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ENGINEERING AND GINNING

Overflow System Particulate Emission Factors for Cotton Gins: Particle Size Distribution Characteristics

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ABSTRACT

This report is part of a project to characterize cotton gin emissions from the standpoint of total particulate stack sampling and particle size analyses. In 2006 and again in 2013, the United States (U.S.) Environmental Protection Agency (EPA) published a more stringent National Ambient Air Quality Standard for particulate matter with nominal diameter less than or equal to 2.5 µm ($PM_{2.5}$). This created an urgent need to collect additional cotton gin emissions data to address current regulatory issues, because EPA AP-42 cotton gin $PM_{2.5}$ emission factors were limited. In addition, current EPA AP-42 emission factor quality ratings for cotton gin PM_{10} (particulate matter with nominal diameter less than or equal to 10 µm) data are questionable, being extremely low. The objective of this study was to characterize particulate emissions for overflow systems from cotton gins across the cotton belt based on particle size distribution analysis of total particulate samples from EPA-approved stack sampling methods. Average measured $PM_{2.5}$, PM_6, and PM_{10} emission factors based on the mass and particle size analyses of EPA Method 17 total particulate filter and wash samples from three gins (9 total test runs) were 0.00048 kg/227-kg bale (0.0011 lb/500-lb bale), 0.0049 kg/bale (0.011 lb/bale), and 0.0089 kg/bale (0.020 lb/bale), respectively. The overflow system particle size distributions were characterized by an average mass median diameter of 18.7 µm (aerodynamic equivalent diameter). Based on system average emission factors, the ratio of $PM_{2.5}$ to total particulate was 1.67%, PM_6 to total particulate was 17.0%, and PM_{10} to total particulate was 31.0%.

In 2006 and again in 2013, the United States (U.S.) Environmental Protection Agency (EPA) published a more stringent standard for particulate matter (PM) with a particle diameter less than or equal to a nominal 2.5-µm ($PM_{2.5}$) aerodynamic equivalent diameter (AED) (CFR, 2013). The cotton industry's primary concern with this standard was the limited cotton gin $PM_{2.5}$ emissions data published in the literature and in EPA's AP-42, Compilation of Air Pollutant Emission Factors (EPA, 1996b). AP-42 was first circulated in 1972 and the last complete document revision was in 1995. Since 1995, only updates and supplements have been added. AP-42 contains air pollutant emission factors for more than 200 industrial sources of air pollution along with information on the processes conducted at these sources.

An emission factor is a relationship between a process and the amount of air pollution emitted by that process into the atmosphere (EPA, 1996b). Emission factors are usually defined as the weight of pollutant emitted per unit weight, volume, distance, or duration of the activity producing the pollutant (e.g., kilograms of particulate emitted per cotton bale ginned). These relationships have been established from source test data, modeling, material balance studies, and engineering estimates and are usually averages of all data that have been gathered for a particular process (EPA, 1996a).

EPA's AP-42 was developed to include emission factors for all criteria pollutants and additional pollutants beyond the scope of the National Ambient Air Quality Standards (NAAQS), including total PM, PM_{10} (PM with a particle diameter less than or equal to a nominal 10-µm AED), and $PM_{2.5}$. Current AP-42 cotton gin emission factors are located in section 9.7 (EPA, 1996b). Further, Appendix B.1 of AP-42 contains particle size distribution (PSD)

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data and emission factors based on these PSDs (EPA, 1996c). The only $PM_{2.5}$ emission factors in the current AP-42 were listed in Appendix B.1 and were based on PSDs. The 1996 AP-42 version only contained cotton ginning PSD data for the battery condenser and combined lint cleaning systems. The information for the battery condenser system equipped with cyclones was based on two tests and the PSD data was determined using a UW Mark 3 Impactor. The information for the combined lint cleaning system equipped with cyclones was based on four tests. The total particulate concentration data was determined using EPA Method 5 and the PSD data was determined by using a Coulter Counter to process the Method 5 samples (Hughs et al., 1982). Hughs et al. (1982) did not specifically state whether the PSD results were based on both the Method 5 wash and filter samples, wash only, or filter only. Table 1 provides examples of the types of data that were provided in EPA's AP-42 Appendix B.1.

Emission factors from EPA AP-42 developed prior to 2013 were assigned ratings to assess the quality of the data being referenced. The ratings ranged from A (excellent) to E (poor). The PSD data quality rating in the 1996 AP-42 for both the battery condenser and combined lint cleaning systems was E (EPA, 1996c).

Cotton ginners' associations across the U.S. cotton belt, including the National, Texas, Southern, Southeastern, and California associations, agreed that there was an urgent need to collect additional PSD data on PM being emitted from cotton ginning system exhausts. Working with cotton ginning associations across the country, state and federal regulatory agencies, Oklahoma State University, and USDA-Agricultural Research Service (ARS) researchers developed a proposal and sampling plan that was initiated in 2008 to address this need. Buser et al. (2012) provided the details of this sampling plan. This article is part of a series that details cotton gin emission factors developed from coupling total particulate stack sampling concentrations and particle size analyses. Each manuscript in the series addresses a specific cotton ginning system. The systems covered in the series include: unloading, 1st stage seed-cotton cleaning, 2nd stage seed-cotton cleaning, 3rd stage seed-cotton cleaning, overflow, 1st stage lint cleaning, 2nd stage lint cleaning, combined lint cleaning, cyclone robber, 1st stage mote, 2nd stage mote, combined mote, mote cyclone robber, mote cleaner, mote trash, battery condenser, and master trash. This manuscript reports on the characterization of $PM_{2.5}$ and PM_{10} emissions from overflow systems.

