EVALUATION OF THE FLOW DOWNWIND OF AN AGRICULTURAL GROUND SPRAYER BOOM

M. E. Teske, H. W. Thistle, T. C. R. Lawton, R. L. Petersen

ABSTRACT. *This article analyzes flow and deposition measurements downwind of a section of a full-scale ground sprayer boom tested in a wind tunnel. The measurements include the velocity and turbulence levels generated by the presence (and absence) of the nozzle spray, in addition to nozzle spray deposition patterns. It is envisioned that a description of the turbulent structure of the tractor wake (obtained previously on a subscale tractor) and the nozzle spray, along with flow velocities in the three principal directions, can be used to provide an initial database for velocities and turbulence levels in the vicinity of a typical full-scale ground boom sprayer. The goal of this effort is to use this parameterized wake model to supplement local atmospheric and surface effects around and behind a tractor and spray boom, to better predict the behavior of spray material released from nozzles on a spray boom during actual ground sprayer operation.*

Keywords. *AGDISP, Full-scale model, Ground sprayer, Nozzle wake, Wind tunnel.*

A recent article (Teske et al., 2011b) summarized the present state of computer model simulation for pesticide deposition predictions, suggesting that aerial spraying was well understood by virtue of the mature status of the AGDISP computer model (Teske et al., 2003, 2011a). Development of an applied ground boom sprayer model appears to be the next needed improvement, in an effort to meet the expectation for a mechanistic, validated model in that area. Such a model was suggested by Teske et al. (2009) based on the same modeling approach used for aerial spraying, with comparisons to available field data demonstrating the potential for this approach.

As an initial step toward describing the details of the wake behind a tractor and spray boom combination, the USDA Forest Service conducted subscale model tests that simulated the wake effects around a generic John Deere tractor. These tests were interpreted by Teske et al. (2015) by summarizing the wind tunnel results and parameterizing the wind and turbulent energy field generated in the wake of the subscale tractor/boom model combination moving directly into the wind.

The next step in the tractor/boom study was measurement of the effects of the nozzle spray on the wake behind the tractor/boom combination. Those results are discussed here.

Submitted for review in July 2015 as manuscript number MS 11442; approved for publication by the Machinery Systems Community of ASABE in March 2016.

Mention of company or trade names is for description only and does not imply endorsement by the USDA. The USDA is an equal opportunity provider and employer.

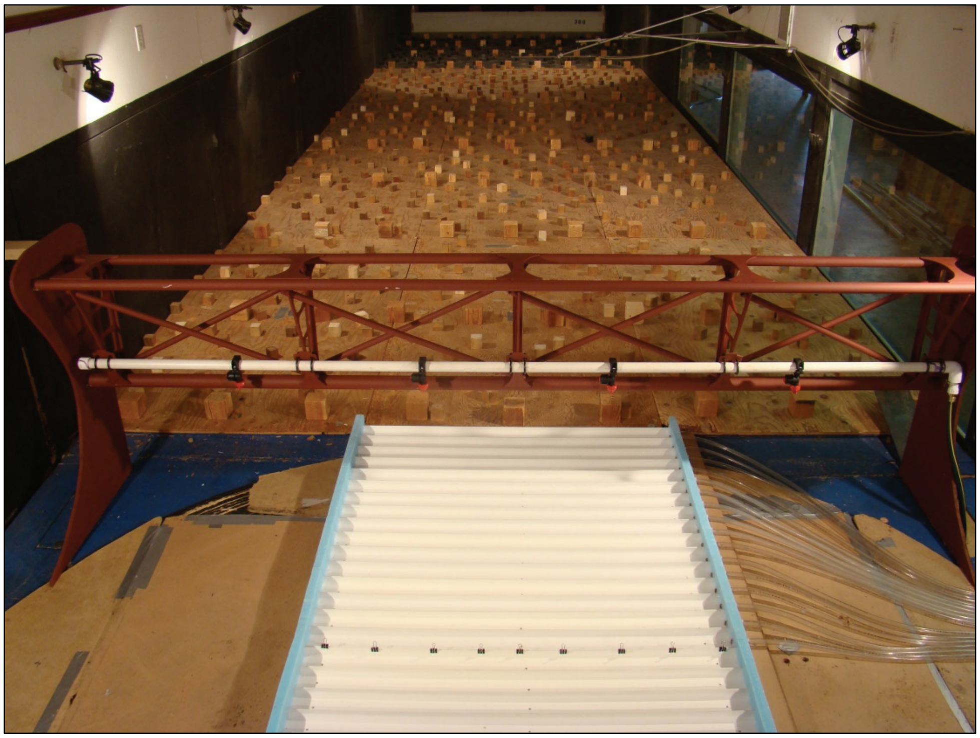
The authors are **Milton E. Teske, ASABE Member,** Senior Associate, Continuum Dynamics, Inc., Ewing, New Jersey; **Harold W. Thistle, ASABE Member,** Program Manager, USDA Forest Service, Morgantown, West Virginia; **Tom C. R. Lawton,** Systems Engineering Manager, and **Ronald L. Petersen,** Vice-President, CPP, Inc., Fort Collins, Colorado. **Corresponding author:** Milton Teske, Continuum Dynamics, Inc., 34 Lexington Avenue, Ewing, NJ 08616; phone: 609-538-0444; e-mail: milt@continuum-dynamics.com.

