SOURCE SAMPLING OF PARTICULATE MATTER EMISSIONS FROM COTTON HARVESTING – SYSTEM DESIGN AND EVALUATION

J. D. Wanjura, C. B. Parnell, Jr., B. W. Shaw, S. C. Capareda, R. E. Lacey

ABSTRACT. State and regional air pollution regulatory agencies are required by federal law to reduce ambient particulate matter concentrations in non-attainment areas to a level in compliance with National Ambient Air Quality Standards. All emission regulations, including reduction regulations, should be based on accurate emission factors. Agricultural particulate matter emission factors are difficult to quantify due to the nature of the emission source, size characteristics of the dust, and environmental factors affecting natural dispersion of the pollutant. Cotton harvesting emission factors developed through previous efforts using indirect techniques employing ambient sampling and dispersion modeling contain substantial levels of uncertainty due to these factors. It was hypothesized that particulate matter emissions from cotton harvesting could be more accurately quantified through direct source measurement than with previously used indirect techniques. The objective of this work was to document the design and evaluation of a system designed to measure emission concentrations onboard a modern six-row cotton picker. The principal functions of the system were to collect all of the seed cotton, air, and foreign material from one cotton transport duct on the harvester, separate the seed cotton from the air stream, and channel the particulate laden air stream through a duct where an isokinetic emission concentration could be measured. Optimization tests were conducted on the baffle separation section of the system to maximize the removal of seed cotton and large foreign material from the conveying air stream. Additional tests were conducted across the exit duct cross section to investigate air velocity profile and particulate matter concentration patterns. Maximum seed cotton removal was achieved with a straight back wall separator configured with a 47-cm baffle installed at a 52° with the top of the box. No differences in air velocity patterns across the duct were detected at varying rates of seed cotton flow and an isokinetic center point measurement adequately represented the duct average emission concentration and particle size distribution. The findings of this work indicate that it is possible to measure cotton harvester emissions on a direct basis at the source. Thus, resulting emission factors will not have the uncertainty contained in previous emission factors developed through indirect techniques.

Keywords. Cotton, Particulate matter, Sampling, PSD, Isokinetic concentration.

Agricultural operations are facing increased pressure from air pollution regulators in some states across the United States due to regional particulate matter (PM) non-attainment status and annual emissions inventories calculated with inaccurate emission factors. Subsequently, agricultural operations are subject to more stringent permitting and control requirements resulting in increased production costs. Specifically, agricultural producers in areas of California and Arizona are required to obtain air quality permits and comply with conservation management or best management practice mandates (AAC, 2000; CARB, 2003; SJVAPCD, 2004a and b). Producers must comply with management practice mandates to reduce fugitive PM emissions from crop production operations such as land preparation, planting, tilling, harvesting, etc. Cotton production is included in the list of agricultural operations targeted for emission reductions.

Limited research quantifies PM emissions from cotton harvesting. Snyder and Blackwood (1977) reported emissions of PM less than 7 micrometers (µm) (mean aerodynamic diameter) on the order of 0.96 kg km⁻² (8.4*10⁻³ lb acre⁻¹) for harvesting operations using cotton pickers that included emissions from the harvesting machine, trailer loading operations, and trailer transporting operations. The emission factors reported in AP-42 (EPA, 1995) based on the work by Snyder and Blackwood (1977) assumed the average picking machine speed was 1.34 m s⁻¹ (3.0 mi h⁻¹), the picking machine basket capacity was 109 kg (240 lb), the transport trailer capacity was 6 picker baskets, and the average lint yield was 2.89 bales ha⁻¹ (1.17 bales acre⁻¹). These reflect older harvesting technologies as harvesters used today typically harvest up to six rows of cotton per pass.
with 4086-kg (9000-lb) or 40-m³ (1400-ft³) basket capacities (Deere and Co., 2007). Similarly, average annual yields have increased to about 4.5 bales ha⁻¹ (1.8 bales acre⁻¹) (USDA, 2007).

Also, no detail was presented as to how measured concentrations were used to determine the emission rate for either the harvesting machine or trailer loading operation. Further, the emission factors reported are based on concentrations of PM less than 7-µm mean aerodynamic diameter, which represents only part of the regulated size fraction of dust in the United States. Federal PM standards are listed for two particle size indicators: PM₁₀ and PM₂.₅. PM₁₀ and PM₂.₅ refer to particulate matter with aerodynamic equivalent diameter (AED) ≤₁₀ and 2.₅ µm, respectively. The primary NAAQS for PM₁₀ was retained during the latest revision of the NAAQS at 150 µg m⁻³ (24 h average) while the PM₂.₅ NAAQS was reduced from 65 to 35 µg m⁻³ (24 h average) (Federal Register, 2006).

Flocchini et al. (2001) conducted a study to measure PM₁₀ emissions from more modern cotton harvesting operations using two to five row pickers. The results indicated that the PM₁₀ emissions from cotton pickers in the San Joaquin valley of California were 1.9 kg ha⁻¹ (1.7 lb acre⁻¹). The protocol utilized ambient PM₁₀ samplers to measure PM₁₀ concentrations both upwind and downwind of the harvesting operation, a series of three mobile towers with PM₁₀ samplers and anemometers mounted at several heights to measure the concentration profile of the dust plume downwind of the operation, and a LIDAR instrument to describe the shape of the plume downwind of the harvesting operation. A mass balance box model was used with the concentration data to determine the area source emission rate from the operation and to assess the influence of the plume shape on the estimated emission factors.

