Volumetric Collection Efficiency and Droplet Sizing Accuracy of Rotary Impactors

B. K. Fritz, W. C. Hoffmann, J. A. S. Bonds, M. Farooq

Abstract. *Measurements of spray volume and droplet size are critical to evaluating the movement and transport of applied sprays associated with both crop production and protection practices and vector control applications for public health. Any sampling device used for this purpose will have an efficiency of collection that is a function of the sampling device itself, the droplet size of the spray being sampled, and the airspeeds under which the sampling is conducted. This study focuses on two rotary impaction devices, the Hock and the FLB samplers, that were evaluated under two droplet sized sprays and four airspeeds. The collected spray concentrations were compared to standard passive samplers whose theoretical collection efficiency was calculated and used to estimate the actual spray volume sampled. Additionally, droplet sizing information derived from image analysis of droplet deposits on the rotary impactor collection surfaces was compared to actual measurements of droplet size of the sampled spray cloud. Generally, overall collection efficiencies ranged from 2.5% to 20%, with the FLB being more efficient than the Hock and with lower efficiencies at higher airspeeds for both samplers. Comparison of the droplet sizing data showed that the FLB sampler tended to underpredict the D_{V10} and D_{V50} data, while the Hock tended to overpredict the D_{V50} and D_{V90} data.*

Keywords. *Collection efficiency, Droplet sizing, Rotary impactor, Spray collection, Spray sampler.*

While atmospheric transport of applied sprays is commonly associated with drift from agrochemical applications, another less common application is vector control, which relies on the movement of applied spray material over long distances to maximize control. Research associated with both of these activities relies on the ability to successfully quantify the amount, and if possible, the droplet size characteristics of these airborne sprays. The droplet size commonly associated with these driftable sprays ranges have been suggested to be between 100 µm (Miller, 1993) and 150 µm (Yates et al., 1985). In vector control applications, optimal droplet sizes are commonly less than 40 µm (Mount, 1998). With potential increases in overall exposure levels from agrochemical application as well as potential increase in the abundance and variety of pathogen vectors due to climate change (Boxall et al., 2009), it is critical to have tools to measure to fate and transport of applied sprays. There are a number of methods that have been developed and used to measure these sprays, including passive sampling devices such as strings, monofilament, ribbons, straws, and screens as well as active sampling devices such as high-volume air samplers, rotary impingers, and rotary rods. Typically, the rotating impactor type sampling devices are deployed when sampling smaller droplets, such as dispersed sprays used in public health entomology, where the size distribution and the spray volume are required to fully characterize the spray (Bonds et al., 2009).

Differences in collection efficiency of various spray samplers confound characterization efforts. The collection efficiency (CE) of any sampling device is simply the ratio of the spray volume or mass measured by the sampler to the actual volume or mass of spray that is in the air and potentially available for the sampler to collect. This CE is dependent upon the geometry and operational characteristic of the sampler as well as the size of the spray droplets being collected and the ambient airspeed under which the measurement is being performed. It is generally accepted that smaller spray droplets prove to be the most difficult to sample using impaction sampling devices and thus are collected with the lowest efficiencies. There have been numerous efforts to quantify the CEs of various sampling devices for different droplet sizes, but the most commonly referenced is the work done by May and Clifford (1967), who developed a series of experimental and theoretical impaction efficiency curves for cylindrical, spherical, ribbon, and disc-shaped targets for monodispersed sprays. Their results generally show that the collection efficiency increases with narrower collection surfaces, larger droplets, and increased velocity of the airstream entraining the droplets.

A number of other studies have examined and documented the collection characteristics of various other stationary samplers. Whitney and Roth (1985) found CEs ranging from over 90% to less than 1% for spray droplet less than 50 µm on string collectors, with higher collection efficiencies for larger droplets and higher airspeeds. Fox et al. (2004)

Submitted for review in September 2010 as manuscript number PM 8761; approved for publication by the Power & Machinery Division of ASABE in December 2010.

The authors are **Bradley K. Fritz, ASABE Member Engineer,** Agricultural Engineer, and **W. Clint Hoffmann, ASABE Member Engineer,** Agricultural Engineer, USDA-ARS Areawide Pest Management Research Unit, College Station, Texas; **Jane A. S. Bonds, ASABE Member,** Associate Professor, Public Health Entomology Research and Education Center (PHEREC), Florida A&M University, Panama City, Florida; and **Muhammad Farooq, ASABE Member Engineer,** Agricultural Engineer, Navy Entomology Center of Excellence, Jacksonville, Florida. **Corresponding author:** Bradley K. Fritz, USDA-ARS, 2771 F&B Road, College Station, TX 77845; phone: 979-260-9584; fax: 979-260-9386; e-mail: brad.fritz@ars.usda.gov.

found that nylon screen collectors had CEs ranging from 50% to 70% for sprays with volume median diameters (VMD) of less than 45 µm for airspeeds of 4 m s^{-1}. Fritz and Hoffmann (2008a) found 9% to 98% efficiencies for nylon screen cylinders sampling a spray with a 19 µm VMD in airspeeds ranging from 0.4 to 3.8 m s^{-1}.