Previous studies by other researchers focused on airborne drift from a crosswind direction parallel to the ground sprayer boom (Phillips and Miller, 1999; Phillips et al., 2000; Nuyttens et al., 2007, 2009). Murphy (1999) and Murphy et al. (2000) examined this problem as well, but they also considered the drift from a wind direction perpendicular to the ground sprayer boom and the effect of entrainment of the free stream airflow into the nozzle spray (i.e., the formation of a spray curtain or barrier). However, for the most part, these studies did not include the effects of the wake of the tractor body or spray boom.

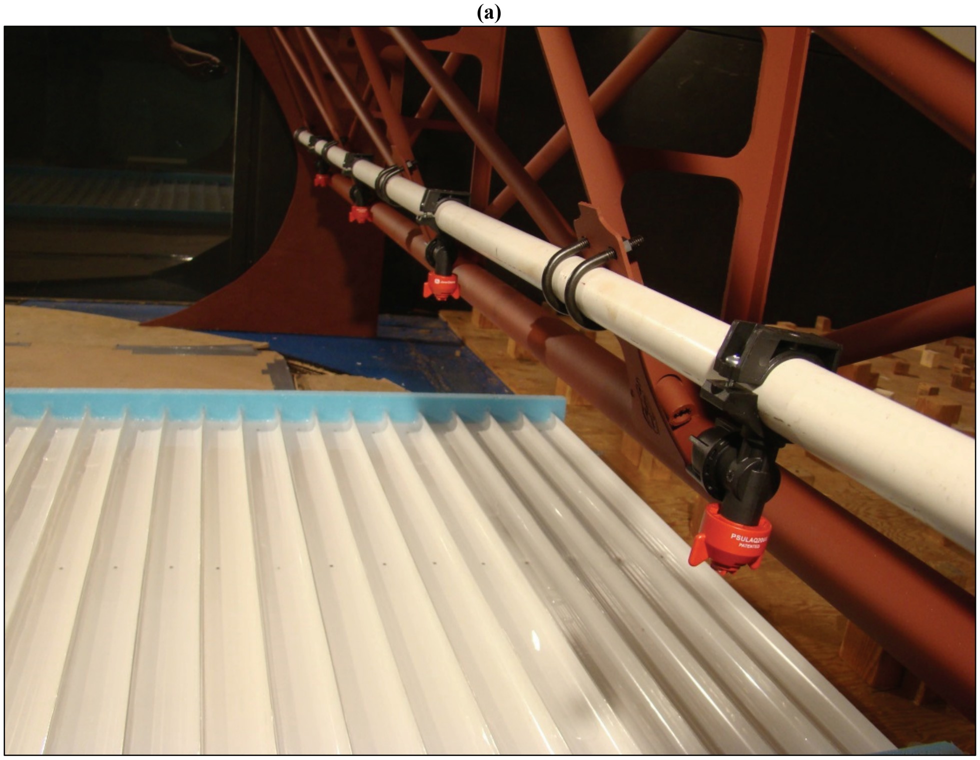
The wake of a tractor and boom sprayer is complex, with the wake reacting to ambient wind effects, the sprayer body, boom geometry, sprayer sheet blockage from the nozzle effluent, tractor thermal exhaust and engine heating, tire motion, and surface effects from the ground and crop. It seems instructive to grasp what details can be obtained from simplified studies before attempting full-scale field experiments or undertaking extensive computational fluid dynamics simulations. Such an approach is therefore well suited for wind tunnel examination.

APPROACH

The wind tunnel used for the sprayer boom section study was an open-circuit boundary-layer wind tunnel, one of three operated by CPP, Inc., in Fort Collins, Colorado. The tunnel was equipped with a traversing system that allowed the probe's *x-y-z* location to be controlled and recorded. CPP wind tunnels have been used to document dispersion, wind loads, and velocity fields in complex flow fields for over 1000 projects since the mid-1980s (Petersen and Cochran, 2008). The position of the spray boom section in the wind tunnel and a close-up view of the spray nozzles are shown in figure 1. This figure includes two views of the water collec-



(a)



(b)

Figure 1. (a) The wind tunnel filled with turbulence-producing ground cover (which generated a surface roughness suggestive of agricultural land) and the spray boom section installed and (b) a close-up of the spray boom section, the four nozzles, and the water collection trays.

tion trays. Deposition from the nozzles was measured directly by collecting nozzle spray in these trays. Each tray was 7.62 cm wide, with seven trays positioned upwind of the nozzles, one directly below the nozzles, and 24 downwind of the nozzles. The tray width was equivalent to two nozzle spacings. Collected water volume was converted to mass to measure deposition.

