INTRODUCTION AND BACKGROUND

There is still a need to minimize spray drift from agricultural sprayers. New sprayer systems, designed to fulfill this need, frequently arrive on the market with unverified claims about reduction in drift (Wolf 1992). These claims are generally over-optimistic, based more on a belief in what ‘ought’ to work rather than on sound testing and evaluation (Ford 1975). SACAM (1994) recommended that commercial crop sprayers be assessed for their potential loss of agricultural chemicals through large drop drip-off and drift losses.

During the last few years, the number of field and lab studies related to drift have increased tremendously, e.g., Bouse (1994); Fox et al. (1993a); Franz et al. (1993); Howard (1993); Khdair et al. (1994); Kirk et al. (1992); Reichard et al. (1992); Salyani and Cromwell (1992); Wang et al. (1993); Womac et al. (1993). In many field studies, the sampling layouts arranged on the downwind side of the spray swath were spread over wide areas (Nordby and Skuterud 1975; Fox et al. 1993a). The advantage of field studies is the natural spray and environmental conditions. However, results of field studies have generally not been consistent (Salyani and Cromwell 1992; Bouse et al. 1992; Picot et al. 1993).

In most field and laboratory studies, samplers are used to collect and measure the amount of spray drift. These have included cylindrical collectors (e.g., Bouse et al. 1992), paper (e.g., Franz et al. 1993), mylar sheets (e.g., Salyani and Cromwell 1992), plant leaves (e.g., Howard 1993), and others (Miller 1993). These collectors are quite inconsistent in providing information on the drift. Deposits from collectors at the same location have been reported to differ by 100% (Fox et al. 1993b).

The study of drift in a wind tunnel has the advantage of controlling and repeating the spraying and atmospheric conditions (Miller 1993; Khdair et al. 1994; Reichard et al. 1992). Flow visualization (Sagi and Derksen 1991), a technique of making invisible flows visible, combined with wind tunnel and image processing, provides an opportunity to study spray droplets under controlled conditions, just after they are produced.

OBJECTIVES

The objective of this study was to develop an instrumented wind tunnel for estimation of spray drift under varying environmental and sprayer operating conditions.

The scope of the instrumented wind tunnel was limited to providing the following capabilities: (1) visualization of wind flow pattern inside the wind tunnel; (2) measurement of environmental factors; (3) control and measurement of spraying parameters; and (4) acquisition of a digital image of the spray pattern for analysis using image processing.

WIND TUNNEL DESIGN

Features

An instrumented wind tunnel was developed with the following features: (a) provision for altering the spraying conditions, i.e., wind speed, wind direction in reference to orientation of nozzle, height above the crop, operating pressure, and flow rate; (b) provision to monitor and record environmental variations, i.e., wind speed profile, temperature and relative humidity; (c) capability to acquire a frozen image of the spray sheet; and (d) provision for using a variety of spray nozzle types and sizes.
The wind tunnel consists of a basic tunnel structure, a suction fan, flow straighteners, spray control system, flow visualization unit, image acquisition unit, and wind speed sensor grid (Fig. 1). The entire set-up is 6.5 m long, 1 m wide and 2 m high. The tunnel is mounted on a frame supported on four wheels. The frame also has four screw-type legs to support the load when the tunnel is in operation.

**Tunnel structure**

The wind tunnel (Fig. 1) is an open circuit type and has a 4 m long test section. The see-through front wall of the tunnel, made of plexiglass, permits recording images of spray and air flow patterns. The other three sides of the tunnel are made of plywood. The cross section of the tunnel increases from 0.91 m x 0.91 m at the entrance to 1 m x 1 m at the exit with a slope of 0.5°. This helps to reduce the friction of the walls to air, to minimize the effect of boundary layer, and to maintain uniform wind speed throughout the section (Pope and Harper 1966). The tunnel contains entrance and exit ducts made of galvanized steel sheet shaped to smooth air flow at both ends of the tunnel. The entrance duct can be opened as an entrance to the tunnel. The exit duct is 0.38 m long and holds the suction fan. A transition duct, 1.62 m long, is placed between the main tunnel and exit duct to get a diversion angle of 6° to 10° to air flow, within the 5-7° recommended for smooth transition from a rectangular to a circular cross section (Pope and Harper 1966). Two acrylic windows have been provided in the top panel of the tunnel, through which the spray pattern is illuminated.

