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EFFECTS OF CYCLONE DIAMETER ON PERFORMANCE OF 1D3D CYCLONES: CYCLONE CUT POINT

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Abstract

Cyclones are a commonly used air pollution abatement device for separating particulate matter (PM) from air streams in industrial processes. Several mathematical models have been proposed to predict the performance of cyclones as cyclone diameter varies. The objective of this research was to determine the relationship between cyclone diameter, cut point, and slope based on empirical data. Tests were performed comparing cut points and slopes of 15.24-, 30.48-, 60.96-, and 91.44-cm (6-, 12-, 24-, and 36-in.) diameter cyclones with poly-disperse PM having an aerodynamic mass median diameter near 10 µm. The mass of PM collected by the cyclones and the mass and particle size distributions of PM that penetrated the cyclones were used to determine the cut point and slope of each cyclone. The cut points of cyclones showed no relationship to cyclone diameter, while the slope of cyclones increased as cyclone diameter increased with statistically different collection efficiencies observed among the 30.48-, 60.96-, and 91.44-cm (12-, 24-, and 36-inch) diameter cyclones. None of the previously published mathematical models analyzed in this paper accurately predicted cyclone cut point.

Introduction

Cyclones are a commonly used air pollution abatement device for separating particulate matter (PM) from air streams in industrial processes. Cyclones are relatively inexpensive, and operational costs and maintenance requirements are low. An air stream containing PM enters a cyclone tangentially near the top of the cyclone and spirals downward. Inertial and centrifugal forces move the particulates outward to the wall of the cyclone where the PM slides down to the trash outlet at the bottom of the cone section and is removed (fig. 1).

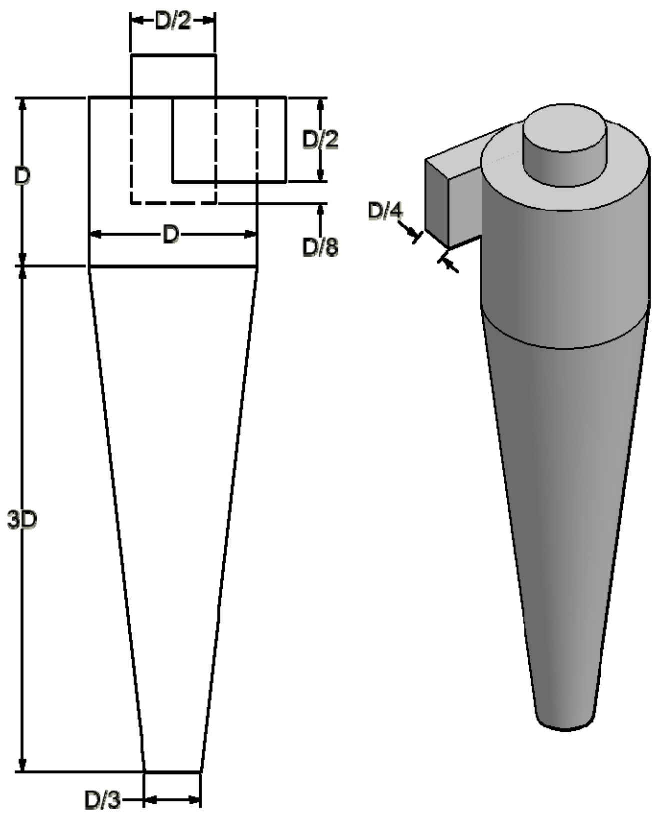

Figure 1. 1D3D cyclone configuration.

The performance of a cyclone is defined by its fractional efficiency curve (FEC), which indicates the efficiency at which a cyclone collects particles of a given size (eq. 1).

$$FEC(d_p, d_{50}, slope) = \frac{1}{d_p \ln(slope)\sqrt{2\pi}} \exp\left[\frac{-(\ln d_p - \ln d_{50})^2}{2(\ln(slope))^2}\right] \quad (1)$$

where: FEC(d_p, d_{50}, slope) = collection efficiency of particle with diameter d_p, and
d_{50} = cyclone cut point.

The cut point of a cyclone is defined as the particle diameter corresponding to a 50% collection efficiency. The slope of the FEC indicates the sharpness of cut of the cyclone and is calculated according to the equation:

$$Slope = \sqrt{\frac{d_{84.1}}{d_{15.9}}} \quad (2)$$

where $d_{84.1}$ and $d_{15.9}$ are particle diameters corresponding to 84.1 and 15.9 percent collection efficiencies, respectively.