Velocity and turbulence measurements were made with a five-hole probe (Aeroprobe Corp., Christiansburg, Va.) connected to pressure transducers (1 INCH-D1-4V-MINI, All Sensors Corp., Morgan Hill, Cal.). Data were acquired with a 16-channel 16-bit data acquisition system (NI-9205, National Instruments Corp., Austin, Tex.) at a sampling rate of 1 kHz for 65.536 s per measurement point, comprising eight contiguous measurement blocks of 8192 samples each. This time interval reflected the time needed to achieve acceptably settled values of mean velocity and turbulence intensity. With slightly more than 1 min of sampling, the mean velocity values settled to a standard error on average of less than 1.5% of their value, the standard deviation of the standard error percentage being less than 0.5%. Maximum standard error was always less than 4.0% of the measured value. Some of the particulars of the tests are the following:

- Three components of velocity and turbulence were measured without the spray boom section in place, at a distance of 2.815 m downwind of the spray boom and at two lateral locations (tunnel centerline 0 m and 0.305 m off center and directly over a nozzle) for one wind speed (6.71 m s^{-1}). These measurements generated the background flow field. Trial runs were performed to ensure Reynolds number independence. If tests were run at too low a Reynolds number, it was possible for the flow to become laminar instead of turbulent. By taking measurements over a range of wind speeds, it was possible to determine a speed at which the nature of the flow did not change with speed.
- Three components of velocity and turbulence were measured with the spray boom section in place, with the nozzle spray off, at the same locations where the background flow field was measured.
- Water deposition was documented for three runs at two wind speeds (5.36, 5.36, and 6.26 m s^{-1}) by collecting the spray from four nozzles in a series of water collection trays (fig. 1).
- One spray boom section height (0.61 m) was evaluated (note that this height was not the height of the tips of the spray nozzles, which was estimated at 0.5 m).
- The coordinate system was (X, Y, Z), with X and Y centered on the center of the spray boom section and Z measured vertically from the surface. X was pointed in the downwind direction, parallel to the tunnel walls (with velocity U), Y was pointed to the right side of the tunnel walls (looking upwind) with velocity V, and Z was pointed vertically toward the tunnel ceiling (with velocity W).
- Tunnel measurements were provided in an Excel spreadsheet for the three wind speeds and the turbulence intensities. Wind speeds were normalized by a reference wind speed (U_{ref} = 6.86 m s^{-1}) measured by a pitotstatic tube positioned upstream of the spray boom at the spray boom height. Turbulence intensities were given in percentages, based on the local U velocity. The data also included the shear stresses, which are not presented here.

Turbulence Intensity

Turbulence intensity is defined as the ratio of the standard deviation of the velocity to a mean value (Lyles et al., 1971) and is defined by the following ratios:

$$I_X = \frac{\left(\overline{u'u'}\right)^{1/2}}{\overline{U}}, I_Y = \frac{\left(\overline{v'v'}\right)^{1/2}}{\overline{U}}, I_Z = \frac{\overline{\left(w'w'\right)^{1/2}}}{\overline{U}} \quad (1)$$

where $\left(\overline{u'u'}\right)^{1/2}$, $\left(\overline{v'v'}\right)^{1/2}$, and $\left(\overline{w'w'}\right)^{1/2}$ are the root mean square of the fluctuating velocity components in the X, Y, and Z directions, respectively, and $\overline{U}$ is the mean velocity. In AGDISP (Teske et al., 2003), twice the turbulence kinetic energy is defined as q^2, such that:

$$q^2 = \overline{u'u'} + \overline{v'v'} + \overline{w'w'} \quad (2)$$

Thus, the turbulence intensity data provided from the tests can be interpreted as:

$$\frac{q^2}{U_{ref}^2} = \left(I_X{}^2 + I_Y{}^2 + I_Z{}^2\right)\left(\frac{\overline{U}}{U_{ref}}\right)^2 \quad (3)$$

Spray Nozzles

The four nozzles used for the spray on tests were identified as John Deere Model PSULAQ2004 (Red) Quick Change Ultra Low-Drift Air Spray Tip nozzles (Ultra Lo-Drift spray nozzles, EULD120-04, Hypro EU Ltd., Cambridge, U.K.), with a nozzle size designation of 04, a spray angle in the Y direction of 120°, and a spray angle in the X direction of 60°. Spray pressure was set at 5.52 bar for the spray on tests, recovering a nozzle flow rate of 2.13 L min^{-1}, resulting in a drop size distribution very similar to the ASABE very coarse reference nozzle. The drop size distribution for the John Deere nozzles was reconstructed from $D_{v0.5}$ = 477.13 µm and relative span = 1.36, using data supplied by W. Steward (personal communication, 2015) and the root-normal technique developed by Simmons (1977) from an idea he attributed to Tate and Marshall (1953). A comparison of the two drop size distributions is shown in figure 2.

Results

The wind tunnel data included the three coordinates of the data collection points (X, Y, Z), the three velocity components (normalized by the reference velocity U_{ref}) in U/U_{ref},

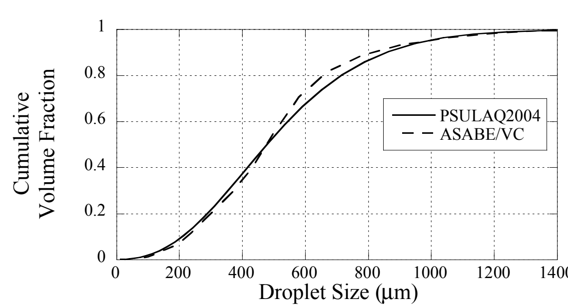


Figure 2. Drop size distribution comparison between the spray nozzles used in the spray boom section tests (PSULAQ2004) and the ASABE very coarse reference nozzle (ASABE/VC).

Table 1. Average values of the three velocity components and turbulence level at each Y location (X = 2.815 m) without the spray boom present. The first value at each height was measured at Y = 0.0 m, and the second value was measured at Y = 0.305 m.