Two flow straighteners have been used to control the air flow pattern inside the test section, one at the inlet and the other at the exit of the section to eliminate disturbance due to the converging of air from around the tunnel edges and the effect of swirling action of the fan, respectively. Reynolds number (Re) for the holes in the flow straighteners was calculated to be from 5000 to 27000 for wind speeds of 1.5 to 8.0 m/s as opposed to values on the order of 10^5 for a 1 x 1 m cross section. The propeller-type suction fan is powered by a 2.2 kW motor and has a maximum discharge of 9.44 m^3/s, which produces a wind speed of 10 m/s in the wind tunnel. The suction fan speed is controlled through a variable frequency AC inverter. This arrangement allows average wind speeds inside the tunnel ranging from 0.8 to 10 m/s.

**Measurement of environmental conditions**

A grid of 24 air velocity sensors was installed across the cross-section of the tunnel upstream of the nozzle. The velocity sensors are simple resistors with constant current passing through. Temperature of each resistor is measured with a T-type thermocouple attached to the surface of the resistor with epoxy and is related to wind speed. The resistors used are a precision, thick film chip, surface mount type rated at 10 Ω and 0.125 W (model SMR8E, Cardinal Electronics, Saskatoon, SK). To obtain higher sensitivity, especially at high wind speeds, the resistors were subjected to 225 mA current with a power dissipation of 0.5 W/resistor.

Three sample sensors were calibrated in a bench-type wind tunnel for wind speeds of 0.15 to 7.5 m/s. Regression analysis resulted in Eq. 1, with coefficient of determination $R^2 = 0.99$, and calibration curve as shown in Fig. 2.

$$\ln V_w = 7.056 - 0.0737 T + 0.0001167 T^2$$

where:

- $V_w$ = wind speed (m/s), and
- $T$ = resistor temperature (°C).

The calibration has an average error of ±3.32%. The direction of the sensor relative to the wind direction altered the wind speed measurement up to 20%. Although the resistors selected were all of the same size, construction errors caused variation in the response of the sensors. To eliminate this variation, three-point calibration of all the sensors was performed using the same type of model. In higher relative humidity (RH) conditions, the sensors indicate higher wind speeds. The effect of air temperature to the response of sensor is opposite to the effect of RH. To correct for the effect of relative humidity and air temperature, all wind speeds are adjusted by the same percent as the difference between the nominal speed and the average speed from all sensors.

The outputs from all the sensors are connected to a data logger (model 8028A, Scimetric Instruments, Manotick, ON) which is connected to a 80286-based computer. A BASIC program

![Fig. 1. Structure of the wind tunnel.](image-url)
converts the voltages from the data logger corresponding to the 24 sensors to temperature and then to wind speed using regression equations developed for each sensor. The program also calculates the average wind speed for each row and column and total average, and displays the results on a monitor along with speeds recorded by individual sensors. The program updates the wind speeds every 4 s on the screen and writes data to a diskette.

A humidity sensor (model RH-5, General Eastern, Woburn, MA) is used to record the relative humidity near the tunnel entrance. A T-type thermocouple is located inside the tunnel close to the nozzle to record the temperature inside the tunnel. The output of the thermocouple and humidity sensor is recorded by the data logger.

**Spray control unit**

The spraying control unit is meant for developing spray and controlling and measuring spray variables, i.e., operating pressure and flow rate. The liquid first passes through a damping tank that eliminates the pressure fluctuation in the downstream flow line. The liquid is then passed to the nozzle which is fixed to a brass bushing at the end of a copper tube. The copper tube passes from the top of the tunnel through a plastic bushing in such a way that the tube can be moved up or down or can be rotated by simply loosening a nut. The brass bushing can accommodate commonly used nozzle bodies. The plastic bushing can be removed from the tunnel along with the copper tube and nozzle when needed to change the nozzle. On the top of the tunnel, a pointer indicates the height of the nozzle from the floor of the wind tunnel. Liquid flow rate is measured using a variable area flowmeter (Cat. no. H-03286-22, Cole-Parmer Instrument Co., Niles, IL). The pressure downstream of the pressure tank is measured with an analogue pressure gauge (Wika Instrument Corp., Hauppauge, NY).

**Visualization and image acquisition**

The visualization unit makes the air flow inside the tunnel visible and was used to confirm laminarity of the air flow along the length of the tunnel. Uniformity of the flow through the cross section is checked with the wind speed sensor grid. Grey smoke is generated by exploding a smoke bomb into a heavy-duty plastic barrel. The smoke is injected into the tunnel from four, equally-spaced pipes along the vertical axis through the flow straightener at the entrance. The smoke in the container remains at atmospheric pressure and is drawn into the tunnel by the fan. Both air and smoke being at atmospheric pressure, the air and smoke in the tunnel maintain the same speed. The rate of smoke injected into the tunnel and thus the density of smoke produced, is controlled by a valve.

