1D2D, 1D3D, 2D2D CYCLONE FRACTIONAL EFFICIENCY CURVES FOR FINE DUST

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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 FECs 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

The impact of the Federal Clean Air Act Amendments (1990) has been more rigorous enforcement of air pollution regulations by State Air Pollution Regulatory Agencies (SAPRAs) on all sources including those perceived to be from agricultural operations. It has, in effect, forced many agricultural operations to reduce their emission rates by installing more expensive and efficient air pollution control technologies.

Cyclones are the most widely used air pollution abatement equipment used in the agricultural processing industry for removal of particulate matter (PM). 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, 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.

A more accurate method of determining cyclone performance is the use of fractional efficiency curves (FECs), inlet concentrations and particle size distributions (PSDs). 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, once an 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 FECs for the 1D3D, 2D2D and 1D2D cyclones would facilitate predicting accurate emission concentrations given inlet loading rates and PSDs of the PM for agricultural operations.

Based upon our previous experience, we know that the FECs 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 FECs 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 FECs 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) 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.

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. For this research, a large number of tests were performed on the 1D3D, 2D2D, and 1D2D cyclones. The

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tests consisted of inlet loadings of 1.5 g/m^3 and 3 g/m^3 utilizing fly ash and three different fine "gin dusts" extracted from cotton gin trash and screened to less than 100 µm utilizing an air wash procedure. The emission concentrations from each test cyclone were measured. The resulting emission concentrations from these tests were less than 50 mg/m^3. The results indicate that a properly designed and operated 1D3D, 2D2D, and 1D2D cyclone can have a collection efficiency of more than 98%. Results using the Lapple model (CCD) are cyclone efficiencies of around 70-90% for most dusts (Cooper and Alley, 1994). Measured collection efficiencies were much higher than efficiencies predicted using the CCD process.

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):

$$EF = (W1-W2)/W1 \qquad \text{Eq.(1)}$$

where

EF = overall collection efficiency,
W1 = total inlet loading (g), and
W2 = 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:

$$\eta = \sum \eta j * Mj \qquad \text{Eq.(2)}$$

where

η = overall collection efficiency,
ηj = efficiency of collection for the j^{th} size range, and
Mj = 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 (PSDs). Kaspar et al (1993) attempted to develop a model that could accurately predict emission concentrations by modifying the CCD "generalized" FECs 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:

$$\eta j = (1-Conc_{out}j / Conc_{in}j) \qquad \text{Eq.(3)}$$

where

ηj = fractional efficiency of j^{th} size range,
$Conc_{out}j$ = outlet concentration of j^{th} size range, and
$Conc_{in}j$ = 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 (D50) 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:

$$Slope = D84.1/D50 = D50/D15.9 \qquad \text{Eq.(4)}$$

where

D84.1 = diameter of particle collected with 84.1% efficiency,
D50 = diameter of particle collected with 50% efficiency, and
D15.9 = diameter of particle collected with 15.9% efficiency (Cooper and Alley, 1994).

Test Emission Concentration & Collection Efficiency

A small-scale cyclone testing system was used to evaluate cyclone performance and efficiency. Three different cyclones designs (1D2D, 1D3D, 2D2D) were tested. The test cyclones were constructed of metal and were six inches in diameter. (The 1D3D had a 2D2D inlet.) Each cyclone was tested at its respective design velocity. Replicated tests for controlled, inlet loading rates of 1.5 g/m^3 and 3 g/m^3 for four test dusts were performed. Emission concentrations, and overall collection efficiencies were measured and calculated. The emission concentrations were determined by the follow equation:

$$EC = (W/(Q*T)) * 1000 \qquad \text{Eq.(5)}$$

where

EC = emission concentration (mg/m^3),
W = weight of dust on the filter (g),
Q = testing system airflow rates (m^3/min), and,
T = length of test (min).

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. A Coulter Counter Multisizer was used to perform particle size distributions (PSD's) of the fine dusts, as well as the fly ash.