Z (m)	U/U_{ref}	V/U_{ref}	W/U_{ref}	q^2/U_{ref}^2
0.170	0.7148, 0.7386	-0.0411, -0.0382	-0.0629, -0.0595	0.0578, 0.0533
0.241	0.7558, 0.7709	-0.0458, -0.0296	-0.0695, -0.0654	0.0528. 0.0501
0.313	0.8036, 0.8445	-0.0346, -0.0339	-0.0703, -0.0798	0.0490, 0.0498
0.384	0.8658, 0.8653	-0.0415, -0.0354	-0.0875, -0.0821	0.0436, 0.0444
0.456	0.9176, 0.8912	-0.0335, -0.0354	-0.0884, -0.0901	0.0412, 0.0446
0.527	0.9322, 0.9154	-0.0350, -0.0389	-0.0923, -0.0951	0.0354, 0.0384
0.599	0.9446, 0.9434	-0.0344, -0.0349	-0.0974, -0.0947	0.0368, 0.0374
0.670	0.9683, 0.9475	-0.0304, -0.0369	-0.1063, -0.1026	0.0352, 0.0385
0.741	0.9866, 0.9716	-0.0297, -0.0410	-0.1071, -0.1017	0.0343, 0.0368
0.813	0.9947, 0.9907	-0.0244, -0.0317	-0.1184, -0.1096	0.0337, 0.0341
0.884	0.9963, 0.0028	-0.0262, -0.0266	-0.1147, -0.1107	0.0340, 0.0351
0.956	1.0169, 1.0207	-0.0248, -0.0288	-0.1161, -0.1114	0.0319, 0.0341
1.027	1.0299, 1.0126	-0.0187, -0.0261	-0.1283, -0.1162	0.0317, 0.0322
1.099	1.0359, 1.0230	-0.0170, -0.0205	-0.1164, -0.1240	0.0287, 0.0301
1.170	1.0454, 1.0366	-0.0163, -0.0230	-0.1240, -0.1222	0.0285, 0.0295
Averages	0.9352, 0.9352	-0.0312, -0.0314	-0.0981, -0.0977	0.0392, 0.0392

V/U_{ref}, and W/U_{ref}, the three turbulence intensities (normalized by the local value of U and presented in percentage), the reference velocity U_{ref}, and the three shear stresses $\overline{u'v'}$, $\overline{u'w'}$, and $\overline{v'w'}$. All velocity data were collected at X = 2.815 m.

The first step in data reduction was to examine the data taken without the spray boom section in the tunnel. These values are shown in table 1 for Y = 0 m (at the center of the tunnel) and Y = 0.305 m (at a spray nozzle position). The average values of the measurements are shown in the last line of the table. The behavior of the background vertical velocity (W) is ascribed to the structure of the roughness elements upwind of the spray boom section. The left-to-right crosswind (V) is small.

Fitting the combined longitudinal data to a logarithmic profile, it may be seen that:

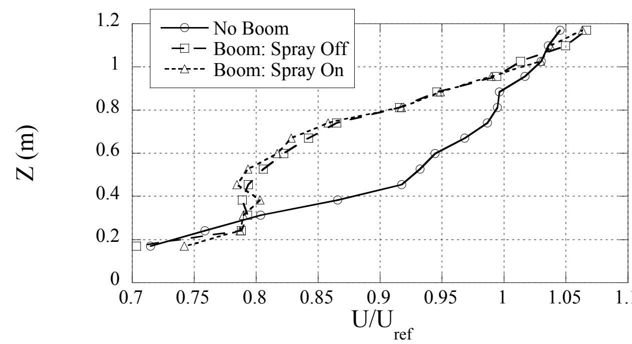
$$\frac{U}{U_{ref}} = \frac{U_0}{U_{ref}} ln\left(\frac{Z}{z_0}\right) \quad (4)$$

where U_0/U_{ref} = 0.1703, with effective surface roughness z_0 = 2.463 mm (R^2 = 0.983). Equation 4 can be used to compute a value of Z_{ref} = 0.874 m for U/U_{ref} = 1.0.

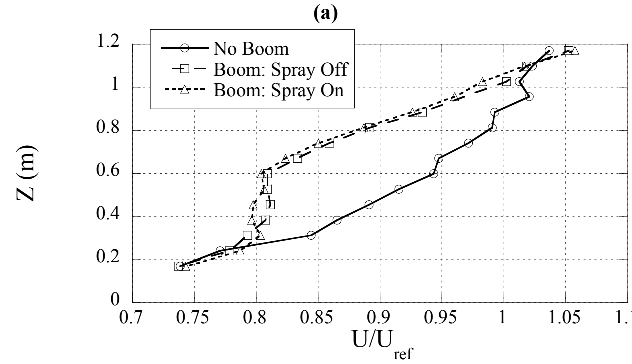
The differences between the values at the two Y positions in table 1 can be used to estimate the accuracy of the wind tunnel measurement technique. The errors are 1.6% (U/U_{ref}), 17.7% (V/U_{ref}), 5.3% (W/U_{ref}), and 4.8% (q^2/U_{ref}^2). Velocity measurements were then made with the spray boom section in the tunnel, with the spray off and on, to complete testing. Results are shown in figures 3 to 6.