Where stationary samplers, such as a wire or string, rely solely on the speed of the airstream carrying the droplet to provide the energy for impaction, active collection devices introduce some mechanical advantage into the sampling system to improve capture efficiency. For example, rotary slide impactors rotate the sampling surface, thereby increasing the relative velocity difference between the droplet being sampled and the sampling surface, resulting in greater impaction efficiency for smaller droplets as compared to a stationary surface. While the total area from which droplets are sampled is simply the frontal area perpendicular to the airstream for stationary collectors, the rotation of the sampling surfaces by rotating impactors changes this sampling area. The sampling surface itself does not continually sample from a stationary area, rather, in the case of the rotary impactor, it is rotated around an axis, resulting in a volumetric sampling rate. The sampling area, or window, for rotating impactors is the vertical area within which passing spray droplets may be captured on the sampling surface. The volume of the airstream passing through this sampling window, or the aspiration rate, is determined by the ambient airspeed. Therefore, while the probability of droplet collection on the sampling surface increases, the probability of a given droplet going through the sampling window being intercepted by the sampling surface decreases.

Cooper et al. (1996) evaluated a string sampler, an isokinetic sampler, and a rotary sampler (6 × 75 mm slides held 130 mm apart and rotating at 2.9 m s^{-1}). After attempting to correct for the variances between the sampling and aspiration rates, Cooper et al. (1996) found dual-slide volumetric CEs ranging from 1% to over 70% for droplet sizes from 10 to 25 µm and airspeeds from 0.25 to 1.5 m s^{-1}. Typically, CEs were greatest for the 20 and 25 µm droplets at the lowest airspeed. As the different CEs at different airspeeds (as reported by Cooper et al., 1996) show, correcting for aspiration rate versus sampling rate did not remove the influence of airspeed on the calculated CE. Bonds et al. (2009) found that rotating slide impactors with narrower slides and higher rotational velocities had higher CEs, ranging from 84% to 98% for a 16 µm VMD spray sampled at airspeeds from 1 to 3.5 m s^{-1}, than wider, slower rotating slides, which had CEs ranging from 66% to 21% for the same droplet size spray and airspeeds. However, these CEs were based on the sampled volume per area of the slide (not the sampling window), with no adjustment for sampling versus aspiration rate. Further details on both the Hock and FLB samplers, as well as design details regarding both, can be found in Bonds et al (2009).

The objective of this work is to evaluate the overall and droplet size specific volumetric CEs of two rotary impactors based on spray concentration measured passing through the sampling window over a range of airspeeds that are expected in field trials. Additionally, the droplet size spectrum of the collected spray is evaluated against that measured by laser diffraction in a wind tunnel.

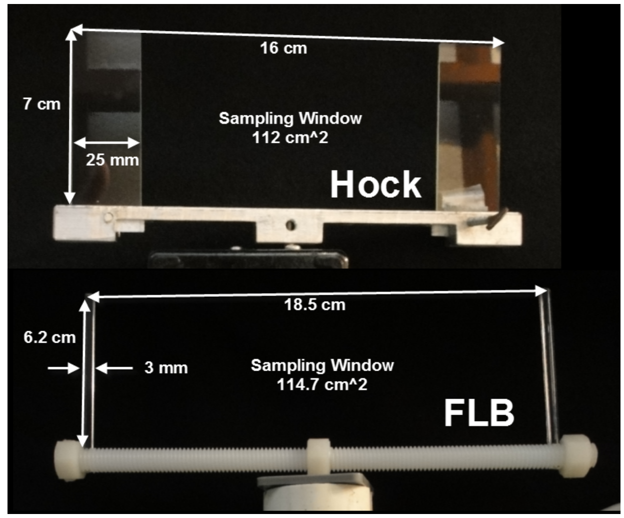

Figure 1. The two rotating impactors under investigation: the 3 mm 5.6 m s^{-1} FLB sampler and the 25 mm 3.6 m s^{-1} Hock sampler.

Materials and Methods

Rotating Impactors

Two rotating impactor samplers were investigated, the Hock and the Florida Latham Bonds (FLB) impactors (fig. 1). The Hock sampler uses 25 mm glass microscope slides that are held 16 cm apart (outside edge to outside edge) and rotated at a velocity of 3.6 m s^{-1}. The FLB uses 3 mm acrylic slides that are held 18.5 cm apart (outside edge to outside edge) and rotated at a velocity of 5.6 m s^{-1}. This corresponds to motors speeds of 510 and 588 rpm for the Hock and FLB samplers, respectively. For this study, both volumetric concentration and droplet size measurements were taken. The Hock sampler used an uncoated glass microscope slide for volumetric data and a Teflon coated slide (BioQuip, Rancho Dominguez, Cal.) for the droplet sizing data. The FLB sampler used two 3 mm acrylic slides cut from extruded acrylic bars (McMaster-Carr, Atlanta, Ga.) coated with FEP (Teflon) tape (McMaster-Carr, Atlanta, Ga.), one for volumetric data and the other for droplet sizing data.

