Rotary Atomizer Droplet Size Distribution Database for Forestry Applications

Teske M. E.[1], Thistle H. W.[2], Hewitt A. J.[3], Ghent J. H.[4]

1. Continuum Dynamics, Inc., 34 Lexington Avenue, Ewing, NJ 08618 USA
2. USDA Forest Service, 180 Canfield Street, Morgantown, WV 26505 USA
3. Stewart Agricultural Research Services, Inc., P.O. Box 509, Macon, MO 63552 USA
4. USDA Forest Service, P.O. Box 2680, Asheville, NC 28802 USA

Wind tunnel measurements of droplet size distributions from a Micronair AU5000 rotary atomizer, operating with varying tank mix, flow rate, air speed, and blade angle conditions, generate a rotary atomizer database and recovery of a highly correlated multiple regression (average R^2 = 0.983) that represents all collected data and forms the basis for a future model library containing these distributions for forestry applications.

1. Introduction

The droplet 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), are 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 United States Department of Agriculture Forest Service (FS), and other agencies and companies, conducted wind tunnel tests to determine droplet 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 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 [1], 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 [2] and developing scaling laws for non-Newtonian fluids [3].

These data were measured with the 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 [4], based on the Malvern laser diffraction analyzer. The resolution of this technique allowed measurements of droplet diameters down to 4 μm. The SDTF field and subsequent modeling studies [5, 6] 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.

The historical rotary atomizer data suffer from the difference in measurement techniques, as droplets in the range of 80-120 μm may be desirable for efficacy in forestry applications. To achieve these droplet sizes, some important fraction of sub-80 μm droplets will be produced below the 34 μm PMS cutoff. The historical database contains 40 AU5000 rotary atomizer entries (out of 250 – the primary use of rotary atomizers by the FS is the spraying of Bacillus thuringiensis in gypsy moth control), 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 the PMS rotary atomizer data to Malvern-like data [7]. However, a revised database of droplet size distributions is necessary, since many of the spray materials tested in the original FS database are no longer sprayed in forestry situations. This paper summarizes additional wind tunnel experiments conducted to generate this database, and the strong statistical correlation generated from the data.

2. Rotary Atomizer Data Collection

The new data consist of 158 droplet size distribution measurements (including replicates), varying tank mix [water, water with 1% w/w Sta-Put® polyacrylamide (Nalco Chemical Company, Naperville, IL), and water with 0.25% w/w Hasten® modified seed oil (Wilbur-Ellis Company, San Antonio, TX)], blade angle [35 to 75°], flow rate [1 to 6.6 gpm], air speed [70 to 140 mph], and loaded (wet) rotation rate [2560 to 8620 rpm]. The database then 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 was used to characterize the droplet size spectra from a Micronair AU5000 rotary cage atomizer with standard length windmill blades. The test protocol [8] was followed.

Test results [9] confirm that the main factor affecting droplet size was the rotation rate of the atomizer. At higher flow rates and lower air speeds, rotation rates were slower and the sprays were coarser. This effect was more pronounced at the smaller (35 to 45°) blade angles tested, although at these blade angles rotation rates were higher. 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. In and of 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 lower dynamic surface tension (water with Hasten®) producing the finest sprays, tank mix with high extensional viscosity (water with Sta-Put®) producing the coarsest sprays, and water alone being intermediate between the other two.

3. Data Correlation

Correlation of these data is desirable, to provide a way of estimating droplet 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 previously followed in correlation studies: multiple regression [10], neural network [11], and dimensional analysis [12]. In [10] Hermansky examined the entire SDTF atomization and physical property database (2000 droplet size distributions, including 15 different nozzle tips, 52 pesticide tank mixtures, six air speeds, 11 tank pressures, and six nozzle angles) and developed correlations for $D_{v0.5}$ and the volumes in droplet sizes below 50 μm, 141 μm, and 220 μm. Multiple regressions were subsequently used in [13] and [14], with a database composed of the most popular agricultural hydraulic nozzles, producing correlations for $D_{v0.5}$, relative span, and the volumes in droplet sizes below 100 μm and 200 μm. The multiple regression approach will also be followed here.