Several observations may be made from these plots:

- The impact of the spray boom section on the ambient tunnel flow can be seen in figure 3, where the boom (at Z = 0.61 m) is responsible for the velocity deficit clearly seen in U/U_{ref} regardless of whether the spray is on or off. Because the U/U_{ref} velocity profiles measured at 2.815 m downwind of the spray boom are very similar whether the spray is on or off, it is unclear what the spray curtain effect, examined in greater detail by Murphy (1999) and Murphy et al. (2000), has on the deposition pattern.
- The crosswind velocity V/U_{ref} appears to increase with the presence of the spray boom regardless of whether the spray is on or off, but the effect is difficult to interpret (fig. 4).
- The vertical flow appears to lift to correct for the spray boom blockage (fig. 5), increasing W/U_{ref} through the boom wake to less negative values.
- The turbulence level q^2/U_{ref}^2 decreases substantially below the spray boom section, regardless of whether the spray is on or off as well (fig. 6).



(a)



(b)

Figure 3. Mean longitudinal velocity profiles U/U_{ref} at (a) Y = 0.0 m (tunnel centerline) and (b) Y = 0.305 m (nozzle centerline) at X = 2.815 m.

DISCUSSION

In a previous article, Teske et al. (2015) presented the wake structure measured behind a subscale tractor and spray boom model in a wind tunnel, with U_{ref} = 10.8 m s^{-1}. Both

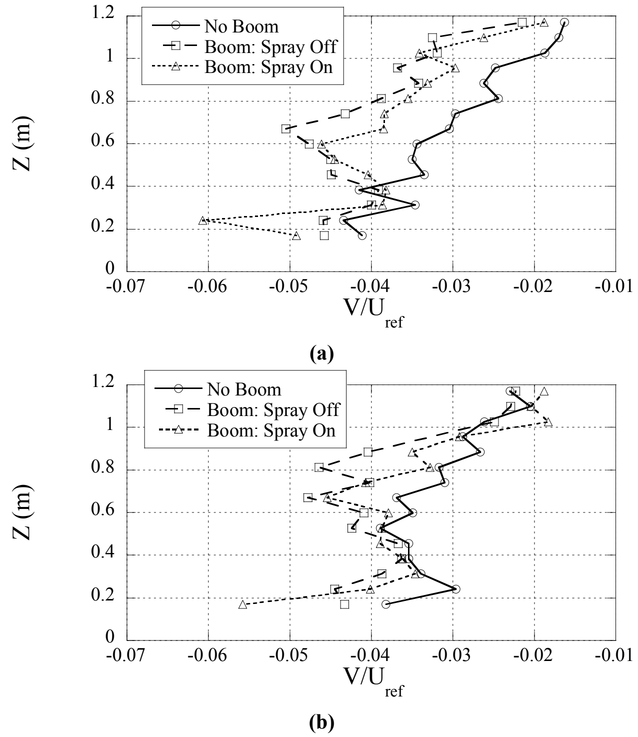


Figure 4. Mean lateral velocity profiles V/U_{ref} at (a) $Y = 0.0$ m (tunnel centerline) and (b) $Y = 0.305$ m (nozzle centerline) at $X = 2.815$ m.

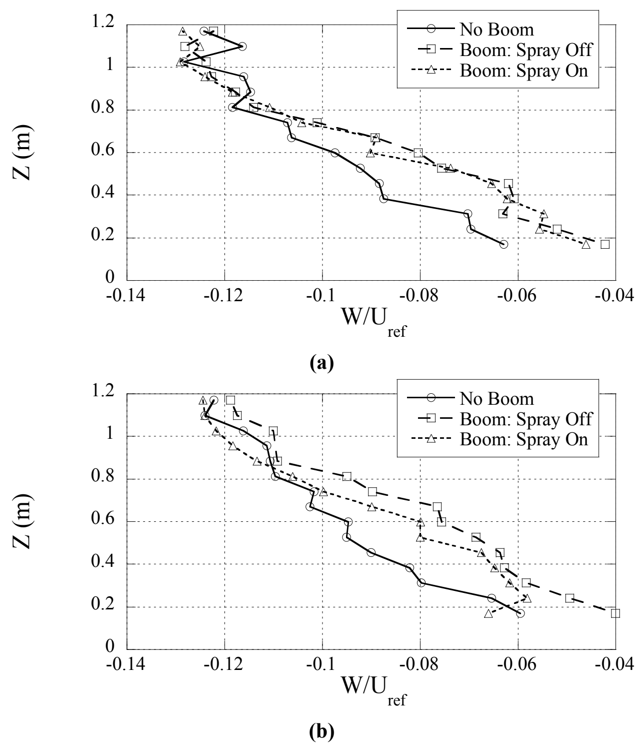


Figure 5. Mean vertical velocity profiles W/U_{ref} at (a) $Y = 0.0$ m (tunnel centerline) and (b) $Y = 0.305$ m (nozzle centerline) at $X = 2.815$ m.

that work and the current analysis first measured the background velocity profiles before inserting the subscale model or the full-scale spray boom section. A comparison of the background parameters is given in table 2, with the U/U_{ref} and q^2/U_{ref}^2 profiles shown in figure 7. It may be seen from

