Performance Characteristics of Cyclones in Cotton–Gin Dust Removal

by
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Abstract

The results of performance testing of four different cyclone designs are included in this paper. The 1D3D, 2D2D, 1D2D and Barrel cyclone designs are typically used to abate particulate matter (PM) emitted by cotton gins. The PM used for testing included three types of cotton gin trash (with and without lint fiber) and fly ash. The performance tests were conducted at different total trash inlet loading rates and at different fine dust inlet loading rates based on the fine dust fractions associated with each trash. The results were used to define the performance characteristics of different cyclone designs. With these characteristics, cotton ginners can utilize different cyclone designs for different processing streams to minimize PM concentrations emitted.

Introduction

The cotton ginning process separates lint fiber from cottonseed while removing the trash from seed cotton and lint fiber. The materials in this system are pneumatically conveyed with numerous processing streams and exhaust points. In the United States, cotton gins are considered a stationary emission source and regulated under the nuisance standard. They are required to have air pollution abatement equipment to comply with State Air Pollution Regulatory Agency's (SAPRA's) rules and regulations.

Cyclones have been used as the primary air pollution control equipment in the cotton ginning industry for many years. The most commonly used cyclone designs are the 2D2D cyclone (Shepherd and Lapple, 1939) and 1D3D cyclone (Parnell and Davis, 1979). The D's in the 2D2D designation refer to the barrel diameter of the cyclone. The numbers preceding the D's relate to the length of the barrel and cone sections respectively. A 2D2D cyclone has barrel and cone lengths of two times the barrel diameter, whereas the 1D3D cyclone has a barrel length equal to the barrel diameter and a cone length of three times the barrel diameter. Two new cyclone designs have been recently developed for the cotton ginning industry. They are the 1D2D low-pressure cyclone (Kaspar and Parnell, 1993 and Simpson, 1996) and the Barrel cyclone (Tullis et al, 1997). The 1D2D cyclone was developed to replace the relatively inefficient covered condenser drums. It is more

Wang, L., C.B. Parnell, Jr., and B.W. Shaw. "Performance Characteristics of Cyclones in Cotton-Gin Dust Removal." Agricultural Engineering International: the CIGR Journal of Scientific Research and Development. Manuscript BC 02 001. Vol IV. August, 2002.

efficient than the covered condenser drums and has a relatively low pressure drop. The goal of this cyclone design was to provide an economical alternative control device for axial-flow fan exhausts (Simpson, 1996).

According to previous research conducted at Texas A&M University (TAMU), the 1D3D and 2D2D are the most efficient collectors for fine dust with 1D3D cyclone more efficient than the 2D2D. As a consequence, a number of states have classified the 1D3D as Best Available Control Technology (BACT) and in many cases require that all emitting points of a gin utilize the 1D3D for the abatement system.

One of the problems with the regulation of PM from cotton gins is the perception by SAPRA engineers that if a cyclone is "the most efficient", it will be the best cyclone for all emitting points. In reality, a cyclone's performance characteristics are highly dependent upon the characteristics of the PM in the inlet air stream. Mihalski et al (1993) and Hughs et al (1996) reported "cycling lint" near the trash exit for the 1D3D and 2D2D cyclone designs when the PM in the inlet air stream contained lint fiber. Mihalski reported a significant increase in the exit PM concentration for these high efficiency cyclone designs and attributed this to small balls of lint fiber "cycling" near the trash exit causing the fine PM that would normally be collected to be diverted to the clean air exit stream. The development of the new 1D2D and barrel cyclone designs addressed this problem. Tulles et al (1997) and Flannigan et al (1997) reported significantly lower PM concentrations emitted by the barrel and 1D2D cyclone designs when the inlet air stream contained cotton gin trash/fine dust and the gin trash contained a relative high fraction of lint fiber (high lint gin trash/fine dust). These results suggest that if a SAPRA were to require that the 1D3D cyclone design be used on all emitting points of a cotton gin under the assumption that this design will result in the least PM emitted by the gin, they would be incorrect! A simpler, low-pressure drop cyclone design (1D2D or barrel) would result in a lower emission rate of PM for all exhausts containing a significant fraction of lint fiber.

Flannigan et al (1997) defined a standard gin consisting of ten process streams similar to EPA AP-42 (1987). These are as follows:

(1) Unloading Separator
(2) 1st Push-Pull
(3) 2nd Push-Pull
(4) Trash
(5) Distributor Separator
(6) Overflow Separator
(7) 1st Stage Lint Cleaner
(8) 2nd Stage Lint Cleaner
(9) Battery Condenser
(10) Mote

The volume rate of flow (Q), trash/PM concentration (C) and the characteristics of the trash/PM entraining in the airflow vary for each process stream. In addition, each process stream will often have multiple emission points. The trash/PM entrained in the air stream of process streams 1,2,3,5 and 6 consists of fine PM (soil and small organic particles) with relatively low fractions of lint fiber. These process streams contain very little large trash. Process stream #4 will contain the largest concentration of large trash. The trash/PM entrained in process streams 7, 8, 9, and 10 will contain fine PM and a relatively high fraction of lint fiber with a relatively small fraction of large trash.