The statistical software package used in the present analysis was JMP, version 3.2.2, SAS Institute, Inc., Cary, NC. The approach was two-fold: (1) air speed, blade angle, and flow rate were used to develop a correlation with the loaded (wet) rotation rate; and (2) air speed, blade angle, flow rate, loaded (wet) rotation rate, dynamic surface tension, and extensional viscosity were used to develop droplet diameter correlations that well represent the structure of the droplet size distribution. The results obtained in [13] and [14] for relative span suggested 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 in [15]. Once correlations for the three diameters are obtained, the representative droplet size distribution can be recovered by an application of the root-normal approach [16].

In the statistical analysis all primary terms were retained, and secondary cross terms were retained only if significant (Prob>F is <0.0001). The independent variables were also 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 1.

4. Results

Figure 1 displays the multiple regression prediction of loaded (wet) rotation rate versus the collected loaded (wet) rotation rate data. The statistical correlation of rotation rate to air speed U, blade angle Θ, and flow rate Q retains the important cross terms of $U\times\Theta$, $U\times Q$, and $\Theta\times\Theta$, with $R^2 = 0.987$ (with a maximum residual of 700 rpm).

Figure 2 displays the multiple regression predictions of $D_{v0.25}$, $D_{v0.5}$, and $D_{v0.75}$ versus the collected droplet size distribution data volume-interpolated for these diameter values. The statistical correlations of diameter to U, Θ, Q, loaded (wet) rotation rate Ω, dynamic surface tension σ, and extensional viscosity ν retain the important cross terms of $U\times\Theta$, $U\times\Omega$, $\Theta\times\Theta$, $\Theta\times\Omega$, $\Theta\times\sigma$, $\Theta\times\nu$, $Q\times\sigma$, $Q\times\nu$, $\Omega\times\Omega$, $\Omega\times\sigma$, and $\Omega\times\nu$, with $R^2 = 0.980$ for $D_{v0.25}$ (with a maximum residual of 20 μm), $R^2 = 0.988$ for $D_{v0.5}$ (maximum residual of 32 μm), and $R^2 = 0.982$ for $D_{v0.75}$ (maximum residual of 80 μm).

Figure 3 displays the accuracy of the multiple regression approach on the dataset for $D_{v0.05}$ to $D_{v0.95}$. The multiple regression is seen to be highly accurate except as cumulative volume fraction approaches 1.

With multiple regression expressions for $D_{v0.25}$, $D_{v0.5}$, and $D_{v0.75}$ in hand, droplet size distributions may be recovered. The root-normal approach [16] approximates the droplet size distribution by a straight line fit in probability space

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

Table 1. Multiple regression coefficients for loaded (wet) rotation rate and the droplet diameters $D_{v0.25}$, $D_{v0.5}$, and $D_{v0.75}$. The independent variables have been normalized so that their correlation values are between ±1.0 (70 mph ≤ U ≤ 140 mph, 35° ≤ Θ ≤ 75°, 1.0 gpm ≤ Q ≤ 6.6 gpm, 2560 rpm ≤ Ω ≤ 8620 rpm, 54.0 dynes/cm ≤ σ ≤ 72.0 dynes/cm, and 3.0 cP ≤ ν ≤ 800.0 cP). The correlation coefficients may then be compared directly by magnitude.

Factor	Ω (rpm)	$D_{v0.25}$ (μm)	$D_{v0.5}$ (μm)	$D_{v0.75}$ (μm)
Intercept	4062.43	391.75	551.80	633.23
U	1866.20	-318.52	-405.28	-413.19
Θ	-2811.84	481.69	596.92	571.49
Q	-275.56	7.63	10.51	13.82
Ω		405.26	486.52	389.63
σ		-0.55	6.48	13.40
ν		18.83	36.77	59.14
U×Θ	-972.67	-670.01	-953.40	-1057.36
U×Q	140.77			
U×Ω		-615.83	-871.12	-945.67
Θ×Θ	873.77	510.37	716.71	786.15
Θ×Ω		985.76	1386.08	1495.44
Θ×σ		-0.35	-5.50	-5.18
Θ×ν		-17.84	-22.86	-41.41
Q×σ		-5.31	-4.18	-3.89
Q×ν		11.37	19.06	21.15
Ω×Ω		482.91	693.85	761.55
Ω×σ		-12.61	-17.82	-16.34
Ω×ν		-10.98	-32.88	-81.91