According to Wang et al. (2000), cyclone performance is a function of the geometry and operating parameters of the cyclone, as well as the particle size distribution (PSD) of the entrained PM. Several mathematical models have been proposed to predict cyclone performance. Lapple (1951) developed a semi-empirical relationship to predict the cut point of cyclones designed according to the Classical Cyclone Design method, but Wang et al. (2000) showed that Lapple's approach does not account for the effects of PSD on cyclone performance.

The Lapple (1951) model was based on the terminal velocity of particles in a cyclone. From the theoretical analysis, equation 3 was derived to determine the smallest particle that will be collected by a cyclone if it enters at the inside edge of the inlet duct.

$$d_p = \sqrt{\frac{9\mu W}{\pi N_e V_i \left(\rho_p - \rho_g\right)}} \tag{3}$$

where: d_p = diameter of the smallest particle that will be collected if it enters on the inside edge of the inlet duct (µm),
μ = gas viscosity (kg/m-s),
W = width of inlet duct (m),
N_e = number of turns of the air stream in the cyclone,
V_i = gas inlet velocity (m/s),
ρ_p = particle density (kg/m^3), and
ρ_g = gas density (kg/m^3).

Theoretically 100% of the particles of size d_p would be collected. Assuming Stoke's regime flow holds in cyclones, it would be expected that the cut point of any cyclone would be modeled by multiplying a constant, C, by the particle diameter calculated using equation 4.

$$d_{50} = C\sqrt{\frac{9\mu W}{\pi N_e V_i \left(\rho_p - \rho_g\right)}} \tag{4}$$

where: d_{50} is the cyclone cut point.

Lapple (1951) determined that the value of C was equivalent to 0.7071, predicting that cyclone cut point can be calculated using equation 5.

$$d_{50} = \sqrt{\frac{9\mu W}{2\pi N_e V_i \left(\rho_p - \rho_g\right)}} \tag{5}$$

Several other mathematical models have also been proposed, including a model by Barth (1956) that predicts cyclone cut point based on force balance as a function of volumetric flow rate, effective cyclone length, and inlet velocity. Wang et al. (2003) corrected the Barth model to more closely match experimental data taken using 15.24-cm (6-in.) diameter 1D3D and 2D2D cyclones. Pant et al. (2002) developed an empirical model to predict the effects of changing cyclone geometric parameters. Their model was intended for application with "miniature" cyclones, but the limits of the model's applicability were not clearly stated. No literature was found characterizing the relationship between cyclone slope and barrel diameter.

The Texas A&M Cyclone Design (TCD) method (Parnell, 1996) specifies cyclone dimensions based on the diameter (D) of the cyclone barrel (fig. 1). The barrel diameter is selected so that the volumetric flow rate of air (determined by the application) through the inlet cross-section (D/2 × D/4) results in the TCD design inlet velocity (975 ± 120 m/min [3200 ± 400 fpm] for 1D3D cyclones [Parnell, 1996]). The Ds in the 1D3D designation refer to the diameter of the cyclone barrel, while the numbers preceding the Ds refer to the relative length of the barrel and cone sections, respectively. Therefore, a 1D3D cyclone has a barrel length equal to the barrel diameter and a cone length equal to three times the barrel diameter.

An accurate assessment of the change in cyclone cut point and slope with changes in barrel diameter is important when designing or evaluating the efficiency of cyclones as PM abatement systems. Given PM with a consistent PSD, the total collection efficiency of a cyclone will increase as the cut point decreases. The relationship between increasing slope and collection efficiency varies according to PSD of the PM and the cyclone cut point. Faulkner et al. (2006) found that, when separating fine PM (mass median diameter ≈ 10 µm) with a consistent PSD, cyclone collection efficiency decreases as cyclone barrel diameter increases. These results indicate that a relationship may exist between barrel diameter and cyclone cut point, slope, or both. The objective of this research was to characterize the changes in cyclone cut point and slope with changes in cyclone diameter.

Materials and Methods

To determine cyclone cut point and slope as a function of barrel diameter, a fourth, simplified mathematical model was proposed based on several simplifying assumptions, and experimental data was collected using 15.24-, 30.48-, 60.96-, and 91.44-cm (6-, 12-, 24-, and 36-in.) diameter cyclones.

