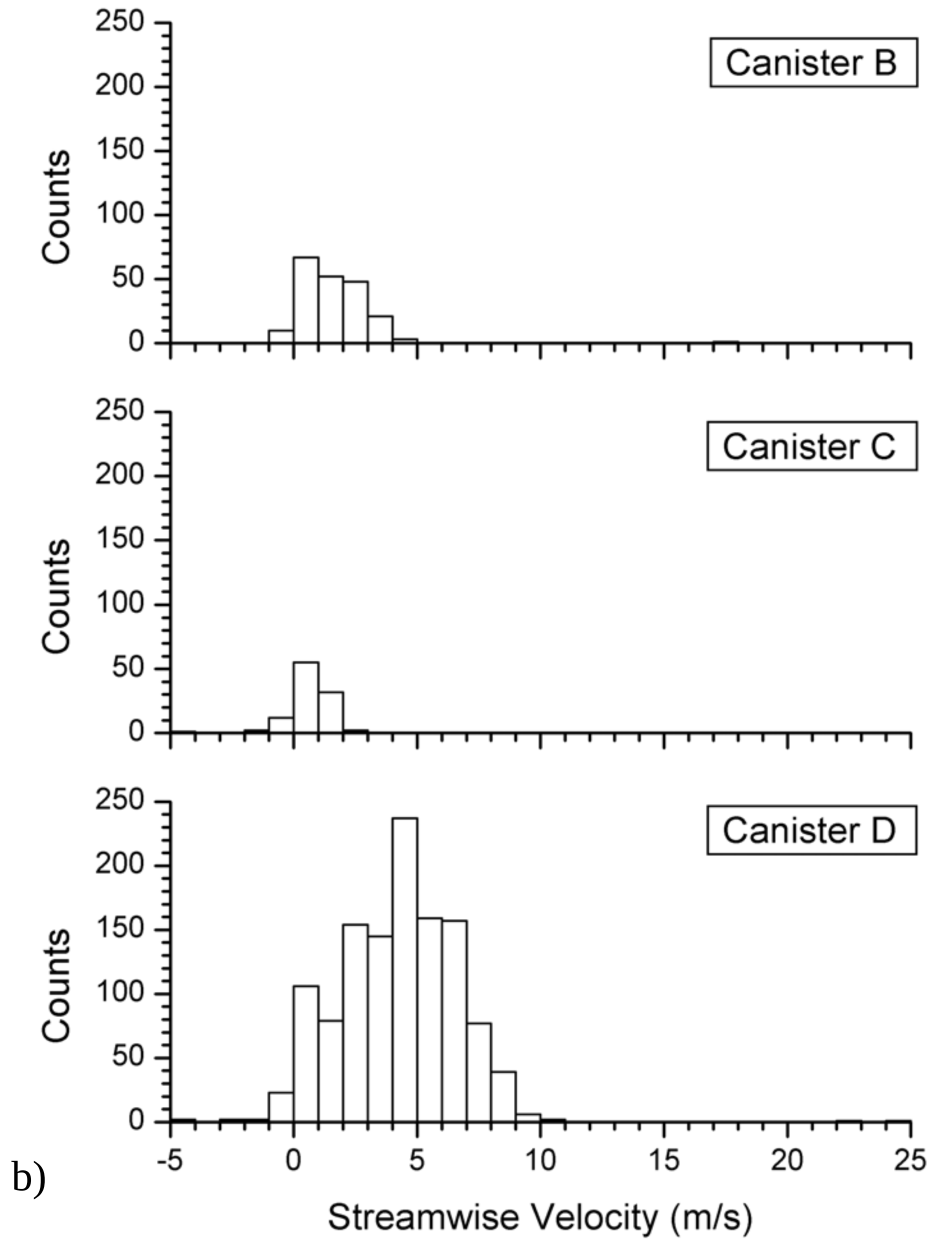

Fig. 5 (b) Droplet streamwise velocity distribution for three unconfined canisters (*B004* from canister group *B*, *C004* from canister group *C*, and *D004* from canister group *D*).