Wind Tunnel Facilities

Sampler testing was conducted at the USDA-ARS Aerial Application Technology low-speed wind tunnel in College Station, Texas. The low-speed tunnel (1.2 × 1.2 × 12.2 m) is a push system with a 0.8 m axial-flow fan outfitted with an electronic variable speed control that can produce airspeeds between 0.5 to 6.5 m s^{-1}. A gridded flow straightener is positioned in the tunnel 0.75 m downwind of the fan outlet. Testing was conducted 10 m downwind of the fan. Both the FLB and the Hock samplers were evaluated at 0.5, 2, and 4 m s^{-1} with two different spray droplet sizes. The spray was generated using air-assisted nozzles (Advanced Special Technologies, Winnebago, Minn.). An unmodified version of the nozzle (fig. 2), called nozzle 1 for this study, spraying BVA oil at 552 kPa (80 psi) produces a spray with a VMD of approximately 15 µm (Hoffmann et al., 2009). A nozzle with reduced airshear across the fluid orifice was manufactured to create a coarser spray by increasing the gap through which the pressured air flowed (fig. 2). The nozzle's original configuration (nozzle 1) had an air orifice diameter of 2.5 mm and, combined with the tube diameter of the fluid orifice of

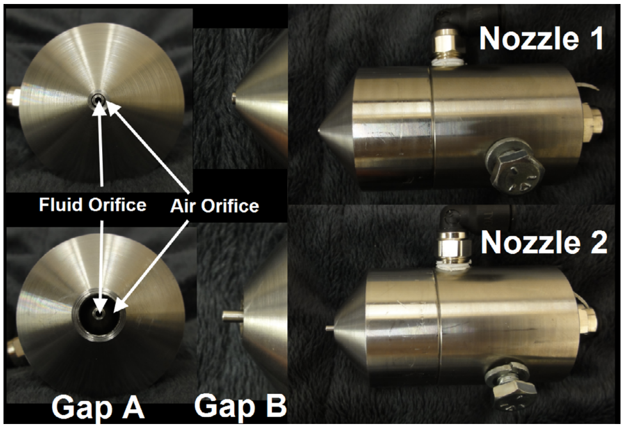

Figure 2. Nozzles used in collection efficiency study.

2.2 mm, had a gap for the air to exit of 0.15 mm around the fluid orifice (gap A in fig. 2) and a distance from the air exit orifice to the fluid exit orifice of 0.7 mm (gap B in fig. 2). This nozzle was modified by boring the air exhaust to 7.6 mm, resulting in gap A increasing to 2.7 mm (fig. 3) and gap B to 3.2 mm. With these modifications made and operating at the same air pressure, a spray with a VMD of approximately 25 µm was produced. This modified nozzle was denoted nozzle 2 for this study. It should be noted that this modification was done in-house and is not commercially available.

Spray Materials

BVA crop oil with Uvitex dye (BASF, Research Triangle Park, N.C.) added at a rate of 2 g L^{-1} was metered to the nozzle using a syringe pump (model NE-4000, New Era Pump Systems, Inc., Farmingdale, N.Y.). A total of 1 mL was metered at a volume feed rate of 10 mL min^{-1} and allowed to disperse down the length of the tunnel for each spray replication. This volume and rate were established through a stepwise alteration of nozzle pressure. For each airspeed and spray nozzle tested, sample slides had to have sufficient spray material deposited on the slides for detection while ensuring that slide saturation was avoided for accurate droplet sizing analyses. Six replicated measurements were made at each sampler, wind speed, and droplet size combination. Previous testing of a similar nature determined that a minimum of six replicated measurements are needed due to the inherent variability in the data.

Collectors with Known Sampling Efficiencies

Determining the collection efficiency for the rotary impactors required determining the actual spray volume presented to the sampler during each test. Using a method detailed by Fritz and Hoffmann (2008b), fine wire samplers (0.559 mm diameter × 152 mm length) were positioned on either side of the rotary sampler being tested. The theoretical collection efficiencies of these samplers were used to correct to true concentrations. Wire samplers were clamped in hemostats (approx. 3 mm of the wire held in the hemostat jaws) and secured to a post that was attached to the tunnel floor such that the center of the wire was centered vertically in the tunnel. The wires were positioned 30 cm apart, centered horizontally (each 15 cm from the tunnel centerline) and 25 cm upwind of the rotary sampler. The rotary samplers were positioned such that the centers of the slides were vertically centered in the tunnel and that the center of rotation of the sampler was centered horizontally in the tunnel.

