Study of the Cyclone Fractional Efficiency Curves

by
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Abstract

The prediction of emission concentrations from cyclone collectors is integral to the permitting of agricultural facilities including cotton gins. One method for predicting emission concentrations utilizes fractional efficiency curves. Fractional efficiency curves (FEC's) were developed for 1D2D, 1D3D, and 2D2D cyclone designs. The procedure used to develop these new FEC's incorporated log-normalized distributions and results of particle sizing using the Coulter Counter. Another method that has been used by many air pollution regulators is the Classical Cyclone Design process (CCD). These new FEC's were used to compare performances of three cyclone designs currently being used by cotton gins to abate PM_{10}. The two methods were compared and the use of the FEC method was far superior to the CCD process. The results indicate that properly designed and operated cyclones are high efficiency collectors and can be used as a final abatement device for agricultural processing facilities.

Introduction

Cyclones are the most widely used air pollution abatement equipment in the agricultural processing industry for removal of particulate matter (PM). The most commonly used cyclone designs are the 2D2D (Shepherd and Lapple, 1939) and the 1D3D (Parnell and Davis, 1979). Simpson and Parnell (1996) introduced a new low-pressure cyclone, called the 1D2D, for the cotton ginning industry. Compared to other air pollution abatement systems, cyclones have a relatively low initial cost, maintenance cost and energy consumption. However, there is a question on the effectiveness of cyclones as a final abatement device. The Classical Cyclone Design (CCD) process (Cooper and Alley, 1994), which is referred to as a standard method, greatly underestimates cyclone collection efficiency. As a result, some agricultural facilities have been forced to replace their cyclones with the more expensive bag filter systems because of the perception that cyclones are less efficient than they really are (Parnell, 1996).

A more accurate method of determining cyclone performance is the use of fractional efficiency curves (FEC's), inlet concentrations and particle size distributions (PSD's). It is usually assumed that the fractional efficiency curve of a specific cyclone design is independent of physical characteristics of the particulate matter being captured. Hence,

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once a FEC for a specific cyclone design has been determined, all that would be needed to determine emitting concentration for an application of this cyclone design would be the inlet loading rate and PSD of the PM being captured. Having more accurate FEC's for the 1D3D, 2D2D and 1D2D cyclones would facilitate predicting accurate emission concentrations given inlet loading rates and PSD's of the PM for agricultural operations.

Based upon our previous experience (Wang, 2000), we know that the FEC's for specific cyclone designs will be affected by the inclusion of trash (PM larger than 100 μm) with the fine dust fraction entering the cyclone collector. This is contrary to the assumption made by many engineers that the FEC's are independent of the physical properties of the entering PM. We have attributed the significant increase of concentrations leaving the cyclone collector when collecting trash plus fine PM as being caused by a disruption of the rather uniform strand pattern inside the cyclone by the tumbling trash particles. The PM of primary interest is particulate matter less than 10 micrometers (PM_{10}) aerodynamic equivalent diameter (AED). Our goal in this research was to determine more accurate FEC's for the three cyclone designs for PM_{10}.

Evaluations of cyclone performance have long been studied to better understand and improve cyclone design theory. Lapple (1951) developed the Classical Cyclone Design process (the CCD process) for designing cyclones and predicting their performance (emission concentrations and pressure drop). This model incorporated the number of effective turns, cut-point diameter, and a "generalized" fractional efficiency curve. For many situations, the Lapple model has been considered acceptable. Previous results from research conducted at Texas A&M University (TAMU) (Kaspar, et al. 1993) indicated that the Lapple methodology for predicting number of effective turns and the use of the "generalized" fractional efficiency curve in the CCD process yielded inaccurate results. The CCD process under-estimates cyclone collection efficiencies and over-predicts emission concentrations.

Objective

Evaluation of cyclone performance and operation is essential in the permitting of facilities that use cyclones for air pollution abatement. The objective of this research was to develop more accurate fractional efficiency curves characterizing 1D3D, 2D2D, and 1D2D cyclones. These curves can be conveniently applied by regulatory agencies and industry to assist in cyclone design and accurately predict emission concentrations.