The work by Flocchini et al. (2001) represented the most up-to-date information regarding PM₁₀ emissions from cotton harvesting operations. However, recent research has shown that some components of the protocol may have introduced significant levels of uncertainty. Faulkner et al. (2007) showed that systematic uncertainty in ground level area source (GLAS) emission factors can be significantly inflated through the use of meteorological instruments with low precision and inappropriate placement of samplers relative to the emitting source. Faulkner et al. (2007) indicate that samplers used to measure PM concentrations for GLAS emission factor development should be located close to the GLAS in order to minimize the influence of outside sources on measured concentrations as well as to minimize the change in particle size distribution (PSD) of the emitted PM as the plume travels downwind. Buser et al. (2006) indicated that the Federal Reference Method (FRM) PM₁₀ sampler could theoretically overstate PM₁₀ concentrations by as much as 340% when sampling a dust with mass median diameter (MMD) and geometric standard deviation (GSD) of 20 µm and 2.0, respectively. FRM PM₁₀ sampler over-sampling errors have also been observed in field work (Capareda et al., 2005; Wanjura et al., 2005a).

In order for agricultural sources to be equitably regulated, accurate emissions inventories must be calculated by air pollution regulators using accurate emission factors based on sound science. It was hypothesized that emission factors developed using source measurement techniques would contain less uncertainty than previous emission factor estimates developed using indirect techniques. The objective of this work was to design and evaluate a system to measure PM emission concentrations onboard a six-row cotton picker.

**METHODS**

**PRELIMINARY DESIGN**

In 2006, a study to develop an accurate science-based emission factor for cotton picking was initiated by Texas A&M University. A prototype, onboard system (figs. 1 and 2) was designed to source sample a state-of-the-art six-row John Deere model 9996 cotton picker. The source sampling system was designed to collect all of the air, seed cotton, and foreign material (plant material, soil, etc.) from one of the ducts on the six-row harvester, separate the seed cotton from the air stream, and exhaust the particulate laden air stream after performing an isokinetic emission concentration measurement.

Pitot tube traverses were performed on the six ducts which transport seed cotton from the picking units to the basket on the harvester to determine the average air velocity in each duct. Average air velocity measurements ranged from 1070 to 1525 m/min (3500-5000 ft/min) across the six ducts with the maximum average velocity observed in duct 3 (numbering the ducts from left to right sitting in the operator seat). The source sampling system was designed specifically for the seed cotton transport duct with highest maximum air velocity so that static pressure loss caused by the source sampler would be less likely to lower the duct air velocity below a value acceptable for conveying the seed cotton. Average air velocity measurements with the prototype sampler installed showed that the air velocity in the seed cotton transport duct on the harvester was only reduced to approximately 914 m min⁻¹ (3000 ft min⁻¹).

PM entrained in the air stream in the cotton conveying duct would be isokinetically sampled, but the seed cotton and other large material needed to be separated first. To this end a baffle-type separator section was designed and installed (figs. 1 and 2). The inlet duct to the separator section maintained the cross sectional area [20.3 × 45.7 cm (8 × 18 in.)] of the harvester duct, so as not to restrict the air flow and maintain the seed cotton and air velocity close to that of the cotton picker conveying duct. The design critical air velocity, as described by Mihalski (1996), was 305 m/min (1000 ft/min) to remove large plant material from an air stream. The critical air velocity was accomplished by increasing the flow area at the trailing edge of the baffle, where the air flow turns to exit the baffle, to four times the inlet cross-sectional area. This produced a critical air velocity lower than that described by Mihalski (1996) [approximately 229 m min⁻¹ (750 ft min⁻¹)] at the edge of the baffle to help remove seed cotton and large foreign material from the air stream. Seed cotton separated from the air stream was dropped into the basket of the harvester via a 38-cm (15-in.) diameter brush wheel revolving at approximately 85 rpm.
Figure 1. Schematic diagram of the separation system designed to separate the seed cotton from the air stream from duct 3 of the six-row harvester.

Figure 2. Schematic drawing of separator box design 1 with general dimensions shown (isometric view). All dimensions are in cm.

The particulate laden air was exhausted from the baffle section via a 1.6-m (63-in.) exit duct with 30.5-× 30.5-cm (1-× 1-ft) cross section. Air velocity in the exit duct was determined from centerline velocity pressure measurements made with a pitot tube located approximately 40.6-cm (16-in.) downstream from the baffle section exit and according to equation 1 (Cooper and Alley, 2002).

\[ V = 14.01 \frac{P_v}{\rho_a} \]  

(1)

where

- \( V \) = air velocity (m s\(^{-1}\)),
- \( P_v \) = velocity pressure measured by pitot tube (cm H\(_2\)O),
- \( \rho_a \) = air density (kg m\(^{-3}\)).

Isokinetic emission concentration measurements were taken at the center of the exit duct approximately 20.3 cm (8 in.) from the exit of the separation system exit duct. The PM-laden air captured by the 47-mm (1.85-in.) diameter isokinetic sampler nozzle was passed through a 15.2-cm (6-in.) diameter barrel-type cyclone (Tullis et al., 1997) to separate the large PM and then the PM which penetrated the cyclone was captured on a bank of four 20.3-× 25.4-cm (8-× 10-in.) coated borosilicate glass microfiber filters (Pallflex Emfab filter material 7224, Pall Corp., East Hills, N.Y.).

The designed maximum air flow rate of the isokinetic sampler was 2.12 m\(^3\) min\(^{-1}\) (75 ft\(^3\) min\(^{-1}\)) and was measured by an orifice meter. To simplify sampler control, the orifice diameter [53.64 mm (2.112 in.)] was specified such that the pressure drop across the orifice plate would equal the centerline velocity pressure in the duct when isokinetic sampling conditions are achieved. The sampler air flow was provided by two fans (Model HP-33, Clements National Co., Chicago, Ill.) installed in series mounted on top of the harvester and controlled from within the harvester cab via fan speed with an AC variable transformer. Throughout testing, data loggers (HOBO H8 RH/Temp/2x External, Onset Computer Corp, Pocasset, Mass.) recorded readings from differential pressure transducers (PX274, Omega Engineering, Inc., Stamford, Conn.) used to measure the velocity pressure from the pitot tube in the exit duct, the pressure drop across the orifice plate, and the pressure drop across the filter housings (to monitor filter loading).