It is common to characterize PSDs of PM to be a log-normal distribution with an mass median diameter (MMD) and a geometric standard deviation GSD. Figures 1-4 show the log-normalized inlet PSD's and the Coulter Counter analyses PSD's (real). An 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:

$$GSD = D84.1/D50 = D50/D15.9 \qquad \text{Eq.(6)}$$

where

D84.1 = diameter such that particles constituting 84.1% of the total mass of particles are smaller than this size,
D50 = mass median diameter (50% of the total mass of particles are smaller than this size), and
D15.9 = 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:

$$GSD = D84.1/MMD=MMD / D15.9 \qquad (6)$$

where
GSD = geometric standard deviation,
MMD = mass median diameter,
D84.1 = diameter where particles constituting 84.1% of the total mass of particles are smaller than this size, and
D15.9 = diameter where particles constituting 15.9% of the total mass of particles are smaller than this size.

Tables 1 and 2 list the MMDs and GSDs of inlet and outlet log-normalized PSD's, respectively.

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 3 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.

Three FECs 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" PSDs were used to develop the FECs for each cyclone referred to as "experiment" in figures 5-12.
2. The Lapple FECs were developed using inlet and outlet log-normalized PSD'S and the CCD process that included the "generalized" FECs that are an integral part of the CCD process.
3. It was assumed that the FECs 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 FECs referred to as "model" FECs in figures 5-12. (See table 4.)

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

The resulting FECs for 1D3D, 2D2D and 1D2D cyclones developed from experimental values, the Lapple model, and the log-normalized models are illustrated in Figures 5-16. The overall collection efficiencies were determined using Equations 1 and 2 for the various FECs. (See Table 5.) A comparison of the overall collection efficiencies measured, calculated using the Lapple and Model FECs illustrate that the new log-normalized models are much more accurate than the Lapple model, although they are still conservative. (See table 3).

Conclusions

The following was concluded:

- The use 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 FECs were different (lower) than the measured (real) 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 PSDs of inlet and outlet PM using the Coulter Counter Multisizer.
  2. Log-normalize the PSDs.
  3. Calculate the FEC using inlet and outlet concentrations and the log-normalized PSDs.
  4. Obtain the "best-fit" lognormal distribution for the FEC obtained in 3 above.
- It is anticipated that the model FECs 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 FECs will be impacted if the inlet PM contains trash particles.

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Table 1. Mass median diameters (MMDs) and geometric standard deviations (GSDs) for the four test dusts (Inlet PSD's) 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	Flyash	13.13	1.71

Table 2. Average mass median diameters (MMDs) and geometric standard deviations (GSDs) for the PM emitted during testing of the three cyclones (Outlet PSD's) assuming a log-normal distribution.

	1D3D		2D2D		1D2D	
	MMD µm	GSD	MMD µm	GSD	MMD µm	GSD
Dust A	3.29	1.424	3.25	1.46	3.35	1.36
Dust B	3.29	1.5	3.004	1.49	3.07	1.54
Dust C	3.95	1.89	4.15	1.57	4.68	1.68
Flyash	3.66	1.32	3.68	1.44	5.15	1.76

Table 3. Resulting measured emission concentrations (mg/m^3) for five replications with four test dusts for the 1D3D, 2D2D, and 1D2D cyclones.

1D3D cyclone

	Dust A Inlet conc. (g/m^3)		Dust B Inlet conc. (g/m^3)		Dust C Inlet conc. (g/m^3)		Flyash Inlet conc. (g/m^3)
Test	1.5	3	1.5	3	1.5	3	1.5
1	5.91	6.22	9.81	21.81	5.41	8.44	52.13
2	5.23	6.26	10.70	18.03	5.39	8.61	48.66
3	5.52	5.16	10.02	16.88	4.94	7.86	49.57
4	3.68	6.14	10.65	16.71	5.04	7.50	49.63
5	3.51	5.57	9.70	16.52	4.20	7.85	
Ave.	4.77	5.87	10.18	17.99	5.00	8.05	50.00
Std.	1.10	0.49	0.47	2.22	0.49	0.46	1.49