Methodology

Cyclone collection efficiency is one of the main parameters considered when evaluating cyclone performance. There are two ways to calculate the overall collection efficiency of a cyclone. The first way is to determine the total collection efficiency on a basis of total mass collected, as shown in Eq. (1):

$$EF=(W_1-W_2)/W_1 \qquad \text{Eq. (1)}$$

where

EF = overall collection efficiency,
W_1= total inlet loading (g), and
W_2= total emission (g).

The second way to calculate the total collection efficiency is based on the cyclone fractional efficiency. The overall efficiency of the cyclone is a weighted average of the collection efficiencies for the various size ranges:

$$\eta=\Sigma\eta_j*M_j \quad \text{Eq. (2)}$$

where

η = overall collection efficiency,
η_j = efficiency of collection for the j^{th} size range, and
M_j = mass fraction of particles in the j^{th} size range.

Cyclone fractional efficiency curves (FEC's) relate percent efficiency to particle diameter and can be obtained from test data given inlet and outlet concentrations and particle size distributions (PSD's). Kaspar et al (1993) attempted to develop a model that could accurately predict emission concentrations by modifying the CCD "generalized" FEC's without success.

Four parameters were required to develop cyclone fractional efficiency curves. They were (1) inlet concentration, (2) inlet particle size distribution (PSD), (3) emission concentration for each cyclone test, and 4) the PSD of dust emitted. The inlet and outlet concentrations for various size ranges were calculated using inlet and outlet dust concentrations and the fraction of particulate in those size ranges obtained from the Coulter Counter PSD analysis. The outlet concentration was divided by the corresponding inlet concentration for each particle size range and subtracted from one with the resulting values being the fractional efficiency for each particle size range:

$$\eta_j=(1-Conc_{outj}/Conc_{inj}) \quad \text{Eq. (3)}$$

where

η_j = fractional efficiency of j^{th} size range,
$Conc_{outj}$ = outlet concentration of j^{th} size range, and
$Conc_{inj}$ = inlet concentration of j^{th} size range.

If the assumption is made that the FEC can be defined by a lognormal distribution, the cyclone FEC can be characterized by the cut-point (D_{50}) and sharpness-of-cut (the slope of the FEC). The cut-point of a cyclone is the Aerodynamic Equivalent Diameter (AED) of the particle collected with 50% efficiency. As the cut-point diameter increases, the cyclone collection efficiency decreases. The sharpness-of-cut (slope) can be determined by the following equation:

$$Slope=D_{84.1}/D_{50}=D_{50}/D_{15.9} \quad \text{Eq. (4)}$$

where

$D_{84.1}$ = diameter of particle collected with 84.1% efficiency,
D_{50} = diameter of particle collected with 50% efficiency, and

$D_{15.9}$ = diameter of particle collected with 15.9% efficiency (Cooper and Alley, 1994).

Cyclones:

For this research, a large number of tests were performed on the 1D3D, 2D2D and 1D2D cyclones. The configurations of these cyclone designs are shown in the Figure1.