Materials separated from the sampled air stream by the cyclone and collected in a sealed container were primarily plant and soil material with small amounts of lint fiber and PM. The material from the container was air washed for 15 min (1.1 m\(^3\) min\(^{-1}\) air flow rate, 60-rpm tumbler rotation speed) to remove the PM smaller than 100 \(\mu\)m (Wanjura et al., 2007). PM extracted by the air wash was collected on 20.3-× 25.4-cm (8-× 10-in.) borosilicate, glass microfiber filters. All of the filters used in the source sampler and in the air washing process of the cyclone bucket material were pre and post weighed according to the procedure described by Wanjura et al. (2005b).

Emission concentrations measured with the source sampler were calculated according to equation 2.

\[ EC_{TSP} = \frac{M_F + M_B}{\sum_i Q_i T_i} \]  

(2)
Where 

\[ ECTSP = \text{Total suspended particulate (TSP) (PM < 100 \mu m) emission concentration (g m}^{-3}) \], \\
\[ MF = \text{PM mass on the four filters used in the source sampler (g)} \], \\
\[ MB = \text{PM mass < 100 \mu m captured in the cyclone bucket (g)} \], \\
\[ Qi = \text{air flow rate during the i\textsuperscript{th} logging interval (m}^3\text{s}^{-1}) \], and \\
\[ ti = \text{duration of i\textsuperscript{th} logging interval (6 s)} \].

The total mass of PM emitted from the single cotton conveying duct tested was estimated by multiplying the emission concentration (eq. 2) by the total volume of air passing through the duct. The assumption was made that the total mass of PM emitted from one duct adequately represented the total mass of emissions from the other ducts because any inter-row variability in PM emissions would be mitigated by the harvester making multiple passes in the field during each test (usually more than 8 field passes per test). Thus, the total mass of PM emitted from the harvester was estimated by multiplying the total PM mass emission from the sampled duct by 6 (the number of picking units/seed cotton transport ducts on the harvester). Area or mass-based TSP emission factors were calculated by dividing the harvester total mass of PM emitted by either the area harvested or the number of 218-kg (480-lb) bales harvested (assuming 34% lint turnout for seed-cotton weights from a load cell equipped boll buggy), respectively. PM\textsubscript{10} and PM\textsubscript{2.5} emission factors were obtained by multiplying the TSP emission factors by the respective mass fractions from the results of PSD analyses on the filters conducted on a Coulter Counter Multisizer 3 according to the procedure described by Faulkner and Shaw (2006).

Wanjura et al. (2007) reported the results from this preliminary design and 2006 system field evaluation. The overall area based average TSP, PM\textsubscript{10}, and PM\textsubscript{2.5} emission factors were 114, 45, and 0.15 g ha\textsuperscript{-1} (0.102, 0.04, and 1.34 E-4 lb acre\textsuperscript{-1}), respectively. The resulting emission factors were calculated by dividing the harvester total mass of PM emitted by either the area harvested or the number of 218-kg (480-lb) bales harvested (assuming 34% lint turnout for seed-cotton weights from a load cell equipped boll buggy), respectively. PM\textsubscript{10} and PM\textsubscript{2.5} emission factors were obtained by multiplying the TSP emission factors by the respective mass fractions from the results of PSD analyses on the filters conducted on a Coulter Counter Multisizer 3 according to the procedure described by Faulkner and Shaw (2006).

\[ Q_i = 210.15 \pi d^2 \sqrt{\frac{P_{c,d}(F)}{\rho_a}} \]  

where 

\[ Q_i = \text{air flow rate from fan i (m}^3\text{min}^{-1}) \], \\
\[ d = \text{duct diameter (m)} \], \\
\[ P_{c,d} = \text{center point velocity pressure (cm H}_2\text{O)} \], \\
\[ F = \text{center point correction factor} \], and \\
\[ \rho_a = \text{air density (kg m}^{-3}) \].

The center point correction factor (F) was the ratio of the duct average velocity pressure, determined by a 20-point pitot traverse, to the center point velocity pressure. All velocity pressure measurements were taken using a pitot tube and digital Maneghelic gage.

Air dry bulb temperature, relative humidity, and barometric pressure were measured during each test using a weather station. These measurements were used to calculate the density of the air as shown in equation 4 (Cooper and Alley, 2002).

\[ \rho_a = \frac{P_b - \phi P_s}{0.0028 \times (t_{db} + 273)} + \frac{\phi P_s}{0.0046 \times (t_{db} + 273)} \]  

Figure 3. Photo of seed cotton separation system mounted in the testing frame configured with the seed cotton feeder and fan system.

**SYSTEM EVALUATION**

The initial development work on the emissions sampling system during 2006 was conducted to evaluate the feasibility of in situ measurement of PM emissions from cotton harvesting. The evaluation and optimization of the sampling system design was carried out during 2007 due to time and resource limitations during 2006. The onboard emissions sampling system was evaluated on a stationary test frame at the Texas A&M University Biological and Agricultural Engineering labs.
where

\[ P_b = \text{barometric pressure (atm)}, \]
\[ \phi = \text{relative humidity (decimal)}, \]
\[ P_s = \text{saturation vapor pressure (atm)}, \]
\[ t_{db} = \text{dry bulb temperature (°C)}. \]

During each test, 18.2-kg (40-lb) lots of seed cotton were fed through the system at nominal feed rates of 22.7, 45.4, and 68.1 kg min\(^{-1}\) (50, 100, and 150 lb min\(^{-1}\)). These feed rates were approximately equivalent to the harvesting rate of a single row unit gathering seed cotton in fields yielding 3.06, 6.12, and 9.19 bales ha\(^{-1}\) (1.2, 2.5, and 3.7 bales acre\(^{-1}\)), assuming: 101.6-cm (40-in.) row spacing, 681 kg (1500 lb) of seed cotton per bale, and 6.4-km h\(^{-1}\) (4-mi h\(^{-1}\)) harvesting speed.