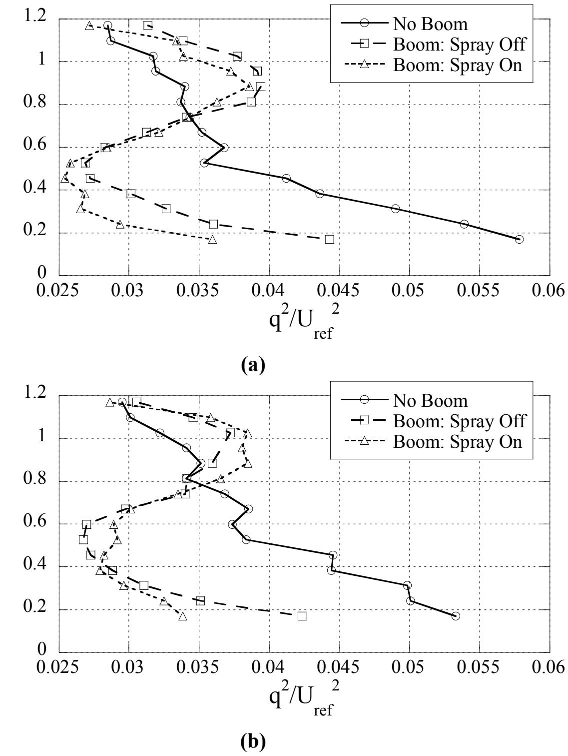


Figure 6. Mean turbulence profiles q^2/U_{ref}^2 at (a) $Y = 0.0$ m (tunnel centerline) and (b) $Y = 0.305$ m (nozzle centerline) at $X = 2.815$ m.

Table 2. Comparison of background profile parameters.

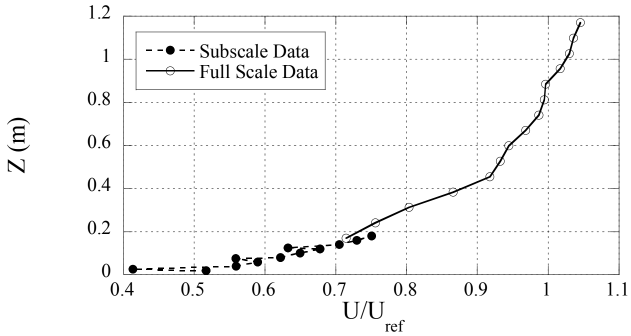
Source	U_{ref} (m s^{-1})	Z_{ref} (m)	z_0 (mm)	U_0/U_{ref}
Teske et al. (2015)	10.8	1.265	0.544	0.129
Current analysis	6.86	0.874	2.463	0.1703

table 2 that the roughness elements in the two tunnels created a factor of 5 difference in surface roughness (z_0), which manifested itself in the difference seen in the q^2/U_{ref}^2 profile shown in figure 7.

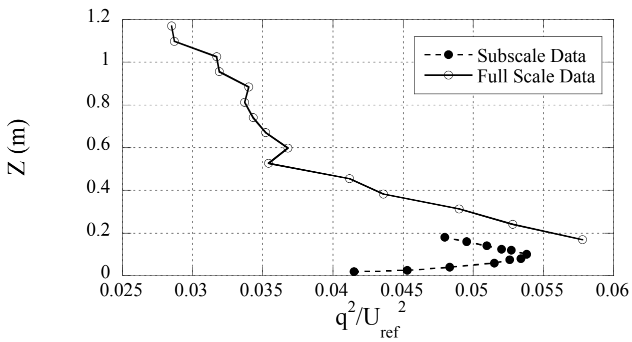
SPRAY DEPOSITION COMPARISON

An important part of this effort was the collection of three sets of deposition data in the trays positioned beneath the spray boom section. The collected data are shown in figure 8. Two tests were conducted at a tunnel speed of 5.36 m s^{-1}, and one test was conducted at a tunnel speed of 6.26 m s^{-1}. The test results were similar below 0.75 m downwind (the four nozzles were positioned at a downwind distance of 0 m). However, the higher wind speed test results were substantially different from 0.75 m to around 1.7 m downwind by an average deposition increase of 52.5%, as computed from figure 8b. One would expect that larger droplets would fall vertically to the water collector trays (since the nozzles are pointed straight down), and that smaller droplets would be more responsive to the higher tunnel speed and therefore deposit farther downwind. Such is the case here, although the fact that a 19% increase in wind speed resulted in a much larger increase in downwind deposition is remarkable.

The velocity profiles shown in figures 3 to 6 can be used

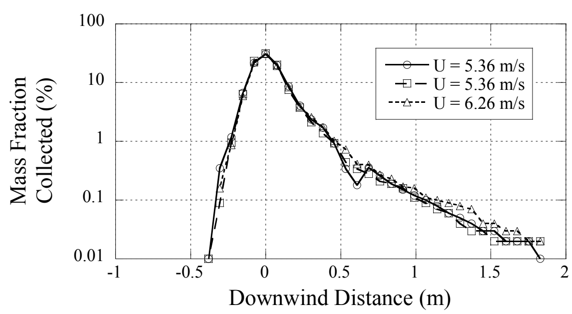


(a)

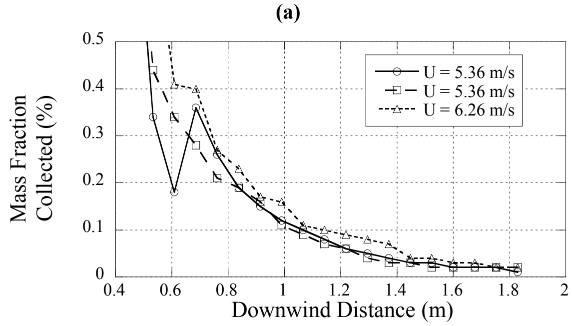


(b)

Figure 7. Comparison of average spray boom section results for (a) U/U_{ref} and (b) q^2/U_{ref}^2.