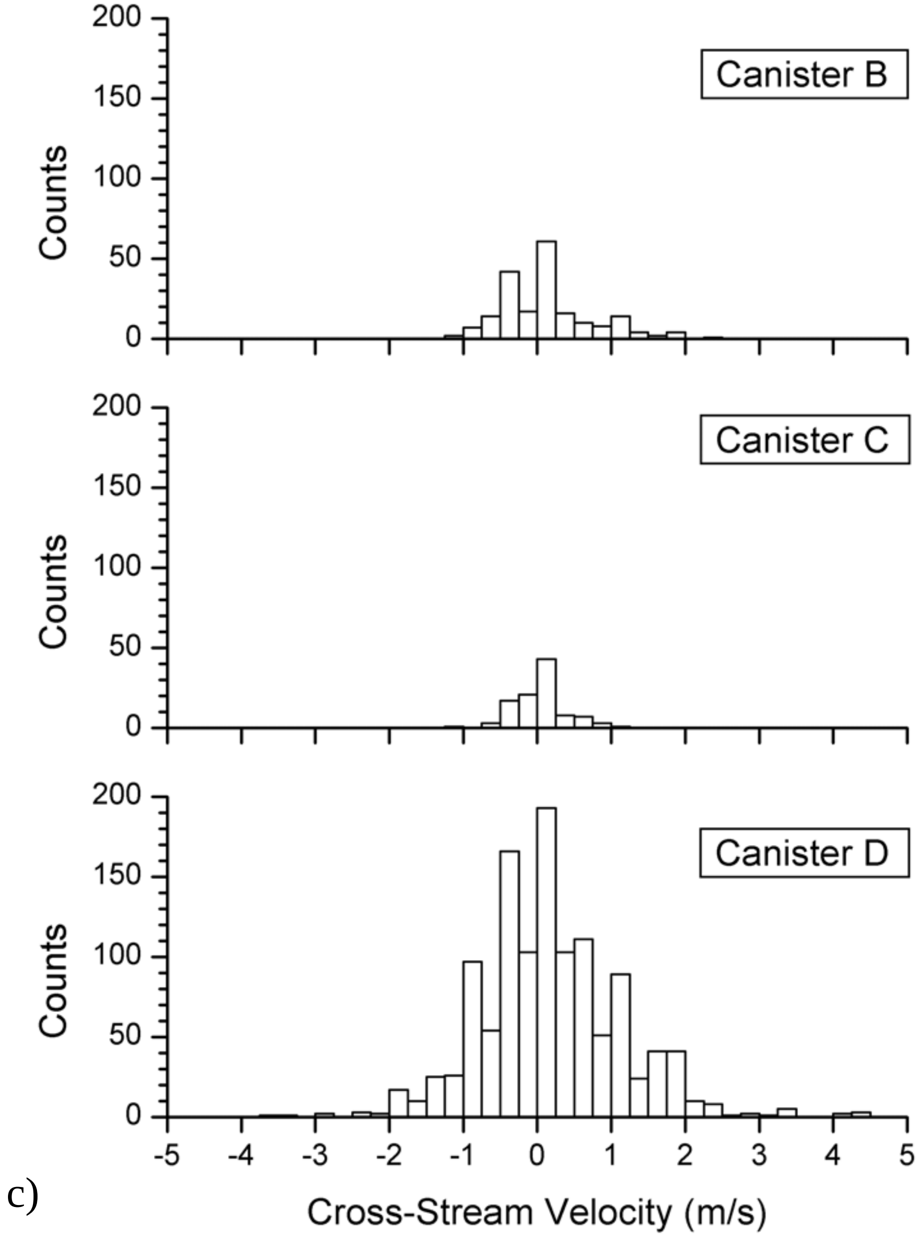

Fig. 5 (c) Droplet cross-stream velocity distribution for three unconfined canisters (*B004* from canister group *B*, *C004* from canister group *C*, and *D004* from canister group *D*).