The hypothesis of this research was that different cyclone designs should be used for different process streams in a cotton ginning system to minimize the total PM emissions. In other words, a different cyclone design should be used for the low lint trash/PM process (LLT/PM) streams (1, 2, 3, 5, and 6) than are used for the high lint trash/PM (HLT/PM) process streams (7, 8, 9, and 10) to minimize the PM emission concentrations.

Objective

The overall goal of this research was to characterize the different cyclone designs for varying inlet concentrations of HLT/PM, LLT/PM, and fine PM (fly ash). Cotton gin trash was obtained from the United States Department of Agriculture (USDA) Cotton Ginning Research Laboratories located in the Messilla Park, New Mexico and Lubbock, Texas. The stripper gin trash from Lubbock, Texas contained burs and sticks and was processed through a hammer mill to reduce the trash particle sizes to facilitate testing. Two trash types were obtained from the Messilla Park, New Mexico laboratory. These were collected from two different process streams. One was characterized as fine trash and the other coarse gin trash. The four cyclone designs were tested with different inlet concentrations of the three types of gin trash. Measurements were made of the fine dust (<100 μm) fraction of each gin trash prior to testing. The testing protocol for one test sequence was to maintain the fine dust concentrations between trash types. A second protocol was to maintain the total trash concentrations constant between trash types. The objectives of this research effort were:

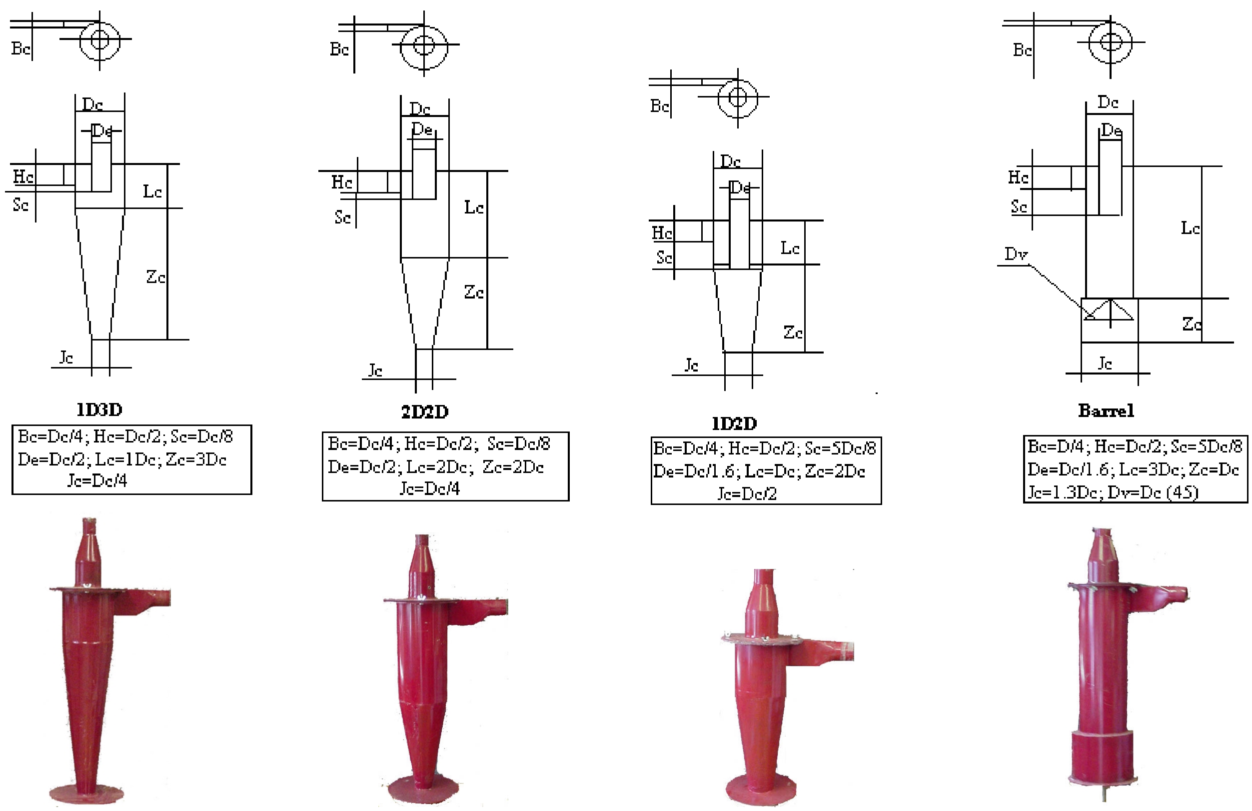
1. Determine which cyclone design is the best suited for LLT/PM, HLT/PM, PM (fly ash) and for fine or large trash without lint fiber.
2. Quantify the effect of the cycling lint on emission concentrations from 1D3D and 2D2D cyclone designs.