2D2D cyclone

	Dust A Inlet conc. (g/m^3)		Dust B Inlet conc. (g/m^3)		Dust C Inlet conc. (g/m^3)		Flyash Inlet conc. (g/m^3)
Test	1.5	3	1.5	3	1.5	3	1.5
1	7.27	10.73	17.35	32.73	5.15	10.55	69.21
2	6.41	9.62	16.92	32.11	6.40	10.25	67.72
3	6.25	9.70	16.42	31.72	5.05	9.67	66.74
4	5.37	9.78	17.28	31.29	4.86	11.81	65.89
5	5.95	10.33	16.67	31.20	5.19	11.03	
Ave.	6.25	10.03	16.93	31.81	5.33	10.66	67.39
Std.	0.69	0.48	0.40	0.63	0.61	0.81	1.43

1D2D

	Dust A Inlet conc. (g/m^3)		Dust B Inlet conc. (g/m^3)		Dust C Inlet conc. (g/m^3)		Flyash Inlet conc. (g/m^3)
Test	1.5	3	1.5	3	1.5	3	1.5
1	9.74	10.82	19.09	39.53	7.88	15.67	70.42
2	7.12	11.53	18.96	40.36	7.13	15.34	76.03
3	6.89	12.52	18.38	39.80	7.90	14.26	75.18
4	5.75	11.44	19.92	38.64	6.33	13.82	78.38
5	7.41	13.30	19.35	42.47	6.12	14.28	
Ave.	7.38	11.92	19.14	40.16	7.07	14.67	75.00
Std.	1.46	0.98	0.56	1.43	0.84	0.79	3.38

Table 4. 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
DustA	2.5	1.40	2.74	1.32	2.82	1.33
DustB	3.55	1.20	3.75	1.20	3.77	1.25
DustC	3.34	1.24	3.54	1.24	3.74	1.28
Flyash	4.25	1.20	4.40	1.20	4.50	1.30

Table 5. Overall Collection Efficiencies(%) for the 1D3D, 2D2D, 2D2D cyclones for the four test dusts.

	Dust A	Dust B	Dust C	Flyash
Lapple Model				
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
Real (measured)				
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				
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

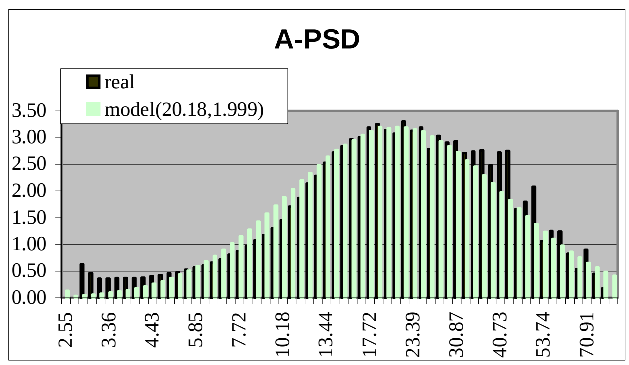

Figure 1. Coulter Counter Analyses PSD (real) & the Log-normalized PSD for Dust A

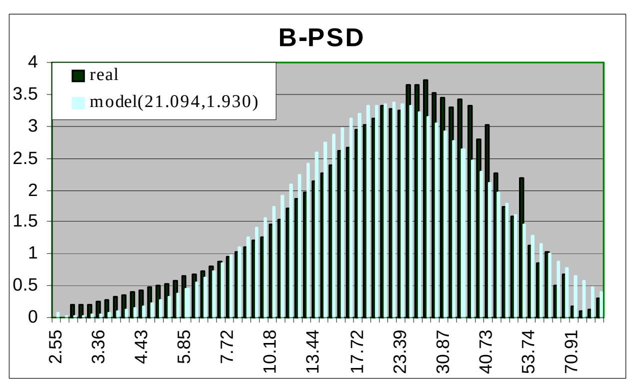

Figure 2. Coulter Counter Analyses PSD (real) & the Log-normalized PSD for Dust B