Droplet Size Measurement via Laser Diffraction

During each test replication, droplet size was measured 0.5 m upwind of the rotary samplers using a Sympatec HELOS laser diffraction droplet sizing system (Sympatec, Inc., Clausthal, Germany). Droplet sizing was done upwind to ensure that the droplet-laden air was undisturbed by the rotating slides and that the laser had an unobstructed line of sight. The Helos system uses a 623 nm He-Ne laser and was setup with a dynamic measurement diameter size range of 0.5 to 875 µm across 32 sizing bins. Tests were performed within the guidelines provided by ASTM Standard E1260 (ASTM, 2009). Droplet size data measured included volume median diameter (VMD or D_{V50}) and the 10% and 90% diameters (D_{V10} and D_{V90}) (ASTM, 2004).

Sample Processing

At the conclusion of each test replication, wire samplers were collected and placed in individually labeled zip-top bags. The slide designated as the volumetric sample for the rotary impactors was also collected and placed in an individually labeled zip-top bag. The other slide, designated as the droplet sizing sample, was attached to a labeled poster board using double-sided tape. The bags were brought back to the laboratory for processing. Fifteen milliliters of hexane were added to each sample bag, which was then agitated for 20 s, after which 6 mL of effluent was poured into a cuvette. The cuvettes were then placed into a spectrofluorophotometer (model RF5000U, Shimadzu, Kyoto, Japan) with an excitation wavelength of 372 nm and an emission of 427 nm to determine the fluorescent concentration. The fluorometric readings were converted to volume of spray collected by comparisons to standards generated using the actual oil and dye mixture. The minimum detection level for the dye and sampling technique was 0.07 ng cm^{-2}.

The spray volumes measured were then expressed as volume of spray per area sampled. The area sampled by the fine wire samplers was calculated simply as the diameter (0.559 mm) of the wire multiplied by the length of wire exposed to spray (149 mm) for a collection area of 0.833 cm^2 (A_{wire}). For the rotary impactors, the collection area was calculated as the window through which spray passed that droplets could be collected by the slides. For both samplers, this window was calculated as the distance between the outermost edge of the slides (16 cm for the Hock and 18.5 cm for the FLB) and the actual length of slide exposed to spray (7 cm for the Hock and 6.2 cm for the FLB) for sampling window collection areas of 112 and 114.7 cm^2 (A_{window}), respectively, for the Hock and FLB samplers (fig. 1). The concentration sampled by the rotary impactors was then calculated using equation 1:

$$C_{rotary} = \frac{V_{single\ slide}}{A_{window}} \quad (1)$$

where

C_{rotary} = spray concentration measured by the rotary impactor over the area of the sampling window (µL cm^{-2})

$V_{single\ slide}$ = volume of spray material that deposited on the single slide sample processed for deposition using fluorescent analysis (µL)

A_{window} = area of sampling window for a given rotary impactor (cm^2).

The concentrations sampled by the fine wires were calculated using equation 2:

$$C_{wire\ i} = \frac{V_{wire\ i}}{A_{wire}} \quad (2)$$

where

$C_{wire\ i}$ = spray concentration measured over the area of the fine wire sampler (µL cm^{-2})

$V_{wire\ i}$ = volume of spray material that deposited on the fine wire sample processed for deposition using fluorescent analysis (µL)

A_{wire} = frontal area of sampling wire (cm^2)

i = 1 or 2, for wire sample 1 or 2 used in each test replication.

The slides saved for droplet size data were analyzed via DropVision image processing software (Leading Edge Associates, LLC, Waynesville, N.C.). Measurements were taken across the width of the slide so as not to bias toward smaller drops that collect at the slides edge. A minimum of 250 drops were counted for each slide. The DropVision software returns results in the form of D_{V50}, D_{V10}, and D_{V90} as well as, the cumulative droplet size distribution and coverage (drops mm^{-2}).

Calculation of Volumetric Collection Efficiencies for the Rotating Impactors

The overall CEs of the rotary impactors for each nozzle at each wind speed were determined by comparison with the true spray concentration as determined by adjusting the fine wire measured concentrations with the theoretical fine wire CE. As only one slide per treatment replication was processed for deposition analysis, the determined CEs are for the concentrations measured by each rotary impactor from the sampling window on a single slide. The CEs of the stationary wire samplers were determined for each of the airspeeds following methods described by Fritz and Hoffmann (2008b). Briefly, this method involves determining the Stokes number, which is the ratio between the stopping distance of the sampled droplet sizes and the diameter of the collection surface. Using the droplet size distribution measured with the Sympatec system and the airspeeds at which testing occurred, particle Reynolds numbers were determined and used to calculate the stopping distances for the multiple droplet sizes sampled. With this and the sampler diameter, the Stokes number was calculated and used to determine the impaction efficiency of the specific droplet sizes based on a sigmoidal curve fit of the May and Clifford (1967) data for cylindrical collectors. The droplet size specific impaction efficiencies were multiplied by the volume fraction measured within specific size bins and then summed over the entire size distribution to determine the overall CE.