To find a suitable setup for image acquisition, different light sources and their positions, film speeds, apertures, and shutter speeds were tested in a series of experiments. The selected image acquisition system is comprised of four, 100-W Britek master/slave flashes having a flash duration of 1/850 s for lighting, and a 35 mm SLR camera with black and white ISO 400 film. The bulbs are placed on top of the wind tunnel, to the rear of the nozzle and are plugged into sockets having multi-directional movement. Three flash bulbs are placed on the downstream side of the nozzle and one on the upstream side. The bulbs can be moved up and down to adjust the light intensity and area covered. Every flash bulb is paired with a 60 W incandescent bulb to illuminate the wind tunnel interior for camera adjustment. The two flash units close to the nozzle are tilted towards the nozzle. All the flash bulbs are also tilted towards the front of the wind tunnel. The bulbs are shielded with black cards in such a way that light falls neither on the background nor on the plexiglass. This is to avoid reflections in the tunnel which reduce spray/background contrast. The flash units are triggered by a set of synchronization cables attached to the camera. The shutter speed of the camera is set at 1/60 s but due to the short duration of the flash illumination, the image is effectively frozen on the film.

The top, bottom and back inner panels of the wind tunnel are painted flat black to eliminate the effect of any light reflection other than the deflection by spray particles during image acquisition. A black cloth was placed between camera and wind tunnel and the camera pointed through a hole in the cloth. This helped in controlling any reflection to the image from behind the camera.

**WIND TUNNEL TESTING**

Tests were conducted to verify (1) that the air flow throughout the cross section of the wind tunnel is uniform and not turbulent, (2) that the setup alters spray pattern with changes in testing conditions, and (3) that the setup is capable of providing information for quantification of drift. In both tests, images of flow were recorded using image acquisition.

For wind flow pattern, the camera was placed 2.7 m away from the tunnel and an image captured of the entire length of the testing section. For the spray pattern, the camera was placed 1.0 m away from the wind tunnel to cover an area from the nozzle to the bottom of the wind tunnel, extending 0.75 m downwind from the nozzle. All the images were taken in complete darkness with the spray illuminated by the flash bulbs.

**Wind flow pattern experiment**

For wind flow pattern visualization, smoke flow in the wind tunnel was photographed at wind speed settings of 1.4, 2.8, 4.2, 5.6, 7.0, and 8.4 m/s. Wind speed was also measured with the velocity sensor grid. The relative humidity and temperature inside the tunnel ranged from 55.4 to 58.5% and 20.8 °C to 21.4 °C, respectively, during these tests.

**Results and discussion** Figure 3 is an image of smoke flow inside the wind tunnel at wind speed of 5.6 m/s. This, and other images, indicated that the flow from the lower outlets is quite laminar throughout the testing section while the flow from the upper outlet rises upward over the last half of the testing section. The turbulent eddies were more evident at speeds of 1.4 and 2.8 m/s than at other speeds. This may be the effect of the nozzle just protruding into the top surface of the tunnel. These images may also have been taken sooner after release of the smoke compared to the times in other speeds. There is also glare near the top of some images due to light reflection from the plexiglass in the tunnel ceiling which exaggerates the turbulent eddies in the upper portion.
The wind speeds measured with the velocity sensors had some spatial variation but the measurements from all sensors at all set speeds were not significantly different at 95% probability level. The mean, maximum, and minimum wind speeds from all the sensors at different set speeds with standard deviation and coefficient of variation are presented in Table I. There is a considerable difference between minimum and maximum speeds, but the coefficient of variation was acceptable for our purposes since uniform wind patterns are not common under field conditions. The fact that the orientation of the sensor changes the measurement by up to 20% of the reading suggests that rigid holders for the sensors are needed.

**Spray pattern experiment**

**Model** The assumption is made that the spatial distribution of particles in a spray sheet is related to particle size. Small particles in the spray were also assumed to reach their terminal velocity before exiting the area in the image and that same sized particles in the spray sheet would be following the same pathlines, referred to as “iso-sized” pathlines. Straight iso-sized pathlines would indicate that particles forming these lines are at terminal velocity and the vertical velocity of the particles is not decreasing.