Cotton Ginning. Seed cotton is a perishable commodity that has no real value until the fiber and seed are separated (Wakelyn et al., 2005). Cotton must be processed or ginned at the cotton gin to separate the fiber and seed, producing 227-kg (500-lb) bales of marketable cotton fiber. Cotton ginning is considered an agricultural process and an extension of the harvest by several federal and state agencies (Wakelyn et al., 2005). Although the main function of the cotton gin is to remove the lint fiber from the seed, many other processes occur during ginning, such as cleaning, drying, and packaging the lint. Pneumatic conveying systems are the primary method of material handling in a cotton gin. As material reaches a processing point, the conveying air is separated and emitted outside the gin through a pollution control device. The amount of PM emitted by a system varies with the process and the composition of the material being processed.

Cotton ginning is a seasonal industry with the ginning season lasting from 75 to 120 days, depending on the crop size and condition. Although the general trend for U.S. cotton production has remained constant at about 17 million bales per year during the last 20 years, production from year to year often varies greatly for various reasons, including climate and market pressure. The number of active gins in the U.S. has not remained constant, but has steadily declined from1,018 in 2000 to 682 in 2011 (NASS, 2001, 2012). Consequently, the average cotton gin production capacity across the U.S. cotton belt has increased to an approximate average of 25 bales per hour (Valco et al., 2003, 2006, 2009, 2012).

Table 1. EPA AP-42 Appendix B.1 particle size distribution data for the battery condenser and combined lint cleaning systems equipped with cyclones on the system exhausts (EPA, 1996c).

System	% < 2.5 µm	Emission Factor kg/bale	% < 6.0 µm	Emission Factor kg/bale	% < 10 µm	Emission Factor kg/bale
Lint cleaner	**1**	**Not Reported**	**20**	**Not Reported**	**54**	**Not Reported**
Battery condenser	**8**	**0.007**	**33**	**0.028**	**62**	**0.053**

Typical cotton gin processing systems include: unloading, dryers, seed cotton cleaners, gin stands, overflow, lint cleaners, battery condenser, bale packaging, and trash handling (Fig. 1); however, the number and type of machines and processes can vary. Each of these systems serves a unique function with the ultimate goal of ginning the cotton to produce a marketable product. Raw seed cotton harvested from the field is compacted into large units called "modules" for delivery to the gin. The unloading system removes seed cotton either mechanically or pneumatically from the module feeding system and conveys the seed cotton to the cleaning systems. Seed-cotton cleaning systems assist in drying the seed cotton and removing foreign matter prior to ginning. Ginning systems also remove foreign matter and separate the cotton fiber from seed. Lint cleaning systems further clean the cotton lint after ginning. The battery condenser and packaging systems combine lint from the lint cleaning systems and compress the lint into dense bales for efficient transport. Gin systems produce by-products or trash, such as rocks, soil, sticks, hulls, leaf material, and short or tangled immature fiber (motes), as a result of processing the seed cotton or lint. These streams of by-products must be removed from the machinery and handled by trash collection systems. These trash systems typically further process the by-products (e.g., mote cleaners) and/or consolidate the trash from the gin systems into a hopper or pile for subsequent removal.

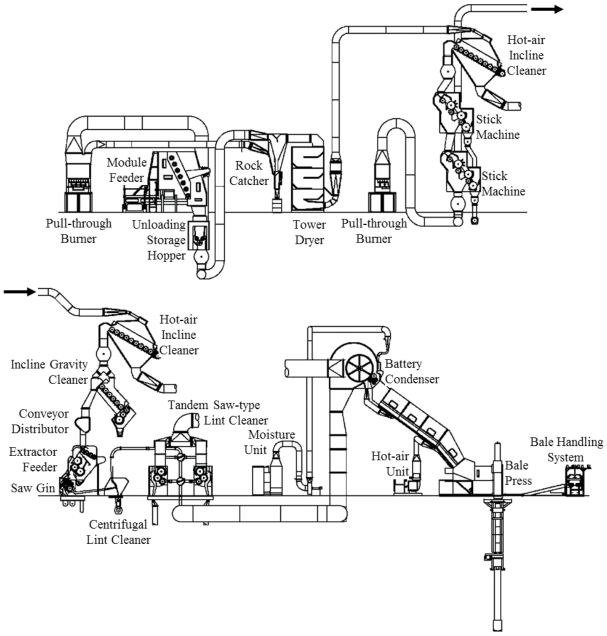

Figure 1. Typical modern cotton gin layout (Courtesy Lummus Corporation, Savannah, GA).

Overflow systems (Fig. 2) follow the seed cotton cleaning systems and are used to help maintain proper flow of seed cotton to the gin stands. Seed cotton drops from the last stage of seed cotton cleaning into the conveyor distributor where it is distributed to the extractor feeders that meter cotton to each gin stand (cotton gins typically split the seed cotton among multiple, parallel gin stands). Excess seed cotton in the conveyor distributor is conveyed to the overflow system storage hopper, recirculated pneumatically, and dropped back into the conveyor distributor via a screened separator as needed. The airstream from the screened separator of the overflow system continues through a centrifugal fan to one or more particulate abatement cyclones. The material handled by the overflow system cyclones typically includes soil, small leaf, and lint fiber (Fig. 3).