locity, and cross-stream velocity for the three unconfined cases (*B004* for the canister from group *B*, *C004* for the canister from group *C*, and *D004* for the canister from group *D*). As indicated above, the number count for the unconfined cases is significantly lower than for the confined case. The range of detected droplet sizes (see Fig. 5a) varied among the three canister groups with the canister from group *D* having the widest detected range and the canister from group *C* the narrowest. Figure 5a also indicates that the droplet diameters detected at the probe volume tend to be smaller for the unconfined sprays than for the confined cases (see Fig. 6a). Comparing these results to the confined case indicates that the smaller diameter droplets tend to be concentrated near the center of the spray, whereas the larger droplets are transported in a more radial direction. The velocity components presented in Figs. 5b and 5c indicate that the droplets detected for canisters *B* and *C* have essentially entrained into the stagnant surrounding air. For canister *D*, there is a somewhat wider range of velocities, but there is no correlation between size and velocity. These results (i.e., the expelled droplets from the unconfined canisters, for the most part, were not detected at the target location) can be attributed to several factors such as canister orientation and droplet dispersion. The droplets that are detected at the target location tend to be small.

A picture of the general spray characteristics for a canister group is presented by combining the results (i.e., all shots) 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 (note the change in scale of the ordinate between canister groups in Figs. 6a and 6b). The largest droplet diameters in Fig. 6a were about 120 μm and the distributions were bimodal with varying skewness and kurtosis (i.e., peakedness). 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 Fig. 6a. The bimodal nature of the diameter distributions was the result of changes in the distribution between the initial and final shots. Figure 7 presents one example (canister *D002*) of the change in the distribution from shot to shot. For the first shot, the diameter distribution was bimodal with the dominant peak around 40 μm. As the shots progress, this peak diminishes and the peak at about 10 μm (which remains relatively unchanged between shots) becomes the prominent peak.

The variation in streamwise velocity between canister groups is presented in Fig. 6b, with only group *D* having a bimodal distribution to correlate with the bimodal diameter distribution. The correlation between droplet diameter and streamwise velocity for each shot from canister *D002* is presented in Fig. 8, providing an example of how the individual droplet diame-