As defined in Fig. 4, \( \theta_0 \) is the angle that the spray sheet makes with the horizontal with no wind. This angle increases to \( \theta_w \) when there is wind in the given direction (i.e., \( \theta_0 = \theta_w \) when \( V_w = 0 \)). The spray angle (\( \theta_t \)) changes with pressure change (Teejent 1993) but may not change with wind speed within the range of wind speeds allowed for spraying. The sheet deflection angle (\( \theta_d \)) is defined as the difference between \( \theta_0 \) and \( \theta_w \). The angle \( \theta_t \) is the slope of the iso-sized pathlines on the image. At higher wind speeds and thus greater drift distances, the slope of these lines will decrease. The angles \( \theta_0, \theta_w, \) and \( \theta_t \) can be measured directly from the image using drawing tools available with most image analysis programs. The average wind velocity \( (V_w) \) was calculated for each test. The initial spray velocity \( (V_I) \), i.e., the velocity of the particles as they exit from the nozzle, depends upon liquid flow rate through the nozzle.

The water droplets at terminal velocity are assumed to move at the same speed as the wind in the horizontal direction. Knowing \( V_w \) and \( \theta_t \) for droplets at terminal velocity (downwind of the nozzle), terminal velocity \( (V_t) \) of the particles can be determined from:

\[
V_t = V_w \times \tan \theta_t
\]  (2)

The size of the droplets can then be estimated using Eq. 3 when the particle Re is up to 2 (Mohsenin 1986). In this study
Fig. 4. Angles and velocities in spray wind interaction.

where:

\[ d_p = 10^6 \sqrt{\frac{18 \eta V_t}{g(\rho_p - \rho_f)}} \]  

\[ \theta_s = \text{Droplet diameter (\(1\mu m\))}, \]
\[ \rho_p = \text{Density of droplet (1000 kg/m}^3\)\), \]
\[ \rho_f = \text{Density of air (1.206 kg/m}^3\)\), \]
\[ \eta = \text{Viscosity of air (1.78 x 10^{-5} Pa.s), and} \]
\[ g = \text{Acceleration due to gravity (9.81 m/s}^2\)\).

**Experimental procedure**  
A flat fan nozzle (F110/06/3, DeLavan, Lexington, TX) was tested under various spray operating pressures and wind speeds. The experiment was designed as a two factor factorial with 4 wind speeds (S1 = 0 m/s; S2 = 1.4 m/s; S3 = 2.8 m/s; and S4 = 4.2 m/s), 3 operating pressures, (P1 = 205 kPa; P2 = 275 kPa; and P3 = 345 kPa) and 3 replicates (R) for a total of 36 tests. The experimental design was completely randomized with the tests randomized over time.

For each test, operating pressure was set and recorded. Sufficient time was given for the pressure, each time it was changed, to stabilize before staring the test. Liquid flow rate for each test was recorded using the flow meter. The wind speed was set by adjusting the input frequency to the fan. Average wind speed, tunnel temperature, and relative humidity were recorded by the data logger.

The prints of the images were digitized using a CCTV camera (model JE3462RGB, Javelin, Japan) and a public domain image analysis program NIH Image 1.55 (U.S. National Institute of Health, Bethesda, MD). Using drawing tools available with this program, iso-sized lines were drawn manually at three locations on the images as shown in Fig. 5. Location 1 was selected as the top edge of the image on the downwind side while locations 2 and 3 were selected where the straight lines were visible. The slopes of these lines were determined by the program. From the slopes of these lines, the falling velocity of the water droplets was determined using Eq. 2, while the diameter of the droplet was determined using Eq. 3.

The data obtained for slope, terminal velocity, and droplet diameter were analyzed using the one-way analysis of variance (ANOVA) module in SPSS statistical software (SSPS Inc., Chicago, IL) to determine the significance of the effect of wind speed, pressure, and replicate on the slope, terminal velocity, and droplet size and to compare the means of these parameters. The same procedure was used to test the relationships of pressure and wind speed with spray sheet deflection angle. The 0.05 probability level was used as the criterion for tests of significance throughout the data analysis.
Table II: Average slope, terminal velocity, and droplet size averaged over pressure at three locations on the image for three wind speeds