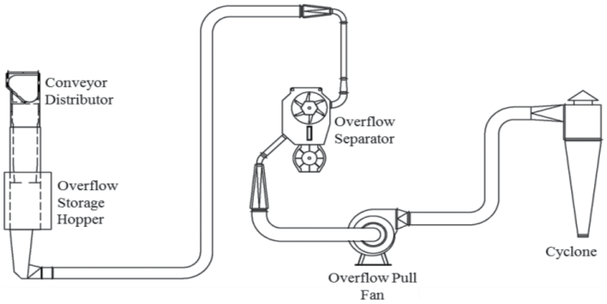

Figure 2. Typical cotton gin overflow system layout (Courtesy Lummus Corporation, Savannah, GA).

Figure 3. Photograph of typical trash captured by the overflow system cyclones.

Cyclones. Cyclones are the most common PM abatement devices used at cotton gins. Standard cyclone designs used at cotton ginning facilities are the 2D2D and 1D3D (Whitelock et al., 2009). The first D in the designation indicates the length of the cyclone barrel relative to the cyclone barrel diameter. The second D indicates the length of the cyclone cone relative to the cyclone barrel diameter. A standard 2D2D cyclone (Fig. 4) has an inlet height of D/2 and width of D/4 and design inlet velocity of 15.2 ± 2 m/s (3000 ± 400 fpm). The standard 1D3D cyclone (Fig. 4) has the same inlet dimensions as either the 2D2D or the original 1D3D inlet with height of D and width D/8. Also, it has a design inlet velocity of 16.3 ± 2 m/s (3200 ± 400 fpm).

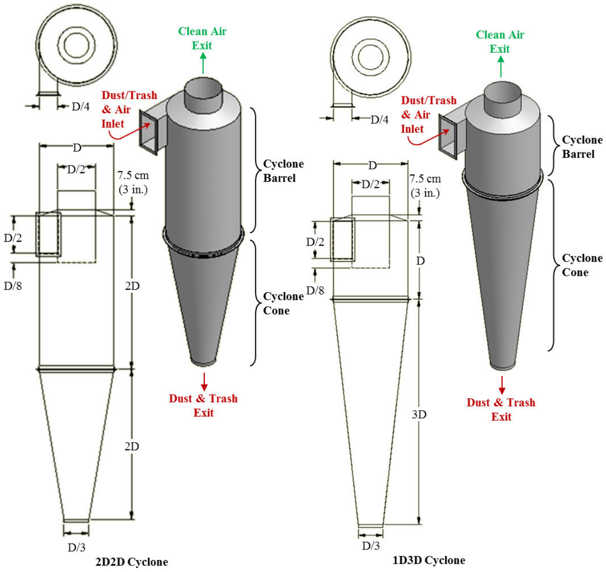

Figure 4. 2D2D and 1D3D cyclone schematics.

Cotton Gin Emission Factors. EPA emission factors for cotton gins are published in EPA's Compilation of Air Pollution Emission Factors, AP-42 (EPA, 1996b). The AP-42 average total particulate emission factor for the overflow fan was 0.033 kg (0.071 lb) per 217-kg (480-lb) equivalent bale with a range of 0.0050 to 0.059 kg (0.011-0.13 lb) per bale (EPA, 1996a, 1996b). This average and range were based on four tests conducted in one geographical location. The EPA emission factor quality rating was D, which is the second lowest possible rating (EPA, 1996a). The AP-42 average PM_{10} emission factor for the overflow fan was 0.012 kg (0.026 lb) per 217-kg (480-lb) equivalent bale with a range of 0.0020 to 0.017 kg (0.0045-0.038 lb) per bale (EPA, 1996a, b). This average and range were also based on four tests conducted in one geographical location, and the EPA emission factor quality rating was D. Currently there are no $PM_{2.5}$ emission factor data listed in the EPA AP-42 for cotton gin overflow systems.

Buser et al. (2012) discussed the plan of a large-scale project focused on developing cotton gin PM emission factors. Part of this project was focused on developing PM emission factors based on EPA-approved methodologies. Three studies focused on overflow systems evolved out of the Buser et al. (2012) project plan. Boykin et al. (2015) reported on one study that used EPA Method 17 (EPA, 1978) to measure total particulate emission factors for the overflow systems. The system average total particulate emission factor was 0.029 kg (0.063 lb) per 227-kg (500-lb) equivalent bale with a range of 0.0068 to 0.053 kg (0.015-0.116 lb) per bale. Boykin et al. (2014) reported on a second study that used EPA Method 201A (CFR, 2010) with only the PM_{10} sizing cyclone to measure overflow system PM_{10} and total particulate emission factors. The system average PM_{10} and total particulate emission factors were 0.013 kg/227-kg bale (0.029 lb/500-lb bale) and 0.033 kg/bale (0.072 lb/bale), respectively. In the third study, reported by Boykin et al. (2013), EPA Method 201A with both the PM_{10} and $PM_{2.5}$ sizing cyclones was used to measure $PM_{2.5}$, PM_{10}, and total particulate emission factors. The average measured $PM_{2.5}$ emission factor was 0.0040 kg/227-kg bale (0.0088 lb/500-lb bale). The PM_{10} and total particulate average emission factors were 0.018 kg/bale (0.040 lb/bale) and 0.041 kg/bale (0.090 lb/bale), respectively.

Particle size distribution analyses have been utilized in conjunction with total particulate sampling methods to calculate PM emissions concentration and factors for agricultural operations for more than 40 years (Wesley et al., 1972). Some examples include: cattle feedlot operations (Sweeten et al., 1998), poultry production facilities (Lacey et al., 2003), nut harvesting operations (Faulkner et al., 2009), grain handling (Boac et al., 2009), swine finishing (Barber et al., 1991), and cotton ginning (Hughs and Wakelyn, 1997). Buser and Whitelock (2007) reported cotton ginning emission concentrations based on EPA-approved $PM_{2.5}$, PM_{10}, and total particulate stack sampling methods and PSD analyses of the total particulate samples coupled with the total particulate concentrations to calculate $PM_{2.5}$ and PM_{10} concentrations. The mass median diameter (MMD) of the PM in the samples ranged from 6 to 8 µm. The study results indicated that the PSD and EPA sampler-based PM_{10} concentrations were in good agreement, whereas the $PM_{2.5}$ EPA sampler concentrations ranged from 5.8 to 13.3 times the PSD-based concentrations.