Two separator box designs (box 1: figs. 1 and 2; box 2: figs. 4 and 5) were evaluated with several different baffle configurations to determine the separator box/baffle configuration which resulted in the lowest mass of seed cotton penetrating the exit duct. The first separator box design (figs. 1 and 2) was tested with three curved baffle configurations with overall lengths of 30.5, 40.6, and 47 cm (12, 16, and 18.5 in.) and each baffle was positioned so that the lower edge of the baffle was 40.6 cm (16 in.) from the front wall of the separator box. Clear polycarbonate material on one sidewall of the separator box designs made visual observations of the cotton flowing through the system possible. During testing of separator box design 1 it was observed that some seed cotton accumulated on the inclined back wall of the separator box and re-entrained in the air stream, penetrating to the exit duct. Therefore, separator box design 2 (figs. 4 and 5) had a straight back wall to minimize the accumulation of seed cotton and subsequent re-entrainment.

Separator box design 2 was tested with four curved and three straight baffle configurations (table 1; figs. 6 and 7). The curved baffles included baffles identical to those tested in separator box design 1 and a 30.5-cm (12-in.) radius baffle with bottom edge located 30.5 cm (12 in.) from the front wall. The three straight baffles were 47-cm (18.5-in.) long installed slanted with top edge 12.7 cm (5 in.) from the front wall and bottom edge 40.6 cm (16 in.) from the front wall (fig. 7), and slanted with top edge 25.4 cm (10 in.) from the front wall and bottom edge 40.6 cm (16 in.) from the front wall, and vertical with both edges 40.6 cm (16 in.) from the front wall.

Each separator box/baffle configuration was tested at the three nominal seed cotton feed rates (22.7, 45.4, and 68.1 kg min\(^{-1}\)) with three replications per feed rate. Each configuration was evaluated based on the mass of seed cotton that penetrated the exit duct of the separator system and collected in a wire mesh bin attached to the discharge end of the exit duct. The collection bin was weighed before and after each test using a laboratory balance (Mettler-Toledo PM30, Mettler-Toledo, Inc., Columbus, Ohio). Analysis of variance (ANOVA) and Tukey’s HSD tests were performed using the general linear model in SPSS (SPSS release 12.0.1, SPSS Inc., Chicago, Ill.) to determine differences in the separator box design/baffle configurations.

**Velocity Profile Testing**

Air velocity profile measurements were taken to evaluate the consistency of air flow patterns in the exit duct. If consistent air flow patterns were present in the exit duct, it was likely that a consistent concentration profile also existed. The air velocity profile was investigated by dividing the cross section of the exit duct into nine equal area sections and locating an air velocity probe (641RM-12, Dwyer Instruments, Inc., Michigan City, Ind.) at the centroid of each equal area region (fig. 8). The velocity probes were installed coplanar to one another at 20.3 cm (8 in.) from the end of the exit duct. Air velocity profile testing was only performed on separator box design 2 with baffle configuration 5 in table 1 as this separator box/baffle configuration allowed the least seed cotton to penetrate the exit duct in the seed cotton separation tests.

The air velocity profile was measured with seed-cotton feed rates of 0, 22.7, and 45.4 kg min\(^{-1}\) (0, 50, and 100 lb min\(^{-1}\)). Five replications at each seed cotton feed rate were...
Figure 5. Schematic drawing of separator box design 2 showing general dimensions (isometric view). All dimensions are in cm.

Figure 6. Schematic showing curved baffle dimensions for baffles 1, 2, 3, and 4 (see table 1).

Figure 7. Schematic showing straight baffle dimensions for baffles 5, 6, and 7 (see table 1).

Figure 8. Schematic diagram of air velocity probe locations across the exit duct (numbers inside the equal area squares represent probe locations). All dimensions are in cm.

Table 1. Description of the baffles tested in separator box designs 1 and 2 (see figs. 6 and 7).

<table>
<thead>
<tr>
<th>Baffle No.</th>
<th>Tested in Separator Box Design Numbers</th>
<th>Baffle Shape</th>
<th>R (cm)</th>
<th>D (cm)</th>
<th>X (cm)</th>
<th>T (cm)</th>
<th>L (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 and 2</td>
<td>Curved</td>
<td>30.5 (12)</td>
<td>40.6 (16)</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>1 and 2</td>
<td>Curved</td>
<td>40.6 (16)</td>
<td>40.6 (16)</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>1 and 2</td>
<td>Curved</td>
<td>40.6 (16)</td>
<td>40.6 (16)</td>
<td>6.4 (2.5)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>2 only</td>
<td>Curved</td>
<td>30.5 (12)</td>
<td>30.5 (12)</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>2 only</td>
<td>Straight</td>
<td>-</td>
<td>40.6 (16)</td>
<td>-</td>
<td>12.7 (5)</td>
<td>47 (18.5)</td>
</tr>
<tr>
<td>6</td>
<td>2 only</td>
<td>Straight</td>
<td>-</td>
<td>40.6 (16)</td>
<td>-</td>
<td>25.4 (10)</td>
<td>47 (18.5)</td>
</tr>
<tr>
<td>7</td>
<td>2 only</td>
<td>Straight</td>
<td>-</td>
<td>40.6 (16)</td>
<td>-</td>
<td>40.6 (16)</td>
<td>47 (18.5)</td>
</tr>
</tbody>
</table>

performed. During each test the system air flow rate was maintained at 85 m$^3$/min$^{-1}$ (3000 ft$^3$/min$^{-1}$). The nine air velocity readings were simultaneously recorded using a data acquisition system (cFP-AI-110, National Instruments, Austin, Tex.) at 1-Hz frequency. Air temperature, relative humidity, and barometric pressure were measured inside the exit duct using a temperature/RH sensor (HX94A, Omega Engineering, Stamford, Conn.) and barometric pressure transducer (PX2760, Omega Engineering, Stamford, Conn.). Air density was calculated using equation 4 and then used to correct the sensor air velocity readings to actual conditions according to equation 5.

