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AEROSOL SAMPLING: COMPARISON OF TWO ROTATING IMPACTORS FOR FIELD DROPLET SIZING AND VOLUMETRIC MEASUREMENTS

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ABSTRACT. This article compares the collection characteristics of a new rotating impactor Florida Latham Bonds (FLB) sampler for ultrafine aerosols with a mimic of the industry standard (Hock-type). The volume and droplet-size distribution collected by the rotating impactors were measured via spectroscopy and microscopy. The rotary impactors were colocated with an isokinetic air sampler for a total volume flux measurement and a laser diffraction instrument for droplet-size distribution measurement. The measured volumetric flux and droplet-size distribution collection efficiencies were compared across 3 wind speeds (1, 1.8, and 3.5 m/sec). The FLB sampler had higher flux collection efficiencies than the Hock-type sampler. The FLB sampler collected 89%, 87%, and 98% of the total volume available per unit area at 1, 1.8, and 3.5 m/sec, respectively, whereas the Hock-type sampler collected 68%, 19%, and 21% of across the same wind speeds. Changes in wind speed had less impact and resulted in less data variability for the FLB sampler.

KEY WORDS Collection efficiency, rotary impactor, aerosol sampling

INTRODUCTION

Mosquito control aerosols are effective when they remain suspended and disperse through the target area to come into contact with the flying insects. To stay suspended the spray material is atomized into droplets of <100 µm in diameter (Miller 1993) at ultra-low volumes (ULV) of <72 ml/ha. Although a precise measure of the mass balance is essential for research in this area, it is very difficult, considering the collection efficiency of the fine droplets and the minute quantities present. The task is further complicated as both volume and droplet-size distribution data are needed. Research has shown that the primary parameter influencing control is atmospheric turbulence, which affects the movement and therefore availability of the chemical (Barber and Greer 2008). The size of the drops, however, will dictate to what extent the drop is susceptible to changes in atmospheric flow. The target must also be considered, as the insect target has a specific collection efficiency (CE), which further necessitates information on the droplet-size distribution at the application site (Johnstone et al. 1988).

Rotating impactors are a commonly used collection device for these small-droplet, highly dispersed sprays, and they return both volume and distribution data. Rotating impactors operate on the principle that if the collection surface is small and rotated at a sufficiently high speed, then capture efficiency is high. Moreover, where sampler size and speed is appropriate, CE is neither a function of wind speed nor droplet size (May and Clifford 1967, Parkin and Merritt 1988). Parkin and Merritt (1988), however, were describing a RotoRod rotating impactor, which spins a 2-mm collecting surface at 15 m/sec. The industry standard for spray capture in agriculture and mosquito control is the Hock impactor (J. W. Hock©, Gainesville, FL) which uses a standard microscope slide 25 mm wide with a rotational velocity of 3.6 m/sec. Large obstacles and slow sampler velocities lead to lower CEs compared to narrower surfaces at higher velocities (May and Clifford 1967). This large obstacle size and slow rotational speed also make CE more dependent upon droplet size and wind speed. The RotoRod was shown not to be significantly affected by wind speed because the sampler rotated at a speed (15 m/sec) significantly higher than any wind speed that would be encountered in the field. Wind speeds typically encountered in the field range from 0.5 to 4.5 m/sec. The speed of the Hock impactor (3.6 m/sec) is within this range, meaning that it will likely be susceptible to wind speed change.

Work has been under way to improve the CE of the industry standard Hock sampler (3.6 m/sec, 25 mm) by development of an alternative sampler referred to as the Florida Latham Bonds (FLB) sampler. The development of the new Florida sampler (3-mm rod rotating at 5.6 m/sec) has been a collaborative effort between the Adulticide Application and Evaluation Section of the John A. Mulrennan Sr. Public Health Entomology Research and Education Center (College of Engineering Science Technology and Agriculture), Florida A&M University and Manatee County Mosquito Control District, specifically Mark Latham. The aim was to provide a research device that would more effectively sample the low-concentration, ultra-fine aerosols relevant to mosquito adulticide efficacy studies. An addi-