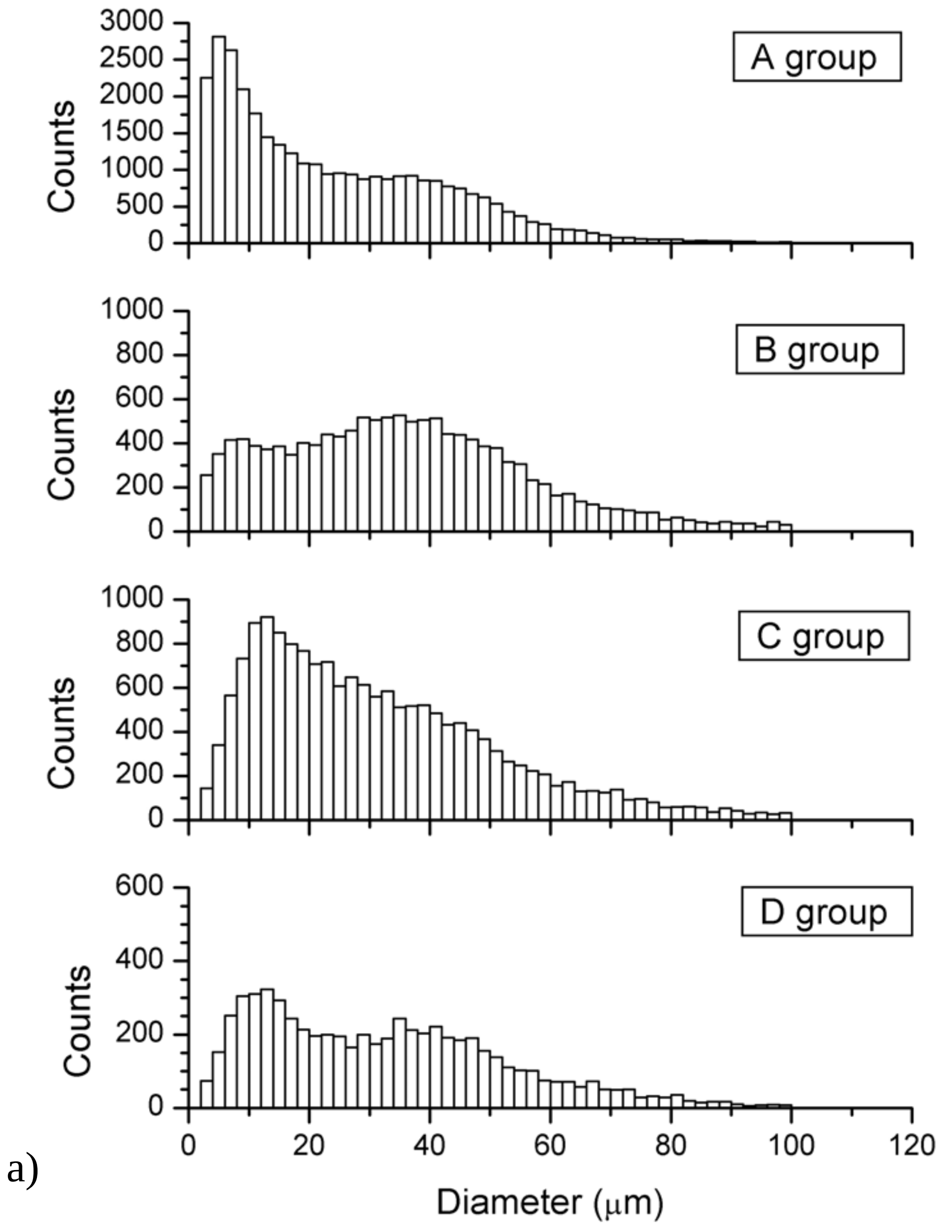

Fig. 6 (a) Droplet diameter distribution summed for all confined canisters in each group.