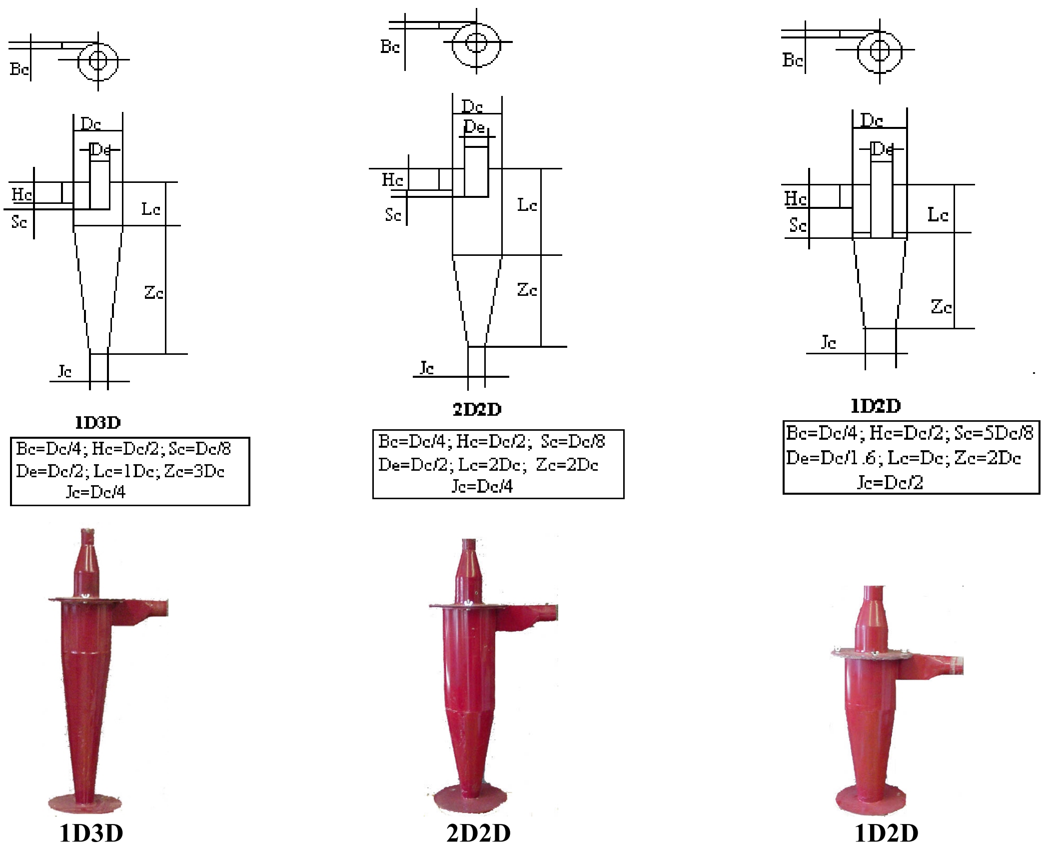

Figure1. Configurations of the cyclone designs

Testing System:

Figure 2 shows the testing system. According to the previous research results at Texas A&M University, different design velocities should be used for different cyclone designs. A dramatic increase in exit concentrations has been observed at velocities significantly higher than the design velocities (Parnell, 1996). The air-flow rates of the testing systems were determined by using the Texas A&M cyclone design (TCD) velocity for each cyclone design. The design velocities and air-flow rates are shown in Table 1.

Table 1. 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)

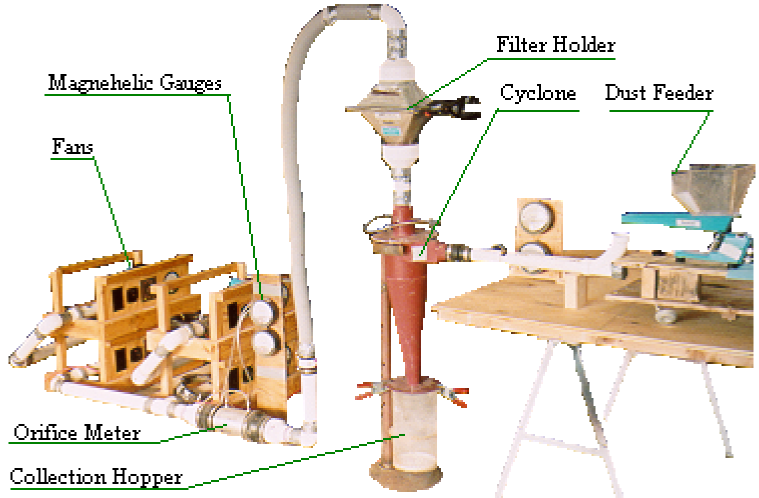

Figure 2. Cyclone testing system

Tests were conducted to evaluate the performance of different cyclone designs with 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 air-flow rate was maintained during the test. The filters were conditioned in an environmental chamber for 24 hours at 25°C and 46% relative humidity as specified by EPA and weighed before and after testing to determine total penetrating weights. The feeding rates and emission concentrations were determined with the following equations:

$$F = L * Q \quad \text{Eq. (5)}$$

where

F = feeding rate (g/min),
L = total inlet loading rate (g/m^3), and
Q = system air- flow rate (m^3/min).

