Development of a Protocol for Characterizing Sprays Generated Under Simulated Aerial Conditions

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Abstract

The purpose of this study was to demonstrate a method to characterize the spray plume generated from a fixed-wing aerial spray system, at simulated flight speeds up to 50 m/s (115 mph). Full-scale testing of a Micronair AU6600 rotary atomizer under simulated aerial application conditions was conducted in the Ambient Breeze Tunnel (ABT) using water as the test liquid. Spray droplet size and velocity distributions were measured using phase Doppler anemometry. Tests of the spray system were conducted at varying liquid flow rates (0.5, 1.0, 2.0 L/min), rotation speeds (10,000, 12,500, 15,000 rpm), and simulated flight speeds (31, 41, 51 m/s). A profile of measurements was collected extending from the center of the spray plume to the periphery, and droplet size data were used to compute a mass-balanced, integrated droplet size distribution that is more accurate for describing a spray than single point measurements. The results indicate the approach is appropriate for characterizing spray performance under aerial application conditions, and that the AU6600 does produce droplets within the desired droplet size range for mosquito vector control.

Key words: rotary atomizer, phase Doppler anemometry, spray droplet distribution, mass-balance

Introduction

Mosquito vector control has received increased global attention due to recent resurgences in mosquito-borne disease (e.g., West Nile Virus). Aerial insecticide application provides the means to treat large areas within a short period of time, compared to ground, truck-based applications. Contrary to agricultural aerial surface sprays (i.e., crop dusting), where small, driftable droplets are avoided, aerial adulticiding relies on the longevity of airborne spray droplets and dispersion throughout the target area to be effective in impacting in-flight adult mosquitoes. Thus, in this case, the generation of small droplets (i.e., <50 μm) is desirable, as droplets this small are less influenced by sedimentation and will stay airborne for longer periods of time.

One problem the mosquito vector control industry continues to face is that there are few commercially available aerial spray systems capable of producing droplet sizes within the optimum size range of between 5 and 30 μm [6]. Conventional flat fan spray systems, which are still being used by many operators [6], produce wide-ranging sprays with a mass median diameter (MMD) of 50 to 100 μm. The larger droplets within the spray distribution are considered inefficient as they will deposit to the ground more quickly, which in high enough concentrations could cause risk to non-target organisms [4].

Rotary atomizers produce narrower droplet size ranges compared to hydraulic nozzles [2], [5]. For a given MMD, this allows application of minimal doses of insecticide in precisely controlled droplet size ranges. Advances in rotary atomizer design may provide aerial operators the ability to generate ultra-fine, ultra-narrow droplet spectra to optimize delivery of minute quantities of pesticide to adult mosquitoes and minimize waste.

Like hydraulic nozzles, rotary atomizers also produce spatially segregated droplet spectra. Rotary atomization involves forces imposed by the centrifugal and air shear energies imposed by the rotation of the atomizer and the high air velocities, respectively, causing droplets of different size (and hence different momentum energy) to reach different radial positions within the spray plume. Thus, an accurate characterization of the atomizer requires a detailed survey of the entire spray plume under realistic aerial application conditions.

Accurate characterization of spray droplet spectra is critical for use in computer models, such as AGDISP [1] and FSCBG [8], to predict the dispersion and deposition of aerially released spray material. Such dispersion

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models are currently being used by regulatory agencies for risk assessment, as well as by researchers and applicators for determining optimal application conditions.

There are essentially no standard protocols that exist to perform these assessments. The objectives of this study were: 1) to demonstrate a method for spray plume characterization generated by a rotary atomizer from a fixed-wing platform, and 2) to evaluate a commercially available atomizer specially designed for the mosquito vector control industry.

Materials and Methods

The commercial atomizer investigated was an electrically-driven Micronair AU6600 [7] rotary atomizer. Manufacturer specifications recommend that the atomizer be operated at liquid flow rates ranging between 0 to 2 L/min, atomizer rotation rates up to 15,000 rpm, and operation airspeeds from 0 to 240 km/h (0 to 150 mph). The manufacturer indicates the atomizer has been designed to produce droplets within the 18-25 μm range, specifically for mosquito vector control.