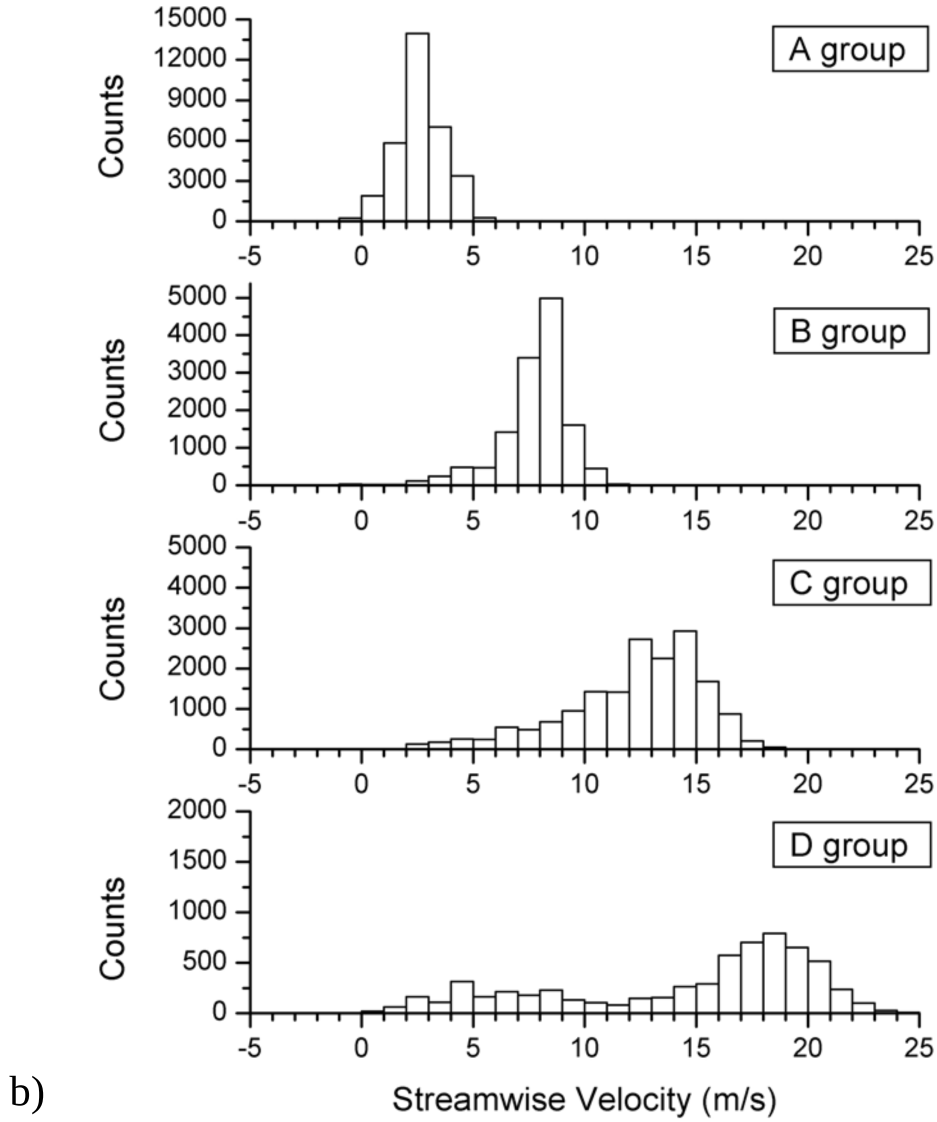

Fig. 6 (b) Droplet streamwise velocity distribution summed for all confined canisters in each group.