$$EC = \frac{FW_2 - FW_1}{Q * T} * 1000 \quad \text{Eq. (6)}$$

where

EC = emission concentration (mg/m^3),
FW_1 = pre-weight of filter (g),
FW_2 = post-weight of filter (g),
Q = system air flow rate (m^3/min.), and
T = testing time for each sample (min).

Five replications were conducted for each treatment, to obtain an average emission concentration. For each test, testing time was 3 minutes. The system was cleaned between tests.

Test Materials

Fly ash plus three fine dusts (A, B, C) extracted from cotton gin trash were used as test dusts in this research. All test dusts were less than 100 μm. (No PM larger than 100 μm (AED) were included in the test dusts.) The fine dust classified as A, B, and C were extracted from cotton gin trash characterized as "high lint fiber", "bulky trash", and "low lint fiber", respectively using an air washing procedure developed in our lab.

It was hypothesized that the emission concentration for a specific cyclone design would be directly related to the fine dust inlet loading, but the cyclone fractional efficiency curve (cut-point and slope) is independent of the inlet loadings. It was estimated that fine dust concentrations of 1, 2 and 3 g/m^3 would span the range encountered by cyclones installed at cotton gins (Simpson, 1995). Tests were conducted with inlet concentrations of fine dust at 1.5 and 3 g/m^3.

There are several methods to determine PSD's such as gravimetric, mechanical sieving, microscopy light-scattering and resistance (Coulter Principle). The Coulter Counter method is many times faster than the other methods (Parnell, 1979). Moreover, the EPA approved method of determining PSD, the cascade impactor, is not accurate (Bush, 1998). Compared to the Cascade Impactor. The PSD's obtained from a Coulter Counter Multisizer is more accurate (Bush, 1999). In this research, a Coulter Counter Multisizer was used to perform particle size distributions (PSD's) of the fine dusts, as well as the fly ash.

The special software @Risk was used to fit the input and output PSD's. When the Coulter Counter PSD's data were brought into @Risk for fitting, the software fitted distributions to data as Log-normal, Pearson, Pareto, Gamma, Weibull, InvGauss, Normal, Uniform or Triangular distributions. The distributions were ranked on the root-mean square error (RMSE) between set of n curve points (Xi, Yi) and a theoretical distribution function f(x) with one parameter α. The RMSE can be expressed by the following function:

$$RMSErr = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(f(x,\alpha) - Y_i\right)^2} \;\ldots\ldots\ldots\ldots \text{Eq. (7)}$$

The value of α that minimizes RMSE is called the least squares fit. The RMSE value minimizes the "distance" between the theoretical curve and the data. It is called the method of Least Squares. In this research, the fitting results shown that the log-normal distribution ranked first for most PSD's, and sometimes it ranked second when the Pearson or Pareto distributions ranks as the first one. In general, the log-normal distribution is the best-fit distribution for the PSD's.

It is common to characterize PSD's of PM to be a log-normal distribution with a mass median diameter (MMD) and a geometric standard deviation GSD. Figures 3-6 show the log-normalized inlet PSD's and the Coulter Counter analyses PSD's. A MMD is the AED where 50% of the PM mass is larger or smaller than this diameter. The GSD is defined by the following equation:

$GSD = D_{84.1}/D_{50} = D_{50}/D_{15.9}$ ………………Eq. (8)

where

$D_{84.1}$ = diameter such that particles constituting 84.1% of the total mass of particles are smaller than this size,

D_{50} = mass median diameter (50% of the total mass of particles are smaller than this size), and

$D_{15.9}$ = diameter such that particles constituting 15.9% of the total mass of particles are smaller than this size.

(Cooper and Alley, 1994).