The primary objective of this study was to develop PSD characteristics for the PM emitted from cotton gin overflow systems. The secondary objective was to develop $PM_{2.5}$ and PM_{10} emission factors for cotton gin overflow systems equipped with cyclones on the system exhausts based on particle size distribution analysis of total particulate samples from EPA-approved stack sampling methods.

METHODS

Seven cotton gins were sampled across the cotton belt for the overall cotton gin sampling project described by Buser et al. (2012). Key factors for selecting specific cotton gins included: 1) facility location (geographically diverse), 2) production capacity (industry representative), 3) processing systems (typical for industry) and 4) particulate abatement technologies (properly designed and maintained 1D3D cyclones). Three of the seven sampled gins had overflow systems where the exhaust airstreams were not combined with other major systems. Another sampled gin had an overflow system where the exhaust was combined with a trash handling system prior to the cyclone. The overflow systems sampled were typical for the industry. The overflow systems at gins A and E were similar. Excess seed cotton in the conveyor distributor dropped into the overflow system hopper where it was picked up and pneumatically conveyed to the overflow system screened separator. The seed cotton was separated from the conveying airstream by the separator and dropped back into the conveyor distributor. The conveying air from the overflow system separator then passed through a fan and exhausted through cyclones. Gin C utilized two, separate and parallel, overflow systems with separate fans and emissions control cyclones. It is not unusual at gins for exhaust airstreams from different systems to be combined before the fan and cyclone(s). The gin C overflow systems exhaust airstreams were combined with a relatively minor system (extractor feeder dust) before the fan. The overflow system at gin D was similar to the systems at gins A and E, except material from a significant trash system (mote trash) was combined with the exhaust airstream of the system. Since the mote trash system combined with the gin D overflow system could significantly impact the overflow system emissions, the data for the gin D system will not be included in the system averages but was included in the data tables for comparison. Boykin et al. (2015) provided system flow diagrams for the overflow systems that were tested.

All overflow systems sampled utilized 1D3D cyclones to control emissions (Fig. 4), but there were some cyclone design variations among the gins. Gins C and D split the system exhaust flow between two cyclones in a dual configuration (side by side as opposed to one behind another). The system airstream for gins A and E was exhausted through a single cyclone. Inlets on all the overflow cyclones were inverted 1D3D type, except gin D that had 2D2D inlets. Expansion chambers were present on overflow cyclones at gins A and D, and gins C and E had standard cones. All of the cyclone variations outlined above, if properly designed and maintained, are recommended for controlling cotton gin emissions (Whitelock et al., 2009). Boykin et al. (2015) provided additional details of the cyclone variations for the systems tested.

Method 17 Stack Sampling. The samples utilized for the PSD analyses and gravimetric sample data used in developing the PSD characteristics and PSD-based emission factors were obtained from EPA Method 17 stack testing (CFR, 1978) that was conducted at the four gins with overflow systems as part of the overall cotton gin sampling project described by Buser et al. (2012). The Method 17 sampling methods and the procedures for retrieving the filter and conducting acetone wash of the sampler nozzle are described in the EPA Method 17 documentation (CFR, 1978). Further details of the project specific sampling methods, procedures, and results of the EPA Method 17 stack testing were reported by Boykin et al. (2015).

Laboratory Analysis. All laboratory analyses were conducted at the USDA-ARS Air Quality Lab (AQL) in Lubbock, TX. All filters were conditioned in an environmental chamber (21 ± 2°C [70 ± 3.6°F]; 35 ± 5% RH) for 48 h prior to gravimetric analyses. Filters were weighed in the environmental chamber on a Mettler MX-5 microbalance (Mettler-Toledo Inc., Columbus, OH; 1 µg readability and 0.9 µg repeatability) after being passed through an anti-static device. The MX-5 microbalance was leveled on a marble table and housed inside an acrylic box to minimize the effects of air currents and vibrations. To reduce recording errors, weights were digitally transferred from the microbalance directly to a spreadsheet. Technicians wore latex gloves and a particulate respirator mask to avoid contaminating the filter or sample. AQL procedures required that each sample be weighed three times. If the standard deviation of the weights for a given sample exceeded 10 µg, the sample was reweighed. Gravimetric procedures for the acetone wash tubs were the same as those used for filters.

In addition to gravimetric analyses, each sample was visually inspected for unusual characteristics, such as cotton lint content or extraneous material. Digital pictures were taken of all filters and washes for documentation purposes. After the laboratory analyses were completed all stack sampling, cotton gin production, and laboratory data were merged.