Testing Procedures

Cyclones

The testing focused on 1D2D, 2D2D, 1D3D and Barrel cyclone designs. The cyclones tested were as follows:

1D2D --- 15.24 cm (6inch) diameter (metal)
2D2D --- 15.24 cm (6inch) diameter (metal)
1D3D --- 15.24 cm (6inch) diameter (metal) (with 2D2D inlet)
Barrel --- 12.70 cm (5inch) diameter (metal)
Barrel --- 12.70 cm (5inch) diameter (plastic)
Barrel --- 15.24 cm (6inch) diameter (metal)



1D3D 2D2D 1D2D Barrel

Figure 1. Configuration of the cyclone designs

Test Materials
There are ten processing streams for a cotton ginning system. The trash/PM characteristics entering the cyclone for the different process streams are very different. The trash can include varying quantities of large gin trash (burs and sticks), fine gin trash (leaf and bract), lint fiber, and soil particles. The fine gin trash and soil were combined into one category that is referred to as fine PM. It was hypothesized that the fraction of fine PM and fraction of lint fiber in each test material would significantly impact the

resulting emission concentration. The following is a rough classification of the different trash/PM characteristics entering the cyclone:

1. Fine dust - soil and fine (<100 µm) trash particles. Fly ash was used to test the performance of the different cyclones for fine dust only. The fly ash will typically have a lower mass median diameter PM than the soil and fine dust fraction of gin trash. Hence, the emission concentrations will likely be higher than that associated with gin trash fine dust. Typically, process streams 1, 2, 3, 5, and 6 could have trash/PM characteristics entering the cyclone that would predominantly be fine dust.
2. LLT/PM (low lint trash/PM) – This material can vary between process streams by the fraction of fine PM present. If the motes were not added back to the trash going to the burr hopper, process stream 4 would have this trash/PM characteristic. Depending upon the mass of trash present, process streams 1, 2, 3, 5, and 6 could have material entering the cyclone with this description.
3. HLT/PM (high lint trash/PM) – All exhausts associated with lint cleaner and battery condensers, and mote fan systems – process streams 7, 8, 9, and 10.

One goal of this research has been to use "real world" materials of cotton gin trash to evaluate different cyclone designs. The test materials were as follows:

Trash A--- gin trash (hammer milled) from Lubbock, Texas. It is a HLT/PM material.
Trash B --- picker gin trash (coarse) from Mesilla, New Mexico. It is a LLT/PM material.
Trash C --- picker gin trash (fine) from Mesilla, New Mexico. It is a LLT/PM material.
Trash D --- trash A after picking out lint fiber
Trash E --- trash B after picking out lint fiber
Trash F --- trash C after picking out lint fiber

trash A trash B trash C

Figure 2. Gin trash collected by the cyclone

The purpose of generating trash D, E and F was for testing material to determine the cycling lint effect on emission concentrations of different cyclone designs. This was accomplished by comparing the testing results (emission concentrations) between materials A, B, and C with D, E, and F.

An air wash system was constructed to wash the trash in order to determine the fine dust (<100 µm) fractions of each test material. The system consisted of a fine mesh (100µm openings) screen box that was enclosed in a wooden box. A filter was placed on a filter holder between the wooden box and the fan/motor. The trash was sealed in the screen box and the wooden box was closed. The system was started and the fan pulled air through the system while the screen box rotated. Particulate matter less than 100µm was pulled through the fine mesh screen and accumulated on the filter. The screen box was rotated to allow all particles less than 100 µm to be separated out. By weighing the filter before and after air washing, the fine dust (<100µm) contents in the trash were determined by dividing net fine dust weights by sample weights.

A Combustion Engineering TYLER, Inc. Portable sieve shaker model RX-24 was used to obtain lint fiber contents of each gin trash. The fine dust and lint fiber contents for each test material are shown in table 1.

Table 1. Fine dust and lint fiber content in the trash

	A	B	C	D	E	F
Fine dust (%)	11.73	2.83	24.49	13.2	4.67	27.45
Lint fiber (%)	7.72	0.57	1.02	0.86	0	0

A Coulter Counter Multisizer was used to perform particle size distributions (PSD's) on 3 representative samples of the fine dust components of each trash (Figure 3). The PSD's indicated that 20% of fine dust component of trash A was less than 10 µm aerodynamic equivalent diameter (AED). By multiplying this fraction times the fine dust fraction (Table 1) we determined that 2.4% of trash A was less than 10 micrometers AED (PM10). For trash B, 22% of fine dust was less than 10 µm (0.62% PM10); for trash C, 16% of fine dust was less than 10 µm (3.9% PM10).

