SPRAY CHARACTERISTICS AND DRIFT REDUCTION POTENTIAL WITH AIR INDUCTION AND CONVENTIONAL FLAT-FAN NOZZLES

H. Guler, H. Zhu, H. E. Ozkan, R. C. Derksen, Y. Yu, C. R. Krause

ABSTRACT: Spray drift potential, spray coverage, droplet size, and spray pattern width for various sizes of air induction and conventional flat-fan nozzles with equivalent orifice areas were investigated and compared under laboratory conditions. Droplet sizes were measured with a laser imaging system; spray coverage on water-sensitive paper (WSP) was evaluated with a boom sprayer at a constant travel speed in a greenhouse, and ground and airborne spray deposits were determined in a wind tunnel at two wind velocities (2.5 and 5.0 m/s). Tests were also conducted to evaluate the effect of air-intake holes being sealed or open on spray characteristics of air induction nozzles. With the equivalent nominal flow rate, air induction nozzles had approximately 2.1 to 2.75 times larger exit orifice areas than the conventional nozzles. With the equivalent orifice area and equal liquid flow rate, there was no significant difference in droplet size, spray pattern width, spray coverage, ground spray deposit, and airborne deposit among regular air induction nozzles, air induction nozzles with two sealed air-intake holes, and conventional flat-fan nozzles. Spray characteristics of air induction nozzles could be achieved by conventional nozzles with the equivalent orifice size operated at the reduced operating pressure.

Keywords. Droplet size, Droplet velocity, Low-drift nozzle, Orifice area, Pesticide, Spray coverage, Spray drift, Spray pattern.

Preventing drift from pesticide sprays has been and will continue to be a concern for pesticide applicators. The airborne spray drift of pesticides from the intended targets not only causes inefficient use of pesticides, but also causes damage to crops in adjacent fields, and potentially contaminates air, soil, and water. Several techniques were developed to minimize spray drift potentials during the past 15 years. Since weather conditions are very difficult to control and vary greatly in the fields, among all the techniques, increasing droplet size is widely recommended by researchers (Ozkan et al., 1993; Ozkan and Derksen, 1998; Miller et al., 2001; SDTF, 1997). Factors such as atomization methods, nozzle types, physical properties of tank mixtures, and weather conditions can affect droplet sizes during spray application. When pesticides are sprayed at wind velocities below 5.0 m/s, droplets smaller than 200 μm are more prone to the drift than larger droplets (Zhu et al., 1994). For conventional boom sprayers, changing nozzle type is a relatively easy way to change droplet size (Zhu et al., 2004).

Since weather conditions cannot be controlled, it is very difficult to repeat spray drift measurements in the field with a high degree of reliability (Phillips and Miller, 1999; Miller and Butler Ellis, 2000), which was the major reason to develop wind tunnel protocols for the direct measurement of spray drift in controlled conditions. Reichard et al. (1992) developed a method using a wind tunnel to evaluate the accuracy of a computer program to simulate spray drift distances. Phillips and Miller (1999) concluded that wind tunnel tests could obtain results similar to field tests when a single static spray nozzle was used at 2 m/s wind velocity.

Considerable research has been conducted to study drift reduction potentials of air induction nozzles (also called low-drift nozzles) (Walklate et al., 1994; Ozkan and Derksen, 1998; Derksen et al., 1999; Ramsdale and Messersmith, 2001; Wolf, 2003; Wolf et al., 1999; Jones et al., 2002; Fietz et al., 2004; Wolf, 2005). During the past ten years, this type of nozzle has been recommended by some nozzle manufacturers and researchers to reduce spray drift because these nozzles produce larger droplets with a smaller portion of drift-prone droplets than conventional hydraulic nozzles. Air induction nozzles are configured with a long fluid chamber and small holes in the chamber upstream from nozzle orifices. These holes are reported to induce air into the liquid flow due to the Venturi effect and reduce pressure at the nozzle orifice. Studies found that the diameter of droplets discharged from air induction nozzles was greatly influenced by the nozzle tip orifice size (Lafferty and Tian, 2001; Butler Ellis et al., 2002). Performance of air induction nozzles was also compared with the same nozzles under the same oper-
Drift reduction of air induction nozzles has not been studied thoroughly from an engineering perspective. In previous studies, researchers selected nozzles with the same nominal flow rate (or the equivalent nozzle labeling number from nozzle manufacturer catalogs) to compare drift reduction potentials between air induction nozzles and conventional nozzles. However, no previous studies compared the drift reduction potentials between air induction nozzles and conventional nozzles with the equivalent orifice size under the same flow rate condition. To obtain a desired spray pattern width, air induction nozzles use a much higher pressure than conventional nozzles. In addition, compared to conventional hydraulic nozzles, applicators have to pay nearly twice as much for air induction nozzles. Thus, it is unclear to spray applicators whether it is practical and economical to use air induction nozzles. Questions still remain about whether air induction nozzle design follows logical engineering principles theoretically and economically to produce droplets with low drift potential.