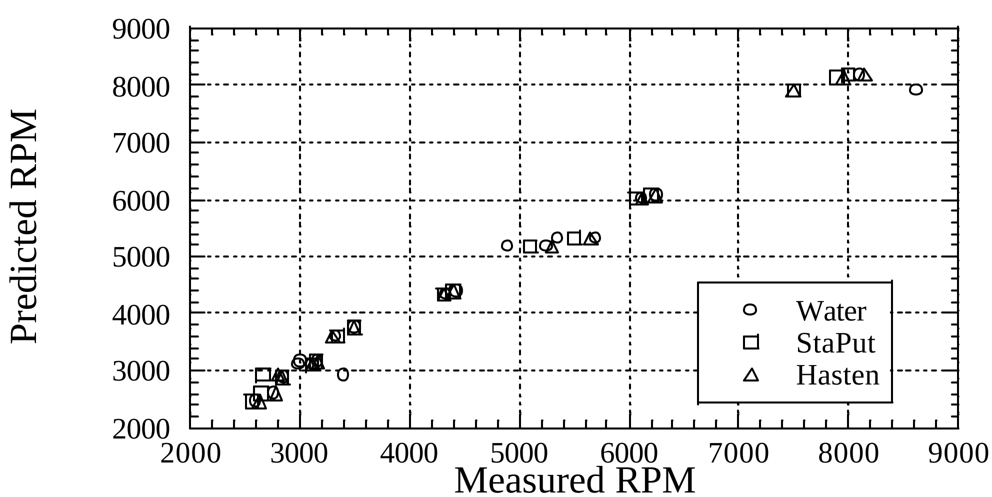

Fig. 1 Comparison of the multiple regression prediction for loaded (wet) rotation rate with the measured loaded (wet) rotation rate, with the primary independent variables of air speed, blade angle, and flow rate. The three tank mixes (water, water with 1% w/w Sta-Put®, and water with 0.25% w/w Hasten®) are combined to produce a single multiple regression, but their data points are identified separately on the figure. The multiple regression approach recovers $R^2 = 0.987$.