Tests were conducted in the Ambient Breeze Tunnel (ABT) (Figure 1), a large scale aerosol wind tunnel test facility developed by Battelle. The facility is 45.7 m (150 ft) long, and has a 6.1 m (20 ft) by 6.1 m (20 ft) (center height) cross section. At the generation end of the tunnel, the ABT is equipped with a high-power air blower (Buffalo Turbine, Model KBII, Gowanda, NY) to simulate aerial application conditions from a fixed-wing platform. The Buffalo Turbine blower was modified by fitting a 3 m (10 ft) long, 0.3 m (12 in) diameter spiral reinforced aluminum duct. Wind speed measurements were taken using a 0.8 cm (5/16 in) Pitot tube mounted in the duct exit. Preliminary characterization of the high-power blower system at the duct exit showed uniform air flow characteristics for wind speeds up to 57 m/s (127 mph).

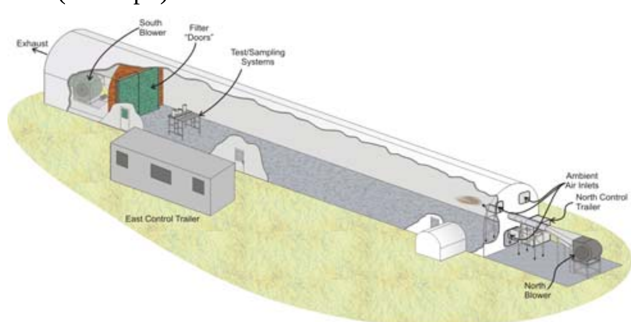

Figure 1. Ambient Breeze Tunnel with High-Velocity Duct

A separate exhaust blower is located at the opposite end of the ABT, providing volumetric airflow rates up to 70.8 m^3/s (150,000 cfm), resulting in ambient wind speeds up to 2.2 m/s (5 mph) within the tunnel. The exhaust blower is preceded by two large filter banks, containing 56 interchangeable high-efficiency filters, which minimize the release of generated materials into the environment.

The test conditions are defined in Table 1. All tests were conducted using water as the test liquid, and varying either the atomizer liquid flow rate (0.5, 1.0, and 2.0 L/min), atomizer loaded (wet) rotation rate (10,000, 12,500, and 15,000 rpm), or the simulated flight speed (31, 41, and 51 m/s; or 70, 92, 115 mph). All test conditions were consistent with the manufacturer's recommendations for atomizer use. The base test condition is defined as 1.0 L/min, 15,000 rpm, and 41 m/s (92 mph).

A Dantec Particle Dynamics Analyzer (PDA) (Dantec Dynamics, Inc., Skovlunde, Denmark) was used to measure the droplet size and velocity produced by the Micronair AU6600 rotary atomizer within the high velocity flow. The PDA sampling volume is defined by the intersection of two coherent Argon-ion laser beams. The PDA accumulates measurements of individual droplets passing through the sampling volume with time, allowing for the distribution of statistical size and velocity moment to be determined, as well as the droplet flux. The PDA was operated using near-forward scatter (first order refraction) with the receiving optics set at an angle of 30^o to the incident beam and arranged to measure the axial component of droplet velocity. This is the typical configuration for the receiving optics when water is the test liquid. Measurement quality was controlled by optimizing the data rate and validation through adjustment of the voltage and gain settings within Dantec's BSA Flow software system monitor. During data acquisition, it was observed that data rate values varied by location within the spray due to differences in droplet concentration from the center (dense) to the periphery (dilute). Validation rates of 90% or greater, as determined by the PDA statistical software, were considered acceptable.