The objectives of this research were: (1) to evaluate if the spray drift reduction potential and other spray characteristics of air induction nozzles could be achieved by conventional hydraulic nozzles with the same orifice size operating at reduced operating pressures, and (2) to determine if air induction nozzles produce the same spray characteristics when the air-intake holes are closed. All tests were conducted under laboratory conditions.

**Materials and Methods**

**Nozzles Orifice Size Measurement**

Orifice dimensions of eight different air induction flat-fan nozzles (AI) and eleven different conventional extended-range flat-fan nozzles (XR) manufactured by Spraying Systems, Inc. (Wheaton, Ill.) were measured with a stereomicroscope (SZX12, Olympus, Tokyo, Japan) equipped with a camera, Spot 4.1 software (Diagnostic Instruments, Inc., Sterling Heights, Mich.), and a computer (table 1). The nozzles were selected in an order from smallest to largest orifice size as listed in the manufacturer’s catalog. The orifice length, width, and area of five nozzle tips for each of the nozzle sizes were measured. The XR nozzles with 110° spray angle were selected because the AI nozzles were only available with a 110° spray angle.

Based on the results of the orifice size measurements, three groups of nozzles representing large, medium, and small sizes of nozzle orifices from the AI and XR nozzles were selected for droplet size and velocity measurements, spray pattern width measurement, and spray drift potential test in a wind tunnel (table 2). In each group, the areas of the AI and XR nozzle orifices were equivalent or very close. To determine the effect of the air-intake holes of the AI nozzles on spray characteristics, similar tests were also conducted for the AI nozzles with sealed air-intake holes (AIS). The three groups, representing large, medium, and small nozzles, along with their operating pressures and flow rates for the tests are given in table 2. In each group, the same flow rate was used for the three different nozzle setups (AI, AIS, XR). The flow rate was selected according to the recommendation for the AI nozzle by the nozzle manufacturer, and then the operating pressure for the other two nozzles was adjusted to obtain that flow rate. To achieve the same flow rate as the air induction nozzles, the operating pressures for the XR 11008 nozzle in the medium group and the XR 11004 nozzle in the small group were selected below the recommended operating pressure range.

**Droplet Size and Velocity Measurement**

Droplet size distributions and droplet velocities for the three groups of nozzles were determined using a particle/droplet laser image analysis system (Oxford Lasers VisiSizer and PIV, Oxfordshire, U.K.). During the tests, lens option 3 was selected at magnification setting 2. At this setting, the system was able to measure droplets from 21.2 to 1732.0 μm. Droplet samples were taken 50 cm below the nozzle orifice and across centerline along the long axis of the spray pattern by scanning within a 90 cm range. Measurement was replicated three times for each condition. At least 10,000 droplets were sampled in each pass across the spray pattern. Particle
Figure 1. Schematic views of the laser system to measure: (a) droplet size, and (b) droplet velocity.

image velocimetry (PIV) with the 2D setting of the laser image analysis system was used to determine average velocities of all droplets passing through a 10 × 10 cm area 50 cm below the nozzle orifice. Velocity measurement results were averaged from at least 20 pairs of frames. Schematic views of the laser image analysis system for droplet size and PIV velocity measurements are shown in figures 1a and 1b, respectively.