Particle Size Analysis. A Beckman Coulter LS230 laser diffraction system (Beckman Coulter Inc., Miami, FL) with software version 3.29 was used to perform the particle size analyses on the filter and wash samples. The instrument sizes particles with diameters ranging from 0.4 to 2000 µm. For this project, the LS230 fluid module was used with a 5% lithium chloride/methanol suspension fluid mixture. Approximately 10-L batches of the suspension fluid were prepared and stored in a self-contained, recirculating, filtration system equipped with 0.2 µm filters to keep the fluid well mixed and free of larger particles. Prior to each test run a background particle check was performed on the fluid to help minimize particulate contamination from non-sample sources. The process of analyzing the samples included the following steps:

1. pour approximately 40 mL of clean suspension fluid into a clean 100-mL beaker;
2. transfer a particulate sample to the 100-mL beaker with clean suspension fluid,
    a. for 47-mm filter media, remove the filter from the Petri dish with tweezers and place the filter in the 100-mL beaker with the suspension fluid,
    b. for the wash samples contained in a sample tub, use a small amount of the suspension fluid and a sterile foam swab to transfer the sample from the tub to the 100-mL beaker;
3. place the 100-mL beaker in an ultrasonic bath for 5 min to disperse the PM sample in the fluid;
4. using a sterile pipette, gradually introduce the PM and suspension fluid mixture into clean suspension fluid that is being monitored by the LS230 until an obscuration level of 10% is reached;
5. activate the LS230 system to measure the diffraction patterns and calculate the PSD;
6. repeat step five a total of three times and average the results; and
7. drain and flush/clean the LS230 system.

Optical models for calculating laser diffraction-based PSDs require input of a refractive index for the suspension fluid and real and imaginary refractive indices for the sample. A refractive index of 1.326 for methanol was used for the suspension fluid (Beckman Coulter, 2011). Hughs et al. (1997) showed that particulate from cyclone exhausts was about 34% ash or fine soil particulate with the balance made up of water and organic material (e.g., cellulose, lignin, protein). Real and imaginary refractive index values for common soil constituents – quartz, clay minerals, silica, and feldspars – are 1.56 and 0.01, respectively (Buurman et al., 2001). These indices were used in the optical model used in calculating the PSD for the cyclone particulate samples. Wang-Li et al. (2013) and Buser (2004) provided additional details on the PSD methodology.

The LS230 PSD results are in the form of particle volume versus equivalent spherical diameter. The PSD results were converted to particle volume versus AED using the following equation:

$$d_a = d_p \left(\frac{\rho_p}{\kappa \rho_w} \right)^{1/2}$$

where ρ_w is the density of water with a value of 1 g/cm^3, ρ_p is the particle density, and κ is the dynamic shape factor. The dynamic shape factor was determined to be 1.4 based on Hinds (1982) factors for quartz and sand dust. The particle density, assumed to be constant for the Method 17 filter and wash samples evaluated in this study, was determined in an earlier study to be 2.65 g/cm^3 (M. Buser, unpublished data, 2013). This earlier study used a helium displacement AccuPyc 1330 Pyconometer (Micromeritics, Norcross, GA) to determine the particle density of cotton gin waste that passed through a No. 200 sieve (particles that pass through a 74-µm sieve opening). The study was based on three random samples collected at 43 different cotton gins.

Results obtained from each average adjusted PSD included: MMD, mass fraction of PM with diameter less than or equal to 10 µm (PM$_{10}$), mass fraction of PM with diameter less than or equal to 6 µm (PM$_6$), and mass fraction of PM with diameter less than or equal to 2.5 µm (PM$_{2.5}$). This information was coupled with the corresponding Method 17 sample mass to calculate the PM$_{10}$, PM$_6$, and PM$_{2.5}$ emission factors using the following equation:

$$EF_i = EF_{tot} \left(\left(\frac{M_F}{M_F + M_W} \right) w_{F_i} + \left(\frac{M_W}{M_F + M_W} \right) w_{W_i} \right)$$

where EF_i = emission factor for particle in the size range i;
EF_{tot} = total particulate emission factor obtained from total particulate tests (Boykin et al., 2015);
M_F = total mass of particulate on filter;
M_W = total mass of particulate in nozzle wash;
w_{Fi} = mass fraction of particles on the filter in the size range i; and
w_{Wi} = mass fraction of particles in the nozzle wash in the size range i.

The overflow systems sampled were typical for the industry, except for the gin D system. The data from gin D was not included in the system average data because the overflow and mote system exhausts were combined, so the data was included for comparison purposes only. The system average ginning rate was 28.5 bales/h and the test average ginning rate at each gin ranged from 23.6 to 35.3 bales/h (based on 227-kg [500-lb] equivalent bales). The capacity of gins sampled was representative of the industry average, approximately 25 bales/h. The 1D3D cyclones were all operated with inlet velocities within design criteria, 16.3 ± 2 m/s (3200 ± 400 fpm). There are criteria specified in EPA Method 17 for test runs to be valid for total particulate measurements (CFR, 1978). Isokinetic sampling must fall within EPA-defined range of 100 ± 10%. All tests met the isokinetic criteria. The stack gas temperatures ranged from 18 to 37°C (64-99°F) and moisture content ranged from 0.8 to 2.1%. The individual systems and cyclone design variations are discussed by Boykin et al. (2015).

RESULTS

The PSD characteristics and mass of the PM captured on the filters are shown in Table 2. The mass of the PM captured on the filter accounted for 30 to 82% of the total PM (filter and wash) collected from the individual test runs. The system average MMD for particulate on the filters was 15.8 μm AED. Test averages ranged from 10.0 to 33.9 μm AED. The test and system averages are based on averaging PSDs and not averaging individual test results. The mass fraction of $PM_{2.5}$, PM_6, and PM_{10} ranged from 1.32 to 2.38%, 9.2 to 28.0%, and 16.4 to 50.1%, respectively. Filter PM PSDs for the four gins and the system average are shown in Fig. 5. Test averages for the gin D (combined overflow and mote trash systems) filter PSD data were consistent with the system average data which was based on gin A, C, and E data. In general, the PSD characteristics for the PM captured on the filters for gins C, D, and E were consistent. The PSD for gin A was shifted to the right and had a larger MMD than the other three gins as shown in Table 2.