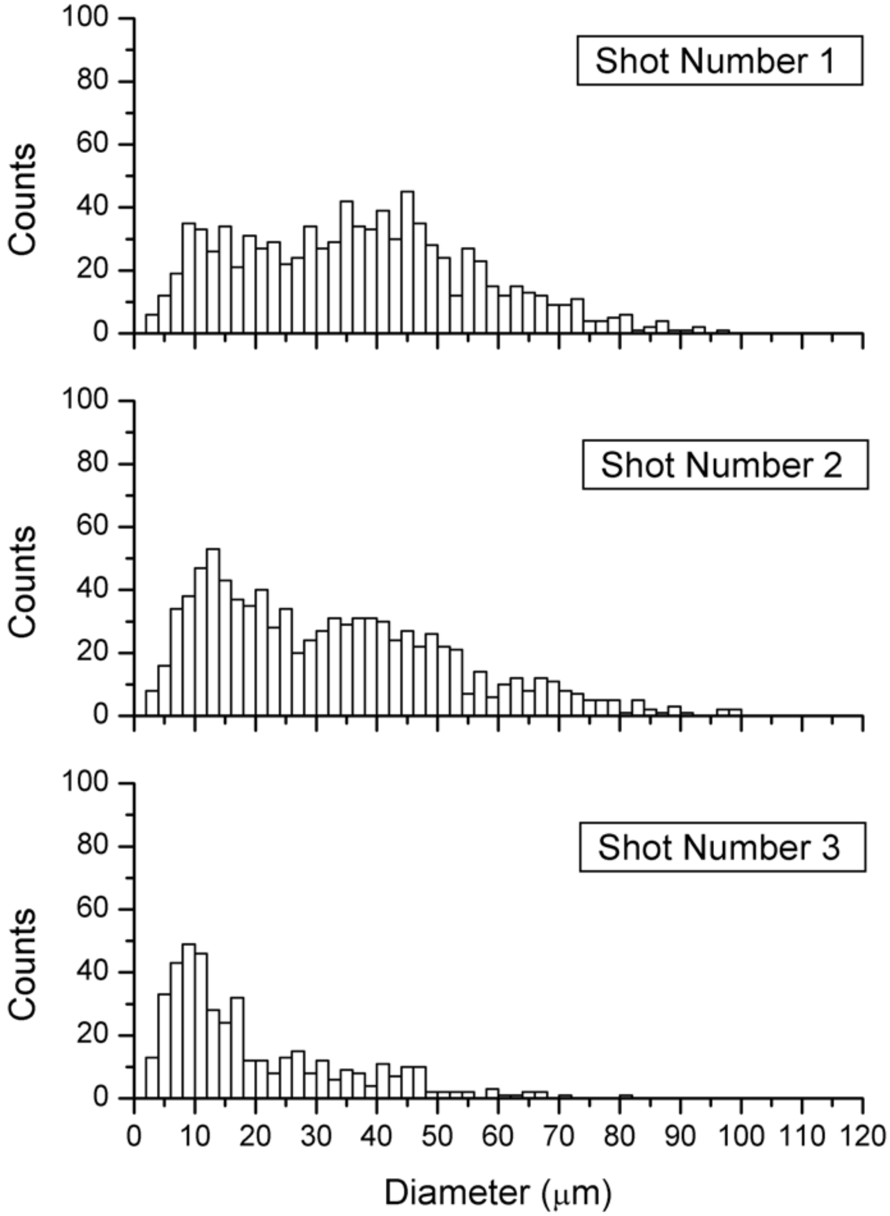

Fig. 7 Droplet diameter distribution for each shot of canister *D002.*

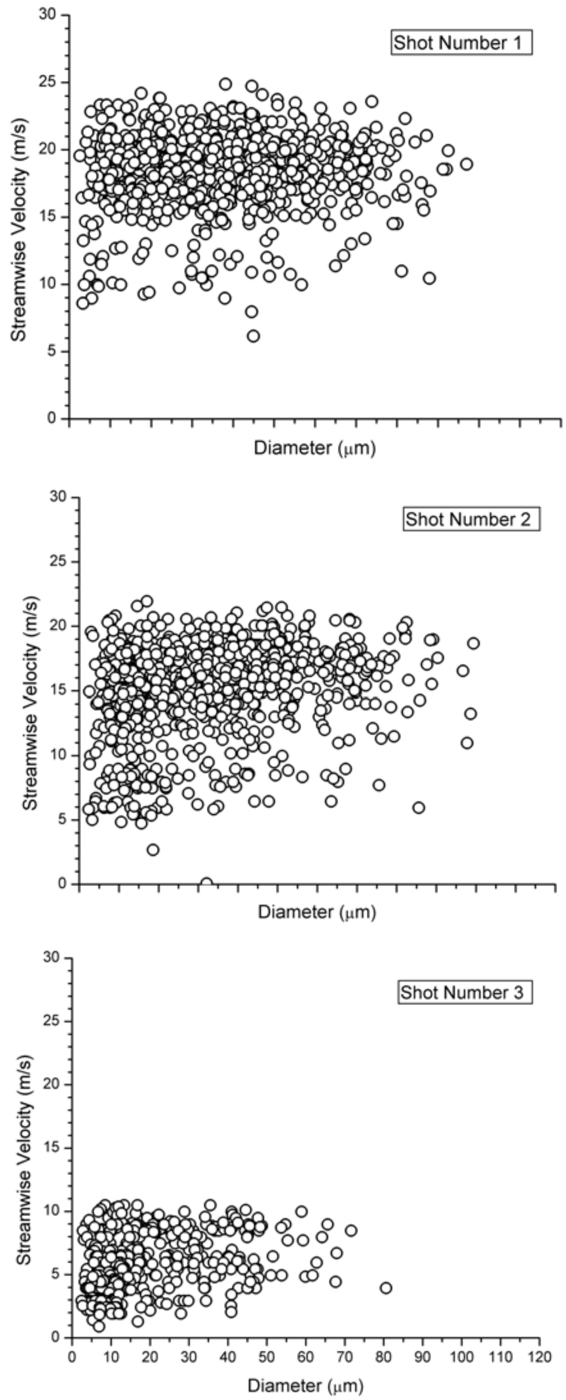

Fig. 8 Droplet diameter-streamwise velocity correlation for each shot of canister *D002*.

ters and corresponding streamwise velocities decrease with each canister shot. The mean cross-stream velocities were small and the distributions narrow, i.e., within velocities of ±3 m/s, which indicated that the flow was essentially in the axial direction because of the confinement cylinder, and thus were not included for brevity.