A lognormal PSD is similar to a fractional efficiency curve in that it can be defined by two parameters (MMD and GSD) and are calculated in a similar manner but they are independent of each other. The FEC is a description of the cyclone performance and a PSD is a physical description of the PM. The relationship between the MMD and GSD is as follows:

$GSD=D_{84.1}/MMD=MMD/D_{15.9}$…………...Eq. (9)

where

GSD = geometric standard deviation,

MMD= mass median diameter,

$D_{84.1}$ = diameter where particles constituting 84.1% of the total mass of particles are smaller than this size, and

$D_{15.9}$ = diameter where particles constituting 15.9% of the total mass of particles are smaller than this size.

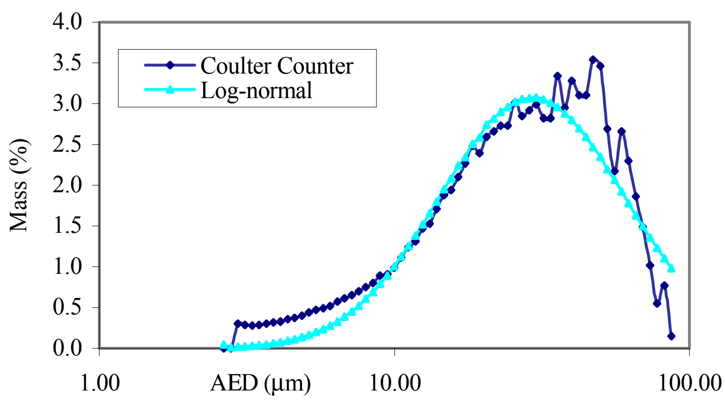

Figure 3. Coulter Counter PSD vs. the log-normalized PSD for dust A

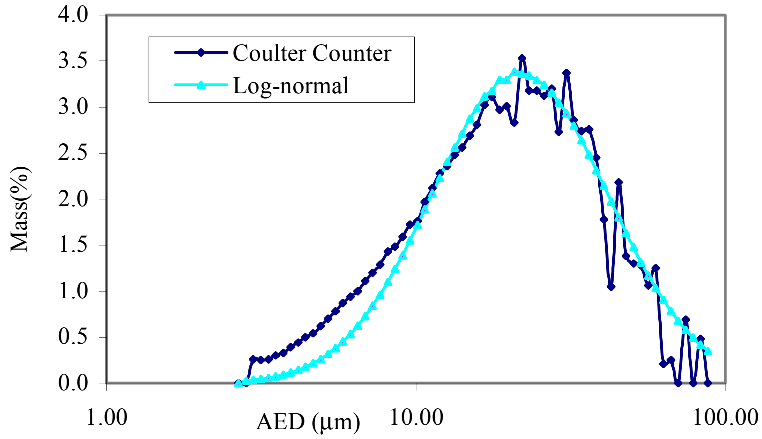

Figure 4. Coulter Counter PSD vs. the log-normalized PSD for dust B

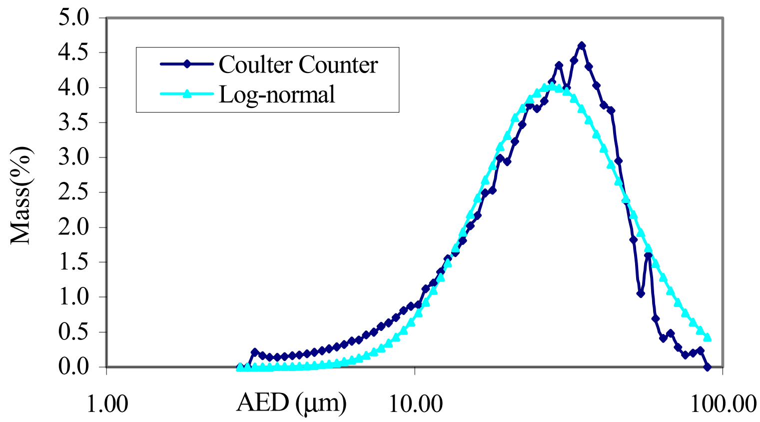

Figure 5. Coulter Counter PSD vs. the log-normalized PSD for dust C

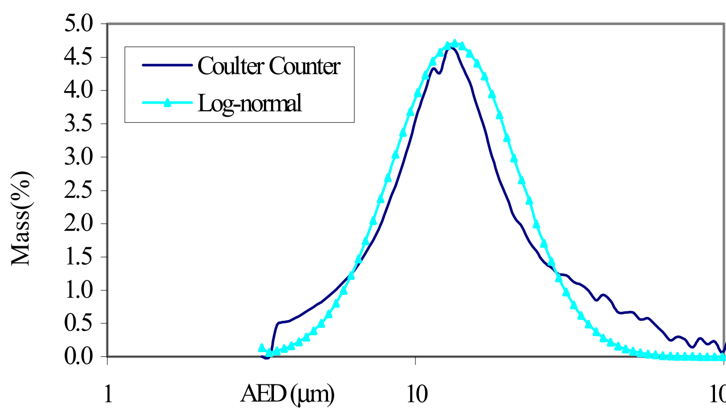

Figure 6. Coulter Counter PSD vs. the log-normalized PSD for fly ash

Tables 2 and 3 list the MMD's and GSD's of inlet and outlet log-normalized PSD's, respectively.

Table 2. Mass median diameters and geometric standard deviations for the four test dusts assuming a log-normal distribution

	MMD (µm)	GSD		MMD (µm)	GSD
Dust A	20.18	1.999	Dust C	22.63	1.82
Dust B	21.09	1.93	Fly ash	13.13	1.71

- MMD: mass median diameter
- GSD: geometric standard deviation

Table 3. Average mass median diameters and geometric standard deviations for the PM emitted during testing of the three cyclones assuming a log-normal distribution

	1D3D		2D2D		1D2D	
	MMD µm	GSD	MMD µm	GSD	MMD µm	GSD
Dust A	3.29	1.424	3.250	1.46	3.35	1.36
Dust B	3.29	1.500	3.004	1.49	3.07	1.54