The calculation of the overall CE for the rotating impactors for each airspeed, nozzle, and replication combination was completed using the following steps:

1. The CEs for the sampling wires were determined using the airspeed and droplet size distribution measured for each replication following the methods mentioned above. These values ranged from 40% to over 80%, increasing with airspeed and droplet size.
2. The measured spray deposition for both wires was then adjusted to an estimate of the true concentration by dividing by the determined CE values (eq. 3):

$$C_{true\ i} = \frac{C_{wire\ i}}{\mathrm{CE}_{wire}} \quad (3)$$

where

$C_{true\ i}$ = estimate of true spray concentration presented to the rotary sampler (µL cm^{-2})

CE_{wire} = volumetric CE efficiency of the fine wire samplers.

3. The true concentrations measured by the two wires ($C_{true\ i}$) were averaged to return an estimate of the true spray concentration that was presented to the rotating impactor (C_{true}).
4. The CE of the rotary sampler was then determined by comparison with the estimated true concentration. The numerical CE for the overall volumetric concentrations was calculated using equation 4:

$$\mathrm{CE}_{rotary} = \left(\frac{C_{rotary}}{C_{true}}\right)100 \quad (4)$$

where

CE_{rotary} = overall single-slide volumetric concentration collection efficiency of spray measured through the sampling window by the rotary impactor.

C_{rotary} = volume of spray solution measured on a single slide from the sampling window of the rotary collector.

C_{true} = estimate of the true spray volume per area presented to the rotary collector as determined by averaging the fine wire corrected concentrations (step 3).

Droplet Size Range Specific Collection Efficiencies

In addition to the overall CE for each of the rotating impactors, the CEs at which the impactors sampled specific droplet size ranges were evaluated. Droplet size range specific CEs were determined by comparing the measured versus true concentrations within the droplet size ranges from 0 to 10 µm, 10 to 20 µm, 20 to 30 µm, 30 to 40 µm, and >40 µm. These CE values were determined following similar steps to those listed for the overall CE, with the exception that the measured concentrations were adjusted based on the fraction of spray contained within the specific droplet size bin of interest. The value of C_{true} was adjusted based on the volume fraction of spray within each of the size bins as measured by the Sympatec laser diffraction system ($D^3_{Sym\_i}$) directly upwind of the sampling location, as described earlier. The value of C_{rotary} was adjusted based on the volume fraction of spray within the droplet size bin of interest sampled on the slide as determined using the DropVision system ($D^3_{DV\_i}$), also described earlier. The droplet size range specific CEs were calculated using equation 5:

$$CE_i = \left(\frac{D^3_{DV\_i} \cdot C_{rotary}}{D^3_{Sym\_i} \cdot C_{true}} \right) 100 \quad (5)$$

where

CE_i = single-slide volumetric concentration collection efficiency of spray measured through the sampling window by the rotary impactor for the *i*th droplet size bin.

$D^3_{DV\_i}$ = volume fraction of spray measured by the rotary sampler as determined by the DropVision system.

$D^3_{Sym\_i}$ = volume fraction of the actual spray for the *i*th droplet size bin presented to the rotary sampler as measured by the Sympatec laser diffraction system.

i = drop bin range: 0 to 10 µm, 10 to 20 µm, 20 to 30 µm, 30 to 40 µm, or >40 µm.

Droplet Sizing Accuracy

Droplet sizing accuracy was determined by comparing the D_{V10}, D_{V50}, and D_{V90} volume diameters measured from the slides using the DropVision software to that measured by the Sympatec system. The percent error between the slide measured data and the Sympatec data was determined using equation 6:

$$DS_{i_{error}} = \left(\frac{\left(D_{Vi\_DV} - D_{Vi\_Sym}\right)}{D_{Vi\_Sym}} \right) 100 \quad (6)$$

where

DS_{i_error} = percent error between the DropVision measured *i*th volume diameter and the Sympatec measured *i*th volume diameter.

D_{Vi_DV} = *i*th volume diameter collected by the rotary impactor as measured by the DropVision software.

D_{Vi_Sym} = *i*th volume diameter of the actual spray presented to the rotary impactor as measured by the Sympatec system.

i = 10%, 50%, or 90% volume.

Data Analyses

Significance testing of airspeed, sampler, and spray nozzle effects on single-slide CE and droplet sizing efficiency (percent error) for the D_{V10}, D_{V50}, and D_{V90} volume diameters was performed using the general linear model analysis of variance in Systat (version 13, Systat Software, Chicago, Ill.). Means separations were determined using Dunnett's T3 test (given the unequal variances between the means) using Systat. All testing was conducted at the $\alpha = 0.05$ significance level.