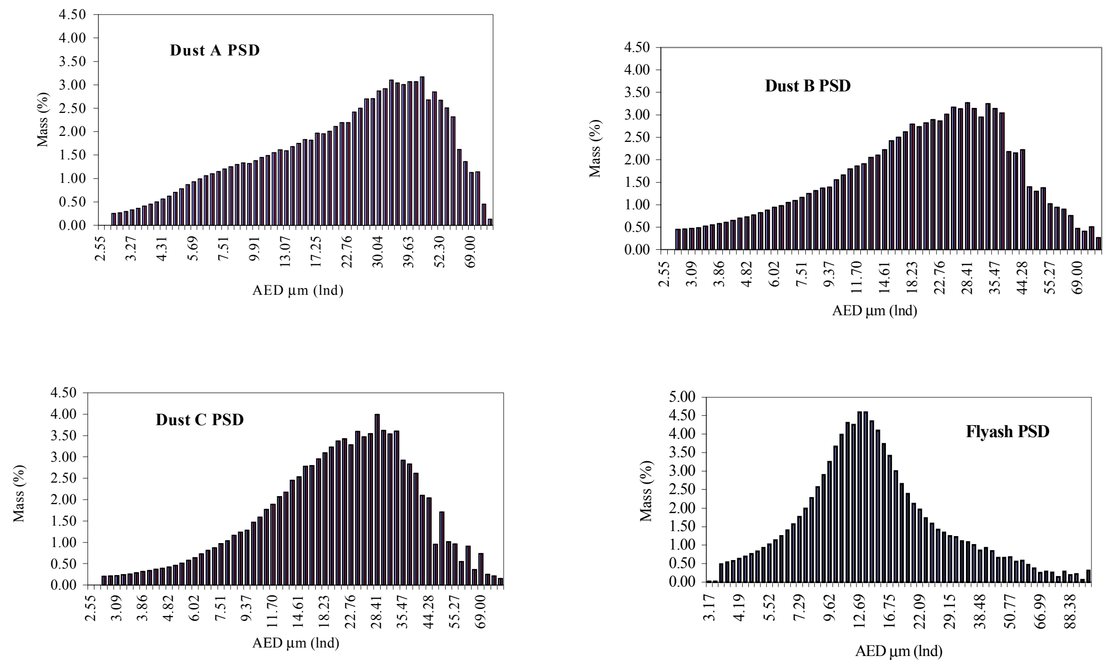


Figure 3. Particle size distributions of fine dust in trash A, B, C and fly ash PSD

Fly ash

Tests were conducted using fly ash to determine cut points of the cyclones and emission concentrations. The fly ash PSD is shown in Figure 3. The fly ash contained 34% PM10.

Testing

Setting the air flow rates of the testing systems:

A testing system (Figure 4) similar to the one developed and constructed by Mihalski (1992) was used. According to the previous research at Texas A & M University, different cyclone designs should be used at the different design velocities. A dramatic increase in exit concentrations has been observed at velocities significantly higher and lower than the design velocities (Parnell, 1996). The airflow rates of the testing systems were determined by using Texas A & M cyclone design (TCD) velocity for each cyclone design. The design velocities and airflow rates are shown in table 2.

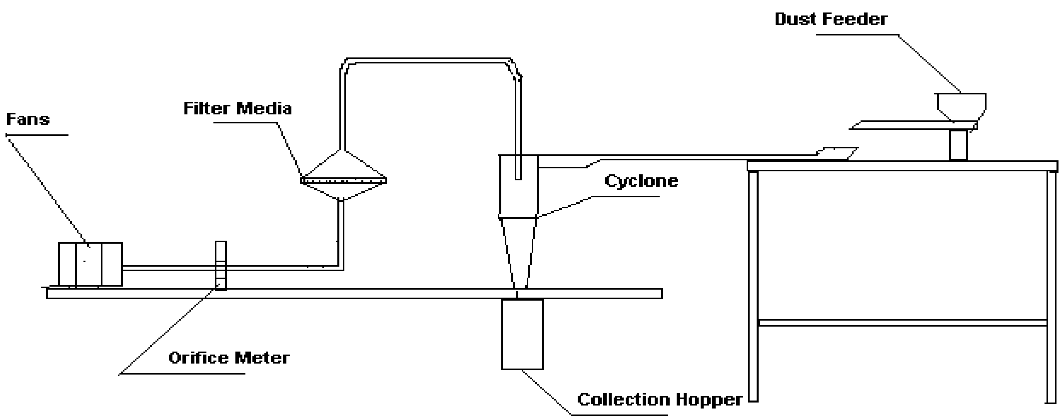


Figure 4. Schematic of the system used for cyclone testing

Table 2. The air-flow rates of the testing system

	Diameter of Cyclone	Design Velocity	Air Flow Rate of System
1D3D	15.24 cm (6 in.)	975 m/min (3200 fpm)	2.832 m^3/min (100 cfm)
2D2D	15.24 cm (6 in.)	914 m/min (3000 fpm)	2.655 m^3/min (93.8 cfm)
1D2D	15.24 cm (6 in.)	732 m/min (2400 fpm)	2.124 m^3/min (75 cfm)
Barrel	12.70 cm (5 in.)	732 m/min (2400 fpm)	1.475 m^3/min (52.1 cfm)
Barrel	15.24 cm (6 in.)	732 m/min (2400 fpm)	2.124 m^3/min (75 cfm)

- fpm: feet per minute,
- cam: cubic feet per minute.