**Spray Pattern Width Measurement**

The spray pattern width for each nozzle was determined with a portable spray pattern analyzing system (Allen Machine Works, Midland, Mich.). The system contains a 120 cm long × 92 cm wide spray table with twenty 6 cm wide × 3.5 cm deep V-shaped gutters. During the tests, the spray table was inclined 6° from the horizontal plane. The nozzle was mounted 50 cm above the spray table. The sprayed water from each gutter was collected in a 3 cm diameter, 26 cm long acrylic tube, and the volume of water in each tube was determined with a graduated cylinder. Since the spray patterns were slightly wider than the width of the spray table, the measurement for each nozzle was conducted with two half-pattern widths, and then the spray pattern width was determined with 99% total volume range collected by the glass tubes. Water discharged from the nozzles was collected for 20 s in the large nozzle group and for 60 s in the medium and small nozzle groups. Each measurement was repeated three times.

**Spray Coverage Test**

A greenhouse with controlled ambient temperature and relative humidity was used to determine spray coverage for the same nozzles used in the wind tunnel tests (table 2). The greenhouse was 6 m wide × 30 m long. A spray boom was mounted on an automatic track with the travel speed of 6.4 m/s. The boom height was 1.6 m above the floor. Water discharged from the nozzles was supplied from a 2 L plastic bottle, which was normally used for soft drinks. The plastic bottle was pressurized by a CO₂ tank, and the pressure was adjusted by a pressure regulator upstream of the nozzle. The spray coverage at 0.5 and 0.7 m below the nozzle orifice was determined with 52 × 76 mm water-sensitive paper (WSP; Syngenta Crop Protection AG, Basel, Switzerland). In this article, spray coverage is defined as the percentage of droplet stain area on the 52 × 76 mm WSP.

Samples were collected at three locations for each test path. A stand was used at each location to support four arms that held WSPs at two elevations. The stands were 1.1 m apart. Two WSPs were placed at each elevation and located at two sides of the stand. The upper face of each WSP was toward the nozzles. The length of the arms that held WSPs at the lower elevation was twice as long as the arms at the upper elevation to avoid interference between WSPs. The centerline of all WSPs was positioned on the same vertical plane under the center of spray pattern. Each trial was repeated three times. The temperature in the greenhouse was controlled between 21°C and 25°C, and relative humidity was between 35% and 52%. The spray coverage on each WSP was analyzed with a computer imaging system. The system included a desktop computer, a Scanjet 5530 photo-smart scanner (Hewlett-Packard, Palo Alto, Cal.), and image analyzing software (Image Tool 3.0, The University of Texas Health Science Center, San Antonio, Tex.).

**Spray Deposition Tests in Wind Tunnel**

A wind tunnel containing a 3.7 m long, 0.61 m wide, and 0.91 m high test section was used to evaluate spray losses to the ground and air for the three groups of nozzles (table 2). Tests were conducted at two wind velocities: 2.5 and 5.0 m/s. The wind velocity was measured with 0.15 mm cylindrical, hot-film, constant-temperature anemometer (CTA) sensors (model 8386, TSI, Inc., St. Paul, Minn.) controlled by an anemometer (model 1050B, TSI, Inc., St. Paul, Minn.). Details of the structure of the wind tunnel and measurement of wind velocities were given by Reichard et al. (1992). A single nozzle was used and mounted in the test section of the wind tunnel at 0.67 m above the wind tunnel floor, midway across the width of the tunnel and 2.5 m upwind from the downstream end of the test section. The nozzle was oriented to discharge downward spray toward the wind tunnel floor. Dimensions and positions of the nozzle, wind velocity probe, and spray deposit sampling targets are given in figure 2.

A 5 cm thick sponge panel was mounted on each sidewall of the wind tunnel to prevent droplets from rebounding from the sidewall to the test section. The liquid flow from the nozzle was controlled with a solenoid valve. A timer was used to operate the valve for 5 s during each test. For AI and
AIS nozzles, liquid was delivered to the nozzle from a diaphragm pump, and the bypass liquid was re-circulated back to the reservoir. For XR nozzles, since their operating pressures were very low, a pressurized spray tank was used to deliver spray liquid to the nozzles. The spray mixture used in tests for quantification of ground and airborne spray deposits in the wind tunnel was prepared with 3 g of fluorescent tracer Brilliant Sulfaflavine (BSF) (MP Biomedicals, Inc., Aurora, Ohio) per liter of water.