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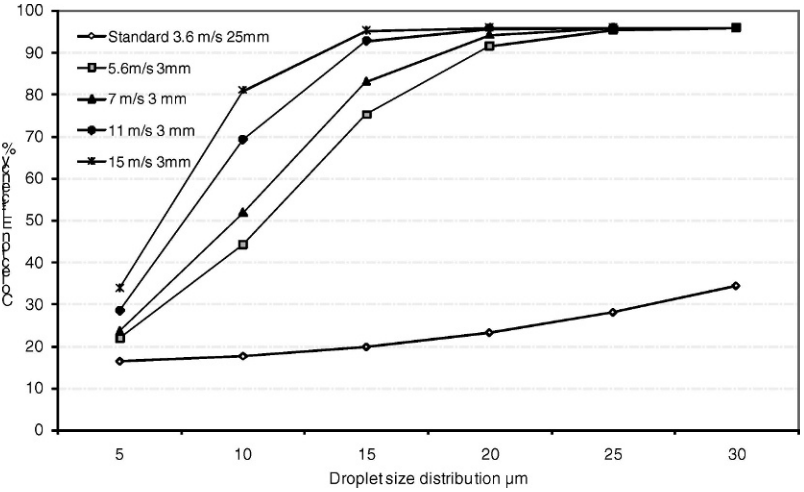

Fig. 1. Graphical representation of the theoretical collection efficiency of the different rotational speeds tested (Parkin and Young 2000).

tional aim was to develop a sampler that would not be affected by changes in wind speed from 1 sample station to the next, allowing habitat comparison. The developers also wanted to create a simple, practical, and inexpensive device that would enable the purchase of multiple impactors to increase sample size and, therefore, reliability and repeatability of field data. Preliminary investigations conducted by the authors explored the use of narrower collection surfaces and higher rotational speeds and found that the smallest slide size practical, in terms of handling, is a 3-mm slide. There was also a limitation on velocity because of shattering of the larger droplets in the spray (>50 µm) at high speeds (Barber et al. 2004). The RotoRod, which rotates a 2-mm slide at 15 m/sec, was created for applications where large droplet shatter was not a concern, as the device was designed for pollution studies and the capture of PM10s (particulate matter <10 µm). Mosquito control sprays, on the other hand, have a volume median diameter of approximately 30 µm (D_{V50}), with the 10% and 90% diameters (D_{V10}, and D_{V90}) at 5 and 80 µm, respectively. Initial tests investigated 3 different direct current (DC) motors, each with different rotational speeds, which resulted in 5.6, 11, and 15-m/sec slide speeds. Both of the high-speed units shattered droplets >50 µm. Presprayed slides retained the droplets, meaning droplet breakup was a function of shatter as opposed to liberation. The motor and rod arm that produced the 5.6-m/sec linear velocity provided consistent and reliable samples.

The motor that produced the 5.6-m/sec slide speed was inexpensive and only required 4 AA batteries, which made it lightweight and practical for field use. A small increase in linear velocity was attempted by increasing the rod arm length. This led to an easily unbalanced rotator. The marginal gains in collection efficiency did not justify the losses in practicality. The arrangements tested during the preliminary trials are presented as theoretical CEs (Fig. 1). These curves were calculated with the use of the calculations prepared by and methods presented by Parkin and Young (2000). This article compares the new FLB sampler with a 3-mm slide at a 5.6-m/sec rotational velocity and a mimic of the Hock sampler with a 25-mm slide at a 3.6-m/sec rotational velocity (Fig. 2).

MATERIALS AND METHODS

To investigate the conditions for 2 different impactor designs, the Hock-type sampler, 3.6-m/sec velocity with a 25-mm slide; and the new FLB sampler, 5.6-m/sec velocity with a 3-mm slide with DC motors (Premotec, Dordrecht, Netherlands), operating at 600 rpm, were used in this study. Changes in linear velocity were accomplished by adjusting the rod arm length. The slides were either 25-mm Teflon®-coated microscope slides (VecTec, Inc., Orlando, FL) or 3-mm Teflon-coated acrylic slides. The 3-mm slides (3 mm wide × 3 mm thick extruded acrylic bars cut to length; McMaster-Carr, Atlanta, GA) were coated with Teflon tape (McMaster-Carr, Atlanta, GA). To mimic the Hock impactor (25-mm slide rotating at 3.6 m/sec), slides were held 115 mm apart (slide center to slide center). Likewise, the 3-mm slides were held 180 mm apart to obtain the 5.6-m/sec velocity. Microscope slides had collection surface areas of 14.3 cm^2 (57 mm height × 25 mm width). The extruded bars had collection surface areas of 1.7 cm^2 (57 mm height × 3 mm width). Both samplers were tested under 3 different wind speeds of 1, 1.8, and 3.5 m/sec. Six replicated

Fig. 2. The 2 rotating impactors under investigation are the 3-mm 5.6-m/sec new Florida sampler and the 25-mm 3.6-m/sec industry standard sampler.

measurements were made at each wind speed for each sampler type.