Tests were conducted to evaluate the performance of different cyclone designs with a varying inlet loading rates at design velocities. The cyclone collection hopper and dust filter were placed in their respective positions, and the system components were connected and sealed. The pressure drop across the orifice meter was monitored during testing to ensure that the proper airflow rate was maintained during the test. The filters were conditioned in an environmental chamber for 24 hours and weighed before and after testing to determine total penetrating weights. Additional replications were made with special filters to facilitate determination of PSD's. The feeding rates, emission concentrations and collection efficiencies were determined with the following equations:

$$F = L * Q \quad \text{--}(1)$$

where

F = Feeding rate (g/min),
L = Total inlet loading rate (g/m^3), and
Q = System airflow rate (m^3/min).

$$EC = \frac{W_2 - W_1}{Q * T} * 1000 \quad \text{-----------------------(2)}$$

Where

EC = Emission concentration (mg/m^3),
W_1 = Pre-weight of filter (g),
W_2 = Post-weight of filter (g), and
Q = system air flow rate (m^3/min.)
T = Testing time for each sample (min)

$$EF = \frac{TD - FD}{TD} * 100 \quad \text{-----------------------------(3)}$$

Where,

EF = Cyclone collection efficiency (%),
TD = Total inlet loading (g), and
FD = Total filter loading = W_2-W_1 (g).

Three or more tests were performed for each inlet-loading rate, to obtain an average emission concentration. Testing time was 3 minutes. The system was cleaned between tests.

PSD's were obtained for a minimum of two of the exposed filters. These PSD's were used to determine fractional efficiency curves of each cyclone design, and to determine PM_{10} emission concentration.

The inlet and outlet concentration of a certain size range were calculated using inlet and outlet dust concentrations and the fraction of particulate in that size range. The outlet concentration was divided by the corresponding inlet concentration for each particle size range and subtracted from one; the resulting values were the fractional efficiencies for each particle size range. Equation (4) shows this calculation:

$$\eta_j = (1 - Con._{out\,j} / Con._{in\,j}) \quad \text{----------------------- (4)}$$

Where

η_j = Fraction efficiency of jth particle size range,
$Con._{out\,j}$ = oulet concentration of jth particle size range, and

$Con._{in\,j}$ = inlet concentration of j^{th} particle size range.

The outlet concentrations were multiplied by the cumulative fraction of particulate less than 10 µm in order to obtain an estimate of PM_{10} concentrations.

Setting the inlet loading rates:
Tests were conducted to determine the performance of the cyclones at the same fine dust inlet loading rates (1.5 g/m^3) and at the same total trash inlet loading rates (15 g/m^3).

Protocol 1. The same fine dust inlet loading rates at 1.5 g/m^3
It was hypothesized that the emission concentration for a specific cyclone design would be directly related to the fine dust inlet loading. Since there is a large difference of fine dust contents in the different gin trash used for test materials, the total trash inlet loading rates varied significantly when the goal was to maintain a constant fine dust inlet loading rate. The total inlet loading rates for each trash at the same 1.5 g/m^3 fine dust inlet loading rates were as follows:

Trash A -----12.79 g/m^3
Trash B -----53.00 g/m^3
Trash C ----- 6.13 g/m^3
Trash D ------ 11.36 g/m^3
Trash E ------ 32.12 g/m^3
Trash F ------- 5.46 g/m^3

Figure 5 illustrates this difference.

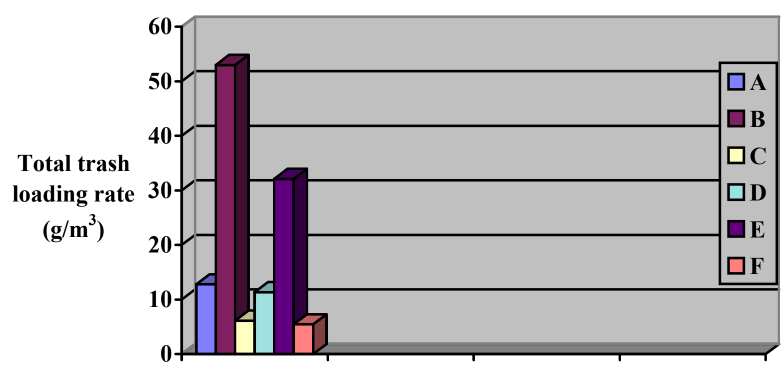


Figure 5. The total trash inlet loading rates (g/m^3) at the same fine dust inlet loading rates

Protocol 2. The same total trash inlet loading rates at 15 g/m^3
For each trash, the fine dust inlet loading rates at the same total inlet loading rates were as follows:

Trash A ------ 1.76 g/m^3
Trash B ------ 0.43 g/m^3
Trash C ------ 3.70 g/m^3
Trash D ------ 1.98 g/m^3
Trash E ------ 0.70 g/m^3
Trash F ------ 4.10 g/m^3

Figure 6 shows the difference of the fine dust inlet loading rates for the trash/PM test materials at a constant (15 g/m^3) total inlet loading rate.