$$V_{act} = V_{cal} \left( \frac{P_{cal}}{P_{a}} \right)$$

where $V_{act}$ = air velocity at actual air density (m s$^{-1}$), $V_{cal}$ = air velocity at calibration air density (m s$^{-1}$), and
The duration of the tests varied by seed-cotton feed rate as lint fiber tended to accumulate on the velocity sensors. The tests with no seed cotton flowing were conducted for 60 s while the tests at 22.7 and 45.4 kg min⁻¹ lasted approximately 10 s.

The air velocity measurements at each location were normalized to the maximum velocity (eq. 6). This procedure was used to account for apparent differences in the air flow patterns between seed cotton feed rates due to the uncertainty associated with measuring and controlling the system air flow rate.

\[
V_{n,i} = \left( \frac{V_i}{V_{\text{max}}} \right) \times 100 \tag{6}
\]

where

\[V_{n,i}\] = normalized velocity of position i represented as a percentage of the maximum velocity (%);

\[V_i\] = air velocity measurement of sensor position i (m s⁻¹); and

\[V_{\text{max}}\] = maximum air velocity measurement of the nine sensor positions in the exit duct (m s⁻¹).

The normalized velocity data were analyzed in SPSS using the multivariate analysis of variance (MANOVA) procedure in the General Linear Model algorithm to test for overall differences in the air velocity patterns between seed cotton feed rates. The test statistic used to evaluate the significance of the MANOVA test was Wilks' \( \lambda \) (Johnson and Wichern, 2002). ANOVA and Tukey's HSD post-hoc test were used to test for differences in normalized velocities between sensor locations within the three seed cotton feed rates.

**Concentration Profile Testing**

Concentration profile testing in the exit duct was conducted using a five point sampling grid, four sampling locations surrounding the center sampling location (fig. 9), to determine the relationship between the isokinetic emission concentration measured at the center of the exit duct relative to the duct average concentration. The results would then be used to correct center point concentration measurements to duct average concentrations for calculating emission rates and subsequent emission factors.

A dust feeding system operated by a linear drive system powered by a 0.187-kW (1/4-hp) DC motor with an 80:1 speed reducing gear drive was used to feed corn starch into the air stream at 12 g min⁻¹. Corn starch was used as the test dust due to its consistent lognormal PSD and availability. The particulate-laden sampled air was pulled through the sampling nozzle and a 47-mm diameter filter (2-μm pore size, Zefluor Membrane Filters, Pall Corp., East Hills, N.Y.). The filters were pre- and post-weighed using a high precision analytical balance (AG245, Mettler-Toledo, Greifensee Switzerland) as described by Wanjura et al. (2005b). The

\[
Q = 3.478 \times K \times D_0^2 \times \frac{\Delta P}{\rho_a} \tag{7}
\]

where

\[Q\] = air flow rate through the orifice meter (m³ s⁻¹),

\[K\] = orifice specific flow coefficient (range 0.7-0.85, dimensionless),

\[D_0\] = orifice diameter (m),

\[\Delta P\] = pressure drop across the orifice (mm H₂O), and

\[\rho_a\] = air density (kg m⁻³).

The velocity of the air passing each nozzle was measured using an air velocity probe (641RM-12, Dwyer Instruments, Inc., Michigan City, Ind.). Isokinetic sampling conditions were maintained by regulating the sampler nozzle flow rate to match the air velocity passing each nozzle with the manually operated ball valve. Few slight adjustments to the ball valves for each sampler were needed during the tests as the velocity of the air entering the sampling nozzles closely matched the air velocity passing the nozzles. The sampler nozzle velocities and velocity of air passing each nozzle were recorded along with air temperature, relative humidity, and barometric pressure readings on a 1-Hz frequency for post-test analysis to determine how precisely isokinetic conditions were maintained. EPA Method 5 criteria state that the ratio of the air velocity entering the nozzle to the air velocity passing the nozzle (isokinetic ratio) should be within 0.9 to 1.1 (CFR, 1999).

The particulate-laden sampled air was pulled through the sampling nozzle and a 47-mm diameter filter (2-μm pore size, Zefluor Membrane Filters, Pall Corp., East Hills, N.Y.). The filters were pre- and post-weighed using a high precision analytical balance (AG245, Mettler-Toledo, Greifensee Switzerland) as described by Wanjura et al. (2005b). The
concentration measured at each location was calculated by dividing the net mass of accumulated PM on the filter by the total air volume pulled through the filter during the test. The concentration data was normalized using the maximum concentration measured during each test. The ratio of the duct average concentration to the center point concentration was calculated and used to identify concentration profile patterns. The univariate ANOVA procedure in the General Linear Model algorithm in SPSS was used to analyze the normalized concentration data.

Investigation of the PSD of the sampled PM was carried out to determine if the sampling system had a significant influence on the PSD of the PM between the system inlet and measurement point as well as at different locations across the duct cross section. PSD analyses of the raw corn starch and PM collected on the filters were conducted with a Coulter Counter Multisizer 3 according to the procedure described by Faulkner and Shaw (2006). A particle density of 1.5 g cm⁻³, measured by an AccuPyc 1330 Pycnometer (AccuPyc 1330 Pycnometer, Micromeritics Instrument Corp., Norcross, Ga.), was used to convert the equivalent spherical diameter PSDs from the Coulter to an AED basis.

