Rotary Atomizer Drop Size Distribution Database

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Abstract. *Wind tunnel measurements of drop size distributions from Micronair AU4000 and AU5000 rotary atomizers were collected to develop a database for model use. The measurements varied tank mix, flow rate, air speed, and blade angle conditions, which were correlated by multiple regressions (average R^2 = 0.995 for AU4000 and 0.988 for AU5000). This database replaces an outdated set of rotary atomizer data measured in the 1980s by the USDA Forest Service and fills in a gap in data measured in the 1990s by the Spray Drift Task Force. Since current USDA Forest Service spray projects rely on rotary atomizers, the creation of the database (and its multiple regression interpolation) satisfies a need seen for ten years.*

Keywords. *AGDISP, Database, Drop size distribution, Multiple regression, Rotary atomizer.*

The drop size distribution of aerially applied spray material atomized by nozzles influences the magnitude of evaporation, spray deposition, drift, and application effectiveness. Droplet size information, in particular the volume fraction in the smaller droplet sizes (which tend to be more prone to drift) and the larger droplet sizes (which fall largely within the application area), is critical to forestry and agricultural applications, where specific levels of spray material in specific droplet size ranges must be deposited to achieve efficacy.

In an effort to build a database of typical formulations and aerial application conditions, the USDA Forest Service (FS), and other agencies and companies, conducted wind tunnel tests to determine drop size distributions of pesticides and simulant spray material when applied through hydraulic and rotary atomizers. These studies, from the 1970s to the 1990s, were intended to provide data to determine the effects of application and tank mix variables on the atomization of aerially applied sprays. The factors considered in these studies included the spray pressure, liquid flow rate, air velocity and shear across the atomizer, physical chemistry (viscosity, specific gravity, and surface tension), and atmospheric conditions. The FS database was summarized in Skyler and Barry (1991) and assembled as a library within the FS aerial spray prediction models AGDISP and FSCBG. A preliminary examination of this database produced techniques for collapsing and correlating the data (Teske et al., 1991) and examining possible non-Newtonian effects (Teske and Bilanin, 1994).

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These data were measured with a Particle Measurement Systems (PMS) optical array probe, with a minimum droplet resolution of 34 μm. Recently, the Spray Drift Task Force (SDTF) developed a large database of spray droplet size information (Hewitt et al., 2002) based on the Malvern laser diffraction analyzer. This technique allowed measurements of droplet diameters down to 4 μm. The SDTF field and subsequent modeling studies (Teske et al., 2002a; Bird et al., 2002) established that knowledge of the droplet spectrum at its smaller droplet sizes is important for drift assessment, and that the Malvern (or similar) instrument range is essential to recover that detail.

Droplets in the range of 80 to 120 μm are often desirable for efficacy in forestry applications. To achieve these droplet sizes, some important fraction of sub-80 μm droplets will always be produced below the 34 μm PMS cutoff. The historical FS database contains 40 AU5000 rotary atomizer entries, out of 250, while the SDTF database contains only three AU5000 entries, out of 1294 (the SDTF was more concerned with hydraulic nozzles spraying agricultural pesticides). To extend the usefulness of the PMS data, an analytical approach was developed to convert PMS rotary atomizer data to Malvern-like data (Teske et al., 2002b). However, a revised database of drop size distributions is now necessary, since many of the spray materials tested in the original FS database are no longer sprayed in forestry situations. For example, the primary use of rotary atomizers by the FS is in spraying *Bacillus thuringiensis* (Bt) in gypsy moth control. Bt is best applied by rotary atomizers (to recover the smaller droplet sizes desired for application efficiency). Generating a model database for rotary atomizers would then provide a ready resource for planning future spray projects. This article summarizes additional wind tunnel experiments conducted to generate this database, and the strong statistical correlation generated from the data.

Rotary Atomizer Data Collection

The new data consist of 310 drop size distribution measurements (including replicates), varying tank mix [water, water with 1% w/w Sta-Put polyacrylamide (Nalco Chemical Company, Naperville, Ill.), water with 0.25% w/w

Table 1. Physical properties of tested substances.