Mathematical models

A mathematical model of the path of a given particle through a cyclone was developed where the particle followed the center of a laminar air stream through the course of the cyclone. Using this simplified model, the total energy imparted to a particle in a cyclone was calculated according to equation 6:

$$E = \int_0^d F dx \tag{6}$$

where: E = energy imparted to the particle (J),
F = force acting on the particle (N),
x = distance traveled by the particle (m), and
d = total path length of a particle through the cyclone (m).

The velocity and travel distance of the air stream within the cyclone were calculated according to the approach outlined by Wang et al. (2001). According to this approach, the tangential velocity of the air stream in the barrel portion of the cyclone is equal to the inlet velocity, and the travel distance in the cyclone barrel is determined by equation 7:

$$L_b = N_b \pi D \tag{7}$$

where: L_b = travel distance in the cyclone barrel (m),
N_b = turns in the cyclone barrel [1.53 for 1D3D cyclones (Wang et al., 2001)], and
D = cyclone barrel diameter (m).

In the cone section of a cyclone, the air stream velocity increases as the cross-sectional area of the cyclone decreases. The tangential velocity in the cone portion of a 1D3D cyclone at time t is described according to equation 8:

$$V_{t,c} = \frac{4D * V_{in}}{Z + 2D_c} \tag{8}$$

where: $V_{t,c}$ = tangential velocity at time t in the cyclone cone (m/s),
D = cyclone barrel diameter (m),
V_{in} = inlet velocity (m/s), and
Z = travel distance in the axial direction at time t (m).

Based on these equations, the centrifugal force acting on a particle was calculated according to equation 9:

$$F = m\frac{v^2}{r} \tag{9}$$

where: F = force acting on the particle (N),
m = mass of particle (kg),
v = tangential velocity (m/s), and
r = radius of the particle's path (m).

The distance traveled in the axial direction at time t can be found using equation 9, assuming that Z is equal to zero when t is equal to zero.

$$Z = \int_0^t \frac{4D * V_{in}}{(Z + 4D_c)\pi} t \tag{10}$$

where: Z = travel distance in the axial direction at time t (m),
D = cyclone barrel diameter (m),
V_{in} = inlet velocity (m/s), and
t = time (s).

Integrating the centrifugal force over the total distance traveled in the barrel and the cone, the diameter terms were reduced such that the amount of energy imparted on the particle in the cyclone did not change, regardless of the cyclone diameter. This model is referred to as the energy dissipation model and implies that, given fixed geometric proportions and inlet velocity, the cut point of a cyclone should not be a function of cyclone diameter.

Each of the aforementioned models: Lapple (1951), Barth model corrected by Wang et al. (2003), Pant et al. (2002), and the Energy Dissipation model, were used to predict the cut point of 1D3D cyclones ranging in size from 10.16 to 152.4 cm (4 to 60 inches) in diameter. TCD design inlet velocity (975 m/min) was used with standard air (air density = 1.18 kg/m^3, air viscosity = 1.85x10^{-5} Pa-s) and particle specific gravity was assumed to be 3.9.

Experimental evaluation

To experimentally determine the relationship between cyclone barrel diameter, cut point, and slope, four 1D3D cyclones (15.24-, 30.48-, 60.96-, and 91.44-cm [6-, 12-, 24-, and 36-inch] diameter) were evaluated. While 15.24-cm (6-in) diameter cyclones are not feasible for use many industrial applications due to their small size, testing cyclones with barrel diameters from 15.24- to 91.44-cm (6- to 36-in) allowed for a preliminary analysis of the relationship between barrel diameter and the FEC parameters. In practice, cyclones with barrel diameters smaller than 60.96-cm (24-in) will likely not operate in many applications because of problems with choking. The system used for testing is shown in figure 2.