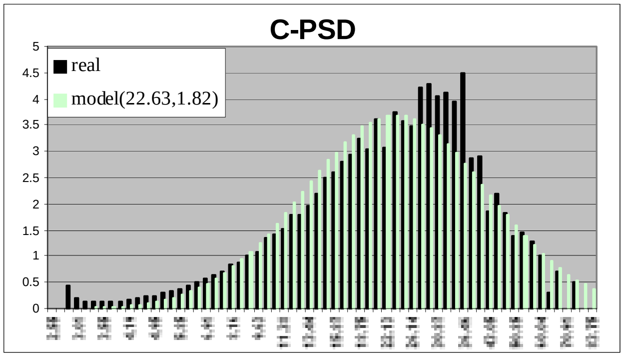

Figure 3. Coulter Counter Analyses PSD (real) & the Log-normalized PSD for Dust C

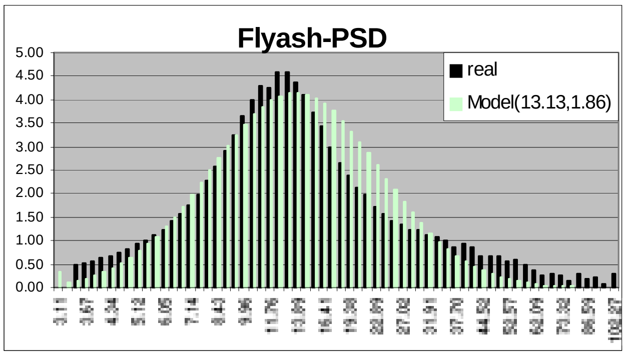

Figure 4. Coulter Counter Analyses PSD (real) & Coulter Counter Analyses PSD (real) & the log-normalized PSD for flyash

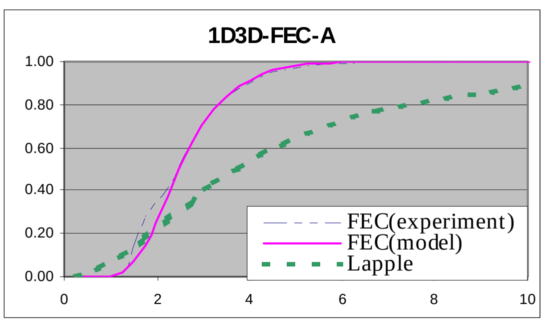

Figure 5. The resulting fractional efficiency curve for 1D3D Experiment: D50=2.5, Slope=1.4 Model: D50=2.5, Slope=1.4,,Lapple: D50=3.74, Slope=2.2

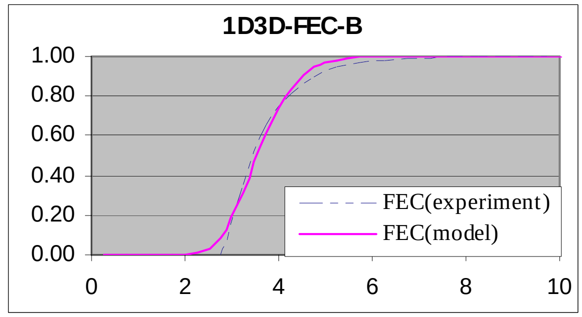

Figure 6. The resulting fractional efficiency curve for 1D3D Experiment: D50=3.49, Slope=1.23, Model: D50=3.55, Slope=1.2