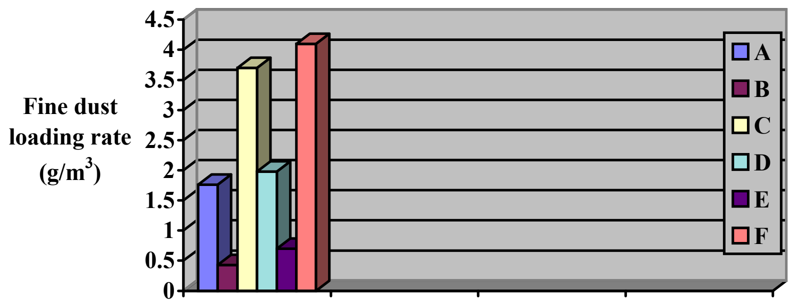


Figure 6. The fine dust inlet loading rates (g/m^3) at the same total trash inlet loading rates

Test Results and Discussion

Average emission concentration

The average emission concentrations are listed in the tables 3 and 4. Standard analysis of variance techniques were used to analyze the data to determine statistically significant differences among the four cyclone designs using the Tukey's Studentized Range (HSD) procedure. The following observations were noted:

Table 3. Average emission concentration (mg/m^3) from cyclones

	1.5 g/m^3 fine dust inlet loading					
	1D3D	2D2D	1D2D	Barrel(5P)	Barrel(5M)	Barrel(6M)
Trash A	27.10^g	29.84^g	17.25^i	6.60^k	34.02^g	24.02^h
Trash B	30.44^g	31.66^g	49.06^e	14.24^j	38.19^f	46.25^e
Trash C	22.65^h	21.78^h	19.15^i	18.76^i	46.36^e	83.93^b
Trash D	7.02^k	6.50^k	17.19^i	7.30^k	13.18^j	11.9^j
Trash E	17.06^i	13.73^i	37.65^f	8.77^k	25.33^h	25.12^h
Trash F	10.03^j	10.63^j	32.10^g	12.81^j	25.85^h	37.16^f
Fly ash	50.00^e	67.39^d	75.00^c	75.86^c	/	165.3^a

- 5P = 12.7 cm (5 inch) plastic cyclone,
- 5M = 12.7 cm (5 inch) metal cyclone,
- 6M = 15.24 cm (6 inch) metal cyclone,
- means with the same letter are not significantly different at 0.05 level.

Table 4. Average emission concentration (mg/m^3) from cyclones

	15 g/m^3 total trash inlet loading				
	1D3D	2D2D	1D2D	Barrel (5P)	Barrel (6M)
Trash A	37.60^e	40.06^e	27.55^g	20.31^h	68.15^c
Trash B	10.12^j	8.01^j	22.82^h	4.71^k	23.53^h
Trash C	90.18^b	88.31^b	57.75^d	56.95^d	/
Trash D	11.14^j	11.40^j	22.62^h	5.53^k	35.93^f
Trash E	11.15^j	9.52^j	17.99^i	4.56^k	16.68^i
Trash F	36.69^f	44.78^e	66.32^c	26.77^g	108.73^a

- 5P = 12.7 cm (5 inch) plastic cyclone,
- 6M = 15.24 cm (6 inch) metal cyclone,
- Means with the same letter are not significantly different at 0.05 level.

1D3D & 2D2D cyclones

Tables 3 and 4 present the emission concentrations for the tests conducted on the 1D3D and 2D2D cyclone designs. The results suggest that with the exception of the tests conducted with fly ash, there was no significant difference between the emission concentrations for the 1D3D and 2D2D for all tests with trash materials A-F. However, the fly ash results indicate that the 1D3D cyclone design is significantly more efficient for fine dust collection – 50 mg/m^3 (1D3D) versus 67.39 mg/m^3 (2D2D). This would suggest that the cut-point of the 1D3D is significantly lower than the 2D2D cyclone design. Another significant observation was the number of times 1D3D and 2D2D cyclone designs "choked" with trash materials A and B (1D3D: 6 times with trash A and 6 times with trash B, 2D2D: 6 times with trash A and 5 times with trash B). The choking of these two high efficiency cyclones for trash A was attributed to the high fraction of lint fiber and the cycling lint problem. Choking with trash B was likely a consequence of the very high trash concentrations of the inlet air stream - 53 g/m^3 of total inlet loading (trash B) versus 12.79 g/m^3 of total inlet loading (trash A). The 53 g/m^3 was needed in order to maintain the fine dust concentration for trash B at 1.5 g/m^3. It was observed that lint fiber and bulky trash clumped together in the cyclone and developed into a ball, which remained near the dust exit which ultimately resulted in a cyclone choke.

The average emission concentration associated with testing 1D3D and 2D2D cyclone designs with trash A, B and C is 2 to 3 times larger than concentrations obtained with trash D, E and F. Since trash materials D, E and F are identical to A, B and C, respectively, with the exception that the lint fiber had been removed, it is apparent that the lint fiber fraction in the trash affected the 1D3D and 2D2D emission concentrations. The most profound effect can be seen by comparing the emission concentrations for trash A and D for the 1D3D or 2D2D cyclone designs. For example the average emission concentration for the 1D3D was 27.10 mg/m^3 (trash A, table 3) versus 7.02 mg/m^3 (trash D, table 3). Trash A had the highest lint fiber fraction.