The rotating impactors were individually placed in a low-speed spray dispersion tunnel as detailed by Fritz and Hoffmann (2008). Spray was generated with the use of an air-assisted nozzle (Advanced Special Technologies, Winnebago, MN) operated at 689 kPa (Fritz and Hoffmann 2008). Droplet size was measured 0.5 m upwind of the rotary samplers with the use of a Sympatec HELOS laser-diffraction droplet-sizing system (Sympatec Inc., Clausthal, Germany). The Helos system uses a 623-nm He–Ne laser and was fitted with an R5 lens, resulting in a dynamic size range of 0.5–875-µm diameter in 32 sizing bins. Tests were performed within the guidelines provided by the American Society of Testing and Materials (ASTM) Standard E1260: Standard Test Method for Determining Liquid Drop Size Characteristics in a Spray Using Optical Non-imaging Light-Scattering Instruments (ASTM 2003). Droplet-sizing data measured included volume median diameter (D_{V50}), the 10% diameter, and the 90% diameter (D_{V10} and D_{V90}; ASTM 2004).

For each replication, an isokinetic air sampler and rotary sampler operated simultaneously in the working area of the dispersion tunnel. The isokinetic sampler (Staplex® Model TFIA High Volume Air Sampler, The Staplex Company, Brooklyn, NY) was positioned such that the center of the sampling area was 45 cm above the tunnel floor. A variable-flow controller was used to change air velocity across the filter (Model TFAGF41 10-cm-diameter glass fiber filters, The Staplex Company) to ensure isokinetic sampling. The rotary samplers were positioned at the same height 40 cm upstream of the isokinetic sampler. With a given volume of spray, as wind speed increases the amount sampled decreases for the rotary samplers due to reduced time in the sample window. To maintain a suitable volume for analysis on the Hock-type sampler, as the wind speed increased the volume atomized had to be increased. This could not be proportional with wind speed because the FLB sampler with a faster rotational speed would become saturated. To provide sufficient spray material to both samplers for analysis 2, 3, and 3.5 ml of solution were metered to the nozzle at air speeds of 1, 1.8, and 3.5 m/sec, respectively. Spray material consisted of Orchex 796 mineral oil (Calumet Lubricants Co., L.P., Indianapolis, IN) with Uvitex fluorescent dye at the rate of 1 g/liter of oil.

After each treatment run, 1 slide (for droplet-size distribution data) from the rotary sampler was collected and placed on a labeled board with the use of double-sided tape. The other slide and the glass fiber filter (for volumetric data) were placed into individually labeled plastic, zip-top bags for transport. The bags were brought back to the laboratory for processing. After 20 ml of hexane was pipetted into each bag, the bags were agitated, and 6 ml of the effluent was poured into a cuvette. The cuvettes were then placed into a spectrofluorophotometer (Shimadzu, Model RF5000U, Kyoto, Japan) with an excitation wavelength of 372 nm and an emission of 427 nm. The fluorometric readings were converted to a volume flux (µl/cm^2) by using the area of the sampler and by comparison to standards generated by using the actual oil and dye mix. There are no time units associated with the reported flux volumes as it is implicit to, and

Table 1. Volume flux measurements, CEs, and droplet densities for isokinetic, Hock-type, and FLB samplers.[1]

	Tunnel air speed (m/sec)		
	1	1.8	3.5
Isokinetic measured flux means (μl/cm^2)			
Across both sampler types	0.0187a[2]	0.0194a	0.0246b
Hock-type samplers only	0.0185	0.0187	0.0204
FLB sampler only	0.0188	0.0201	0.0287
	$P = 0.015$		
Slide measured volume flux (μl/cm^2)			
Hock-type sampler	0.0123b	0.0037c	0.0053c
FLB sampler	0.0158b	0.0168b	0.024a
	$P < 0.001$		
Slide volume flux CE (%)			
Hock-type sampler	66%	19%	21%
FLB sampler	84%	87%	98%
Slide-measured droplet density (droplets/mm^2)			
Hock-type sampler	25	11	10
FLB sampler	183	184	160

[1] CEs, collection efficiencies; FLB, Florida Latham Bonds.

[2] Means followed by the same letter in a row are not significantly different, based on the least-significant-difference values.

corresponds with, the total time period of each replication. The minimum detection level for the dye and sampling technique was 0.07 ng/cm^2.