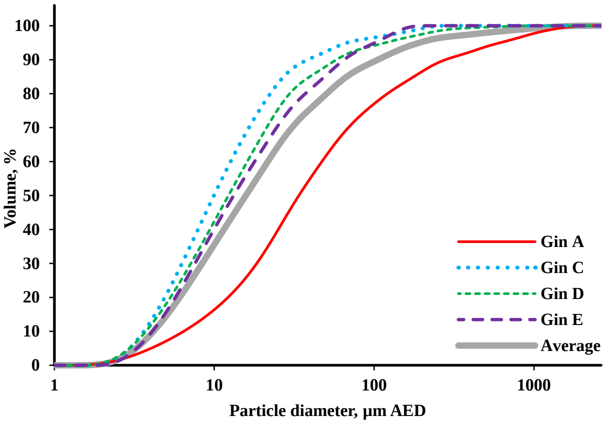

Figure 5. Gin average cumulative particle size distributions for the PM captured on a EPA-Method 17 filter from the overflow systems.

The PSD characteristics and mass of the PM captured in the washes are shown in Table 3. The mass of the PM captured in the sampler nozzle and retrieved in the wash accounted for 18 to 70% of the total PM (filter and wash) collected from the individual test runs. The system average MMD was 23.4 μm AED. Test average MMDs ranged from 17.1 to 45.1 μm AED. The mass fraction of $PM_{2.5}$, PM_6, and PM_{10} ranged from 1.16 to 1.92%, 6.6 to 17.2%, and 11.6 to 31.5%, respectively. PSDs for the PM captured in the nozzle for the four gins and the system average are shown in Fig. 6. The gin D (combined overflow and mote trash systems) wash PSD data were within the range of PSD data for gins A, C, and E data. The PSD for gin A was shifted to the right and had a larger MMD than the other three gins as shown in Table 3.

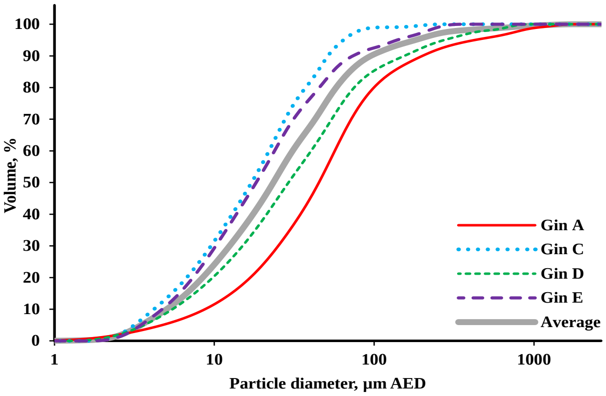

Figure 6. Gin average cumulative particle size distributions for the PM captured in the EPA-Method 17 sampler nozzle wash from the overflow systems.

Table 2. EPA Method 17 filter particle size distribution data for the overflow system.

Gin	Test Run	Mass Median Diameter µm AED	$PM_{2.5}$ %	PM_6 %	PM_{10} %	Sample Total mg
A	1	40.6	1.28	7.6	13.7	145.45
	2	29.0	1.82	11.1	19.5	216.98
	3	33.8	1.50	8.8	15.9	55.24
Test Average (n = 3)[y]		33.9	1.53	9.2	16.4	
C	1	10.6	2.33	26.5	47.7	5.95
	2	9.7	2.57	29.3	51.4	7.79
	3	9.7	2.23	28.2	51.3	2.58
Test Average (n = 3)[y]		10.0	2.38	28.0	50.1	
D	1	12.2	2.45	23.6	42.3	31.30
	2	12.0	2.77	24.9	43.4	36.10
	3	12.7	2.60	23.3	41.3	39.54
Test Average (n = 3)[zy]		12.3	2.61	23.9	42.3	
E	1	13.3	1.27	21.4	39.9	9.05
	2	13.1	1.41	22.1	40.5	7.91
	3	13.3	1.27	21.4	39.9	9.28
Test Average (n = 3)[y]		13.2	1.32	21.6	40.1	
System Average (n = 3)[y]		15.8	1.74	19.6	35.5	

[z] Omitted from the system average because the overflow exhaust airstream was combined with the mote trash system exhaust

[y] Based on averaged particle size distributions

Table 3. EPA Method 17 nozzle wash particle size distribution data for the overflow system.

Gin	Test Run	Mass Median Diameter µm AED	$PM_{2.5}$ %	PM_6 %	PM_{10} %	Sample Total mg
A	1	40.3	1.90	6.4	11.5	33.48
	2	42.0	2.21	7.8	13.5	47.51
	3	55.0	1.63	5.6	9.7	27.21
Test Average (n = 3)[y]		45.1	1.92	6.6	11.6	
C	1	13.8	1.84	20.1	36.9	3.04
	2	18.0	2.00	16.6	30.2	4.20
	3	21.0	1.72	15.0	27.3	5.91
Test Average (n = 3)[y]		17.1	1.85	17.2	31.5	
D	1	37.9	1.76	9.7	17.1	10.17
	2	22.4	1.85	13.6	25.1	6.38
	3	30.4	2.11	10.7	19.1	10.55
Test Average (n = 3)[zy]		29.1	1.91	11.3	20.4	
E	1	16.6	1.45	16.4	31.9	3.71
	2	15.9	0.98	16.1	32.5	3.90
	3	23.4	1.06	12.0	23.5	3.84
Test Average (n = 3)[y]		18.3	1.16	14.9	29.3	
System Average (n = 3)[y]		23.4	1.64	12.9	24.1	