(a)



(b)

Figure 8. Spray data collected in three tests of the spray boom section spraying water: (a) logarithmic plot in the vertical scale, and (b) linear plot in the vertical scale and focused on area of interest.

to make a prediction of spray behavior from the spray nozzles to the water collection trays. This prediction used the AGDISP ensemble averaged Lagrangian equations discussed by Teske et al. (2003):

$$\frac{d^2 X_i}{dt^2} = [U_i - V_i]\left[\frac{1}{\tau_p}\right] + g_i \quad (5)$$

$$\frac{dX_i}{dt} = V_i \quad (6)$$

where t is time, X_i is the mean droplet location, U_i is the mean tunnel velocity, V_i is the mean droplet velocity, g_i is gravity (0,0, -g), and the drag force on the droplet is represented by the droplet relaxation time:

$$\tau_p = \frac{4}{3}\frac{D\rho}{C_D \rho_a |U_i - V_i|} \quad (7)$$

where D is the droplet diameter, ρ is the droplet density, C_D is the droplet drag coefficient, and ρ_a is the air density. C_D is evaluated empirically for spherical droplets (Langmuir and Blodgett, 1949) as:

$$C_D = \frac{24}{Re}\left[1 + 0.197\, Re^{0.63} + 0.00026\, Re^{1.38}\right] \quad (8)$$

where Re is the Reynolds number:

$$Re = \frac{\rho_a D |U_i - V_i|}{\mu_a} \quad (9)$$

and μ_a is the viscosity of air. The relaxation time τ_p (appearing in eq. 5 and defined in eq. 7) is the e-folding time required for a droplet to catch up to its local velocity (for V_i to approach U_i).

These equations were solved by randomly releasing droplets within the spray cone angles specified for the PSULAQ2004 nozzles and summing the deposition results. Droplets were released across the drop size distribution shown in figure 2, straight down from the nozzle tip height of 0.5 m, at a speed of 33.2 m s^{-1} as computed by Bernoulli's law for the assumed spray pressure of 5.52 bar.

Linear interpolation was used between the vertical data points recorded for velocity and turbulence, except near the floor of the wind tunnel, where a consistent logarithmic profile (eq. 4) was used for U/U_{ref}, a linear profile was used for V/U_{ref} and W/U_{ref}, and a quadratic profile was used for q^2/U_{ref}^2. Pertinent model input data included the temperature (20.5°C), relative humidity (39.7%), and atmospheric pressure (840.38 mb). The assumed evaporation rate of water was the default rate in the AGDISP model (from Trayford and Welch, 1977). Wet bulb temperature depression (5.79°C) was computed by iteration from the Carrier equation (Jennings and Lewis, 1950) and the saturation line in the steam tables (Meyer et al., 1979), although very little evaporation was predicted by the model in this application.

The result of the calculation is shown in figure 9, compared with the average mass fraction collected from the three water tests. It may be seen that the model tracks the data quite well, with an average error of 1.6% based on the peak mass fraction collected.

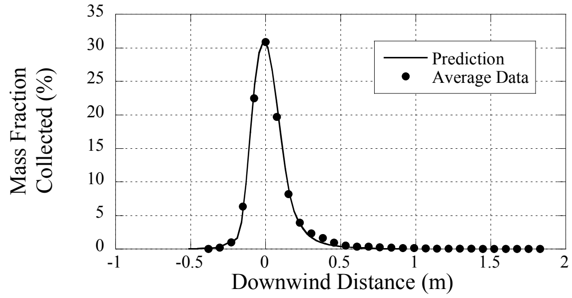


Figure 9. Model comparison with deposition data.

Conclusions and Recommendations

This article examined wind tunnel test data generated from a full-scale section of a ground sprayer spray boom. The tunnel data provide wind speed and turbulence measurements near and behind the spray boom section, recovering the local wind field that provides the ambient background setting into which a water spray was released from the spray boom. The spray was then collected in trays, measured, and compared against a computer simulation. These wind tunnel tests support three important conclusions:

- The most interesting (and unanticipated) measurement result from this work suggests that the velocity and turbulence fields behind the spray boom are essentially the same whether the nozzle boom spray is on or off. Some initial work has been done by several researchers, as discussed earlier, that points to the development of a spray curtain that, depending on the strength of the nozzle flow, the nozzle spacing, and the approaching air stream, could influence the spray deposition pattern downwind. Variations in spray plume porosity, due to nozzle type, spacing, and boom pressure, need additional attention so as to quantify these effects and their possible impact on ground sprayer deposition patterns, especially with regard to the apparent sensitivity of deposition downwind of the spray nozzles to wind speed, as shown in figure 8.
- Nonetheless, the wind speed and turbulence measurements provide ambient flow behavior in and around the spray boom section tested here, and when combined with the previous subscale tractor wake results described by Teske et al. (2015), generate a dataset that can be used to establish the flow patterns that influence the release of spray material from spray nozzles on a ground boom.
- The accurate simulation of deposition from the spray boom section supports the suggestion that a Lagrangian model is applicable in ground boom studies.