Spray Material	Dynamic Surface Tension (dyne cm^{-1})	Extensional Viscosity (cP)
Water	72.4	3.0
Water with Hasten	61.7	2.0
Water with Sta-Put	65.0	200.0
Foray 76B	71.5	9.6

Hasten modified seed oil (Wilbur-Ellis Company, San Antonio, Texas), and Foray 76B neat (*Bacillus thuringiensis* var. kurstaki, Valent BioSciences Inc., Libertyville, Ill.)], blade angle (35° to 75°), flow rate (3.75 to 45 L min^{-1}), air speed (22.4 to 76 m s^{-1}), and loaded (wet) rotation rate (2480 to 11200 rpm). The physical properties of the tested substances are summarized in table 1.

The collected database affords variation in air speed, blade angle, flow rate, dynamic surface tension, and extensional viscosity. The tests were conducted in the wind tunnel facilities at the University of Queensland, Gatton, Australia. A Malvern 2600c laser diffraction particle size analyzer (Malvern Instruments, Ltd., Worcestershire, U.K.) was used to characterize the droplet size spectra from Micronair AU4000 and AU5000 rotary-cage atomizers (Micron Sprayers, Ltd., Herefordshire, U.K.) with standard-length windmill blades. The test protocol described by Hewitt (1994) was followed.

Data Interpretation

Test results confirm that the main factor affecting droplet size is the rotation rate of the atomizer. In the wind tunnel, atomizer rotation rate can be held constant, whereas during actual applications, rotation rate varies with air speed and with position along the wing (Teske et al., 2005). At higher flow rates and lower air speeds, wind tunnel results suggest that rotation rates were slower and the sprays were therefore coarser. This effect was more pronounced at the smaller (35° to 45°) blade angles tested, although rotation rates were higher at these blade angles. Higher air speeds caused more air shear across the atomizer, which can produce finer sprays, although the relative liquid to air velocity is an important consideration. By itself, flow rate did not have a large effect on atomization, while tank mix had a large effect on droplet size, with the tank mix with low dynamic surface tension (water with Hasten) producing the finest sprays, the tank mix with high extensional viscosity (water with Sta-Put) producing the coarsest sprays, and water alone being intermediate between the other two.

Preliminary results for water, water with Hasten, and water with Sta-Put were presented previously (Teske et al., 2003a). The results shown here summarize the complete database development.

Data Correlation

Correlation of the data is desirable to provide a way of estimating drop size distributions for conditions not specifically tested in the wind tunnel (other air speeds, blade angles, flow rates, or physical properties). Within the agricultural community, three regression techniques have emerged as target approaches: multiple regression (Hermansky, 1998), neural network (Esterly, 1998), and dimensional analysis (Teske and Thistle, 2000). Hermansky examined the entire SDTF atomization and physical property database (2000 drop size distributions, including 15 different nozzle tips, 52 pesticide tank mixtures, 6 air speeds, 11 tank

Table 2. Multiple regression coefficients for droplet diameters $D_{V0.25}$, $D_{V0.5}$, and $D_{V0.75}$. The independent variables have been normalized so that their correlation values are ±1.0 (air speed = 22.4 m s^{-1} ≤ U ≤ 76 m s^{-1}, blade angle = 35° ≤ Θ ≤ 75°, flow rate = 3.75 L min^{-1} ≤ Q ≤ 45 L min^{-1}, rotation rate = 2480 rpm ≤ Ω ≤ 11200 rpm, dynamic surface tension = 61.7 dyne cm^{-1} ≤ σ ≤ 72.4 dyne cm^{-1}, and extensional viscosity = 3.0 cP ≤ ν ≤ 200.0 cP). Blank entries (--) represent insignificant terms, while NM denotes that blade angle was not measured for the AU4000.