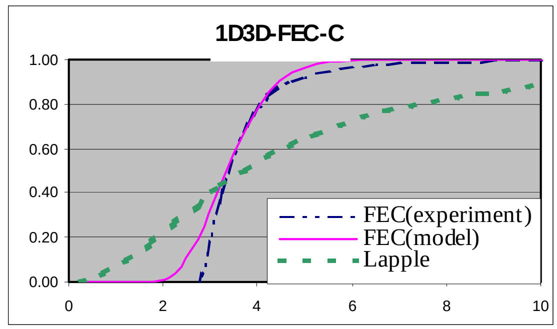

Figure 7. The resulting fractional efficiency curve for 1D3D Experiment: D50=3.34, Slope=1.25, Model: D50=3.34, Slope=1.24, Lapple: D50=3.74, Slope=2.2

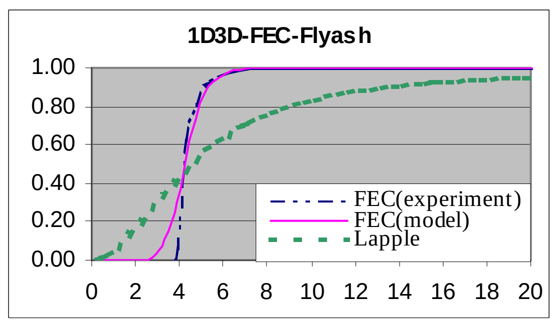

Figure 8. The resulting fractional efficiency curve for 1D3D Experiment: D50=4.25, Slope=1.18, Model: D50=4.25, Slope=1.2, Lapple: D50=3.74, Slope=2.2

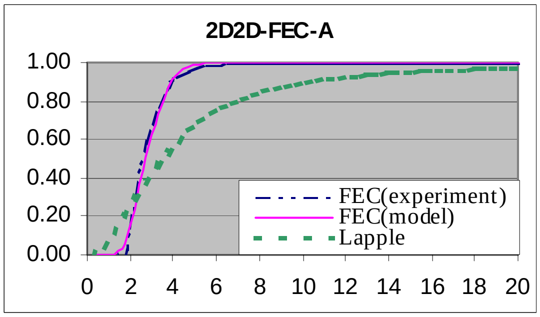

Figure 9. The resulting fractional efficiency curve for 2D2D Experiment: D50=2.7, Slope=1.3, Model: D50=2.74, Slope=1.32, Lapple: D50=3.53, Slope=2.12

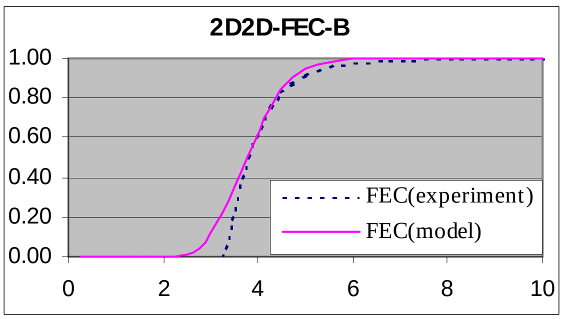

Figure 10. The resulting fractional efficiency curve for 2D2D Experiment: D50=3.75, Slope=1.2, Model: D50=3.75, Slope=1.2

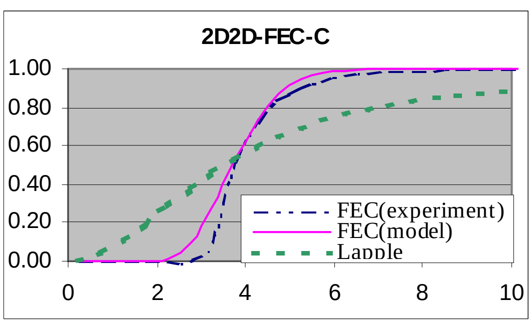

Figure11. The resulting fractional efficiency curve for 2D2D Experiment: D50=3.59, Slope=1.21, Model: D50=3.54, Slope=1.24, Lapple: D50=3.53, Slope=2.12