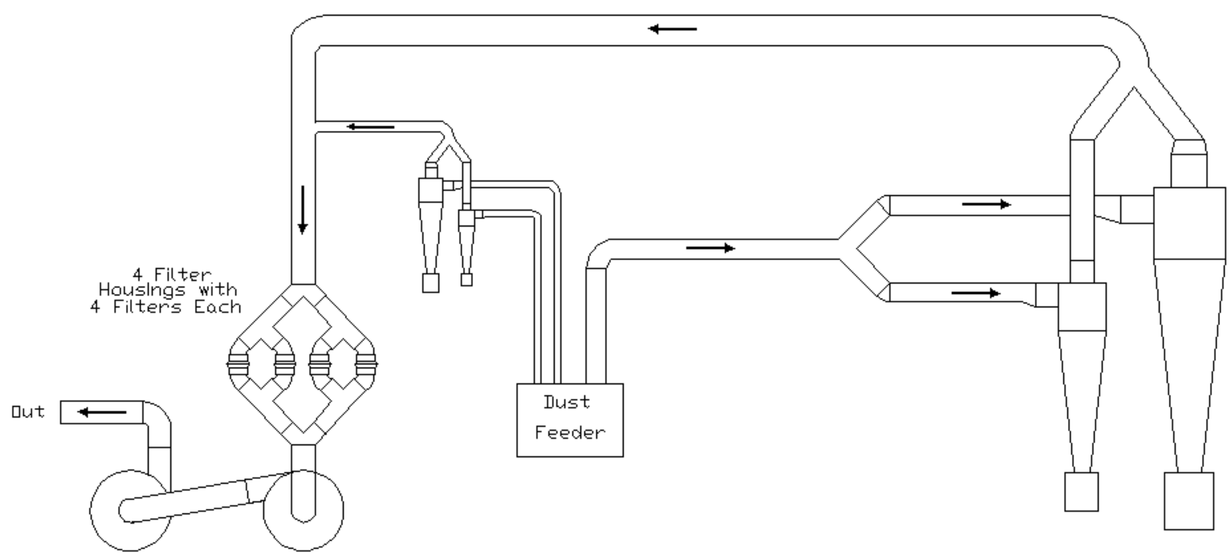

Figure 2. Cyclone testing system.

With this system, PM was introduced at a rate of about 3 g/m^3 into the air stream in the ductwork leading to the cyclone being tested with an AccuFeeder vibratory screw feeder (VibraScrew, Inc.; Totowa, NJ). PM captured by the cyclone was deposited in a sealed container at the cyclone trash exit. PM emitted by the cyclone was collected as the air was pulled through a bank of sixteen 20.3 cm × 25.4 cm glass fiber filters by twin high pressure blowers in series.

The PM used for these tests was #5 microalumina (K.C. Abrasive Company, Kansas City, KS). This material was used because the manufacturer certified it to have a consistent PSD (fig. 3) with mass median diameter (MMD) = 10.3-µm aerodynamic equivalent diameter (AED) and geometric standard deviation (GSD) = 1.40. The particle density was determined to be 3.9 g/cm^3, and a shape factor of 1.44 was used (Mark et al., 1985). Microalumina was chosen because the MMD of the aerosol was near the cut points we expected to see from the cyclones. By having an MMD near the cut point of the cyclone, the collection efficiency was more sensitive to changes in cut point than if a larger aerosol, more typical of agricultural operations, was used.

