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Effects of Cyclone Diameter on Performance of 1D3D Cyclones: Collection Efficiency

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Abstract. *Cyclones are the most commonly used air pollution abatement device for separating particulate matter (PM) from air streams in agricultural processes, such as cotton gins. 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 and collection efficiency based on empirical data. Tests were performed comparing cyclone collection efficiency 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 of PM that penetrated the cyclones was used to determine the collection efficiency of each cyclone. The collection efficiency of cyclones decreased nonlinearly as cyclone diameter increased with statistically different collection efficiencies observed among the 30.48-, 60.96-, and 91.44-cm (6-, 12-, 24-, and 36-in.) diameter cyclones. None of the mathematical models analyzed in this paper accurately predicted cyclone performance.*

Keywords. Cyclone, collection efficiency, particulate matter, PM, similitude, dust, abatement

Introduction

Cyclones are the most commonly used air pollution abatement device for separating particulate matter (PM) from air streams in agricultural 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).

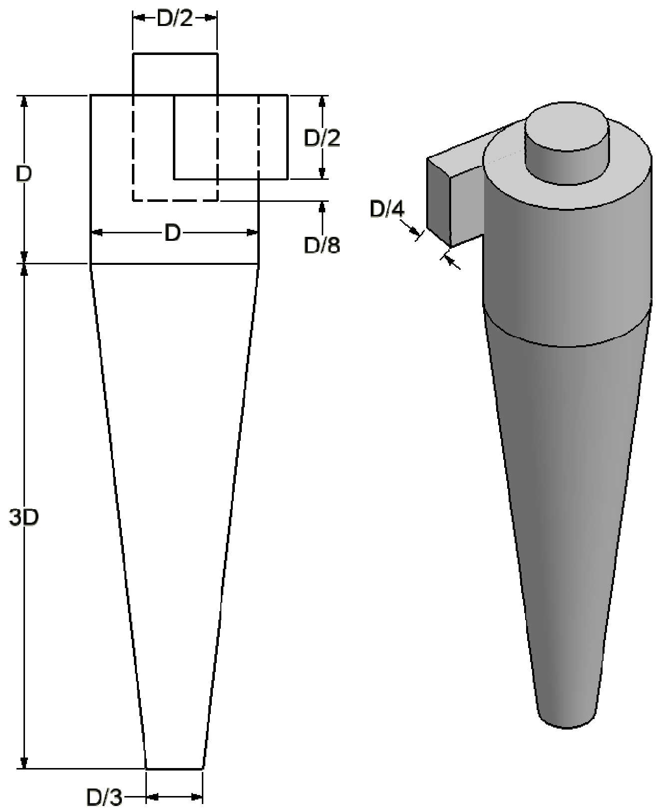

Figure 1. 1D3D cyclone configuration.

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, where cyclone cut point is defined as the particle diameter corresponding to a 50% collection efficiency. 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 1 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:

$$d_p = \sqrt{\frac{9\mu W}{\pi N_e V_i (\rho_p - \rho_g)}} \tag{1}$$

where: d_p = diameter of the smallest particle that will be collected by the cyclone 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 1:

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

where d_{pc} 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 3:

$$d_{pc} = \sqrt{\frac{9\mu W}{2\pi N_e V_i\left(\rho_p - \rho_g\right)}} \tag{3}$$

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. Barth's model (1956) was subsequently corrected by Wang et al. (2003) 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.

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 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. If cut point is a function of cyclone diameter, there may be significant benefits in utilizing smaller diameter cyclones to reduce PM emissions from process streams. The objective of this research is to characterize the change in cyclone performance with changes in cyclone diameter.

Materials and Methods

To determine cyclone collection efficiency 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 fourth mathematical model of the parth 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 4:

$$E = \int_0^d F dx \tag{4}$$

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 5:

$$L_b = N_b \pi D \tag{5}$$

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 6:

$$V_{t,c} = \frac{4D * V_{in}}{Z + 2D_c} \tag{6}$$

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 7:

$$F = m\frac{v^2}{r} \tag{7}$$

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 8, assuming that Z is equal to zero when t is equal to zero.

$$Z = \int_0^t \frac{4D * V_{in}}{(Z + 4D_c)\pi} t \tag{8}$$

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), Wang et al's corrected Barth model (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 and cut point, four 1D3D cyclones (15.24-, 30.48-, 60.96-, and 91.44-cm [6-, 12-, 24-, and 36-inch] diameter) were evaluated based on collection efficiency. The system used for testing is shown in figure 2.