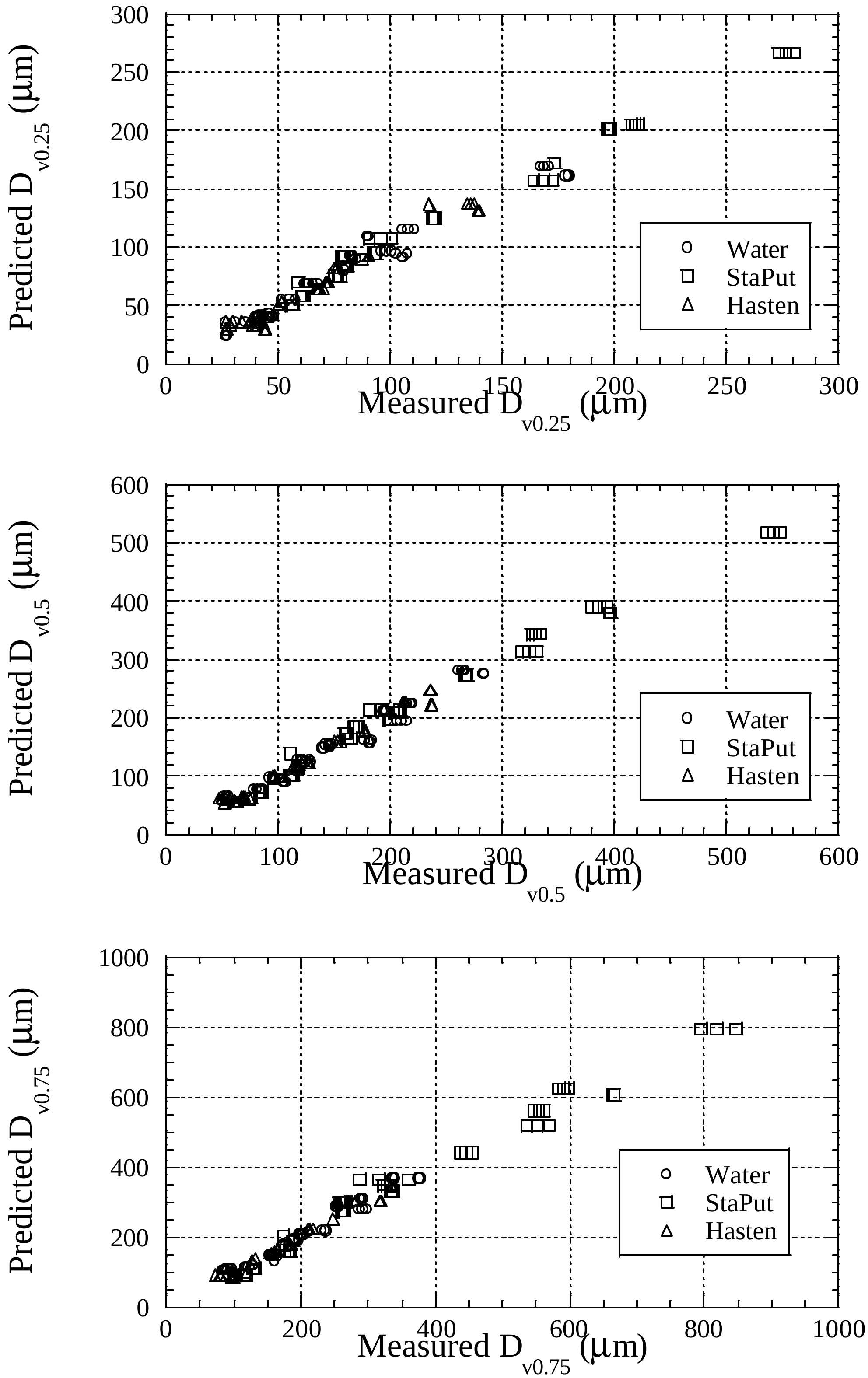

Fig. 2 Comparison of the multiple regression prediction for $D_{v0.25}$ (top), $D_{v0.5}$ (middle), and $D_{v0.75}$ (bottom) with the measured $D_{v0.25}$, $D_{v0.5}$, and $D_{v0.75}$, respectively, with the primary independent variables of air speed, blade angle, flow rate, rotation rate, dynamic surface tension, and elongational viscosity. The three tank mixes (water, water with 1% w/w Sta-Put®, and water with 0.25% w/w Hasten®) are combined to produce a single multiple regression, but their data points are identified separately on the figure. The multiple regression approach recovers an average $R^2 = 0.983$.

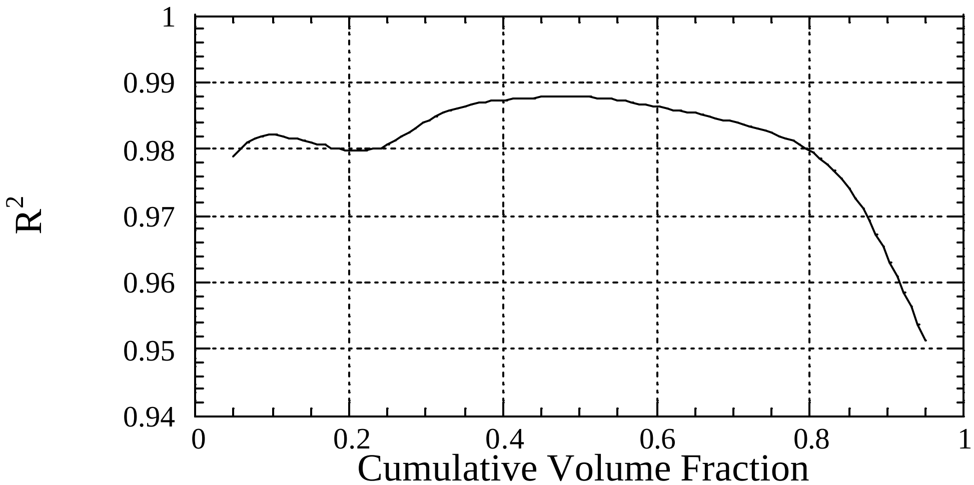

Fig. 3 Multiple regression accuracy for $D_{v0.05}$ to $D_{v0.95}$.

where D is the droplet diameter, S is the root-normal slope, and Pr is the probability function [17]. A least squares approach using $D_{v0.25}$, $D_{v0.5}$, and $D_{v0.75}$ recovers the slope comparisons shown in Figure 4. While the correlation appears weak (R^2 = 0.729), the inverse operation (recovering the droplet size distribution as a function of cumulative volume fraction) results in the highly-correlated prediction (R^2 = 0.997) shown in Figure 5.

It can therefore be concluded that the predicted droplet 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 (R^2 = 0.988). Figure 5 shows that variability is higher at the lower and higher values of cumulative volume fraction, an effect that warrants additional investigation.