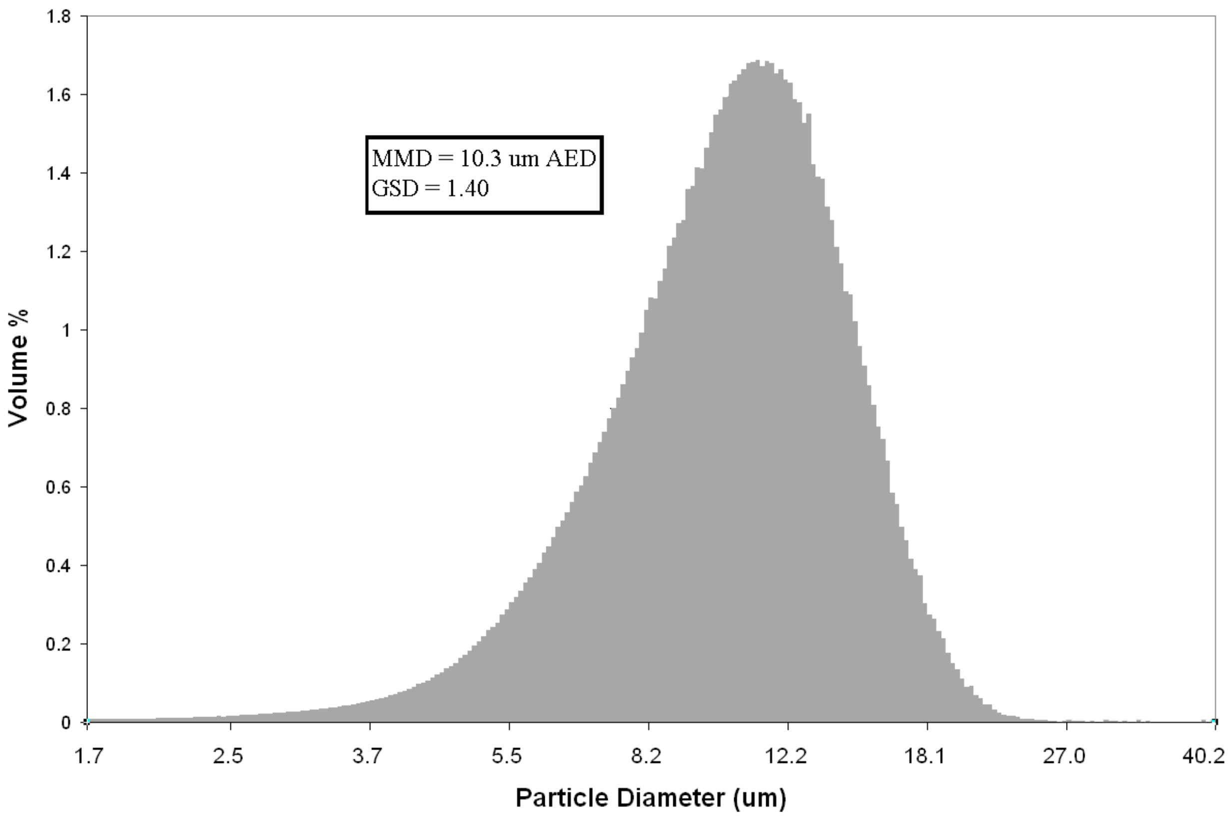

Figure 3. Particle size distribution of #5 microalumina used (in equivalent spherical diameter).

Before each test, the system was run with no filters for several minutes to clean out any residual PM in the ducts. Tests were conducted for 30 minutes for the 15.24-, 30.48-, and 60.96-cm (6, 12, and 24-in.) diameter cyclones. This time period was selected in an effort to minimize the startup and stopping effects associated with the tests. The duration of tests for the 91.44-cm (36-in.) diameter cyclone was limited because the static pressure drop across the filters increased rapidly as the PM that penetrated the cyclone was deposited on the filters. The 91.44-cm (36-in.) diameter cyclone tests were run until the system flow rate fell to the point that the cyclone inlet velocity was 853.2 actual m/min (2800 afpm) , which is the low end of the TCD recommended inlet velocity range (Parnell, 1996). The cyclone inlet velocity was determined by measuring the velocity pressure before the cyclone prior to dust being fed into the system. This inlet velocity was correlated to the system flow rate measured after the fans, and any change in flow rate during the tests was assumed to correlate to a change in the cyclone inlet velocity. Baffles on the exhaust side of the fans were used to adjust the system flow rate to compensate for reduced flow that occurred as the filters were loaded. Static pressures were measured throughout the system during each test to ensure that the system functioned properly and to monitor the static pressure loss associated with different cyclone sizes. Ambient temperature, relative humidity, and barometric pressure were also recorded at the beginning of each test.

The mass of PM captured by the cyclone and collected in the sealed containers was determined using an A&D model HP-20K scale (Milpitas, CA) with a 0.1 g resolution. The filters containing the PM that penetrated the cyclones were conditioned for a minimum of 48 hr in an environmental chamber at 21.1°C (70°F) and 35% relative humidity. The filters were weighed to the nearest 10 µg before and after the tests using a Mettler Toledo AG-285 balance (Columbus, OH) to determine the mass of PM that penetrated the cyclones. For quality control purposes, each filter weight was an average of three balance readings. If the standard deviation of the three readings exceeded 50µg, the filter was re-weighed. The mass of PM entrained in the system was determined by adding the mass collected in the sealed containers at the trash exit of the cyclone to the mass of PM collected on the filters. Tests were conducted in a randomized complete block design with replication as the blocking factor.