Table 1. Experimental Test Conditions

Experiments	Liquid Flow Rate (L/min)	Device Rotation Speed (rpm)	Simulated Flight Speed (m/s)
Base Test Condition	1.0	15,000	41
Variation of Liquid Flow Rate	0.5	15,000	41
	2.0	15,000	41
Variation of Rotation Speed	1.0	10,000	41
	1.0	12,500	41
Variation of Flight Speed	1.0	15,000	31
	1.0	15,000	51

For each test condition, a radial profile of PDA measurements was completed, starting at the center of the spray plume and extending outward, as shown in Figure 2 (left illustration). A total of six points were measured in the profile, spaced at 2.5 cm (1 in) intervals out to a radius of 12.7 cm (5 in). All measurements were performed 25.4 cm (10 in) downstream from the atomizer. In addition, gravitational effects were investigated by comparing measurements at points located 5.1 cm (2 in) and 10.2 cm (4 in) above and below the plume center. For each day of testing, a measurement at the center of the plume for the base test condition was repeated as a control. Also, because the droplet distribution for the atomizer varies as a function of position, each measurement point was assumed to be representative of a particular area associated with that measurement location. In this case, the area assigned to each measurement point was one of a series of concentric rings, beginning and ending midway between the measurement points, as shown in Figure 2 (right illustration).

A total of 15,000 droplets were sampled per measurement. The droplet size parameters used for analysis in this study were the mass median diameter (MMD) and the geometric standard deviation (GSD). The MMD, or $D_{0.5}$, represents the droplet diameter such that 50% of the mass is in droplets of smaller diameter. The GSD, which gives an indication of the spray's dispersity, is computed as the ratio of $D_{0.86}$ and $D_{0.5}$. The average droplet velocity was also computed for each test condition.

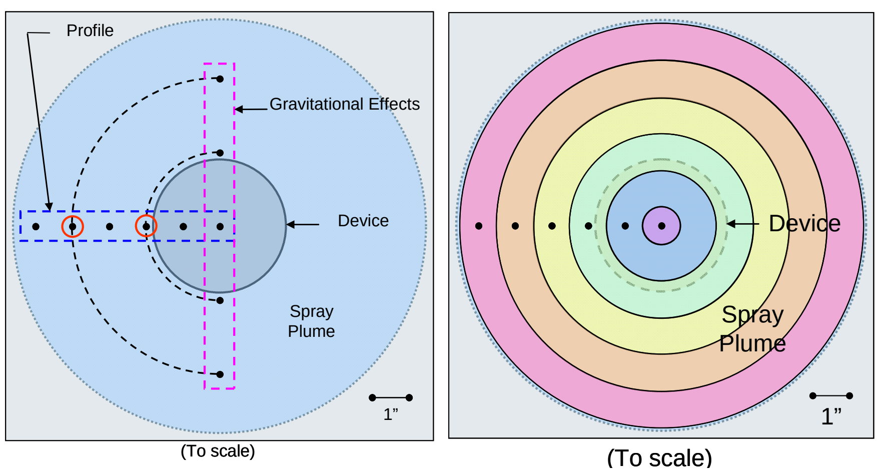

Figure 2. Profile Measurement Locations and Assigned Plume Areas

From the profile of PDA measurements, the droplet size data were used to compute a mass-balanced, integrated droplet size distribution representative of the entire spray plume.

For a given test condition, droplet size data (d) were converted to the corresponding mass (m) for each profile point (p) according to:

$$m_i = \rho \frac{\pi}{6} d_i^3 \qquad (1)$$

where i is the individual data value, the density of water (ρ) is 1000 kg/m^3, and the assumption of spherical droplets of constant density was made.

The total mass flow (M) through the PDA sampling volume at each profile point was computed according to:

$$M_p = \frac{\sum_i^n m_i}{t_n} \qquad (2)$$

where the total number of droplets measured was n=15,000, and t_n was the elapsed time, which varied for different profile locations and test conditions.