Factor	AU4000 $D_{V0.25}$ (µm)	AU4000 $D_{V0.5}$ (µm)	AU4000 $D_{V0.75}$ (µm)	AU5000 $D_{V0.25}$ (µm)	AU5000 $D_{V0.5}$ (µm)	AU5000 $D_{V0.75}$ (µm)
Intercept	45.082	67.734	89.637	14.110	145.493	220.394
U	--	--	--	--	−90.522	−123.339
Θ	NM	NM	NM	−84.307	55.897	75.294
Q	5.600	7.199	11.306	--	23.397	33.892
Ω	−54.891	−66.666	−89.626	−139.341	−48.972	−74.225
σ	--	--	--	7.594	--	--
ν	--	--	--	--	43.234	75.548
U × U	--	--	--	27.573	38.530	32.225
U × Θ	NM	NM	NM	−52.615	−63.390	−66.532
U × Ω	34.577	48.938	68.312	−26.067	--	--
U × σ	--	--	--	−7.651	--	--
U × ν	--	--	--	15.188	−24.729	−46.694
Θ × Θ	NM	NM	NM	−21.360	--	--
Θ × Q	NM	NM	NM	−12.054	−−	−−
Θ × Ω	NM	NM	NM	−43.087	38.378	74.120
Θ × σ	NM	NM	NM	6.350	--	--
Θ × ν	NM	NM	NM	−28.163	--	--
Q × Ω	--	--	--	−11.089	--	--
Q × σ	--	--	--	--	−14.132	−18.145
Q × ν	--	--	--	6.749	14.952	25.878
Ω × Ω	24.478	33.672	45.300	41.098	71.742	121.876
Ω × ν	--	--	--	−45.048	−27.895	−68.013

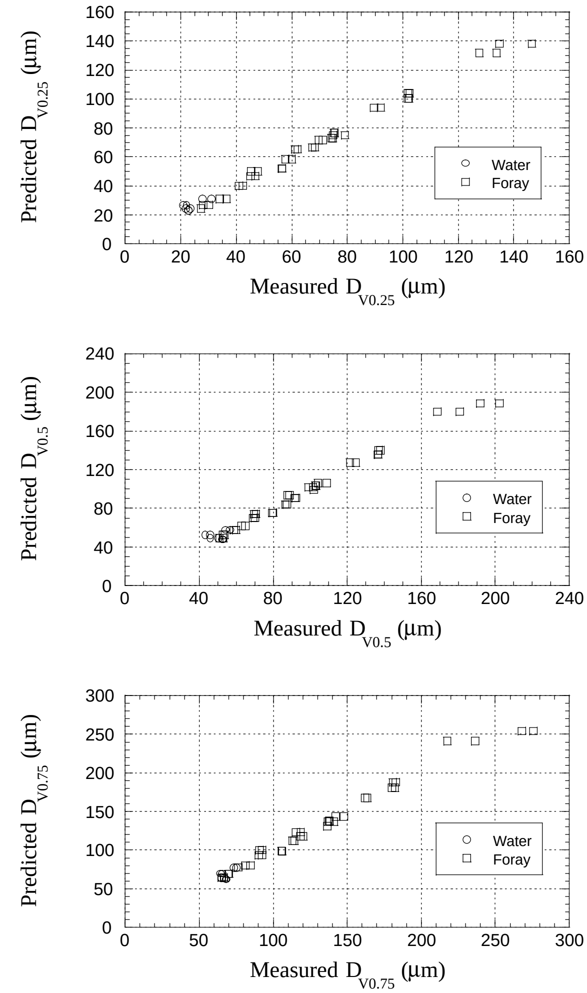

Figure 1. Comparison of the multiple regression prediction for $D_{V0.25}$ (top), $D_{V0.5}$ (middle), and $D_{V0.75}$ (bottom) with the measured $D_{V0.25}$, $D_{V0.5}$, and $D_{V0.75}$, respectively, for AU4000, with air speed, flow rate, and rotation rate. All measured data were used to form the regression.