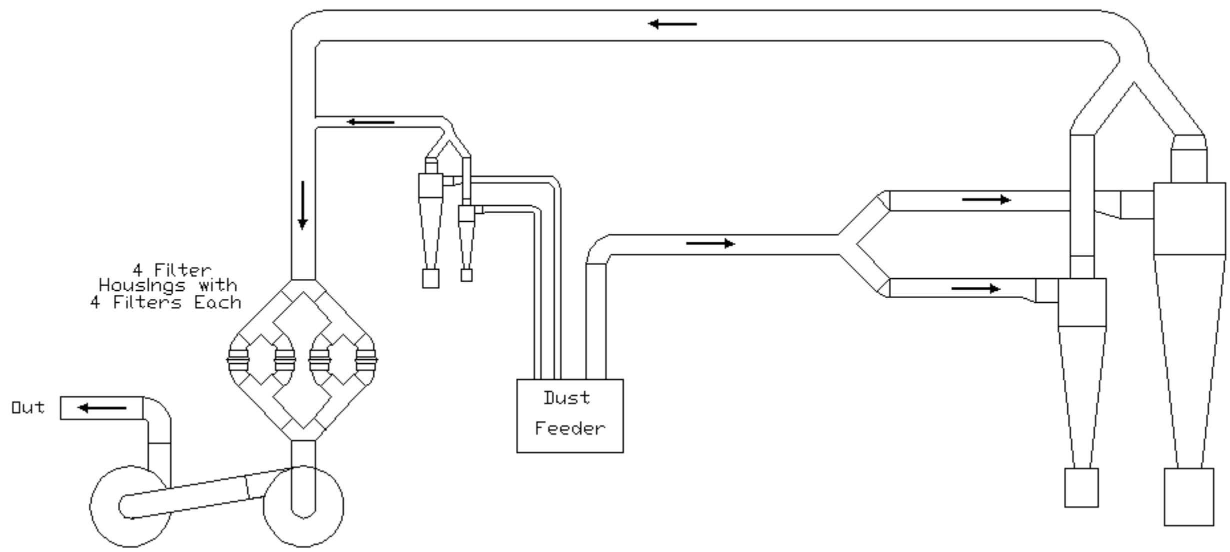

Figure 2. Cyclone testing system.

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 is 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 would be more sensitive to changes in cut point than if a larger aerosol was used.