The mass flux ($\dot{M}$) at each profile point was then computed from the mass flow passing through the PDA sampling area (A_s) according to:

$$\dot{M}_p = \frac{M_p}{A_s} \qquad (3)$$

The PDA sampling volume is defined by the volume of intersection between the two laser beams, which forms an ellipsoid. For the optical settings used during testing, the sampling volume diameter and length were 0.189 mm and 3.97 mm, respectively [3]. Thus, the flux area defined by an ellipse with these dimensions is 0.59 mm^2.

Thus, the total mass (TM) flow for the assigned plume area represented by that point was determined according to:

$$TM_P = \dot{M}_p \times A_p \qquad (4)$$

where A_p are the plume areas represented by the 2.5 cm (1 in) thick concentric rings corresponding to each profile point, as shown in right most illustration of Figure 2.

The mass fraction (W) for each plume area was then determined by:

$$W_P = \frac{TM_P}{\sum_P TM_P} \qquad (5)$$

For a given test condition, the mass data were weighted according to profile location, and then all the data were pooled to create a combined mass distribution as follows:

$$W_0 \times (m_i)_0 + W_1 \times (m_i)_1 + W_2 \times (m_i)_2 + W_3 \times (m_i)_3 + W_4 \times (m_i)_4 + W_5 \times (m_i)_5 \qquad (6)$$

The mass distribution was then transformed back to a droplet size distribution using the inverse of Equation 1 and converting the number of droplets to a mass fraction. The MMD and GSD of the mass-balanced, integrated droplet size distribution were then determined. This analysis was completed for each of the test conditions shown in Table 1.

Results and Discussion

Droplet Size Distributions: Measured droplet data was collected at each of the six locations indicated on the left most illustration of Figure 2 using the seven conditions described in Table 1. Consistently, for the range of tested conditions, the droplet size increased and the mass distribution became less disperse with distance from the center of the spray toward the periphery. These results are consistent with the operation of a rotary atomizer, where the largest droplets having greater momentum move to the outer edge of the spray, while the smaller droplets become entrained with the air currents developed within the central region of the spray.

Consistent with the manufacturer's claim, the Micronair 6600 produces a majority of droplets within the 18 to 25 μm range. With radial distance, however, the droplet sizes increase to values greater than 50 μm. It is important that these largest droplets are included in the droplet spectra being used within spray dispersion models to achieve the most representative predictions.

Device Effects: At the highest rotation speed tested (15,000 rpm), the droplet size did not vary appreciably with an increase in the liquid flow rate. Smaller droplets were produced with an increase in rotation speed due to the increased centrifugal energy. This effect became more pronounced with distance from the center of the plume, where a reduction in rotation rate afforded less effective atomization and lower centrifugal momentum of the droplets produced.

These results are consistent with findings reported for a similar rotary atomizer (i.e., Micronair AU5000) [9]. The rotation rate of the atomizer was identified as the main factor affecting droplet size, while liquid flow rate was found to not have a large effect on atomization.

Simulated Flight Speed Effects: For the range of flight speeds tested, the increase in air speed did not appear to have a secondary effect on droplet breakup leading to a shift in droplet size. As the flight speed was increased, the spray plume immediately downwind from the device became more streamlined as evidenced by the larger droplets located near the edge of the plume, as well as from observation. The high-speed air flow serves to shape the plume and transport the droplets downstream.

Spray Droplet Velocity: The droplet velocities steadily increase toward the experimental simulated flight speeds in each of the cases. Near the spray periphery, the droplet velocities were within approximately 5 to 10% of the simulated flight speeds. The wind speed was expected to be slightly less than the planned test condition due to drag losses between the blower outlet and the PDA measurement location. Thus, the measured droplet velocities agree well with the expected wind speeds immediately downstream of the device.

Mass-Balanced, Integrated Spray Plume: Comparison of the spray's mass-balanced cumulative distribution to cumulative distributions measured at each profile point is presented in Figure 3 (left illustration) for the base test condition. Note that the MMD for the integrated distribution is 32.0 μm, while the range of MMDs for the individual measurement locations is 17.4 to 49.3 μm; significant error could be realized if any of the individual measurements were exclusively used within a dispersion model. Hence, the mass-balanced, integrated approach provides a better global characterization of the overall size distribution represented in the spray plume.