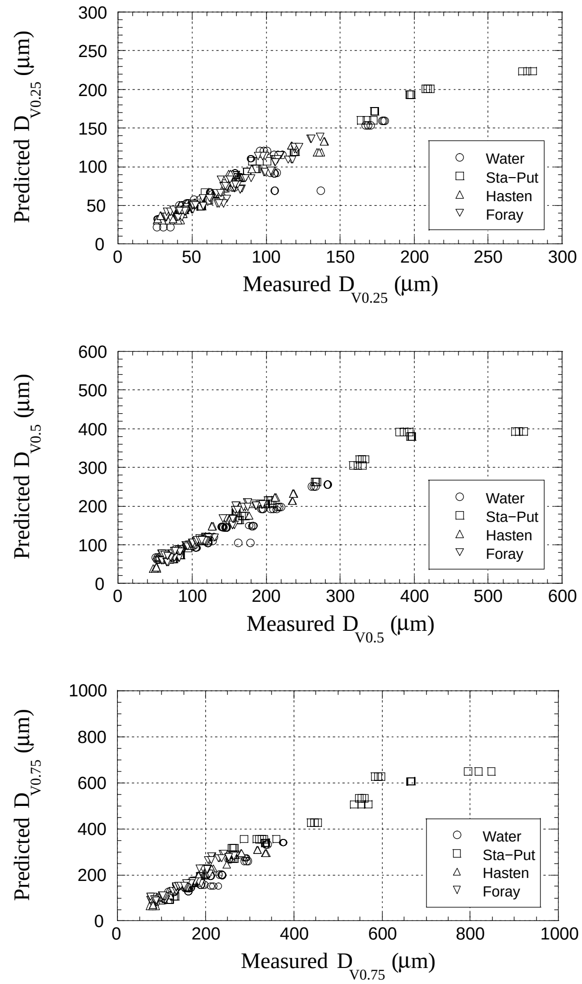

Figure 2. Comparison of the multiple regression prediction for $D_{V0.25}$ (top), $D_{V0.5}$ (middle), and $D_{V0.75}$ (bottom) with the measured $D_{V0.25}$, $D_{V0.5}$, and $D_{V0.75}$, respectively, for AU5000, with air speed, blade angle, flow rate, rotation rate, dynamic surface tension, and extensional viscosity. All measured data were used to form the regression.

pressures, and 6 nozzle angles) and developed correlations for $D_{V0.5}$ and the volumes in droplet sizes below 50 µm, 141 µm, and 220 µm. Multiple regression was subsequently used by Kirk (2001, 2002), with a database composed of the most popular agricultural hydraulic nozzles, correlating $D_{V0.5}$, relative span, and the volumes in droplet sizes below 100 µm and 200 µm. Various data collection approaches for rotary atomizers have been followed previously by Parkin et al. (1980), Spillman (1982), van Vliet and Picot (1987), Picot et al. (1989), Parkin and Siddiqui (1990), Hewitt and Matthews (1991), and Hewitt et al. (1994). The multiple regression approach will be followed here.

The statistical software package used in the analysis was JMP, version 3.2.2 (SAS Institute, Inc., Cary, N.C.). The approach was two-fold: (1) for the AU4000 data, only water and Foray were tested, and blade angle measurements were not available, thus air speed, flow rate, unloaded (dry) rotation rate, dynamic surface tension, and extensional viscosity were used to develop droplet diameter correlations; while (2) for the AU5000 data, all four test substances were available, and air speed, blade angle, flow rate, loaded (wet) rotation rate, dynamic surface tension, and extensional viscosity were used to develop droplet diameter correlations. The results obtained by Kirk (2001, 2002) for relative span suggest that $D_{V0.1}$ and $D_{V0.9}$ may not be strongly correlated, and it was decided to generate $D_{V0.25}$ and $D_{V0.75}$, along with $D_{V0.5}$, as suggested by Parkin and Siddiqui (1990). Once the three diameters are correlated, the representative drop size distribution can be recovered by an application of the root-normal approach (Simmons, 1977).

In the statistical analyses, all primary terms were retained, and product terms were retained only if significant (Prob > F is <0.0001). The independent variables were air speed (U, m s^{-1}), blade angle (Θ, deg), flow rate (Q, L min^{-1}), rotation rate (Ω, rpm), dynamic surface tension (σ, dyne cm^{-1}), and extensional viscosity (ν, cP). These variables were normalized across their test ranges (normalizing their minimum values at −1.0 and their maximum values at 1.0), so that the resulting multiple regression expressions could be visually inspected for magnitude effects. The statistical results are summarized in table 2.