Pepper sprays are generally aimed at the face for maximum effect with droplet diameters equal to or less than PM_{10} having the potential to reach the upper airways of the lung, and droplet diameters equal to or less than $PM_{2.5}$ penetrating further. Along with a general characterization of the sprays fired over a typical target distance of 1.83 m (6 ft), this study compared the ratio of droplets with diameters less than or equal to 10 μm to the total count for each canister group. Averaging the three confined canisters from each of the four groups, this ratio by number count for group *A* was 29.9% with a standard deviation of 3.9%, and for groups *B*, *C*, and *D* the ratios were between 10% and 13% with standard deviations of 1.4% to 2.7%. For group *A*, the average of the ratio by mass was 0.199% with a standard deviation of 0.035% and for groups *B*, *C*, and *D* the ratios were between 0.041% and 0.073% with standard deviations of 0.005% to 0.030%. We note that the ratios for the three unconfined canisters, measured on one canister per group, were similar to the confined cases. The values for the unconfined cases were 49.8% (*B004*), 12.5% (*C004*), and 13.5% (*D004*) by number count, and 0.47%, 0.14%, and 0.09% by mass, respectively. These data, when combined with information on toxicity of the components of the sprays, should indicate whether the potential hazard is sufficient to warrant further study.

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. Three of the four canister sets gave very similar diameters with an average of 54.0 μm and a standard deviation of 2.4 μm. The droplet diameters of the other group were substantially different, with an average of the mean diameters of 41.1 μm and a standard deviation of 10.2 μm. A significant mass fraction of droplets with diameters less than 10 μm (droplet diameters that potentially can be inhaled) were present in the sprays, the amount depending on the characteristics of the canisters. These results are a preliminary estimate based on products presently on the market that, combined with data on the toxicity of the sprays, should allow determination of whether further health effect studies are justified.

REFERENCES

1. National Institute of Justice Technology Assessment Program, Hand-Held Aerosol Tear Gas Weapons, NIJ Standard 0110.00, U.S. Government Printing Office, Washington, DC, Sept., 1985.
2. P. W. Longest and C. Kleinstreuer, Computational Models for Simulating Multicomponent Aerosol Evaporation in the Upper Respiratory Airways, *Aerosol Sci. Technol.*, vol. 39, pp. 124–138, 2005.
3. J. A. Fay and D. S. Golomb, *Energy and the Environment*, Oxford University Press, New York, pp. 231–232, 2002.
4. L. K. Pershing, C. A. Reilly, J. L. Corlett, and D. J. Crouch, Assessment of Pepper Spray Product Potency in Asian and Caucasian Forearm Skin Using Transepidermal Water Loss, Skin, Temperature and Reflectance Colorimetry, *J. Appl. Toxicol.*, vol. 26, pp. 88–97, 2006.
5. R. Q. Thompson, K. W. Phinney, L. C. Sander, and M. J. Welch, Reversed-Phase Liquid Chromatography and Argentation Chromatography of the Minor Capsaicinoids, *Anal. Bioanal. Chem.*, vol. 381, pp. 1432–1440, 2005.
6. J. Granfield, J. Onnen, and C. S. Petty, Pepper Spray and In-Custody Deaths, Science and Technology, International Association of Chiefs of Police, March 1994.
7. T. C. Chan, G. M. Vilke, J. Clausen, R. Clark, P. Schmidt, T. Snowden, and T. Newman, Pepper Spray's Effects on a Suspect's Ability to Breathe, National Institute of Justice Research in Brief, NCJ 188069, International Association of Chiefs of Police, Dec., 2001.
8. http://www.pepper-spray-store.com/relatedinfo/whatis.shtml
9. D. S. Miller, Review of Oleoresin Capsicum (Pepper) Sprays for Self-Defense Against Captive Wildlife, *Zoo Biol.*, vol. 20, pp. 389–398, 2001.
10. J. D. Batchelor and B. T. Jones, Determination of the Scoville Heat Value for Hot Sauces and Chilies: An HPLC Experiment, *J. Chem. Educ.*, vol. 77, no. 2, pp. 266–267, 2000.