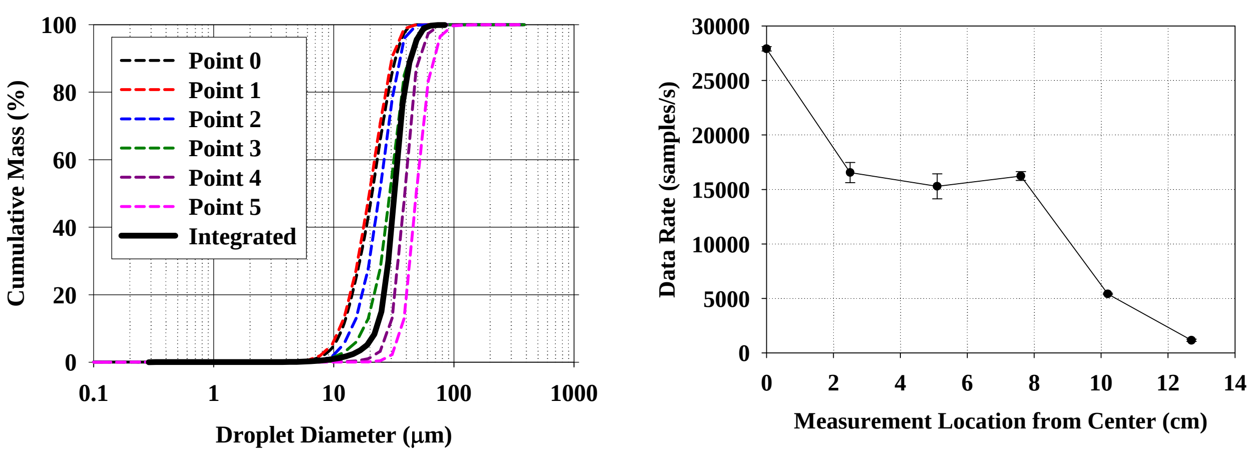

Figure 10. Mass-Balanced, Integrated Results (left) and PDA Data Rates (right)

For the range of test conditions, the droplet size distributions were consistently log-normal, with a MMD in the range of 30-40 μm and a GSD of approximately 1.3. Variations in MMD were consistent with device operating conditions, where a high rotation rate (15,000 rpm) resulted in the smallest droplets, irrespective of simulated air speed. The higher liquid flow rate (2.0 L/min) had a larger MMD compared to the base test condition, which is likely due to the presence of larger droplets near the periphery of the spray plume.

Using the mass-balanced, integrated method, the total mass flow rates based on PDA measured data were computed to be within 22 to 56% of the device experimental flow rates. While the computed values do not demonstrate mass closure, it is interesting to note that these values were computed from a total measurement area of 3.5

mm^2, or approximately 0.005% of the total considered plume area. The PDA data rate, a measure of the number of droplets sampled per second, became increasingly low near the periphery of the plume, as shown in right most illustration of Figure 3. Nonetheless, an appreciable number of droplets (i.e., nearly 1000 samples/s) were still measured at the outermost profile location. It is expected that by extending the measurement periphery beyond the 12.7 cm (5 in) boundary, the mass closure would be improved by including more of the largest droplets found at the edge of the plume. In addition, greater resolution within the measurement profile may also help improve the mass closure.

Conclusions

Results from this study demonstrate that a mass-balanced, integrated methodology using data measured with phase Doppler anemometry in a simulated aerial environment can be used to determine a droplet distribution that is representative of the entire spray plume. While mass closure was not achieved, with computed mass flows found to be within approximately 25 to 50% of the operating conditions, the method may be improved by extending the measurement profile to capture more of the largest droplets at the periphery of the spray plume. The performance of the Micronair 6600 was found to be consistent with the manufacturer's claims, as the majority of droplets produced were within the 18 to 25 μm range. However, it is important to note that droplets increased in size to greater than 50 μm at the edge of the spray plume.

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