**Final Isokinetic Sampling System Design**

The isokinetic sampling system was modified from the 2006 design to include an automated control system as well as improved sampling train duct work to minimize dust losses and prevent plugging by locks of seed cotton penetrating the seed cotton separation system. The isokinetic nozzle (diameter = 59.563 mm), mounted inside the exit duct, was designed for a sampling velocity of 732 ± 122 m min⁻¹ (2400 ± 400 ft min⁻¹) based on onboard duct velocity measurements from 2006. The sampling flow rate was based on the design inlet velocity of the barrel cyclone and was specified at 2.124 m³ min⁻¹ (75 ft³ min⁻¹). The airflow through the system was provided by two fans mounted in series (Model HP-33, Clements National Co., Chicago, Ill.) and controlled by an automated ball valve (PBVPV1206, Dwyer Instruments Inc., Michigan City, Ind.). The sample air flow rate was measured by the orifice meter used in the original design while the duct air velocity was measured by a pitot tube (Model 160-8, Dwyer Instruments Inc., Michigan City, Ind.). The pressure drop across the orifice meter and the duct velocity pressure, measured by the pitot tube, were measured by pressure transducers (Series 677, Dwyer Instruments Inc., Michigan City, Ind.). Air temperature and relative humidity as well as barometric pressure were measured inside the exit duct using a T/RH probe (HIX94A, Omega Engineering Inc., Stamford, Conn.) and barometric pressure transmitter (Model 278, Setra Systems Inc., Boxborough, Mass.). The measurement and control system (cFP-AI-110 input module, cFP-AO-200 output module, National Instruments, Austin, Tex.) used with the source sampling system was operated by a laptop computer running LabView 8.0 (LabView v. 8.0, National Instruments, Austin, Tex.). The measurement and control system monitored and recorded the readings from the pressure transducers, T/RH probe, and barometric pressure transmitter and performed the calculations for controlling the airflow rate through the system on a 1-Hz frequency.

**Results and Discussion**

**Seed Cotton Separation System Evaluation**

The seed cotton penetration test results for separator box design 1 with baffles 1, 2, and 3 (table 1) are shown in table 2. No significant interaction was observed between the baffle and seed cotton feed rate factors (P = 0.734). However, there were significant differences among baffle designs (P = 0.016) and nominal seed-cotton feed rates (P < 0.001). Significant differences (α = 0.05) were observed among the baffle designs at the 45.4 and 68.1 kg min⁻¹ feed rates according to Tukey’s HSD test (table 2). The results indicated that the mass of seed cotton penetrating the exit duct increased with the length of the baffle as well as seed cotton feed rate. For separator box design 1, baffle 1 resulted in the lowest mass of seed cotton penetrating the exit duct over all seed cotton feed rates.

Seed cotton penetration test results for separator box design 2 are shown in table 3. In general, the mass of seed cotton penetrating the exit duct was lower for baffles 1, 2, and 3 tested in box design 2 than for baffles 1, 2, and 3 tested in separator box design 1. ANOVA of the seed cotton penetration data for separator box design 2 indicated significant differences among baffle designs (P < 0.001) and among seed cotton feed rates (P = 0.022). Also, the interaction between the baffle design and seed cotton feed rate was significant (P < 0.001). The seed cotton penetration means for the two straight baffles installed at an angle (baffles 5 and 6) were significantly lower than the other baffles tested at 45.4 and 68.1 kg min⁻¹ according to Tukey’s HSD test with

| Table 2. Mass of seed cotton penetrating (g) separator box design 1 with baffles 1, 2, and 3 (see table 1) at three seed cotton feed rates.[a] |
|---|---|---|
| **Nominal Feed Rate (kg min⁻¹)** | 22.7 | 45.4 | 68.1 |
| **Baffle No.** | Mean (g)[b] | St. Dev. (g) | Mean (g) | St. Dev. (g) | Mean (g) | St. Dev. (g) |
| 1 | 115.0[a] | 13.0 | 129.7[a] | 11.7 | 181.3[a] | 13.8 |
| 2 | 129.3[a] | 33.7 | 147.0[a] | 21.7 | 216.5[a,b] | 43.5 |
| 3 | 166.0[a] | 40.9 | 192.0[a,b] | 10.6 | 275.0[b] | 15.6 |

[a] During each test, an 18.2-kg lot of seed cotton was fed through the system and each test was replicated three times.

[b] Means within a column with the same letter are not significantly different according to Tukey’s HSD test (α = 0.05).

| Table 3. Mass of seed cotton penetrating (g) separator box design 2 with baffles 1-7 (see table 1) at three seed cotton feed rates.[a] |
|---|---|---|
| **Seed Cotton Feed Rate (kg min⁻¹)** | 22.7 | 45.4 | 68.1 |
| **Baffle No.** | Mean (g)[b] | St. Dev. (g) | Mean (g) | St. Dev. (g) | Mean (g) | St. Dev. (g) |
| 1 | 47.0[a,b] | 6.1 | 79.3[a] | 3.1 | 91.0[a] | 13.5 |
| 2 | 34.3[a,c] | 4.5 | 78.7[a] | 18.5 | 106.3[a] | 10.8 |
| 3 | 129.3[d] | 3.1 | 200.3[a] | 12.5 | 208.3[c] | 15.8 |
| 4 | 55.0[b] | 10.1 | 80.7[a] | 5.7 | 104.3[a] | 19.1 |
| 5 | 20.7[c] | 5.5 | 24.0[b] | 2.6 | 35.7[b] | 2.3 |
| 6 | 27.3[e] | 4.5 | 41.7[b] | 2.5 | 52.0[b] | 8.7 |
| 7 | 105.0[e] | 4.4 | 119.7[d] | 13.3 | 125.3[e] | 9.9 |

[a] During each test, an 18.2-kg lot of seed cotton was fed through the system and each test was replicated 3 times.