Dust C	3.95	1.890	4.150	1.57	4.68	1.68
Fly ash	3.66	1.320	3.680	1.44	5.15	1.76

- MMD: mass median diameter
- GSD: geometric standard deviation

Experiment Design and Analysis

The experiment was conducted as a 3-factorial experiment. The 3 factors were: (1) cyclone designs (1D3D, 2D2D, 1D2D), (2) inlet PSD's (dusts A, B, C, and fly ash), and (3) inlet loading rates (1.5 g/m^3 and 3 g/m^3). Each treatment was based on five repeating observations for a total of 120 observations. ANOVA tests, using Tukey's Studentized Range (HSD) test at 95% confidence interval, were performed on the results to determine if there were any interactions between factors.

Test Results and FEC's

Table 4 lists the emission concentrations of the cyclones with dusts A, B, C, and fly ash. The statistical analyses suggested that the cyclone emission concentrations were highly dependant upon cyclone design, inlet loading rates, and inlet PSD's.

Table 4. Resulting measured emission concentrations (mg/m^3) for the 1D3D, 2D2D, and 1D2D cyclones.

	Dust A		Dust B		Dust C		Flyash
	Inlet con. (g/m^3)		Inlet con. (g/m^3)		Inlet con. (g/m^3)		Inlet con. (g/m^3)
Cyclone	1.5	3	1.5	3	1.5	3	1.5
1D3D	4.77	5.87	10.18	17.99	5.00	8.05	50.00
2D2D	6.25	10.03	16.93	31.81	5.33	10.66	67.39
1D2D	7.38	11.92	19.14	40.16	7.07	14.67	75.00

Three FEC's were developed with this data (experiment, model and Lapple). They were calculated as follows:

1. Experiment cyclone fraction efficiency curves were determined using Eq. (3) with inlet concentrations, measured emission concentrations and inlet and outlet PSD'S. Using a trial and error method, lognormal distributions were developed that approximated the inlet and outlet Coulter Counter PSD data. These "log-normalized" PSD's were used to develop the FEC's for each cyclone referred to as "experiment" in Figures 7-9.