During the experiments, two different types of collectors were used for collecting ground spray deposits on the wind tunnel floor and airborne deposits in the air. The ground deposits were captured with a horizontal collector, which was a combination of 1.70 m long × 0.10 m wide strips of a muslin fabric and plastic. To prevent tracer contamination from the muslin fabric to the plywood surface, a plastic film was placed between the plywood and the fabric (Derksen et al., 1999). The plywood was supported horizontally with its upper surface 0.17 m above the wind tunnel floor to avoid collecting any droplets rebounding from the floor (fig. 2). The target was placed in the center of the wind tunnel and with its long axis parallel to the wind direction. The upwind side of the target was placed 0.40 m downstream from the nozzle to avoid collecting any droplets rebounding from the floor (fig. 2). The target was placed in the center of the wind tunnel and with its long axis parallel to the wind direction. The upwind side of the target was placed 0.40 m downstream from the nozzle to avoid collecting unusually large droplets during the brief period of starting or stopping spray. The airborne deposit collector was seven pieces of 10 × 10 cm nylon screen. These were mounted vertically in an array at the downstream end of the plywood to collect airborne droplets above the fabric strip (fig. 2). Detailed information about collection efficiency of nylon screens was given by Fox et al. (2004).

After each spray run, the fabric and plastic film were allowed to dry and then evenly cut into seventeen 10 × 10 cm pieces. Each piece of the combined fabric and plastic sample was placed in a clean glass bottle. For the airborne targets, each screen sample was placed in another clean bottle after each spray run. For fluorescence analysis, 30 mL of distilled water was added to each bottle to wash the tracer from the sample surfaces, and the bottles were shaken approximately for 3 min. After completing the washing process, approximately 4 mL of washing liquid was transferred to a clear cuvette. The fluorescence intensity of each sample was then determined with a luminescence spectrometer (model LS 50B, Perkin-Elmer, Ltd., Beaconsfield, U.K.) at an excitation wavelength of 460 nm.

Each wind tunnel test was replicated three times. Data were averaged from the three replications of each test condition. The fluorescence tracer recovery rate from the muslin fabric with distilled water was higher than 92%.

Test data were analyzed with analysis of variance based on factorial design. Differences among means were determined with Duncan’s new multiple-range test using ProStat version 3.8 (Poly Software International, Inc., Pearl River, N.Y.) at the 0.05 level of significance.

RESULTS AND DISCUSSION

NOZZLE ORIFICE SIZE

AI nozzles had much larger orifice sizes than XR nozzles if their labeling numbers were the same (table 3). For example, the AI 11003 nozzle orifice had 3.03 mm length, 0.83 mm width, and 2.09 mm² area, while the XR 11003 nozzle orifice had 1.97 mm length, 0.50 mm width, and 0.87 mm² area. With the same labeling number, the orifice area of AI nozzles was 2.1 to 2.75 times larger than the orifice area of XR nozzles.

DROPLET SIZE AND VELOCITY

Table 4 shows droplet size distributions and average droplet velocities for the three groups of nozzles 50 cm below the nozzle discharge point. For the large nozzle group, there was no significant difference in Dv0.5 between the AI and XR nozzles.
nozzles, while the AIS nozzle produced significantly higher \( D_{V0.5} \) than the AI and XR nozzles. In addition, the large AI nozzles produced significantly greater spray volume in droplets smaller than 100 \( \mu m \) and 200 \( \mu m \) than the XR and AIS nozzles. For the small nozzle group, there was no significant difference in both \( D_{V0.5} \) and percent spray volume of droplets smaller than 100 \( \mu m \) and 200 \( \mu m \) among the AI, AIS, and XR nozzles. Hence, the significant difference in droplet sizes depended on which nozzle group was selected. The data in table 4 also illustrate that relative spans of droplet sizes from the AI nozzles were always higher than from the AIS and XR nozzles for all three nozzle groups. Nozzles with higher relative spans produced higher variations in droplet size distributions.