11. B. V. Thomas, A. A. Schreiber, and C. P. Weisskopf, Simple Method for Quantitation of Capsaicinoids in Peppers using Capillary Gas Chromatography, *J. Agri. Food Chem.*, vol. 46, pp. 2655–2663, 1998.
12. S. M. Edwards, J. Granfield, and J. Onnen, Evaluation of Pepper Spray, National Institute of Justice Research in Brief, NCJ 162358, International Association of Chiefs of Police, Feb., 1997.
13. National Institute of Justice Technology Assessment Program, Oleoresin Capsicum: Pepper Spray as a Force Alternative, International Association of Chiefs of Police, Mar., 1994.
14. National Institute of Justice, The Effectiveness and Safety of Pepper Spray, National Institute of Justice Research in Brief, NCJ 195739, Apr., 2003.
15. J. M. Holopainen, J. A. O. Moilanen, T. Hack, and T. M. T. Tervoa, Toxic Carriers in Pepper Sprays May Cause Corneal Erosion, *Toxicol. Appl. Pharmacol.*, vol. 186, pp. 155–162, 2003.
16. C. A. Reilly, J. L. Taylor, D. L. Lanza, B. A. Carr, D. J. Crouch, and G. S. Yost, Capsaicinoids Cause Inflammation and Epithelial Cell Death Through Activation of Vanilloid Receptors, *Toxicol. Sci.*, vol. 73, pp. 170–181, 2003.
17. J. F. Widmann, C. Presser, and S. D. Leigh, Improving Phase Doppler Volume Flux Measurements in Low Data Rate Applications, *Meas. Sci. Technol.*, vol. 12, pp. 1180–1190, 2001.
18. F. Durst and M. Zare, Laser Doppler Measurements in Two-Phase Flows, *Proc. of LDA Symp.*, Copenhagen, pp. 403–429, 1975.
19. W. D. Bachalo and M. J. Houser, Development of the Phase/Doppler Spray Analyzer for Liquid Drop Size and Velocity Characterizations, *AIAA/SAE/ASME 20th Joint Propulsion Conference*, AIAA-84-1199, Cincinnati, June, 1984.
20. W. D. Bachalo and M. J. Houser, Phase/Doppler Spray Analyzer for Simultaneous Measurements of Droplet Size and Velocity Distributions, *Opt. Eng.*, vol. 23, pp. 583–590, 1984.
21. W. D. Bachalo, Experimental Methods in Multiphase Flows, *Int. J. Multiphase Flow*, vol. 20, pp. 261–295, 1994.
22. C. Presser and C. T. Avedisian, Transport of High Boiling-Point Fire Suppressants in a Droplet-Laden Homogeneous Turbulent Flow Past a Heated Cylinder, *Atomization and Sprays*, vol. 16, no. 6, pp. 627–656, 2006.

23. TSI/Aerometrics Phase Doppler Particle Analyzer Operations Manual, TSI, Inc., St. Paul, pp. 1–15, 1999.
24. B. N. Taylor and C. E. Kuyatt, Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, NIST Technical Note 1297, National Institute of Standards and Technology, Gaithersburg, 1994.
25. J. F. Widmann, S. R. Charagundla, C. Presser, and A. Heckert, Benchmark Experimental Database for Multiphase Combustion Model Input and Validation: Baseline Case, Progress Report, NISTIR 6286, National Institute of Standards and Technology, Gaithersburg, Feb., 1999.
26. A. H. Lefebvre, *Atomization and Sprays*, Hemisphere, New York, pp. 90–92, 1989.