Results

Overall Volumetric Collection Efficiencies

The overall single-slide volumetric CEs determined for both the FLB and the Hock samplers tested using both nozzle 1 and nozzle 2 at airspeeds of 0.5, 2, and 4 m s^{-1} were calculated using the methods described earlier. All sampler, nozzle, airspeed combinations had a minimum of four acceptable replicated data points. The average airspeeds and D_{V10}, D_{V50}, and D_{V90} values for the FLB and Hock replications for nozzles 1 and 2 are shown in table 1. There was no significant nozzle effect ($p = 0.3596$), but sampler type ($p = 0.0144$), airspeed ($p < 0.001$), and the interaction between sampler type and airspeed ($p = 0.0298$) were significant. The averages and standard deviations, by sampler type and airspeed, and means separations are given in table 2. The FLB sampler had significantly higher CEs ($p = 0.015$) than the Hock sampler at 2 and 4 m s^{-1} airspeeds, but there were no differences in CE at 0.5 m s^{-1} airspeeds.

The CEs for both samplers were higher at the lower airspeeds as a result of slower-moving droplets having a longer residence time within the volume of space being sampled by each rotary sampler, allowing for greater opportunity for impaction on the rotary surface. For the given sampling window sizes (Hock = 112 cm^2 and FLB = 114.7 cm^2) and for targeted airspeeds of 0.5, 2, and 4 m s^{-1}, the corresponding aspiration rates (volume per time rate that droplet-laden air passes through the sampling window) are 0.34, 1.34, and 2.69 m^3 min^{-1} for the Hock sampler and 0.34, 1.38, and 2.75 m^3 min^{-1} for the FLB sampler. Both samplers have similar aspiration rates, as the sampling window sizes are similar, but based on the rotational speeds and the exposed area of a single slide, the sampling rates are 0.38 and 0.064 m^3 min^{-1} for the Hock and FLB samplers, respectively. While the Hock and FLB samplers have similar CEs at the 0.5 m s^{-1} airspeed, given the 6× greater sampling rate over approximately the same sampling window, the 25 mm Hock slide has a much lower deposition efficiency of droplets relative to the volume of air

Table 1. Mean airspeed and droplet size parameters for sampler testing for nozzles 1 and 2.

Nozzle	Mean Airspeed (m s^{-1})	Average Sympatec Measurements (µm) D_{V10}	D_{V50}	D_{V90}
FLB Sampler				
1	0.7	9.2 ±1.3	16.1 ±1.8	24.9 ±2.5
	2.0	8.3 ±1.6	14.9 ±1.1	23.7 ±1.0
	4.1	8.8 ±1.6	16.2 ±1.8	24.7 ±3.0
2	0.7	15.8 ±2.2	27.0 ±3.3	46.7 ±7.2
	2.0	12.0 ±2.2	23.7 ±3.6	41.7 ±11.3
	4.1	11.6 ±2.5	21.0 ±3.4	32.9 ±11.3
Hock Sampler				
1	0.7	8.7 ±0.5	15.2 ±0.6	23.6 ±0.6
	1.9	8.2 ±0.5	14.7 ±0.6	23.2 ±0.6
	4.0	8.4 ±0.5	14.9 ±0.3	22.8 ±1.3
2	0.6	14.6 ±1.2	26.6 ±2.4	46.2 ±8.9
	2.1	14.7 ±3.9	24.0 ±1.5	39.8 ±5.4
	4.0	13.2 ±1.7	25.8 ±2.1	46.6 ±9.0

Table 2. Overall collection efficiencies (means ±SD) for the rotating impactors by airspeed.

Sampler	Mean Airspeed (m s^{-1})	Overall Single-Slide Collection Efficiencies (mean ±SD)[a]
FLB	0.7	19.5 ±7 a
	2	15.2 ±8.1 ab
	4.1	7.3 ±3.1 b
Hock	0.7	14.9 ±8.3 ab
	2.0	2.8 ±1.3 c
	4.0	2.5 ±0.6 c

[a] Means followed by the same letter are not significantly different as determined by Dunnett's T3 test for unequal variances at $\alpha = 0.05$.

Table 3. Single-slide droplet size range specific collection efficiencies for the FLB and Hock samplers.

Sampler	Airspeed ($m\ s^{-1}$)	Droplet Size Range Specific Collection Efficiencies (bin ranges in μm)[a]		
		0 to 10	10 to 20	20 to 30
FLB	0.5	40.8 a	24.0 a	14.4 a
	2	38.3 a	15.8 a	8.0 a
	4	25.9 a	5.9 b	3.9 b
Hock	0.5	23.3 ab	17.0 a	5.8 b
	2	4.9 b	2.5 b	2.1 b
	4	6.5 b	2.5 b	2.0 b

[a] Means in the same column followed by the same letter are not significantly different as determined by Dunnett's T3 test at $\alpha = 0.05$.

sampled. This follows results reported by May and Clifford (1967), who showed that for narrow flat-face surfaces (ribbons), narrower collectors have increased droplet impaction efficiencies as compared to wider surfaces.