Similarly, the incident of significant difference in average droplet velocities among the AI, AIS, and XR nozzles varied with large, medium, or small nozzle group (table 4). The AI nozzles in the large nozzle group had a significantly higher average droplet velocity than the XR nozzles, while this was not true for the small nozzle group. However, this velocity difference was very small compared to the variation in the velocities of all droplets passing through the measurement area. For example, the average velocity of droplets 0.5 m below the nozzle orifice from the AI 11003 nozzle was 5.9 m/s (table 4), while the range of overall droplet velocities in the 10 \( \times \) 10 cm test area was 0.8 to 13.5 m/s. Similarly, the average velocity of droplets 0.5 m below the nozzle orifice from the XR 11004 nozzle was 4.5 m/s (table 4), while the range of overall droplet velocities in the 10 \( \times \) 10 cm test area was 0.9 to 12.7 m/s. Additional test results indicated that the average droplet velocity within the 10 \( \times \) 10 cm test area 0.5 m below the nozzle orifice from the XR 11004 nozzle at 276 kPa was 5.3 m/s, while the overall velocity of droplets passing through the area varied from 1.4 to 10.8 m/s. For the same XR 11004 nozzle at 276 kPa, the average droplet velocity within the 10 \( \times \) 10 cm area 0.04 m below the nozzle orifice was 21.7 m/s, while the overall velocity of droplets passing through the area varied from 2.1 to 37.7 m/s.

It is important to realize that AI nozzles produce larger droplets than conventional nozzles based on the comparison of two types of nozzles with the same nominal capacity (or equivalent labeling number), but not based on equal orifice size. For example, our preliminary measurement indicates that, with a flow rate of 1.13 L/m, \( D_{V0.5} \) is 627 \( \mu m \) from the AI 11003 nozzle at 276 kPa, and \( D_{V0.5} \) is 204 \( \mu m \) from an XR 11003 nozzle at 276 kPa. However, the orifice area of XR 11003 is 0.87 mm\(^2\), while the orifice area of the AI 11003 is 2.09 mm\(^2\). The orifice area of AI 11003 is 2.4 times the area of XR 11003. Therefore, to have an accurate comparison of droplet sizes between AI and XR nozzles, an equal nozzle orifice size producing an equal flow rate should be selected, instead of using the nominal capacity (or equivalent labeling number) with an equal flow rate.

### Spray Pattern Width

The spray pattern width of each nozzle within 99% total volume range is given in table 4. The average pattern width was 121 cm with 2.5% coefficient of variation for the three nozzles in the large group, 119 cm with 5.4% coefficient of variation for the three nozzles in the medium group, and 119 cm with 2.6% coefficient of variation for the three nozzles in the small group. In field conditions, sprays with up to 10% pattern variation over the target areas are normal and acceptable. In addition, the nominal spacing between nozzles on boom sprayers is 45 to 50 cm, as recommended by most nozzle manufacturers. Theoretically, the ideal spray pattern width should be 100 cm to produce a uniform spray pattern on targets 50 cm below these nozzles. Therefore, the difference in spray pattern widths among the AI, AIS, and XR nozzles was negligible.

### Spray Coverage

The greenhouse tests illustrated that spray coverage on WSP was higher than 70% for all three nozzles in the large group at both 50 and 70 cm below the nozzle orifice (table 5, fig. 3). It was very difficult to obtain accurate coverage values from the scanner when over 70% of the WSP surface was covered.
covered by water droplets. The application rate was 950 L/ha at 6.4 km/h travel speed and 4.65 L/m nozzle flow rate with a nozzle spacing of 46 cm. Such a high application rate would be very rare for field crops, but not for dense nursery crops.

For the medium group, the three nozzles did not produce significantly different spray coverage on WSP at the same height (table 5, fig. 4). The spray coverage was about 29% on WSP at 50 cm below the nozzle orifice and was about 21% at 70 cm below the nozzle orifice for all three nozzles. For the small nozzle group, the AI nozzle had the lowest spray coverage and the XR nozzle had the highest spray coverage on WSP among the three nozzle treatments at both 50 and 70 cm.
Figure 6. Spray deposit on horizontal ground targets between 0.4 and 2.1 m downwind from the large nozzle group in the wind tunnel at (a) 2.5 m/s wind velocity, and (b) 5.0 m/s wind velocity.

Table 6. Total volume of spray deposits on horizontal ground targets between 1.0 and 2.1 m downwind from the nozzle discharge point for large, medium, and small nozzle groups at 2.5 and 5.0 m/s wind velocities.