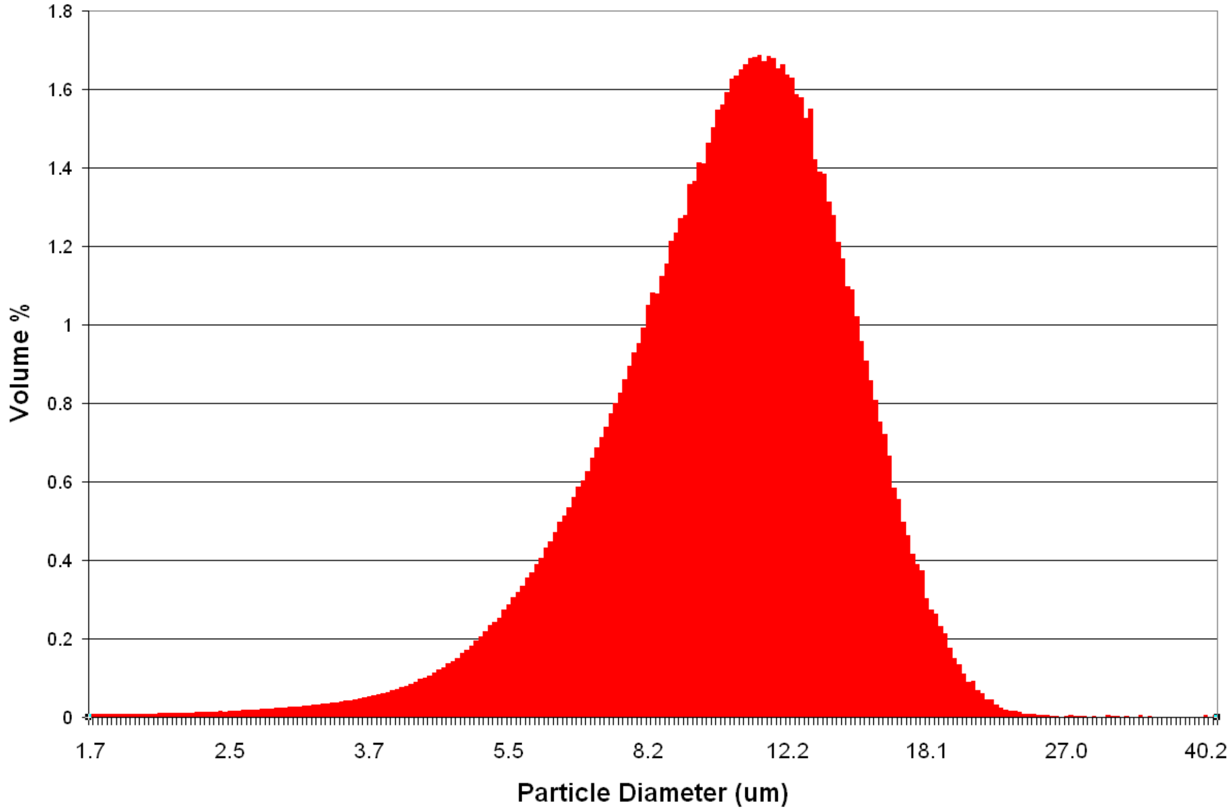

Figure 3. Particle size distribution of microalumina (in equivalent spherical diameter).

According to the TCD method, 1D3D cyclones should be operated with an inlet velocity of 975 ± 120 m/min (3200 ± 400 fpm) in order to balance the desire for maximum collection efficiency with the need for low pressure drop through the abatement device (Parnell, 1996). However, there is some debate as to whether the inlet velocity should be measured in terms of actual or standard flow rate. Therefore, tests were conducted using both actual and standard inlet velocities for all the 15.24-, 30.48-, and 60.96-cm [6-, 12-, and 24-in.] diameter cyclones. Due to limitations in air flow capabilities of the test system, it was not possible to test the 91.44-cm (36-in.) diameter cyclone using standard inlet velocities. The standard flow rate of air was calculated based upon a standard air density of 1.20 kg/m^3 (0.075 lb/ft^3) using equation 9:

$$Q_{std} = Q_{act} \frac{\rho_{act}}{\rho_{std}} \tag{9}$$

where: Q_{std} = flow rate of standard air (m^3/min),

Q_{act} = measured flow rate (m^3/min),

ρ_{act} = measured density of air (kg/m^3), and

ρ_{std} = density of standard air (kg/m^3).

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 PM feed rate was verified by weighing the feeder before and after each test to the nearest 4.5 g (0.01 lb). 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 10μg 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 50 micrograms, the filter was re-weighed.

Tests were conducted in a randomized complete block design with replication as the blocking factor. All 11 tests, shown in table 1, were run, in random order, within each block. The blocks were replicated five times for a total of 55 runs. Blank runs were used to account for the residual PM in the system from previous runs that may have dislodged and collected on the filters. Blanks were run for all the cyclones in same manner and time interval as the regular test runs, except no PM was fed and blank runs were only performed at actual air flow rates. The mass of PM collected on the filters and in the cyclone trash exit containers during the blank tests were intended to be used as correction values for the equivalent size cyclone tests in the same block.

Table 1. Summary of treatments tested within each block.

Cyclone Diameter	**Cyclone Inlet Air Velocity (975 m/min [3200 fpm])**	**Particulate Loading Rate (g/m^3)**
15.24 cm (6 in.)	Actual	0 (blank)
	Actual	3
	Standard	3
30.48 cm (12 in.)	Actual	0 (blank)
	Actual	3
	Standard	3
60.96 cm (24 in.)	Actual	0 (blank)
	Actual	3
	Standard	3
91.44 cm (36 in.)	Actual	0 (blank)
	Actual	3

The cyclone collection efficiency was calculated using equation 10:

$$\eta = \frac{m_{trash}}{m_{trash} + m_{filter}} x100\% \quad (10)$$

where: η = collection efficiency of the cyclone (%),

m_{trash} = mass of PM collected in the trash bin of the cyclone (g), and

m_{filter} = mass of PM collected on the filter (g).

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:

$$d_{50} = ax^b \quad (11)$$

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 2. All R^2 values are equal to 1.00.