<table>
<thead>
<tr>
<th>Wind speed (m/s)</th>
<th>Slope of iso-sized line (degrees)</th>
<th>Terminal velocity of the droplet (m/s)</th>
<th>Droplet diameter (μm)*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Location 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>22.5 (1.8) a</td>
<td>0.58 (0.05) a</td>
<td>137 (6.25) a</td>
</tr>
<tr>
<td>2.8</td>
<td>13.2 (1.6) b</td>
<td>0.66 (0.08) ab</td>
<td>146 (9.12) ab</td>
</tr>
<tr>
<td>4.2</td>
<td>8.3 (1.1) c</td>
<td>0.61 (0.08) b</td>
<td>141 (9.42) b</td>
</tr>
<tr>
<td>Location 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>33.9 (3.9) a</td>
<td>0.94 (0.14) a</td>
<td>175 (12.9) a</td>
</tr>
<tr>
<td>2.8</td>
<td>21.5 (4.3) b</td>
<td>1.10 (0.24) ab</td>
<td>188 (21.7) ab</td>
</tr>
<tr>
<td>4.2</td>
<td>17.3 (3.0) c</td>
<td>1.30 (0.24) b</td>
<td>205 (19.0) b</td>
</tr>
<tr>
<td>Location 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>45.5 (5.4) a</td>
<td>1.44 (0.30) a</td>
<td>216 (21.4) a</td>
</tr>
<tr>
<td>2.8</td>
<td>31.3 (3.1) b</td>
<td>1.70 (0.20) b</td>
<td>235 (14.5) b</td>
</tr>
<tr>
<td>4.2</td>
<td>24.8 (3.0) c</td>
<td>1.93 (0.27) b</td>
<td>251 (17.3) b</td>
</tr>
</tbody>
</table>

- Values in parenthesis are standard deviations.
- Means with similar letters in each column (separate comparisons for each location) are not significantly different from each other at the 0.05 probability level.
* Droplet diameter calculated using Eq. 3.

Results and discussion

The effect of replicate on all the spray sheet characteristics was not significant at the 0.05 probability level, showing that the tunnel can be used to conduct repeatable experiments.

The analysis of variance indicated that the slope of the iso-sized lines, terminal velocity, and calculated droplet size were not affected by the operating pressure at locations 1 and 2 on the images but were affected at location 3. These parameters were averaged over pressure for each wind speed and the statistics determined for the averaged parameters (Table II). As expected, the slope of iso-sized lines ($\beta_i$) decreased with increasing wind speed, indicating a larger drift distance. The wind speed did not significantly affect terminal velocity and droplet size at locations 1 and 2, but did at location 3. The average droplet size at locations 1, 2, and 3 was calculated as 141, 189, and 234 μm, respectively.

The sheet deflection angle ($\theta_d$) increased from 2.7° ± 1.0°) to 4.6° ± 1.6° as wind speed increased from 1.4 to 4.2 m/s. This was due to increase in angle $\theta_w$ with increasing wind speed. The sheet deflection angle increased from 2.6° ± 1.1°) to 4.4° ± 1.9° as operating pressure increased from 205 to 345 kPa. This was due to decrease in angle $\theta_p$ with increased pressure. The ANOVA indicated that these changes in sheet deflection angle were statistically significant.

The above results indicate that the responses of the spray sheet characteristics to spray control parameters were similar at locations 1 and 2 but different at location 3. There was some bias in manually selecting a line at locations 2 and 3 since, unlike location 1, the position of these lines, being subject to human judgement, is difficult to locate in a consistent manner. The analysis used is helpful only for estimating the drift potential of the particles on the downwind upper edge of the image unless the area of interest is marked on the image field before an image is captured. There is a need to develop a program to estimate the drift potential of the particles on the rest of the image. There is also a need to compare the drift data from the tunnel with other techniques and to calibrate the system to find the relationship between intensity of the image and number of particles.

CONCLUSIONS

The results of the testing of the instrumented wind tunnel have led to the following conclusions.

1. The flow inside the test section of the wind tunnel is essentially laminar in the lower 75% of the tunnel cross-section. This is the portion of the cross-section which is most important for the study of nozzles. Although there is variation in measurements of wind speeds among the sensors, the spatial variation across the cross-section is insignificant and random. The presence of the nozzle itself causes some downstream turbulence.

2. The system responds in a meaningful way to changes in environmental and spray parameters such as wind speed and operating pressure.

3. The wind tunnel provides similar conditions for repeated tests.

4. The image acquisition successfully captures the information about spray sheet and spray drift. It was possible to identify and trace relevant information from the image.

RECOMMENDATIONS

1. The flow along the tunnel cross-section does not simulate the wind speed pattern over the crop canopy as a uniform sized grid was used for the flow straighteners. It would be useful to further study the role of flow straighteners, i.e., variable resistance flow straighteners, or the use of baffles, to simulate a wind velocity profile over a crop canopy.

2. It is recommended that an alternate rigid mount for the
velocity sensors inside the tunnel be designed and implemented.

3. There is still a need to develop an image analysis program that automates the analysis process and transforms information in the image about the number of particles, particle velocities, and the size of particles to the potential drift of particles.

4. The system should be calibrated for particle sizes and velocities using mono-sized droplet generators and laser velocimeters.

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