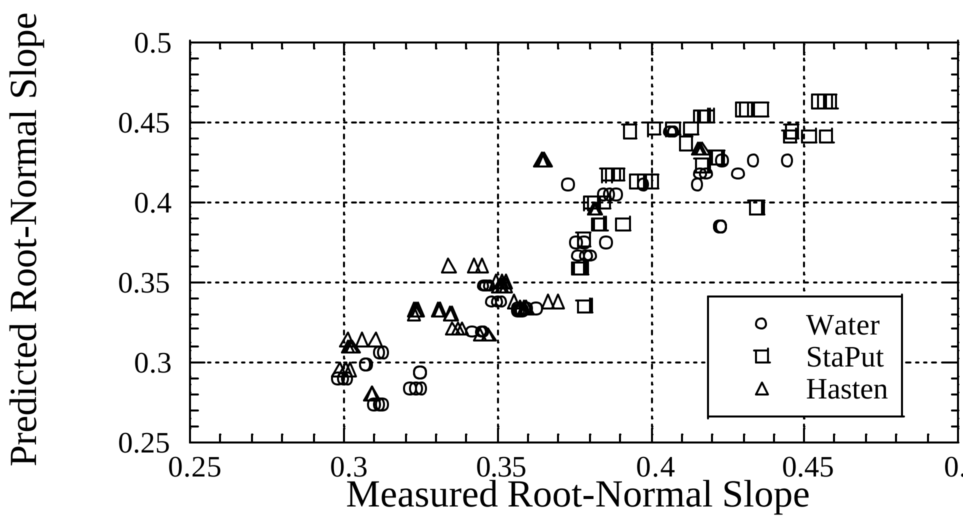

Fig. 4 Comparison of the predicted root-normal slope S from the multiple regression predictions for $D_{v0.25}$, $D_{v0.5}$, and $D_{v0.75}$ with the measured root-normal slope from the collected data. The three tank mixes (water, water with 1% w/w Sta-Put®, and water with 0.25% w/w Hasten®) are combined to produce a single correlation, but their data points are identified separately on the figure. The correlation recovers R^2 = 0.729.

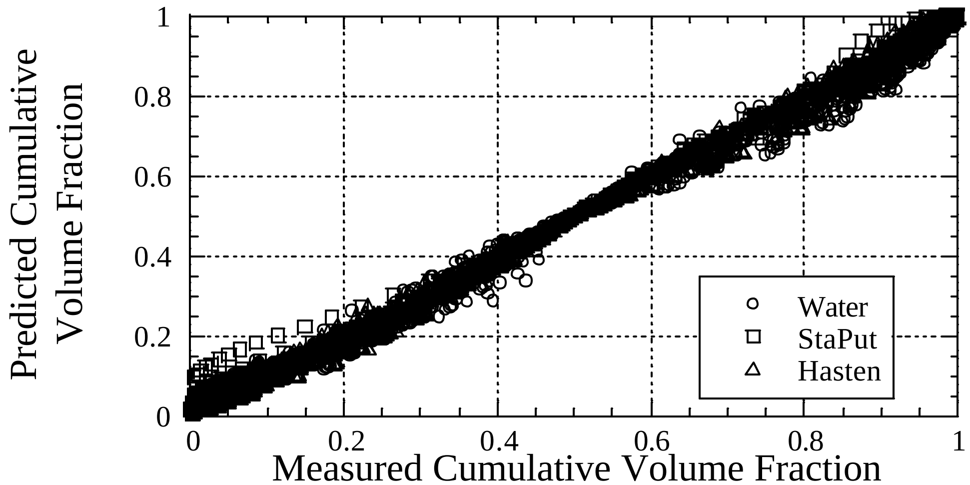

Fig. 5 Comparison of the predicted cumulative volume fraction from the root-normal approach with the measured cumulative volume fraction from the collected data. The three tank mixes (water, water with 1% w/w Sta-Put®, and water with 0.25% w/w Hasten®) are combined to produce a single correlation, but their data points are identified separately on the figure. The correlation recovers $R^2 = 0.997$, with a mean difference between measured and predicted cumulative volume fraction of 0.015 and a maximum difference of 0.116.

In addition, while multiple regressions may correlate the data precisely, they do not provide direct physical insight into the effect of the independent variables (U, Θ, Q) on the dependent variables (Ω, $D_{v0.25}$, $D_{v0.5}$, $D_{v0.75}$), other than confirming the anticipated effects of rotation rate and the physical properties on droplet diameter (the cross terms involving Θ, Q, and Ω with σ and ν). Basically, correlation techniques are used on large databases because the exact effect of the independent variables on the dependent variables has not been quantified. Alternate approaches [3, 18, 19] involving power laws and the appropriate nondimensional parameters of Reynolds number and Weber number – prominent in the theory behind droplet breakup [20] – are currently being explored.