It is anticipated that:

- Additional subscale tractor/boom studies will expand the description of the wind direction approaching the tractor body, in effect generalizing ambient conditions around the tractor with regard to wind speed and turbulence.
- A computational fluid dynamics (CFD) model of the subscale tractor used in the wind tunnel studies will be developed and then generalized to estimate the effects of the tractor body on the wind and turbulence fields expected by the nozzle sprays.

References

Jennings, B. H., & Lewis, S. R. (1950). *Air conditioning and refrigeratio*n. Scranton, Pa.: International Textbook Company.

Langmuir, I., & Blodgett, K. B. (1949). A mathematical investigation of water droplet trajectories. Report No. RL225. Schenectady, N.Y.: General Electric.

Lyles, L., Disrud, A., & Krauss, R. K. (1971). Turbulence intensity as influenced by surface roughness and mean velocity in a wind-tunnel boundary layer. *Trans. ASAE, 10*(2), 285-289. http://dx.doi.org/10.13031/2013.38277

Meyer, C. A., McClintock, R. B., Silvestri, G. J., & Spencer, R. C. (1979). *ASME steam tables: Thermodynamic and transport properties of steam* (4th ed.). New York, N.Y.: ASME.

Murphy, S. D. (1999). Spray transport from a moving boom. EngD thesis. Cranfield, U.K: Cranfield University, Silsoe College.

Murphy, S. D., Miller, P. C. H., & Parkin, C. S. (2000). The effect of boom section and nozzle configuration on the risk of spray drift. *J. Agric. Eng. Res., 75*(2), 127-137. http://dx.doi.org/10.1006/jaer.1999.0491

Nuyttens, D., De Schampheleir, M., Baetens, K., & Sonck, B. (2007). The influence of operator-controlled variables on spray drift from field crop sprayers. *Trans. ASABE, 50*(4), 1129-1140. http://dx.doi.org/10.13031/2013.23622

Nuyttens, D., Taylor, W. A., De Schampheleire, M., Verboven, P., & Dekeyser, D. (2009). Influence of nozzle type and size on drift potential by means of different wind tunnel evaluation methods. *Biosystems Eng., 103*(3), 271-280. http://dx.doi.org/10.1016/j.biosystemseng.2009.04.001

Petersen, R. L., & Cochran, B. C. (2008). Chapter 24A: Wind tunnel modeling of pollutant dispersion. In *Air quality modeling: Theories, methodologies, computational techniques, and available databases and software, Volume 3: Special issues* (pp. 397-432). Fremont, Cal.: EnviroComp Institute, and Pittsburgh, Pa.: Air and Waste Management Association.

Phillips, J. C., & Miller, P. C. H. (1999). Field and wind tunnel measurements of the airborne spray volume downwind of single flat-fan nozzles. *J. Agric. Eng. Res., 72*(2), 161-170. http://dx.doi.org/10.1006/jaer.1998.0359

Phillips, J. C., Miller, P. C. H., & Thomas, N. H. (2000). Airflow and droplet motions produced by the interaction of flat-fan sprays and cross flows. *Atomization Sprays, 10*(1), 81-101. http://dx.doi.org/10.1615/AtomizSpr.v10.i1.40

Simmons, H. C. (1977). The correlation of drop-size distributions in fuel nozzle sprays: Part I. The drop-size/volume-fraction distribution. *J. Eng. Power, 99*(3), 309-314. http://dx.doi.org/10.1115/1.3446488

Tate, R. W., & Marshall, W. R. (1953). Atomization by centrifugal pressure nozzles. *Chem. Eng. Prog., 49*, 226-234.

Teske, M. E., Miller, P. C. H., Thistle, H. W., & Birchfield, N. B. (2009). Initial development and validation of a mechanistic spray drift model for ground boom sprayers. *Trans. ASABE, 52*(4), 1089-1097. http://dx.doi.org/10.13031/2013.27779

Teske, M. E., Thistle, H. W., & Ice, G. G. (2003). Technical advances in modeling aerially applied sprays. *Trans. ASAE, 46*(4), 985-996. http://dx.doi.org/10.13031/2013.13955

Teske, M. E., Thistle, H. W., & Londergan, R. J. (2011a). Modification of droplet evaporation in the simulation of fine droplet motion using AGDISP. *Trans. ASABE, 54*(2), 417-421. http://dx.doi.org/10.13031/2013.36444

Teske, M. E., Thistle, H. W., Schou, W. C., Miller, P. C. H., Strager, J. M., Richardson, B., Butler Ellis, M. C., Barry, J. W., Twardus, D. B., & Thompson, D. G. (2011b). A review of computer models for pesticide deposition prediction. *Trans. ASABE, 54*(3), 789-801. http://dx.doi.org/10.13031/2013.37094

Teske, M. E., Thistle, H. W., Gross, G. M., Lawton, T. C. R., Petersen, R. L., & Funseth, T. G. (2015). Evaluation of the wake

of an agricultural ground sprayer. *Trans. ASABE, 58*(3), 626-628. http://dx.doi.org/10.13031/trans.58.10996
Trayford, R. S., & Welch, L. W. (1977). Aerial spraying: A simulation of factors influencing the distribution and recovery of liquid droplets. *J. Agric. Eng. Res., 22*(2), 183-196. http://dx.doi.org/10.1016/0021-8634(77)90062-2