The PM that penetrated the cyclones was more heavily deposited on eight of the sixteen filters, particularly for the 15.24- and 30.48--cm (6- and 12-in.) diameter cyclones. Therefore, the PSD of PM that penetrated the cyclone during any one run was determined by weighting the PSD of PM on each of the eight heaviest loaded filters by the mass of PM deposited on each filter. The total mass that penetrated the cyclone was determined by summing the change in mass of all sixteen filters during any one run. The PSD of PM deposited on each filter was determined using a Beckman Coulter Counter Multisizer™ 3 (Beckman Coulter, Miami, Fla.) using the method described by Faulkner and Shaw (2006).

The mass of PM deposited on the filters in each size range measured by the Beckman Coulter Counter Multisizer™ 3 was determined using equation 11:

$$m_{filt,i} = m_{total} \times f_i \tag{11}$$

where: $m_{filt,i}$ = mass of PM deposited on the filters in the i^{th} size range,
m_{total} = total mass deposited on the filters, and
f_i = mass fraction of particles on the filters in the i^{th} size range.

The efficiency of collection for each size range was determined according to equation 12:

$$\eta_i = \frac{1 - m_{filt,i}}{m_{in,i}} \tag{12}$$

where: η_i = cyclone efficiency of collection of particles in the i^{th} size range,
$m_{filt,i}$ = mass of PM deposited on the filters in the i^{th} size range, and
$m_{in,i}$ = mass of PM entering the cyclone in the i^{th} size range.

The lognormal distribution that best fit the measured collection efficiency data was determined by simultaneously minimizing equations 13 and 14 to solve for d_{50} and slope:

$$J = \int_o^\infty \left[\left(f_{in}(d_p) \right) \left(1 - FEC(d_p, d_{50}, slope \right) - f_{filter}(d_p) \right] dd_p \tag{13}$$

$$K = \frac{m_{filter}}{m_{in}} - \int_0^\infty \left[\left(f_{in}(d_p) \right) \left(1 - FEC(d_p, d_{50}, slope) \right) \right] dd_p \tag{14}$$

where: $f_{in}(d_p)$ = mass fraction of particles entering the cyclone of size d_p,
$FEC(d_p, d_{50}, slope)$ = fractional efficiency of the cyclone,
d_{50} = cyclone cut point,
$f_{filter}(d_p)$ = mass fraction of particles deposited on the filters of size d_p,
m_{filter} = mass of PM deposited on the filters, and
m_{in} = mass of PM entering the cyclone.

The log-normality of the distribution of collection efficiencies for each cyclone test was examined using a chi-square test ($\alpha = 0.05$) with the null hypothesis that the distributions were not log-normal. The smallest 0.1 percent of particles by mass were excluded from the analysis because the extreme variability in the measured collection efficiencies of these particles. In all cases, the null hypothesis was rejected, indicating that a log-normal distribution characterized by a cut point and slope was appropriate to characterize the performance of the cyclones.

Results and Discussion

Mathematical Models

All models except the energy dissipation model predicted an increase in cut point as cyclone diameter increased (fig. 4). The predicted cut points increased according to the equation:

$$d_{50} = ax^b \tag{11}$$

where: d_{50} = cyclone cut point (µm),
x = cyclone diameter (cm), and
a and b = curve-fit coefficients.

The values of a and b for each model are shown in table 1. All R^2 values are equal to 1.00.