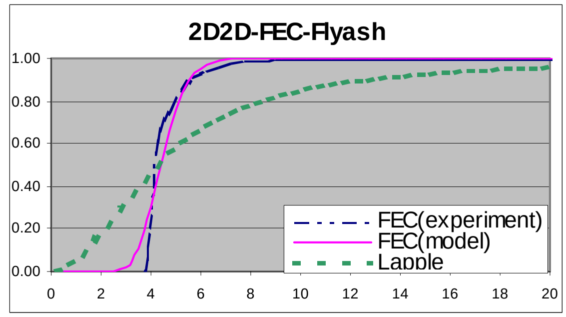

Figure 12. The resulting fractional efficiency curve for 2D2D Experiment: D50=4.0, Slope=1.25, Model: D50=4.4, Slope=1.2, Lapple: D50=3.53, Slope=2.12

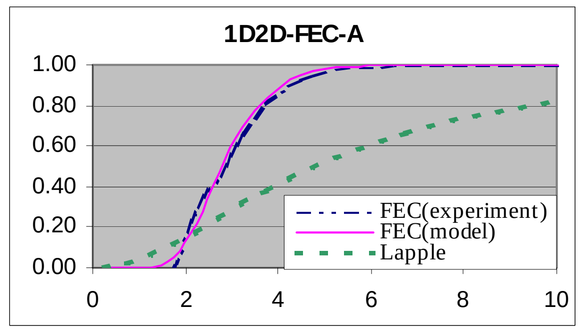

Figure13. The resulting fractional efficiency curve for 1D2D Experiment: D50=2.87, Slope=1.31, Model: D50=2.82, Slope=1.33, Lapple: D50=4.83, Slope=2.12

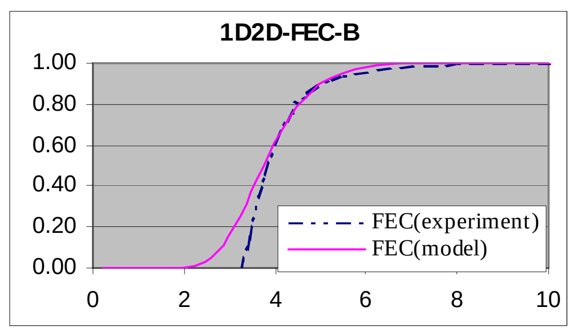

Figure14. The resulting fractional efficiency curve for 1D2D Experiment: D50=3.78, Slope=1.24, Model: D50=3.77, Slope=1.25, Lapple: D50=4.83, Slope=2.12

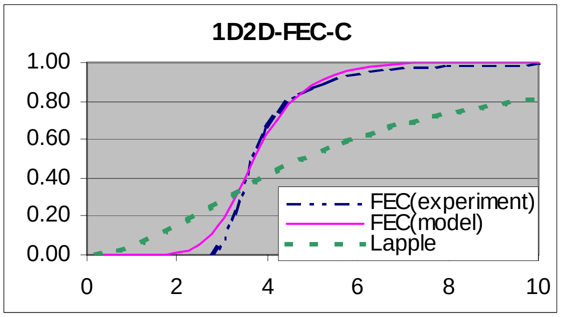

Figure15. The resulting fractional efficiency curve for 1D2D Experiment: D50=3.72, Slope=1.27, Model: D50=3.74, Slope=1.28, Lapple: D50=4.83, Slope=2.12

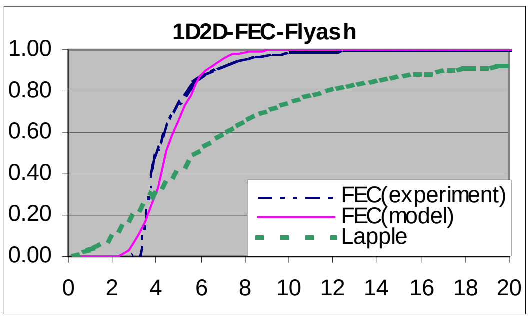

Figure16. The resulting fractional efficiency curve for 1D2D Experiment: D50=4.1, Slope=1.34, Model: D50=4.5, Slope=1.3, Lapple: D50=4.83, Slope=2.12