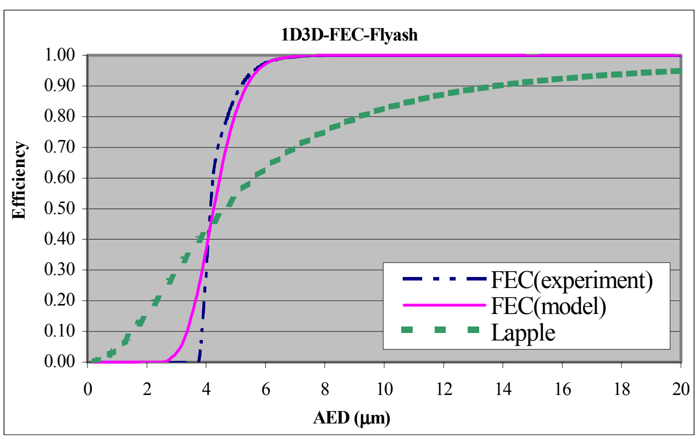

Figure 7. The resulting fractional efficiency curve for 1D3D
Experiment: D_{50}=4.25 (µm), Slope=1.18,
Model: D_{50}=4.25 (µm), Slope=1.20,
Lapple: D_{50}=3.74 (µm), Slope=2.20

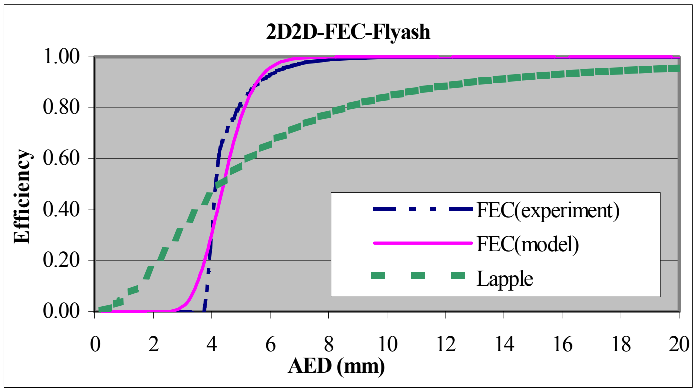

Figure 8. The resulting fractional efficiency curve for 2D2D
Experiment: D_{50}=4.00 (µm), Slope=1.25,
Model: D_{50}=4.40 (µm), Slope=1.20,
Lapple: D_{50}=3.53 (µm), Slope=2.12

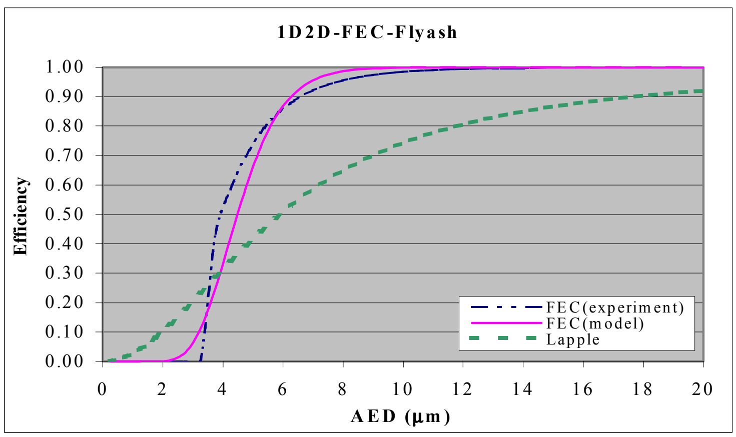

Figure 9. The resulting fractional efficiency curve for 1D2D
Experiment: D_{50}=4.10 (µm), Slope=1.34,
Model: D_{50}=4.50 (µm), Slope=1.30,
Lapple: D_{50}=4.83 (µm), Slope=2.12

2. The Lapple FEC's were developed using inlet and outlet log-normalized PSD'S and the CCD process that included the "generalized" FEC's that are an integral part of the CCD process.
3. It was assumed that the FEC's should have a lognormal distribution. Hence, a trial and error approach was used to obtain the best fit lognormal distribution for the each experiment FEC. (See 1 above.) The results of this log-normalizing process were the FEC's referred to as "model" FEC's in Figures 7-9. (See Table 5.)