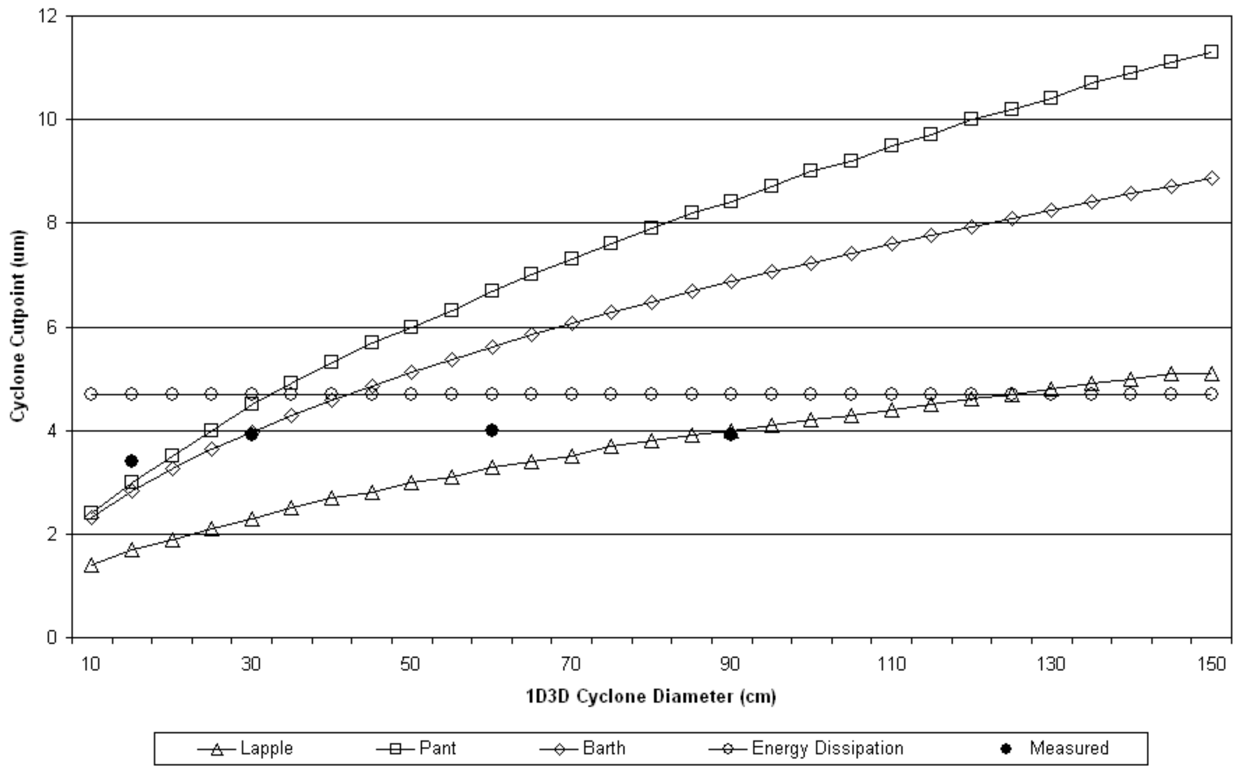

Figure 4. 1D3D cyclone cut point models and measured cut points.

Table 1. Constant values for equation 4 predicted by mathematical models.

Model	a	b
Lapple	0.4412	0.4880
Corrected Barth	0.7305	0.4963
Pant, et al	0.6242	0.5767
Energy Dissipation	4.3000	0.0000

Experimental Evaluation

The average air density during testing was 1.10 kg/m^3 (0.069 lb/ft^3). The average inlet velocity for all cyclones was 922 m/min (3024 fpm) (standard deviation = 41 m/min [134 fpm]), and the inlet velocities of all runs were within the range of the specified TCD method.

Figure 5 shows that average PSD of PM deposited on the filters located downstream of the cyclone.