5. Future Study

Additional wind tunnel data are being collected, in an effort to include additional spray materials more typical of forestry applications (*Bacillus thuringiensis* formulations, for example). These data will be combined with the data presented here, not only to assemble an extensive rotary atomizer database for forestry applications but also to explore the exact effect of the independent variables on the atomization process.

References

[1] Skyler P J and Barry J W 1991 *Compendium of Drop Size Spectra Compiled from Wind Tunnel Tests* USDA Forest Service Report No. FPM 90-9

[2] Teske M E, Skyler P J and Barry J W 1991 *A Drop Size Distribution Data Base for Forest and Agricultural Spraying: Potential for Extended Application* ICLASS 5th International Conference NIST Special Publication **813** 325-332

[3] Teske M E and Bilanin A J 1994 Drop Size Scaling Analysis of Non-Newtonian Fluids *Atomization and Sprays* **4** 473-483

[4] Hewitt A J, Johnson D R, Fish J D, Hermansky C G and Valcore D L 2002 Development of the Spray Drift Task Force Database for Aerial Applications *Environmental Toxicology and Chemistry* **21** 648-658

[5] Teske M E, Bird S L, Esterly D M, Curbishley T B, Ray S L and Perry S G 2002. AgDRIFT: A Model for Estimating Near-Field Spray Drift from Aerial Applications *Environmental Toxicology and Chemistry* **21** 659-671

[6] Bird S L, Perry S G, Ray S L and Teske M E 2002 Evaluation of the AGDISP Aerial Spray Algorithms in the AgDRIFT Model *Environmental Toxicology and Chemistry* **21** 672-681

[7] Teske M E, Thistle H W, Hewitt A J and Kirk I W 2002 Conversion of Droplet Size Distributions from PMS Optical Array Probe to Malvern Laser Diffraction *Atomization and Sprays* **12** 267-281

[8] Hewitt A J 1994 *Measurement Techniques for Atomization Droplet Size Spectra Using Particle Size Analyzers in Wind Tunnels* SDTF Report No. T94-001 EPA MRID No. 43485603

[9] Hewitt A J 2002 *Atomization Droplet Size Spectra for AU5000 Atomizer* Stewart Agricultural Research Services, Inc. Project No. FS02-002

[10] Hermansky C G 1998 *A Regression Model for Estimating Spray Quality from Nozzle, Application, and Physical Property Data* ILASS Americas 11th Annual Conference: Sacramento CA

[11] Esterly D M 1998 *Neural Network Analysis of Spray Drift Task Force Atomization: DropKick II* Paper No. 98-1014 ASAE Annual International Meeting: Orlando FL

[12] Teske M E and Thistle H W 2000 Droplet Size Scaling of Agricultural Spray Material by Dimensional Analysis *Atomization and Sprays* **10** 147-158

[13] Kirk I W 2001 *Droplet Spectra Classification for Fixed-Wing Aircraft Spray Nozzles* Paper No. 011082 ASAE Annual International Meeting: Sacramento CA

[14] Kirk I W 2002 Measurement and Prediction of Helicopter Spray Nozzle Atomization *Transactions of the ASAE* **45** 27-37

[15] Parkin C S and Siddiqui H A 1990 Measurement of Drop Spectra from Rotary Cage Aerial Atomizers *Crop Protection* **9** 33-38

[16] Simmons H C 1977 The Correlation of Drop Size Distributions in Fuel Nozzle Sprays *Transactions of the ASME Journal of Engineering for Power* **99** 309-314

[17] Abramowitz M and Stegun I A 1968 *Handbook of Mathematical Functions with Formulas, Graphs and Mathematical Tables* National Bureau of Standards Applied Mathematics Series No. 55 Chapter 26

[18] Picot J J C, van Vliet M W and Payne P J 1989 Droplet Size Characteristics for Insecticide and Herbicide Spray Atomizers *Canadian Journal of Chemical Engineering* **67** 752-761

[19] Hewitt A J 1993 Droplet Size Spectra Produced by Air-Assisted Atomizers *Journal of Aerosol Science* **24** 155-162

[20] Lefebvre A H 1989 *Atomization and Sprays* Hemisphere: New York NY