[b] Means within a column with the same letter are not significantly different according to Tukey’s HSD test (α = 0.05).
\( \alpha = 0.05 \) (table 3). Although the means for baffles 5 and 6 are not significantly different at any seed cotton feed rate, baffle 5 tended to produce the lowest mass of seed cotton penetrating the exit duct. Therefore, baffle 5 was selected for use in separator box design 2 onboard the six row harvester.

**Velocity Profile Testing**

MANOVA performed on the normalized velocity data indicated that there was no significant difference in the air velocity patterns among the seed cotton feed rates. The value of Wilks’ \( \lambda \) calculated in SPSS was 0.077 with an F statistic value of 1.625 (\( P = 0.220 \)). The results of the velocity profile tests are shown in table 4 and figure 10.

ANOVA tests on the normalized velocity data indicated significant differences between the sensors for the 0 (\( P < 0.001 \)), 22.7 (\( P < 0.001 \)), and 45.4 kg min\(^{-1} \) feed rates (\( P < 0.001 \)). Tukey’s HSD test indicated that the center point normalized velocity was significantly different than at all other sensor locations for the 0 and 22.7 kg min\(^{-1} \) feed rates (\( \alpha = 0.05 \)). However, the same test indicated that the normalized velocity at sensor locations five (center point) and eight were not significantly different at the 45.4 kg min\(^{-1} \) feed rate. The air velocity profiles consistently indicate that the maximum air velocity in the exit duct is at the center point (probe location 5). In addition, the velocity of the air in the exit duct generally increases from the top to the bottom side.

**Concentration Profile Testing**

The results of the concentration tests performed on the exit duct of the seed cotton separation system are shown in table 5. ANOVA indicated significant differences in mean concentrations among probe locations (\( P = 0.005 \)). The mean center point correction factor, calculated as the ratio of the duct average concentration to the center point concentration, for all five tests was 93%. However, an ANOVA test on the concentration data indicate that there is no significant difference between the duct mean concentration and center point (probe location 3) concentration measurements (\( P = 0.248 \)). Thus, an isokinetic concentration measurement taken at the center point of the exit duct is likely to adequately represent the duct average emission concentration without adjustment using the center point correction factor.

Isokinetic sampling conditions were evaluated for each sampler during each test. However, isokinetic sampling conditions were consistently maintained (0.9 \( \leq \) ratio \( \leq 1.1 \)) for each sampler during each test. However,

### Table 4. Mean normalized air velocity measurements (% of maximum duct velocity) from five replicated tests at three seed cotton feed rates.\(^{[a]}\)

<table>
<thead>
<tr>
<th>Probe No.</th>
<th>0</th>
<th>22.7</th>
<th>45.4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>St. Dev.</td>
<td>Mean</td>
</tr>
<tr>
<td>1</td>
<td>82.6(^a)</td>
<td>1.18</td>
<td>82.6(^a)</td>
</tr>
<tr>
<td>2</td>
<td>90.9(^c)</td>
<td>0.48</td>
<td>90.7(^d)</td>
</tr>
<tr>
<td>3</td>
<td>82.2(^a)</td>
<td>0.27</td>
<td>82.5(^a)</td>
</tr>
<tr>
<td>4</td>
<td>83.2(^a)</td>
<td>0.60</td>
<td>84.1(^b)</td>
</tr>
<tr>
<td>5</td>
<td>100.0(^d)</td>
<td>0.00</td>
<td>100.0(^d)</td>
</tr>
<tr>
<td>6</td>
<td>93.6(^d)</td>
<td>0.84</td>
<td>94.0(^d)</td>
</tr>
<tr>
<td>7</td>
<td>87.4(^b)</td>
<td>0.62</td>
<td>88.5(^c)</td>
</tr>
<tr>
<td>8</td>
<td>98.4(^c)</td>
<td>0.58</td>
<td>98.5(^c)</td>
</tr>
<tr>
<td>9</td>
<td>94.6(^d)</td>
<td>0.56</td>
<td>94.3(^d)</td>
</tr>
</tbody>
</table>

Maximum air velocity (m min\(^{-1} \))

1078.8 4.20 1077.5 4.20 1077.7 9.10

\(^{[a]}\) The probes were located coplanar to one another at nine evenly spaced points across the cross section of the exit duct (see fig. 8).

\(^{[b]}\) Means within a column with the same letter are not significantly different according to Tukey’s HSD test (\( \alpha = 0.05 \)).

### Table 5. Concentration data collected during five tests at five coplanar locations across the cross section of the exit duct of the seed cotton separation system.

<table>
<thead>
<tr>
<th>Probe Location</th>
<th>Concentration Mean (mg m(^{-3} ))(^{[a]})</th>
<th>St. Dev. (mg m(^{-3} ))</th>
<th>Relative Concentration Mean (%) of Max Conc.</th>
<th>St. Dev. (%) of Max Conc.</th>
<th>Center Point Correction Factor Mean (%)</th>
<th>St. Dev. (%)</th>
<th>Duct Mean Concentration Mean (mg m(^{-3} ))</th>
<th>St. Dev. (mg m(^{-3} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>71.0(^{a,b})</td>
<td>5.1</td>
<td>90.5</td>
<td>8.4</td>
<td>93.0</td>
<td>9.97</td>
<td>70.1</td>
<td>3.84</td>
</tr>
<tr>
<td>2</td>
<td>72.3(^{a,b})</td>
<td>7.5</td>
<td>92.1</td>
<td>4.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3(^{[b]})</td>
<td>75.3(^{a,b})</td>
<td>8.7</td>
<td>96.0</td>
<td>8.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>78.5(^{a,b})</td>
<td>10.2</td>
<td>100.0</td>
<td>5.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>58.5(^{a,b})</td>
<td>4.6</td>
<td>74.6</td>
<td>10.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^{[a]}\) Mean concentrations with the same letter are not significantly different according to Tukey’s HSD test (\( \alpha = 0.05 \)).