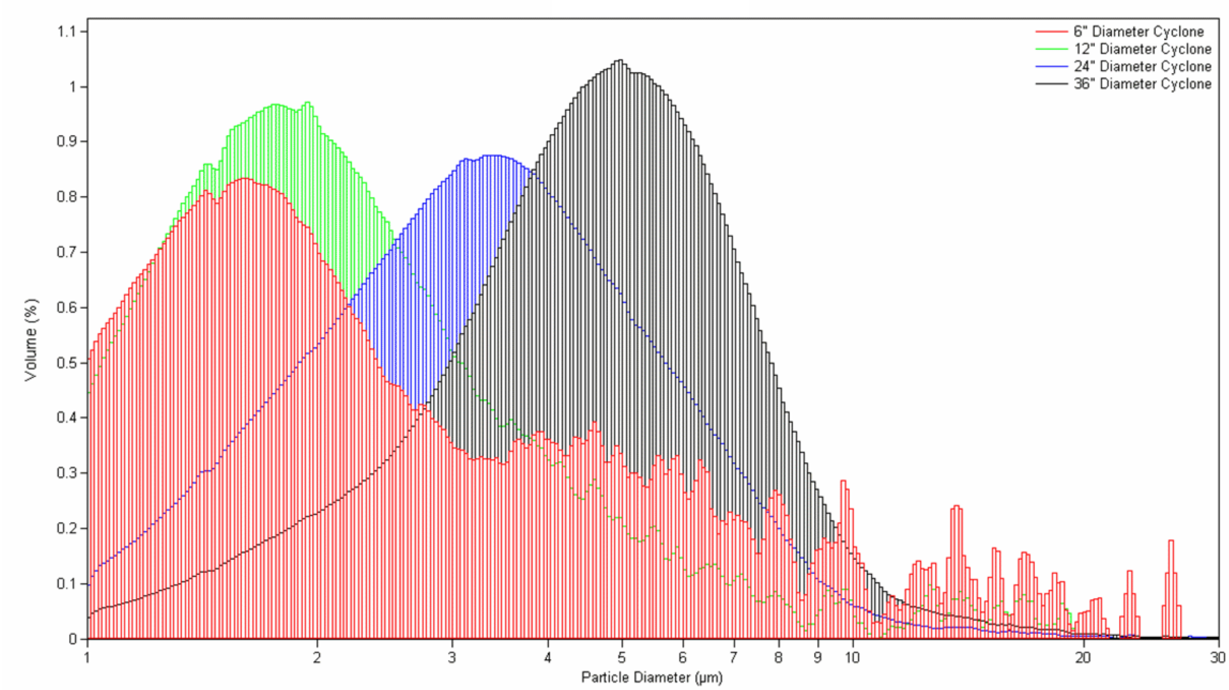

Figure 5. Average PSDs of PM collected on filters downstream of cyclones.

Analysis of variance tests were conducted on the cut points and slopes of all treatments using SPSS (SPSS, Inc., Chicago, IL). A two-tailed post hoc Tukey's HSD procedure was used with the null hypothesis ($\alpha = 0.05$) that the cut points for each treatment were equal, and a second test was conducted with the null hypothesis ($\alpha = 0.05$) that the slopes of the FECs for each treatment were equal.

The cut points and slopes for each treatment are shown in table 2. No significant difference was detected in cut point among any of the cyclones tested. The average cut point was 3.8 ± 0.2-μm aerodynamic equivalent diameter.

No significant difference was detected between the slopes of the two smallest cyclone sizes: 15.24- and 30.48-cm (6- and 12-in.). Significant differences ($\alpha < 0.05$) in slope were detected between the 60.96 cm (24 in.) cyclone and all other cyclones as well as the 91.44 cm (36 in.) cyclone and all other cyclones. The slope of the FEC increased as cyclone barrel diameter increased.

Table 2. Cyclone cut points and slopes with 95 percent confidence intervals.[y]

Cyclone Diameter cm (in.)	**d_{50}[z] (um)**	**Slope**
15.24 (6)	3.4 ± 0.2[a]	1.47 ± 0.11[a]
30.48 (12)	3.9 ± 0.4[a]	1.47 ± 0.17[a]
60.96 (24)	4.0 ± 0.6[a]	1.79 ± 0.14[b]
91.44 (36)	3.9 ± 0.4[a]	2.29 ± 0.10[c]

[y] Values in a column followed by the same letter are not statistically different ($\alpha = 0.05$) as determined by Tukey's HSD.
[z] Cut point values are given in aerodynamic equivalent diameter.

Model Evaluation

Of the aforementioned mathematical models, only the energy dissipation model predicted no change in cyclone cut point with changes in cyclone barrel diameter, indicating that this model may be the most appropriate model for determining cyclone cut point. However, additional research should be conducted to determine whether the cut point is affected by the PSD of the PM. Furthermore, additional work should be done to determine the nature of the relationship between cyclone barrel diameter and the FEC slope.

Conclusions

The cut points and slopes of 15.24, 30.48, 60.96, and 91.44 cm (6, 12, 24, and 36 inch) diameter 1D3D cyclones operated with similar inlet velocities were compared using fine PM to maximize differences in cyclone collection efficiency due to differences in cyclone barrel diameter. The cut point of the tested cyclones showed no relationship to barrel diameter while the slope of the FEC increased with increasing barrel diameter with statistically significant ($\alpha = 0.05$) differences found among the 30.48, 60.96, and 91.44 cm (12, 24, and 36 inch) diameter cyclones. None of the previously published mathematical models analyzed in this study accurately predicted the cut point of the 1D3D cyclones.

A proper understanding of the relationship between cyclone diameter and performance is important for the design of air pollution abatement systems in order to accurately predict the abatement efficiency. In future work, research should be conducted to determine whether the cut point is affected by the PSD of the PM. Furthermore, additional work should be done to determine the nature of the relationship between cyclone barrel diameter and the FEC slope. Also, further analysis (both engineering and economic) should be done to determine the impact of changes in cyclone performance with diameter on the use of cyclones in industrial applications.

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Disclaimer

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