<table>
<thead>
<tr>
<th>Wind Velocity (m/s)</th>
<th>Large Group</th>
<th>Medium Group</th>
<th>Small Group</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Nozzle</td>
<td>Deposit (µL)</td>
<td>Nozzle</td>
</tr>
<tr>
<td>2.5</td>
<td>AI 11008</td>
<td>492 e</td>
<td>AI 11003</td>
</tr>
<tr>
<td></td>
<td>AIS 11008</td>
<td>344 d</td>
<td>AIS 11003</td>
</tr>
<tr>
<td></td>
<td>XR 11015</td>
<td>290 d</td>
<td>XR 11008</td>
</tr>
<tr>
<td>5.0</td>
<td>AI 11008</td>
<td>659 f</td>
<td>AI 11003</td>
</tr>
<tr>
<td></td>
<td>AIS 11008</td>
<td>606 f</td>
<td>AIS 11003</td>
</tr>
<tr>
<td></td>
<td>XR 11015</td>
<td>772 f</td>
<td>XR 11008</td>
</tr>
</tbody>
</table>

[a] Values in the same column followed by the same letter are not significantly different at the 0.05 level.

Figure 7. Spray deposit on horizontal ground targets between 0.4 and 2.1 m downwind from the small nozzle group in the wind tunnel at (a) 2.5 m/s wind velocity, and (b) 5.0 m/s wind velocity.

below the nozzle orifice (table 5, fig. 5). The difference in coverage between XR 11004 and AI 110015 was 7.8% at the 50 cm position and 6.1% at the 70 cm position, which was mainly caused by the XR nozzle having a slightly narrower spray pattern width than the AI nozzle (table 4).

**GROUND DEPOSITION IN WIND TUNNEL**

**Large Nozzle Group**

Figure 6 shows ground spray deposits on the targets in the wind tunnel between 0.4 and 2.1 m downhill from the nozzle discharge point with the large nozzle group at 2.5 and 5.0 m/s wind velocities. The value at each point in figure 6 represents the average spray deposit from three replications. The largest portion of the spray volume was expected to deposit on the floor within 0.4 m downhill from the nozzle. At 2.5 m/s wind velocity, spray deposits on ground targets between 0.4 and 1.0 m downhill from the XR nozzle were slightly higher than deposits from the AI and AIS nozzles, but they were lower than the deposits from the AI and AIS nozzles on targets between 1.0 and 2.1 m downhill. The XR nozzle had 41% and the AIS nozzle had 30% less total spray deposit on ground targets between 1.0 and 2.1 m downhill from the nozzle than the AI nozzle, and the difference in total deposits between XR and AI or between AIS and AI was statistically significant (table 6). However, there was no significant difference in the total spray deposits on the ground targets within the range from 1.0 and 2.1 m downhill from the nozzles among the AI, AIS, and XR nozzles at 5.0 m/s wind velocity (table 6).

**Small Nozzle Group**

Figure 7 shows ground spray deposits on the targets between 0.4 and 2.1 m downhill from the nozzle discharge point with small nozzle group at 2.5 and 5.0 m/s wind velocities in the wind tunnel. At 2.5 m/s wind velocity, spray deposits on ground targets between 0.4 and 2.1 m downhill from the XR and AIS nozzles were significantly higher than the...
Table 7. Total volume of airborne deposits on vertical screen targets beyond 2.1 m downwind from the nozzle discharge point for large, medium and small nozzle groups at 2.5 and 5.0 m/s wind velocities.

<table>
<thead>
<tr>
<th>Wind Velocity (m/s)</th>
<th>Large Group</th>
<th>Medium Group</th>
<th>Small Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nozzle</td>
<td>Deposit (µL)[a]</td>
<td>Nozzle</td>
</tr>
<tr>
<td>2.5</td>
<td>AI 11008</td>
<td>366 c</td>
<td>AI 11003</td>
</tr>
<tr>
<td></td>
<td>AIS 11008</td>
<td>264 c</td>
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<tr>
<td></td>
<td>XR 11015</td>
<td>364 c</td>
<td>XR 11008</td>
</tr>
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<td>AI 11003</td>
</tr>
<tr>
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<td></td>
<td>XR 11015</td>
<td>776 d</td>
<td>XR 11008</td>
</tr>
</tbody>
</table>

[a] Values in the same column followed by the same letter are not significantly different at the 0.05 level.

AIRBORNE DEPOSITION IN WIND TUNNEL

Total airborne deposits on vertical screens, for all size nozzle groups, at 2.5 and 5.0 m/s wind velocities are given as the average of replications in table 7.