Table 5. Cyclone fractional efficiency curves (cut point and slope) for the 1D3D, 2D2D, and 1D2D cyclone designs assuming a lognormal model for the four test dusts.

	1D3D		**2D2D**		**1D2D**	
	Cut Point µm	Slope	Cut Point µm	Slope	Cut Point µm	Slope
Dust A	2.5	1.40	2.74	1.32	2.82	1.33
Dust B	3.55	1.20	3.75	1.20	3.77	1.25
Dust C	3.34	1.24	3.54	1.24	3.74	1.28
Fly ash	4.25	1.20	4.40	1.20	4.50	1.30

The results suggest that the cut-points of the three cyclones were not independent of the cyclone designs and inlet PSD's. However, the cut-points were independent of the inlet loading rates.

The resulting FEC's for 1D3D, 2D2D and 1D2D cyclones developed from experimental values, the Lapple model, and the log-normalized models are illustrated in Figures 7-9. The overall collection efficiencies were determined using Equations 1 and 2 for the various FEC's. (See Table 6.) A comparison of the overall collection efficiencies measured, calculated using the Lapple and Model FEC's illustrate that the new log-normalized models are much more accurate than the Lapple model, although they are still conservative. (See Table 4).

Table 6. Overall Collection Efficiencies (%) for the 1D3D, 2D2D, 2D2D cyclones for the four test dusts.

	Lapple Model			
	Dust A	Dust B	Dust C	Fly ash
1D3D	85.20	85.20	85.20	85.20
2D2D	88.60	88.60	88.60	88.60
1D2D	78.90	78.90	78.90	78.90
	Measured			
	Dust A	Dust B	Dust C	Fly ash
1D3D	99.65	99.29	99.68	96.7
2D2D	99.57	98.87	99.63	95.5
1D2D	99.52	98.74	99.53	95.30
	Log-normalized Model			
	Dust A	Dust B	Dust C	Fly ash
1D3D	94.22	94.23	94.95	95.4
2D2D	94.18	94.11	95.37	94.8
1D2D	94.13	94.02	94.79	94.58

Conclusions

The following was concluded:

- The use of the CCD process to estimate emission concentrations and overall collection efficiencies for these three cyclone designs will result in significant errors. It is likely that regulators using this process will not accept cyclones as an acceptable air pollution abatement device. This process will yield inaccurate evaluations of a cyclone's overall collection efficiency.

- The new 1D3D, 2D2D, and 1D2D fractional efficiency curves produced better estimates for collection efficiencies and emission concentrations. They also allow for comparison of cyclone designs and indicate that properly designed cyclones are highly efficient and can reduce emissions to levels that are likely to allow cotton ginners to comply with air pollution rules and regulations.

- The overall collection efficiencies determined using the new FEC's were different (lower) than the measured values. It was observed that the PSD of the PM emitted by the cyclones was not ideally represented by a lognormal distribution. It is assumed that errors were introduced when the outlet PSD's were log-normalized. We anticipate conducting additional research to solve this problem.

- The process used in this research can be used to more accurately characterize cyclone performance. This process is as follows:

    1. Obtain PSD's of inlet and outlet PM using the Coulter Counter Multisizer.
    2. Log-normalize the PSD's.
    3. Calculate the FEC using inlet and outlet concentrations and the log-normalized PSD's.
    4. Obtain the "best-fit" lognormal distribution for the FEC obtained in 3 above.

- It is anticipated that the model FEC's reported in this paper can be used to characterize the performance of the 1D3D, 2D2D, and 1D2D cyclones when used to capture fine dust only. These FEC's will be impacted if the inlet PM contains trash particles.

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