Droplet Size Range Specific Collection Efficiencies

Significance testing for sampler, airspeed, and nozzle effects showed that nozzle was not a significant effect for any of the droplet size bin specific CEs (p values from 0.964 to 0.5733) but that sampler type (p values from <0.0001 to 0.0011) and airspeed (p values from <0.0001 to 0.0051) were both significant factors, with a couple of exceptions. The 30 to 40 μm droplet size range specific CEs were not significantly influenced by airspeed ($p = 0.1526$), with the FLB having a significantly higher CE (15.5%) as compared to the Hock sampler (6.6%). The CE results for droplets >40 μm were not significantly influenced by sampler type ($p = 0.924$), with significantly higher CEs at 0.5 $m\ s^{-1}$ (27.6%) as compared to the 2 and 4 $m\ s^{-1}$ airspeeds (14.8% and 6.8%, not significantly different). The remaining droplet size range specific CEs, with means separations, are given in table 3.

Droplet Sizing Accuracy

The prediction errors for both samplers for the D_{V10}, D_{V50}, and D_{V90} values are given in table 4. Significance testing for the droplet sizing error between the slide collected (analyzed with DropVision) and the Sympatec measured data for the D_{V10} showed that neither nozzle ($p = 0.1406$) nor airspeed ($p = 0.3723$) were significant effects, but that sampler type ($p < 0.001$) was. The FLB sampler underpredicted D_{V10} by 37% as compared to the Hock sampler, which only underpredicted by 0.8%. When examining the D_{V50} values from both the slides and the Sympatec, neither airspeed ($p = 0.0587$) nor nozzle type (p 0.0650) were significant effects, but sampler type ($p = 0.0030$) was, with the FLB sampler underpredicting by 19.2% and the Hock sampler overpredicting by 8.3%. Likewise, neither nozzle ($p = 0.0589$) nor airspeed ($p = 0.42$) were significant effects with respect to the prediction errors for the D_{V90} data, but sampler type ($p = 0.0163$) was, with the Hock overpredicting by 21.6% and the FLB overpredicting by 5.5%.

Table 4. Prediction errors for slide measured D_{V10}, D_{V50}, and D_{V90} values as compared to Sympatec measured data.

Sampler	Prediction Errors (%)[a]		
	D_{V10}	D_{V50}	D_{V90}
FLB	-37.0 b	-19.2 b	5.5 a
Hock	-0.8 a	8.3 a	21.6 b

[a] Means in the same column followed by the same letter are not significantly different as determined by Dunnett's T3 test at $\alpha = 0.05$.

Table 5. Droplet densities (drops mm^{-2}) for the FLB and Hock samplers at 0.5, 2, and 4 $m\ s^{-1}$ airspeeds.

Sampler	Airspeed ($m\ s^{-1}$)	Mean Drop Density (drops mm^{-2})[a]
FLB	0.5	154.4 a
	2	88.6 b
	4	51.7 c
Hock	0.5	15.8 d
	2	12.1 de
	4	10.9 e

[a] Means followed by the same letter are not significantly different as determined by Dunnett's T3 test at $\alpha = 0.05$.

Drop Density Data

The drop density data (drops mm^{-2}) showed no significant nozzle effects ($p = 0.2326$), but both sampler type ($p < 0.001$) and airspeed ($p < 0.0001$) were significant. The FLB sampler had significantly higher droplet densities as compared to the Hock sampler, with both samplers generally having significantly higher droplet densities at lower airspeeds. The mean droplet densities and means separations for each sampler, at each airspeed tested, are given in table 5.

Discussions and Conclusions

Two rotary impactor samplers, the FLB and the Hock, were evaluated for volumetric and droplet sizing collection efficiency. While the initial goal was to test both samplers under multiple airspeeds and spray droplet sizes, the resulting sprays were not sufficiently different enough, with regard to droplet size, to significantly impact the results. Both samplers typically had decreased volumetric CEs with increasing airspeed, as reflected in both the single-slide CEs (table 2) and the droplet densities (table 5). While the FLB collected a greater number of droplets per area than the Hock at the same airspeed, the overall single-slide volumetric CEs were only significantly higher at the 2 and 4 $m\ s^{-1}$ airspeeds.