Large Nozzle Group

The average airborne deposits on seven vertical screens for the large nozzle group at 2.5 and 5.0 m/s wind velocities are given in figure 8. For all three nozzles, the airborne deposit decreased as the screen height increased at both wind velocities, and the airborne deposit increased as the wind velocity increased. At both wind velocities, there was no significant difference in cumulative airborne deposits across the seven screens among the AI, AIS, and XR nozzles (table 7).

Small Nozzle Group

The AI nozzle had lower average airborne deposits on the screen at 0.05 m above the ground targets than the AIS and XR nozzles at 2.5 m/s wind velocity (fig. 9a), but it had higher average airborne deposits than the AIS and XR nozzles at 5.0 m/s wind velocity (fig. 9b). However, the differences were not statistically significant (table 7). Although there was a significant difference in the cumulative amount of airborne deposits across the seven screen targets among the AI, AIS, and XR nozzles at 2.5 m/s wind velocity, the difference was not significant at 5.0 m/s wind velocity (table 7).

Medium Nozzle Group

Wind tunnel tests also indicated that the medium nozzle group had ground spray deposits (table 6, fig. 10) and airborne deposits (table 7, fig. 11) that were very similar to those of the large and small nozzle groups at 2.5 and 5.0 m/s wind velocities.

Figure 8. Airborne spray deposit on seven vertical screens 2.1 m downwind from the nozzle discharge point in the wind tunnel for the large nozzle group at (a) 2.5 m/s wind velocity, and (b) 5.0 m/s wind velocity.

Figure 9. Airborne spray deposit on seven vertical screens 2.1 m downwind from the nozzle discharge point in the wind tunnel for the small nozzle group at (a) 2.5 m/s wind velocity, and (b) 5.0 m/s wind velocity.
intake holes. Energy loss also occurs when the fluid passes
sufficient, then some of the liquid will flow out of the air-
through the air-intake holes. If the nozzle orifice size is not
which requires large exit orifices to prevent liquid flow
air holes outside the fluid chamber, additional energy is re-
Because air induction nozzles are configured with two small
nozzle orifice. The AI nozzle pressure drop is mainly due to
a great pressure drop occurs between the spray boom and the
chamber and the Venturi effect with the two air-intake holes.
nozzle orifice. The AI nozzle pressure drop is mainly due to
a high restriction of liquid flow by the small internal fluid
nozzle orifice. The AI nozzle pressure drop is mainly due to
a great pressure drop occurs between the spray boom and the
chamber only 0.37 cm long and 0.5 cm in diameter. There-
research had a 3.8 cm long internal fluid chamber and 0.15
cm diameter Venturi section, while the XR nozzles had a fluid
operating pressure below the manufactur-
er’s recommended pressure range. It would be unfair to
compare drift reduction potentials between the two types of
nozzles by choosing the same nominal capacity instead of the
same exit orifice size.
AI nozzles were introduced into the market mainly for
spray drift reduction, and they were claimed to have high effi-
cacy because of an assumption that droplets from AI nozzles
contain air bubbles. However, no scientific proof has shown
that this assumption is true. The assumption that droplets
from AI nozzles contain air bubbles does not follow from
common engineering principles. When air gets into a nozzle
chamber, it will be compressed by the liquid pressure before
discharged from the nozzle. It has been shown that the
liquid discharged from AI nozzles forms a thin sheet, and
droplets form as the sheet disintegrates (Miller and Butler El-
lis, 2000). The section containing the compressed air should
be the weakest area in a thin spray sheet, and the compressed
air bubbles in the thin liquid sheet would burst in the atmo-
sphere to accelerate the liquid sheet breakup into smaller
droplets. Therefore, theoretically, entrained air inside AI
nozzles should actually increase the number of small dro-
lets. Our additional laboratory tests showed that visible air

velocities. Therefore, with the equivalent exit orifice size and
the same flow rate, AI nozzles did not produce larger droplets
and greater drift reduction than XR nozzles to reduce drift po-
tential; however, AI nozzles used much higher operating
pressure than XR nozzles. High operating pressure could re-
cude the life of pumps and other fluid components and in-
crease the power required for operating the spray system.

In addition, when the same flow rates were used, the AIS
nozzles produced droplet size distributions, spray pattern
widths, and spray deposits in the wind tunnel that were very
similar to the results for the AI nozzles. Therefore, the two
air-intake holes on the AI nozzles did not have a significant
effect on spray drift reduction and atomization quality while
AI nozzles operated at a higher operating pressure than AIS
nozzles.