The slides saved for droplet-size distribution and density were analyzed via microscopy (AO Spencer, Buffalo, NY). Approximately 100 droplets were counted per slide, with 6 slides used. Measurements were taken across the width of the slide so as not to bias toward smaller drops that collect at the edges. Only those droplets that were within the graticule as it progressed across the slide were counted; by completing a full traverse of the slide a known area had been viewed. This method allows calculation of the droplet density per unit area. The count distribution was converted to a volume distribution, which was then used in the volume CE analysis.

RESULTS

The data are presented both quantitative and qualitatively. The isokinetic data were assessed to see if there was a significant difference in the volume measurable across the different treatments (flux mean, Table 1). As anticipated, the mean volume flux increased with each wind speed, but there was no significant difference in volume within each wind speed category between the 2 sampler treatments ($P = 0.015$, SE = 0.00125, LSD = 0.0042).

Based on the total material available (isokinetic sampler measured volume flux) and the amount measured by each rotating sampler (measured volume flux, Table 1) the calculated CE values for the Hock-type and FLB ranged from 19% to 98% (CE%, Table 1). The volume collected by the FLB sampler at 3.5-m/sec wind speed was significantly higher than all the FLB and Hock treatment volumes. The 1.8- and 3.5-m/sec wind speeds with the Hock collected significantly lower volumes than all the other treatments (Table 1). The volume collected by the Hock-type sampler at the 1-m/sec wind speed was markedly, but not significantly, different in volume to the 1- and 1.8-m/sec FLB treatments. The volumes collected by the FLB sampler correlated with the volumes collected by the isokinetic sampler, in that they increased with wind speed. The volumes collected by the Hock sampler were opposite to that of the isokinetic sampler. The FLB sampler had 89%, 87%, and 98% CE at the 1-, 1.8-, and 3.5-m/sec wind speeds. The Hock sampler had a 68%, 19%, and 21% CE at the 1-, 1.8-, and 3.5-m/sec wind speeds ($P < 0.001$, SD = 0.0016, LSD = 0.0046).

The measured droplet densities were significantly different between the 2 sampler types (Table 1). The Hock-type sampler collected significantly fewer drops per area than the FLB sampler. The FLB sampler, on average, collected 13.4 times the number of droplets per area than the Hock-type sampler (Table 1).

Figures 3 and 4 provide a qualitative description of the volume fractions collected with the Sympatec laser and the 2 rotating impactors. The air-assist nozzle provided a consistent droplet-size spectrum across all conducted replications, as measured by the Sympatec laser diffraction system an average of $Dv_{0.1} = 10$ μm, $Dv_{0.5} = 16$ μm, and $Dv_{0.9} = 27$ μm. Because the droplet-size distribution is <30 μm, the slide-measured droplet-size distributions are presented as volume distribution with Yeomans' correction applied (Yeomans 1949). These 2 charts further illustrate the effects of wind-speed change on the Hock-type sampler

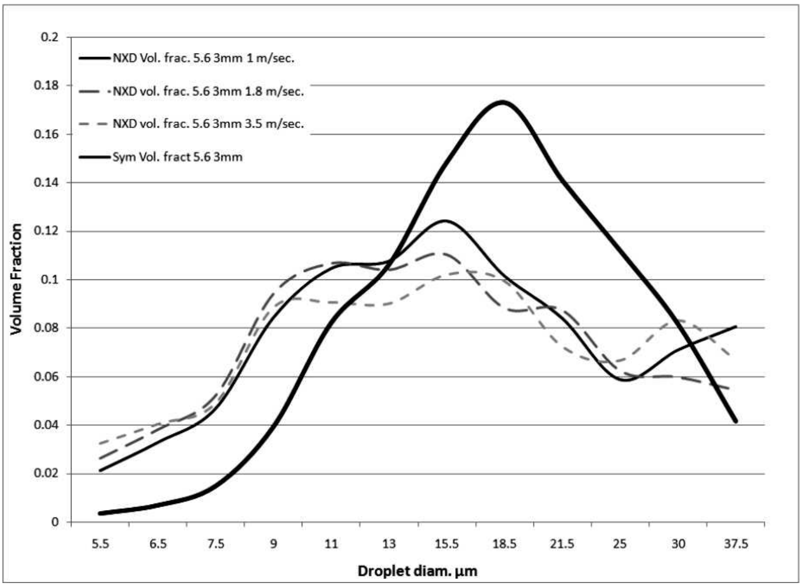

Fig. 3. Droplet-size distributions for the FLB sampler as $N \times D$ (number × diameter) for each wind speed compared to the volume fractions from the Sympatec laser.