The difference between 1D3D or 2D2D emission concentrations with trash C and F at 1.5 g/m^3 fine dust inlet loading rates (6 g/m^3 total trash inlet loading rate) is much lower than that at 15 g/m^3 total trash inlet loading rates. The emission concentrations (trash C) for the 6 and 15 g/m^3 total trash inlet loading rates were 22.65 and 90.18 mg/m^3, respectively. Whereas, the emission concentrations (trash F) for the 6 and 15 g/m^3 total trash inlet loading rates were 10.03 and 36.69 mg/m^3, respectively. This suggests that as the total trash feed rate increased (with 1% fiber), the emission concentration of 1D3D or 2D2D increased more rapidly. This was attributed to the cycling lint. Cycling lint greatly affects the emission concentrations and collection efficiencies of 1D3D and 2D2D cyclone designs.

For trash D, E and F (without lint fiber or with much lower lint fiber), 1D3D and 2D2D had higher collection efficiencies and significantly lower emission concentrations both at the same fine dust inlet loading rates (1.5 g/m^3) and at the same total trash inlet loading rates (15 g/m^3). Comparing the 15 g/m^3 emission concentration results for trash D, E, and F, there was no significant difference between the emission concentrations (11.14 and 11.15 mg/m^3) for the 1D3D cyclone with trash D and E tests even though the fine dust fraction was much higher for trash D (13% versus 5%). However, the results from the trash F tests suggest that the fine dust fraction does play a role in the emission concentration. At the same total inlet-loading rate, the emission concentration increased from 11.14 to 36.69 mg/m^3 for a fine dust fraction of 27%.

For fine dust only or LLT/PM, the 1D3D and 2D2D had low emission concentrations and relatively high collection efficiencies.

1D2D cyclone

The test results of 1D2D cyclone design are also included in tables 3 and 4. For trash A (HLT/PM) and trash C (LLT/PM), the 1D2D cyclone design had significantly lower average emission concentrations for both at the same fine dust inlet loading rates (1.5 g/m^3) and the same total trash inlet loading rates (15 g/m^3). There was no cycling lint effect on 1D2D emission concentrations.

For trash B (low lint fiber / bulky trash) and trash E (large trash without lint fiber), the 1D2D cyclone design had significantly higher emission concentrations for both the 1.5 g/m^3 fine dust inlet loading and the 15 g/m^3 total trash inlet loading.

The results of testing the 1D3D cyclone for the HLT/PM (Trash A) compared to LLT/PM (Trash D) were dramatic with emission concentrations decreasing from 27.10 to 7.02 mg/m^3. This reduction in emission concentration was attributed to removing the lint fiber from trash A to form trash D. However, when the 1D2D cyclone was tested with trash D, the average emission concentration was 17.19 mg/m^3 suggesting that the 1D2D cyclone design is not as good as the 1D3D for trash without lint fiber. Again, for very high fine dust loading without lint fiber (trash E @ 27% fine dust) the 1D2D results were not as good as the 1D3D or the 2D2D – 17.06 versus 37.65 mg/m^3.

The 1D2D cyclone design emission concentrations with fly ash were significantly higher than that of 1D3D and 2D2D suggesting that it is not as good a fine dust collector as either the 1D3D or the 2D2D. It is a much better collector for HLT/PM.

Barrel cyclones

Three Barrel cyclones were tested. Again, the test results of the Barrel cyclone design are included in tables 3 and 4.

Three Barrel cyclones used in testing were the same design, but there were some problems with 12.7 cm (5 inch) metal Barrel and 15.24 cm (6 inch) metal Barrel cyclones. The vortex inverter of 12.7 cm (5 inch) Barrel cyclone was fixed. We were not able to adjust the inverter to the desired height and it was not located at the optimum placement. For 15.24 cm (6 inch) metal Barrel cyclone, there was a big deviation of the axis of vortex inverter relative the cyclone's axis. This problem resulted in the big trash remaining in the relatively narrow opening between the inverter and the wall of the cyclone. This problem was not detected until after the tests were conducted and is the probable reason why there were higher emission concentrations for the 15.24 cm (6 inch) Barrel cyclone with trash B, C, and F compared with 12.7 cm (5 inch) metal Barrel cyclones. If the vortex inverter and the cyclone's vertical axis were aligned and the inverter was positioned properly, the 15.24 cm (6 inch) metal Barrel cyclone would have the same performance as 12.7 cm (5 inch) metal Barrel cyclone.

The roughness of the cyclone inside surface greatly affected the cyclone's emission concentrations, especially when the cyclone was tested with HLT/PM. The 12.7 cm (5 inch) plastic Barrel cyclone had the lowest emission concentrations of all cyclones tested for trash A, B, and C. These results were attributed to the smooth inside surface of the plastic Barrel cyclone.

For trash A, B, C, D, E, and F, the Barrel cyclone (5P) had the lowest emission concentrations of all cyclones tested (See table 4.) For fly ash, the 12.7 cm (5 inch) plastic Barrel cyclone had an average emission concentration of 75.86 mg/m^3 compared to 75.00 and 67.39 mg/m^3 for the 1D2D and 2D2D cyclone designs, respectively. This suggests that the cut points of these three cyclones are similar.