[z] Omitted from the system average because the overflow exhaust airstream was combined with the mote trash system exhaust

[y] Based on averaged particle size distributions

The combined PSD characteristics for the PM captured on the filter and PM captured in the wash are shown in Table 4. The overflow system average combined filter and wash PSD MMD was 18.7 µm AED (12.8 to 37.0 µm test average range). Less than 0.02% of the particles had a diameter of 1 µm or smaller. The combined filter and wash PM$_{2.5}$, PM$_{6}$, and PM$_{10}$ mass fractions ranged from 1.27 to 2.14%, 8.5 to 22.7%, and 15.2 to 40.9%, respectively. Combined PM PSDs for the four gins and the system average are shown in Fig. 7. In general, the PSD characteristics for the combined filter and nozzle wash PM for gins C, D, and E were consistent even though the overflow system exhaust for gin D was combined with a mote trash system exhaust. The combined filter and wash PSD for gin A followed the same trends that were observed in the separate filter and wash PSD data. The PSD for gin A was shifted to the right and had a larger MMD than the other three gins. These combined PSDs were more consistent with the filter PSDs than the wash PSDs. This was expected because the majority of the PM mass was captured on the filter as compared to the nozzle wash.

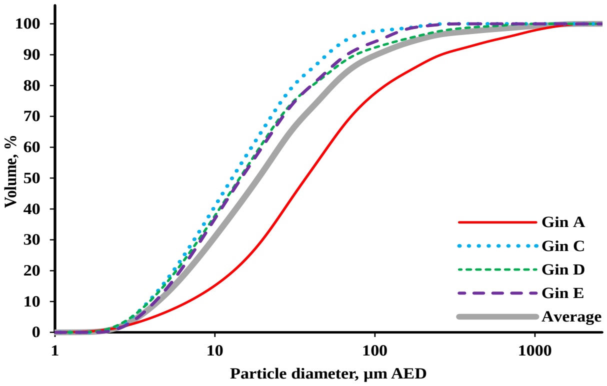

Figure 7. Gin average cumulative particle size distributions for the EPA-Method 17 combined filter and wash samples from the overflow systems.

Table 4. EPA Method 17 combined filter and wash particle size distribution data for the overflow system.

Gin	Test Run	Mass Median Diameter µm AED	PM$_{2.5}$ %	PM$_{6}$ %	PM$_{10}$ %
A	1	40.5	1.39	7.4	13.3
	2	30.9	1.89	10.5	18.4
	3	40.8	1.55	7.7	13.9
Test Average (n = 3)^{y}		37.0	1.61	8.5	15.2
C	1	11.6	2.16	24.3	44.1
	2	11.8	2.37	24.9	43.9
	3	16.0	1.87	19.1	34.6
Test Average (n = 3)^{y}		12.8	2.14	22.7	40.9
D	1	15.1	2.28	20.1	36.1
	2	13.0	2.63	23.2	40.6
	3	14.9	2.50	20.6	36.6
Test Average (n = 3)^{zy}		14.3	2.47	21.3	37.8
E	1	14.2	1.32	19.9	37.6
	2	14.0	1.27	20.2	37.8
	3	15.7	1.21	18.6	35.1
Test Average (n = 3)^{y}		14.6	1.27	19.6	36.8
System Average (n = 3)^{y}		18.7	1.67	17.0	31.0

[z] Omitted from the system average because overflow exhaust airstream was combined with the mote trash system exhaust

[y] Based on averaged particle size distributions

The PSD-based emission factors for the overflow systems are shown in Table 5. The system average $PM_{2.5}$ emission factor was 0.00048 kg/227-kg bale (0.0011 lb/500-lb bale). $PM_{2.5}$ emission factors ranged from 0.000079 to 0.0015 kg (0.00017-0.0032 lb) per bale. The overflow system average PM_6 emission factor was 0.0049 kg/bale (0.011 lb/bale). The PM_6 emission factors ranged from 0.0012 to 0.081 kg/bale (0.0027-0.018 lb/bale). The overflow system average PM_{10} emission factor was 0.0089 kg/bale (0.020 lb/bale) and ranged from 0.0023 to 0.014 kg (0.0050-0.032 lb) per bale. The ratios of $PM_{2.5}$ to total particulate, PM_6 to total particulate, and PM_{10} to total particulate, based on the system averages, were 1.67, 17.0, and 31.0%, respectively.

The PSD-based overflow system $PM_{2.5}$ emission factor was approximately 12% of the $PM_{2.5}$ emission factor reported by Boykin et al. (2013) and measured using EPA Method 201A, 0.0040 kg (0.0088 lb) per 227-kg (500-lb) bale. The PSD-based overflow system PM_{10} emission factor was 75% of the EPA AP-42 published value for the overflow fan, 0.012 kg (0.026 lb) per bale (EPA, 1996a). Also, the PSD-based system PM_{10} emission factor was 67% of the Method 201A (PM_{10} sizing cyclone only) PM_{10} emission factor reported by Boykin et al. (2014), 0.013 kg (0.029 lb) per bale. The PSD-based PM_{10} emission factor was 49% of the Method 201A (PM_{10} and $PM_{2.5}$ sizing cyclones) PM_{10} emission factor reported by Boykin et al. (2013), 0.018 kg (0.040 lb) per bale. The differences among the methods could be attributed to several sources. First, due to constraints in the EPA methods, the three studies utilizing Method 17 for total particulate sampling and PSD analyses, Method 201A for PM_{10} sampling, and Method 201A for $PM_{2.5}$ and PM_{10} sampling could not be conducted simultaneously. Combined with the fact that emissions from cotton ginning can vary with the condition of incoming cotton, PM concentrations measured among the three studies may have varied. Second, for reasons described by Buser (2007a, b, c) and documented by Buser and Whitelock (2007), some larger particles could penetrate the Method 201A sampler PM_{10} or $PM_{2.5}$ sizing cyclones and collect on the filter. Finally, cotton fibers have a cross-sectional diameter much larger than 10 µm and are difficult to scrub out of air streams. These fibers could cycle in the sizing cyclones and pass through to deposit on the filters. This behavior was observed during some of the Method 201A testing where cotton fibers were found in Method 201A sampler washes and on filters (Fig. 8). Currently there are no EPA-approved guidelines to adjust Method 201A PM_{10} or $PM_{2.5}$ concentration measurements to account for these fibers.