Based on these results, both the FLB and Hock samplers can be successfully deployed in the field and used to measured volumetric spray concentrations, and for given field studies, adjusted appropriately, if possible, for airspeed specific collection efficiencies. With aerial application field trials involving minute quantities of spray material moving through a target area over a long time period, typically 1 h for vector control applications, significant changes in wind speed may prevent any meaningful corrections. However the impactors would still provide an inexpensive method for use in a comparative survey of flux through the experimental area. The more detailed measures of flux described in this article would be viable in close proximity to truck-mounted mosquito control operations or agricultural field applications, where shorter drift periods, often not exceeding 15 min, result in more uniform wind fields, allowing for a more accurate correction of the measured data. For example, if the FLB sampler were deployed in a field situation measuring drift downwind of a spray application with a mean wind speed of 3 $m\ s^{-1}$, the CE can be interpolated from table 2 to be approximately 11%. As a sampler of this sort will likely be deployed to measure small droplet drift (i.e., positioned at a downwind distance likely greater than 50 to 100 m), it can be assumed that the spray droplet size sampled would be similar to that tested in this study. If a concentration of 0.1 μL cm^{-2} were measured, the corrected value would then be 0.9 μL cm^{-2} (0.1 μL cm^{-2} / 0.11). If the application were an oil-based spray (typical in vector control studies) and the droplet sizes were the measurement of interest, then the D_{V10}, D_{V50}, and D_{V90} accuracies could be determined from table 4. For measured D_{V10}, D_{V50}, and D_{V90} values of 10, 22, and 45 μm, respectively, the corrected values are calculated by solving equation 6 for D_{Vi_Sym} and inserting the values from table 4. The corrected values would then be 15.9, 27.2, and 42.7 μm for the D_{V10}, D_{V50}, and D_{V90} values, respectively.

Overall, the results indicate that the FLB sampler provides greater CE for the smaller droplet fraction of the spray, at equivalent airspeeds, than the Hock sampler, resulting in a greater number of droplets per area being collected. While neither sampler offers a perfect measure of either spray volume or droplet size, both can be used effectively with appropriate corrections for airspeed-dependent collection efficiency. Additionally, these samplers offer the benefit of sampling from a relatively large area, as compared to typical string or wire type stationary collectors, with the added benefit of providing information on the droplet size of the sampled spray.

Acknowledgements

This study was supported in part by a grant from the Deployed War-Fighter Protection (DWFP) Research Program, funded by the U.S. Department of Defense through the Armed Forces Pest Management Board (AFPMB).

References

ASTM. 2004. E 1620-97: Standard terminology relating to liquid particles and atomization. West Conshohocken, Pa.: ASTM International.

ASTM. 2009. E 1260-03: Standard test method for determining liquid drop Size characteristics in a spray using optical non-imaging light-scattering instruments. West Conshohocken, Pa.: ASTM International.

Bonds, J. A. S., M. J. Greer, B. K. Fritz, W. C. Hoffmann. 2009. Aerosol sampling: Comparison of two rotating impactors for field droplet sizing and volumetric measurements. *J. American Mosq. Control* 25(4): 474-479.

Boxall, A. B. A., A. Hardy, S. Beulke, T. Boucard, L. Burgin, P. D. Falloon, P. M. Haygarth, T. Hutchinson, R. S. Kovats, G. Leonardi, L. S. Levy, G. Nichols, S. A. Parsons, L. Potts, D. Stone, E. Topp, D. B. Turley, K. Walsh, E. M. H. Wellington, and R. J. Williams. 2009. Impact of climate change on indirect human exposure to pathogens and chemicals from agriculture. *Environ. Health Persp.* 117(4): 508-514.

Cooper, J. F., D. N. Smith, and H. M. Dobson. 1996. An evaluation of two field samplers for monitoring spray drift. *Crop Prot*. 15(3): 249-257.

Fox, R. D., R. C. Derksen, H. Zhu, R. A. Downer, and R. D. Brazee. 2004. Airborne spray collection efficiency of nylon screen. *Applied Eng. in Agric*. 20(2): 147-152.

Fritz, B. K., and W. C. Hoffmann. 2008a. Collection efficiencies of various airborne spray flux samplers used in aerial application research. *J. ASTM Intl*. 5(1): Paper JAI101493.

Fritz, B. K., and W. C. Hoffmann. 2008b. Development of a system for determining collection efficiency of spray samplers. *Applied Eng. in Agric.* 24(3): 285-293.

Hoffmann, W. C., T. W. Walker, T. Gwinn, V. L. Smith, D. Szumlas, Y. Lan, and B. K. Fritz. 2009. Spray characterization of ultra-low volume sprayers typically used in vector control. *J. American Mosq. Control* 25(3): 332-337. 2009.

May, K. R., and R. Clifford. 1967. The impaction of aerosol particles on cylinders, spheres, ribbons, and discs. *Ann. Occup. Hyg*. 10(1): 63-95.

Miller, P. C. H. 1993. Spray drift and its measurement. In *Application Technology for Crop Protection*, 101-122. G. A. Matthews and E. C. Hislop. eds. Wallingford, U.K. CAB International.

Mount G. A. 1998. A critical review of ultralow-volume aerosols of insecticide applied with vehicle-mounted generators for adult mosquito control. *J. American Mosq. Control* 14(3): 305-334.

Whitney, R. W., and L. O. Roth. 1985. String collectors for spray pattern analysis. *Trans. ASAE* 28(6): 1749-1763.

Yates, W. E., R. E. Cowden, and N. B. Akesson. 1985. Drop size spectra from nozzles in high-speed airstream. *Trans ASAE* 28(2): 405-410.