PM_{10} emission concentrations & cut-point

Table 5 shows the PM_{10} emission concentrations of the cyclones for each test material and an estimate of the cut-points for each of the cyclones tested. The cut-point of a cyclone is the aerodynamic equivalent diameter (AED) of the particle collected by the cyclone with 50% efficiency. The smaller the cut-point the higher efficiency. In this research, only test data from fly ash were used to develop cyclone fractional efficiency curves and to determine the cyclone cut-point. PM_{10} were calculated by using PM_{10} fraction from dust particle size distribution times dust emission concentration. Only test results at 1.5g/m^3 fine dust inlet loading were used to determine PM_{10} emission concentration.

Table 5. PM_{10} emission concentrations & cut-point

	1D3D		2D2D		1D2D	
	PM_{10}	cut-point	PM_{10}	cut-point	PM_{10}	cut-point
Trash A	14.09		26.86		13.63	
Trash B	25.26		27.86		40.23	
Trash C	18.57		19.38		17.62	
Trash D	5.69		5.20		14.44	
Trash E	14.84		12.22		30.50	
Trash F	8.02		8.61		26.32	
Fly ash	44.00	4.10	57.96	4.20	69.75	4.30
	Barrel(5P)		Barrel(5M)		Barrel(6M)	
	PM_{10}	cut-point	PM_{10}	cut-point	PM_{10}	cut-point
Trash A	5.15		18.03		11.77	
Trash B	11.11		27.88		35.61	
Trash C	16.13		34.77		52.04	
Trash D	6.21		7.91		7.97	
Trash E	7.45		19.25		19.09	
Trash F	10.38		21.20		27.13	
Fly ash	71.00	4.40	/		148.77	5.90

- 5P = 12.7 cm (5 inch) plastic cyclone,
- 5M = 12.7 cm (5 inch) metal cyclone,
- 6M = 15.24 cm (6 inch) metal cyclone,
- cut-point : μm, PM_{10} concentration: mg/m^3.

Comparisons of average emission concentration and PM_{10} concentrations

Tables 3, 4 and 5 allow for comparisons of the emission concentrations of different cyclone designs. The following observations were noted:

1. For trash B, the Barrel cyclone design had lowest emission concentrations and PM_{10} concentrations without the choke problem. The Barrel cyclone is the best suited for bulky gin trash with low lint fiber.
2. For trash A and C, the 1D2D cyclone design had the lowest emission concentrations and PM_{10} Concentrations both at 1.5 g/m^3 fine dust inlet loading rates and at 15 g/m^3 total trash inlet loading rates. There was little effect of cycling lint on emission concentrations for this cyclone design.
3. 1D3D and 2D2D emission concentrations and PM_{10} concentrations significantly decreased from trash A, B and C to trashes D, E and F both at 1.5 g/m^3 fine dust inlet loading rates and at 15 g/m^3 total trash inlet loading rates. These results suggest that

as lint fiber fraction of the trash increases, the emission concentration increases at a rate that is not linear.

4. The difference between 1D3D and 2D2D emission concentration with trash C and trash F at 1.5 g/m^3 fine dust inlet loading is much lower than that at 15 g/m^3 total trash inlet loading rates. As the lint fiber contents in the trash increased, the emission concentrations of 1D3D and 2D2D cyclones increased substantially because of the increase in cycling lint.
5. Cycling lint greatly affected the emission concentrations and PM_{10} concentrations of 1D3D and 2D2D.
6. Cyclone emission concentrations are not only a function of inlet fine dust loading rates, but also are a function of total trash inlet loading rates.
7. 1D3D and 2D2D designs had the lowest emission concentration and PM_{10} concentrations with fine dust trash or large trash without lint fiber.

Conclusions

1. The 1D3D and 2D2D cyclone designs are high efficiency collectors for fine dust and large trash, but lint fiber will greatly affect their performance. The cycling lint problem was observed in the 1D3D and 2D2D with trash A and C. It resulted in a large emission concentration increase. There were choking problems with trash B for the 1D3D and 2D2D cyclone designs, even though the lint fiber content in this trash was much lower.
2. No cycling lint affected the 1D2D performance. The 1D2D cyclone design had significantly lower emission concentrations with trash A (high lint fiber / fine dust) and trash C (low lint fiber / high fine dust) than all other cyclones tested, except for the plastic Barrel cyclone.
3. The Barrel cyclone had low emission concentration with lint fiber /bulky gin trash, but further research needs to be done to find the best location of the vortex inverter and to find a good way to insure that the axis of cyclone and inverter are aligned.

Guidelines for cotton ginners to use different cyclone design:
The concept of using the different cyclone designs for the different processing streams in a cotton ginning system depending upon the trash characteristics in the stream is worthwhile.
(1) the Barrel cyclone is the best design for lint fiber/large trash.
(2) the 1D2D cyclone is the best design for lint fiber/ fine dust gin trash.
(3) the 1D3D and 2D2D are the best designs for fine dust only or large trash with low lint fiber.

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Appendix – List of Acronyms

AED: Aerodynamic equivalent diameter.

BACT: Best available control technology.

EPA: Environmental Protection Agency.

HLT / PM: High lint trash / fine dust.

LLT / PM: Low lint trash / fine dust.

MMD: Mass median diameter.

PM: Particulate matter.

PSD: Particle size distribution.

SAPRA's: State air pollution regulatory agencies.

TAMU: Texas A & M University.

TCD: Texas A & M Cyclone Design.