Table 5. EPA Method 17 total particulate and particle size distribution-based $PM_{2.5}$, PM_6, and PM_{10} emission factor data for the overflow system.

Gin	Test Run	Total[x]		$PM_{2.5}$[w]		PM_6[w]		PM_{10}[w]	
		kg/bale[z]	lb/bale[z]	kg/bale[z]	lb/bale[z]	kg/bale[z]	lb/bale[z]	kg/bale[z]	lb/bale[z]
A	1	0.057	0.125	0.00079	0.0017	0.0042	0.0093	0.0076	0.017
	2	0.078	0.171	0.0015	0.0032	0.0081	0.018	0.014	0.032
	3	0.023	0.051	0.00036	0.00079	0.0018	0.0039	0.0032	0.0071
C	1	0.025	0.056	0.00055	0.0012	0.0062	0.014	0.011	0.025
	2	0.032	0.069	0.00075	0.0016	0.0078	0.017	0.014	0.031
	3	0.023	0.050	0.00043	0.00094	0.0044	0.010	0.0079	0.017
D	1[y]	0.033	0.074	0.00076	0.0017	0.0067	0.015	0.012	0.027
	2[y]	0.029	0.064	0.00076	0.0017	0.0067	0.015	0.012	0.026
	3[y]	0.034	0.074	0.00084	0.0019	0.0070	0.015	0.012	0.027
E	1	0.0070	0.015	0.000093	0.00021	0.0014	0.0031	0.0026	0.0058
	2	0.0070	0.015	0.000089	0.00020	0.0014	0.0031	0.0026	0.0058
	3	0.0065	0.014	0.000079	0.00017	0.0012	0.0027	0.0023	0.0050
System Average		0.029	0.063	0.00048	0.0011	0.0049	0.011	0.0089	0.020

[z] 227-kg (500-lb) equivalent bales

[y] Omitted from the system average because overflow exhaust airstream was combined with the mote trash system exhaust

[x] Taken from Boykin et al. (2015)

[w] Factors are the product of the corresponding PM percentage from Table 4 and the total particulate emission factor

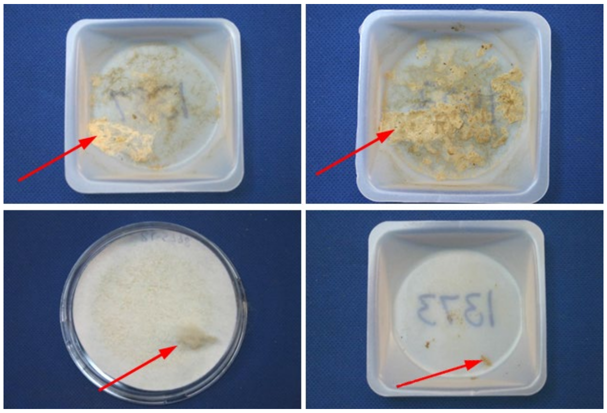

Figure 8. Example EPA Method 201A filter and sampler head acetone washes with lint (indicated by arrows) in the washes and on the filter. Clockwise from top left: > 10 µm wash, 10 to 2.5 µm wash, ≤ 2.5 µm wash, and filter.

SUMMARY

Cotton gins across the U.S. cotton belt were sampled using EPA-approved methods to fill the data gap that exists for $PM_{2.5}$ cotton gin emissions data and to collect additional data to improve the EPA AP-42 total and PM_{10} emission factor quality ratings for cotton gins. Samples were further analyzed to characterize the PSD of the particulate measured. Four selected cotton gins had overflow systems that used pneumatic conveyance. One of the measured systems was combined with a mote trash system and the data from this system was not included in the overall system average even though the data collected from this system was consistent with the system average. All tested systems were similar in design and typical of the ginning industry and were equipped with 1D3D cyclones for emissions control. In terms of capacity, the gins were typical of the industry, averaging 28.5 bales/h during testing. The average PSD-based overflow system $PM_{2.5}$, PM_6, and PM_{10} emission factors from the three gins tested (nine total test runs) were 0.00048 kg/227-kg bale (0.0011 lb/500-lb bale), 0.0049 kg/bale (0.011 lb/bale), and 0.0089 kg/bale (0.020 lb/bale), respectively. The PSDs were characterized by an average MMD of 18.7 µm AED. Based on system average emission factors, the ratio of $PM_{2.5}$ to total particulate was 1.67%, PM_6 to total particulate was 17.0%, and PM_{10} to total particulate was 31.0%. PSD-based system average $PM_{2.5}$ and PM_{10} emission factors were 12% and 67% of those measured for the overall cotton gin sampling project utilizing EPA-approved methods. The PSD-based PM_{10} emission factor was 75% of that currently published in EPA AP-42 for the overflow fan.

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DISCLAIMER

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