The AU4000 did not correlate with air speed except in a product term with rotation rate. In addition, the fact that blade angle was not measured for the AU4000 diminishes the usefulness of the results presented here. The AU5000 multiple regression results reflect the dominant correlation among all independent variables. However, with the limited amount of data, no independent data were used that were not a part of the regression.

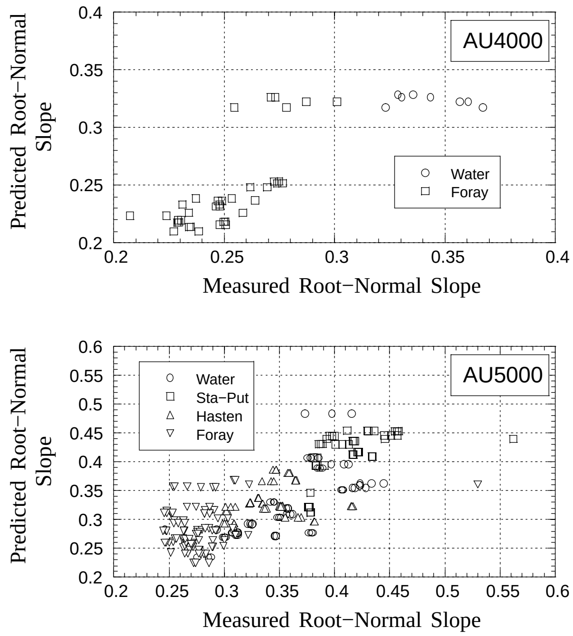

Figure 3. Comparison of the predicted root-normal slope from the predictions for $D_{V0.25}$, $D_{V0.5}$, and $D_{V0.75}$ with the root-normal slope from the collected data.

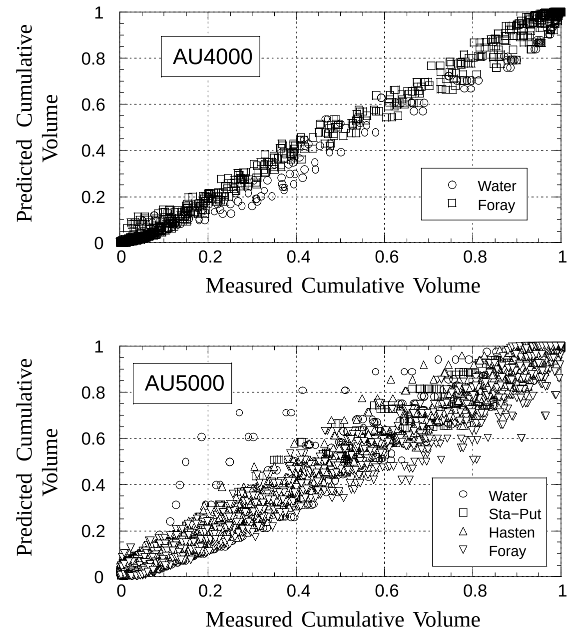

Figure 4. Comparison of predicted cumulative volume with measured cumulative volume.

RESULTS

Figure 1 displays the multiple regression predictions of $D_{V0.25}$, $D_{V0.5}$, and $D_{V0.75}$ versus the collected drop size distribution data volume-interpolated for these diameter values for the AU4000. The statistical correlation of diameter to air speed U, flow rate Q, and unloaded (dry) rotation rate Ω (variations in dynamic surface tension σ and extensional viscosity ν are statistically insignificant) retains several product terms, with R^2 = 0.992 for $D_{V0.25}$, R^2 = 0.989 for $D_{V0.5}$, and R^2 = 0.985 for $D_{V0.75}$.