For a given spray mixture, the atomization quality of hy-
draulic nozzles mostly depends on the nozzle exit orifice
shape and size, the fluid pressure acting on the orifice, and the
flow velocity passing through the orifice. For the AI nozzles,
a great pressure drop occurs between the spray boom and the
nozzle orifice. The AI nozzle pressure drop is mainly due to
a high restriction of liquid flow by the small internal fluid
chamber and the Venturi effect with the two air-intake holes.
Because air induction nozzles are configured with two small
air holes outside the fluid chamber, additional energy is re-
quired to seal these holes by using the Venturi flow field,
which requires large exit orifices to prevent liquid flow
through the air-intake holes. If the nozzle orifice size is not
sufficient, then some of the liquid will flow out of the air-
intake holes. Energy loss also occurs when the fluid passes
through the small diameter, long internal fluid chamber of air
induction nozzles. For example, all AI nozzles tested in this
research had a 3.8 cm long internal fluid chamber and 0.15
cm diameter Venturi section, while the XR nozzles had a fluid
chamber only 0.37 cm long and 0.5 cm in diameter. There-
fore, air induction nozzles use very high operating pressure
to produce spray characteristics similar to those of conven-
tional nozzles operated at a pressure below the manufactur-
er’s recommended pressure range. It would be unfair to
compare drift reduction potentials between the two types of
nozzles by choosing the same nominal capacity instead of the
same exit orifice size.

AI nozzles were introduced into the market mainly for
spray drift reduction, and they were claimed to have high effi-
cacy because of an assumption that droplets from AI nozzles
contain air bubbles. However, no scientific proof has shown
that this assumption is true. The assumption that droplets
from AI nozzles contain air bubbles does not follow from
common engineering principles. When air gets into a nozzle
chamber, it will be compressed by the liquid pressure before
discharged from the nozzle. It has been shown that the
liquid discharged from AI nozzles forms a thin sheet, and
droplets form as the sheet disintegrates (Miller and Butler El-
lis, 2000). The section containing the compressed air should
be the weakest area in a thin spray sheet, and the compressed
air bubbles in the thin liquid sheet would burst in the atmo-
sphere to accelerate the liquid sheet breakup into smaller
droplets. Therefore, theoretically, entrained air inside AI
nozzles should actually increase the number of small dro-
lets. Our additional laboratory tests showed that visible air

Figure 10. Spray deposit on horizontal ground targets between 0.4 and 2.1 m downwind from the medium nozzle group in the wind tunnel at (a) 2.5
m/s wind velocity, and (b) 5.0 m/s wind velocity.

Figure 11. Airborne spray deposit on seven vertical screens 2.1 m downwind from the nozzle discharge point in the wind tunnel for the medium nozzle
group at (a) 2.5 m/s wind velocity, and (b) 5.0 m/s wind velocity.
bubbles in droplets could be created from both AI and XR nozzles by spraying water mixed with dishwashing detergent. The entrained air in the spray drops must have originated from air surrounding the liquid sheet because there is no air inside XR nozzles. Therefore, air bubbles entrained in spray drops could be formed by changing the physical properties of the spray liquid.

**CONCLUSIONS**

Based on laboratory experiments to compare droplet size distributions, spray pattern widths, and ground and airborne spray deposits in a wind tunnel for the AI, AIS, and XR nozzles, the following conclusions can be made:

With the same orifice size and flow rate, AI and XR nozzles had no significant differences in droplet sizes, spray pattern width, spray coverage, and drift reduction potential, but AI nozzles operated at a much higher pressure than XR nozzles. Therefore, the spray characteristics of AI nozzles were actually similar to the spray characteristics of XR nozzles with equivalent orifice sizes operated at pressures close to or below the manufacturer’s recommended pressure range.

With the same flow rate, AI nozzles with sealed air-intake holes produced droplet size, spray pattern width, and drift reduction potential similar to the same AI nozzles with open air-intake holes.

With the same nominal capacity (or equivalent labeling number), AI nozzles had an orifice area at least 2.1 times larger than XR nozzles. AI nozzles used a much larger orifice size than XR nozzles to prevent liquid flow through the air-intake holes and to produce larger droplets.

**REFERENCES**