\(^{[b]}\) Indicates center point probe location.
during the first test, isokinetic sampling conditions were not maintained for probe five for 93 s due to an equipment malfunction. The procedure described by Hinds (1999) was used with equation 8 to estimate the magnitude of concentration measurement errors due to anisokinetic sampling conditions on a time weighted average basis.

\[ F_a C + F_i C_o = C_m \] (8)

where

- \( C \) = probe concentration (\( \mu g \) m\(^{-3} \)),
- \( C_o \) = free stream concentration (\( \mu g \) m\(^{-3} \)),
- \( F_a \) = fraction of sampling time when conditions were anisokinetic,
- \( F_i \) = fraction of sampling time when conditions were isokinetic, and
- \( C_m \) = measured concentration (\( \mu g \) m\(^{-3} \)).

This analysis indicated that the measured concentration was 3% greater than the free stream concentration in the duct at the location of probe 5. Thus, the measurement error resulting from the anisokinetic sampling conditions was considered to be negligible and the measured concentration from probe 5 was used as reported for all analyses.

The AED MMD and GSD of the best fit lognormal distribution for each isokinetic sampling probe location are shown in Table 6 along with the mass weighed average PSD representing the duct average PSD. Also shown in Table 6 are the PSD analysis results of the corn starch fed into the system during each test. The mass weighted average PSD was calculated using the PSDs and net filter masses from the sampling probes at locations 1, 2, 4, and 5 (fig. 9). No significant differences were observed between the MMD or GSD values for any of the sampling locations (MMD \( P = 0.749 \), GSD \( P = 0.054 \)). Further analysis indicated no significant difference between the MMD of the mass weighted average PSD and the center point location PSD (\( P = 0.780 \)). However, a significant difference between the GSD values for the mass weighted average and center point location PSDs was observed (\( P = 0.038 \)). Although there was a significant difference between the mean GSD values for the mass weighted average and center point location PSDs of 0.06, no appreciable difference between the duct mean and center point PSDs was observed (fig. 11). The overlapping of the three PSDs shown in figure 11 was typical of all the tests. The mean AED MMD and GSD of the PSD for the corn starch used in the tests were 18.4 \( \mu m \) and 1.36, respectively. No significant difference was observed between the mean MMD values for the inlet corn starch, center point sampling location, and mass weighted average PSDs (\( P = 0.109 \)). However, significant differences in the GSD values from these PSDs were observed (\( P = 0.008 \)). Further analysis using Tukey’s HSD test indicated that the GSD values for the inlet corn starch and the mass weighted average PSDs were significantly different while the center point GSD was not significantly different from either.

**CONCLUSION**

Extensive testing and evaluation of a system designed to measure emission concentrations onboard a six-row cotton picker were conducted. Evaluation tests showed that the

<table>
<thead>
<tr>
<th>Probe Location</th>
<th>MMD (( \mu m ))</th>
<th>GSD</th>
<th>MMD (( \mu m ))</th>
<th>GSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet corn starch</td>
<td>18.4</td>
<td>0.4</td>
<td>1.36</td>
<td>0.03</td>
</tr>
<tr>
<td>1</td>
<td>18.0</td>
<td>1.6</td>
<td>1.48</td>
<td>0.07</td>
</tr>
<tr>
<td>2</td>
<td>17.1</td>
<td>1.2</td>
<td>1.41</td>
<td>0.05</td>
</tr>
<tr>
<td>3[a]</td>
<td>17.4</td>
<td>1.1</td>
<td>1.39</td>
<td>0.05</td>
</tr>
<tr>
<td>4</td>
<td>17.7</td>
<td>0.7</td>
<td>1.42</td>
<td>0.06</td>
</tr>
<tr>
<td>5</td>
<td>17.3</td>
<td>1.0</td>
<td>1.47</td>
<td>0.05</td>
</tr>
<tr>
<td>Mass WA PSD[b]</td>
<td>17.6</td>
<td>0.5</td>
<td>1.45</td>
<td>0.02</td>
</tr>
</tbody>
</table>

[a] Indicates center point sampling location.
[b] The mass weighted average (WA) PSD characteristics were calculated from the net filter mass and PSD of probe locations 1, 2, 4, and 5.

![Figure 11. Center point, mass weighted average, and input corn starch PSDs measured during test 4.](image-url)
optimum configuration of the baffle-type seed cotton separation system incorporated separator box geometry with a straight back wall to minimize the accumulation and subsequent re-entrainment of seed cotton. Minimum seed cotton penetrated the exit duct with a 47-cm (18.5-in.) long straight baffle installed at a 52° angle with the top of the separator box [separator box 2 and baffle 5 (table 3)]. The optimum configuration exhibited an eight-fold improvement in the mass of seed cotton removed from the air stream compared to the initial separation system design. Test results for both separator box designs indicate that the mass of seed cotton penetrating the system increased with seed cotton feed rate and baffle length.

The air velocity profile in the exit duct of the seed cotton separation system was not significantly different between replicated tests conducted with seed cotton feed rates of 0, 22.7, and 45.4 kg min⁻¹. Further, the maximum air velocity was consistently measured at the center point of the duct.

Concentration profile tests conducted in the exit duct of the optimum separator box/baffle configuration indicated that an emission concentration measurement taken at the center point of the duct adequately represented the duct average emission concentration. Additionally, results of PSD analyses on PM collected at the center of the exit duct adequately represent the mean PSD of the PM emitted from the duct.

These findings indicate that it is possible to quantify PM emissions from a cotton harvester on a source basis using the system design documented in this work. The methodology developed in this work can be extended to other agricultural machinery to quantify emission factors using source measurement. Emission factors developed through source measurement techniques do not contain the error and uncertainty of emission factors developed through traditional indirect methods which use downwind sampling and dispersion modeling. Accurate emission factors help regulators and agricultural producers focus their emission reduction efforts on the operations or processes that produce the highest level of emissions.

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