(Figs. 3 and 4). The FLB sampler returned relatively consistent droplet-size distributions across the 3 different wind speeds, whereas the Hock-type sampler collected very different distributions, especially at the lower wind speed.

DISCUSSION

The FLB sampler has a significantly higher CE compared to the Hock-type sampler. The droplet-size distribution charts (Figs. 3 and 4) show that the Hock-type sampler collects poorly at the lower end of the spectrum compared to the FLB sampler. This is supported by the differences in volume per unit area and drop density. The FLB collected 3× more by volume and 14× more by number. This difference is due to the significant increase in the CE of the smaller-droplet-size bins with the FLB sampler, which contribute to number. The fact that the FLB sampler CE does

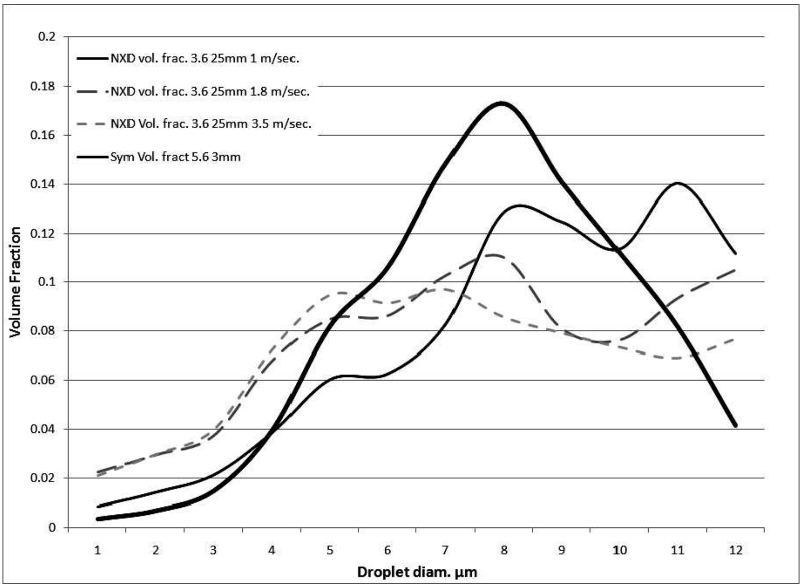

Fig. 4. Droplet-size distributions for the Hock sampler as $N \times D$ (number × diameter) for each wind speed and compared to the volume fractions from the Sympatec laser.

not vary with wind speed provides for more reliable and consistent data collection for field studies conducted at different times and under different conditions. It is possible that the increase in velocity (with wind speed) between the obstacle and the entrained droplet leads to a significant increase in collection of droplets and that it nullifies the effects of reduced aspiration rate with increased wind speed. This study reveals that the processes involved with rotary impaction devices are still not clear and requires further investigation.

Over the years there have been a number of attempts to account for low CEs. Previous research conducted by Cooper et al. (1996) developed a method to calculate for sampling rate that theoretically corrected for changes in wind speed. May and Clifford (1967) provided information on CE for cylinders and ribbons via a set of smooth sigmoid curves showing CE increasing with droplet size. Parkin and Young (2000) investigated the same droplet ranges showed that there were limits or break points to the CE curves, implying it was not a smooth-line prediction. Yeomans (1949), in an attempt to provide a simple correction for collection inefficiency, noted that with droplets less than 30 μm, CE was directly related to the square of the droplet diameter; one could therefore calculate correct droplet-size distributions via number (N) $\times$ diameter (D) as opposed to $N \times D^3$. These discussions are complex and predominantly focus on stationary systems (Yeomans 1949, May and Clifford 1967, Parkin and Young 2000), which are a far simpler model than the rotary one proposed here.

It is often assumed that the May and Clifford data, along with an adjustment for aspiration and sampling rate to account for differences between samplers, is appropriate. This study has shown that the logic of the sampling-rate equation does not agree with the measured numbers. This is likely due to peculiarities in the rotation of a sampling device. Fog and smoke studies have shown that these types of rotary sampling devices aspirate air into the center from outside of the collection window. This aspiration caused by rotation could be considered actively drawing spray into the sampling area. The Hock-type sampler collected lower volume fluxes and droplet densities when compared to the FLB sampler. The droplet-size distributions collected by the FLB sampler were more consistent across the wind speeds tested. The ability to collect data independently of wind speed is very important in field research. Flux comparisons between habitats with different wind regimes is often necessary. Where the FLB sampler is used and wind speeds remain in the range of this experimentation differences in data are not going to be confounded by sampler bias. The FLB sampler offers a more effective and robust field device for the measurement of public health aerosols.

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