Figure 2 displays the multiple regression predictions of $D_{V0.25}$, $D_{V0.5}$, and $D_{V0.75}$ versus the collected drop size distribution data volume-interpolated for these diameter values for the AU5000. The statistical correlation of diameter to air speed U, blade angle Θ, flow rate Q, loaded (wet) rotation rate Ω, dynamic surface tension σ, and extensional viscosity ν retains product terms involving all six variables, with R^2 = 0.961 for $D_{V0.25}$, R^2 = 0.971 for $D_{V0.5}$, and R^2 = 0.964 for $D_{V0.75}$.

With multiple regression expressions for $D_{V0.25}$, $D_{V0.5}$, and $D_{V0.75}$ in hand, drop size distributions may be recovered. The root-normal approach (Simmons, 1977) approximates the drop size distribution by a straight-line fit in probability space:

$$\sqrt{\frac{D}{D_{v0.5}}} = 1 + S\,\mathrm{Pr} \tag{1}$$

where D is the droplet diameter, S is the root-normal slope, and Pr is the probability function (Abramowitz and Stegun, 1968). A least squares approach using $D_{V0.25}$, $D_{V0.5}$, and $D_{V0.75}$ recovers the slope comparisons shown in figure 3. While the correlation appears weak (R^2 = 0.696 for AU4000 and R^2 = 0.599 for AU5000), the inverse operation (recovering the drop size distribution as a function of cumulative volume) results in highly correlated predictions (R^2 = 0.995 for AU4000 and R^2 = 0.988 for AU5000), as shown in figure 4. Similar behavior with regard to the accuracy of the least squares slope and the reconstructed drop size distribution was found when analyzing other droplet data (Teske and Thistle, 2000; Teske et al., 2002b).

It may therefore be concluded that the predicted drop size distributions are a weak function of the root-normal slope, and more strongly dependent on $D_{V0.5}$, which is highly correlated in these data. Figure 4 shows that variability is higher for the AU5000 with this data set.

While multiple regression shows the data to be highly correlated, it does not provide direct physical insight into the effects of the independent variables on the dependent variables, other than confirming the anticipated effects of rotation rate and the physical properties on droplet diameter (the product terms involving U, Θ, Q, and Ω with σ and ν). The AU4000 data set, with multiple regression dependence only on U, Q, and Ω, is amenable to curve fitting, resulting in the following functional relationships:

$$D_{V0.25} = 28.122\left(\frac{U}{U_{max}}\right)^{-0.331}\left(\frac{Q}{Q_{max}}\right)^{0.103}\left(\frac{\Omega}{\Omega_{max}}\right)^{-0.992} \tag{2}$$

$$D_{V0.5} = 50.258\left(\frac{U}{U_{max}}\right)^{-0.327}\left(\frac{Q}{Q_{max}}\right)^{0.056}\left(\frac{\Omega}{\Omega_{max}}\right)^{-0.714} \tag{3}$$

$$D_{V0.75} = 67.129\left(\frac{U}{U_{max}}\right)^{-0.359}\left(\frac{Q}{Q_{max}}\right)^{0.068}\left(\frac{\Omega}{\Omega_{max}}\right)^{-0.706} \tag{4}$$

where U_{max} = 76 m s^{-1}, Q_{max} = 45 L min^{-1}, and Ω_{max} = 11200 rpm, with R^2 = 0.974, 0.972, and 0.980, respectively. These R^2 are comparable to those obtained with multiple regression. A similar approach was used in Parkin and Siddiqui (1990) for the Micronair AU3000, resulting in power-law dependence of $U^{0.156}$, $Q^{0.170}$, and $\Omega^{-0.493}$ (R^2 = 0.965) for $D_{V0.5}$. The results presented here are somewhat different, and they may be attributed to the PMS instrument used for their measurements.

CONCLUSIONS

The results shown here demonstrate strong correlation among the parameters thought to be important in the atomization process. These correlations have been used to develop a rotary atomizer library option in AGDISP (Teske et al., 2003b), complimenting the hydraulic nozzle library option (based on Kirk, 2001, 2002) and the SDTF nozzle library (Hewitt et al., 2002). This extended database now provides FS managers with a tool for estimating drop size distributions when planning many of their spray projects, especially those involving Bt.

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