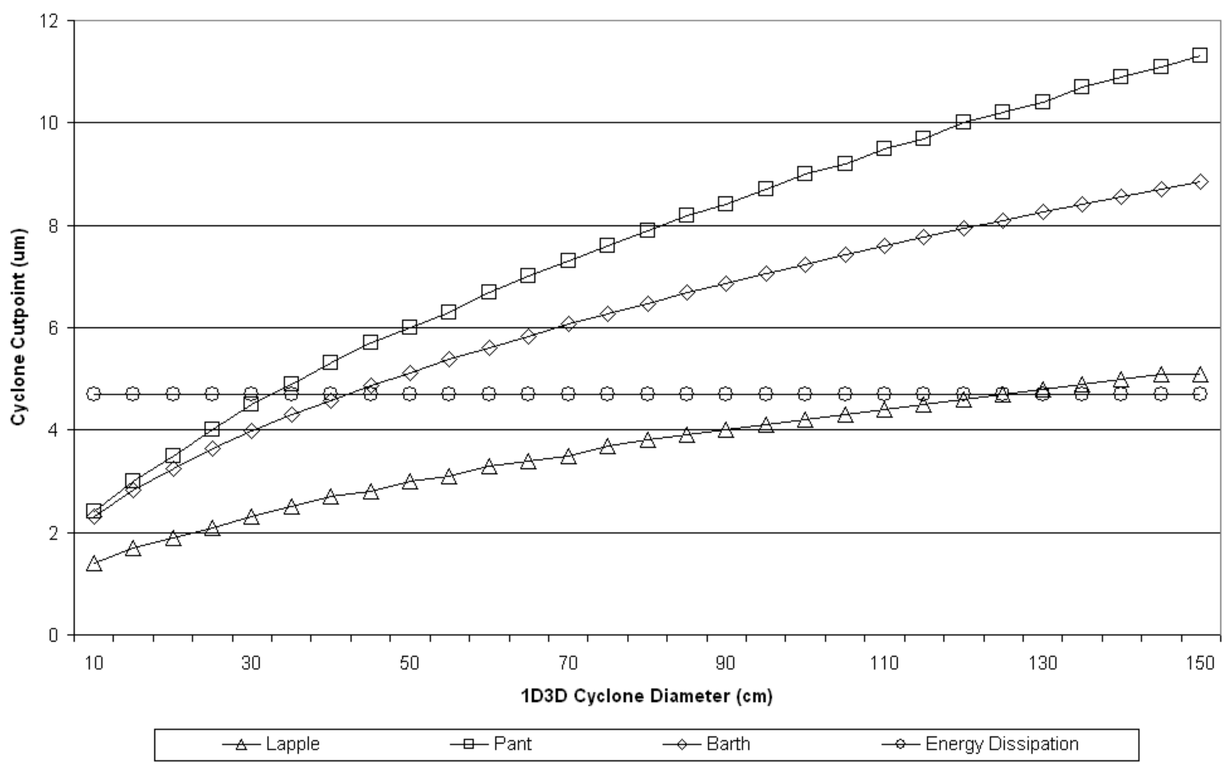

Figure 4. 1D3D cyclone cut point models.

Table 2. 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 #/ft^3). The average inlet velocity for all cyclones run at actual conditions was 922 actual m/min (3024 afpm) (standard deviation = 41 m/min [134 fpm]). The average inlet velocity for all cyclones run at standard conditions was 931 standard m/min (3056 sfpm) (standard deviation = 23 m/min [75 fpm]). The inlet velocities of all runs were within the range of the specified TCD method inlet velocity (i.e. all runs at actual conditions were between 853 and 1097 actual m/min [2800 and 3600 afpm]; all runs at standard conditions were between 853 and 1097 standard m/min [2800 and 3600 sfpm]).

The static pressure drop across all cyclones are shown in table 3:

Table 3. Static pressure drop across cyclones.

Barrel Diameter	Pressure Drop
15.24 cm (6 in.)	0.67 kPa (2.7 in H_2O)
30.48 cm (12 in.)	0.85 kPa (3.4 in H_2O)
60.96 cm (24 in.)	0.67 kPa (2.7 in H_2O)
91.44 cm (36 in.)	1.00 kPa (4.0 in H_2O)

The static pressure drop across the cyclones demonstrated no correlation to cyclone diameter. The average static pressure drop across all cyclones was 0.74 kPa (3.0 in. H_2O), with a standard deviation of 0.11 kPa (0.5 in H_2O). This pressure drop was only 70% of the pressure drop predicted using the TCD method.

An analysis of variance test was conducted on the collection efficiencies 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 collection efficiency of each treatment was equal. For each cyclone diameter, no difference was detected between trials run at actual conditions and standard conditions. Therefore all subsequent analyses were conducted only by cyclone diameter and not by inlet velocity treatment.

The collection efficiency of each cyclone size is shown in table 3. No significant difference was detected between the two smallest cyclone sizes: 15.24- and 30.48-cm (6- and 12-in.). Significant differences ($\alpha < 0.05$) 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.

Table 3. Cyclone collection efficiencies.

Cyclone Diameter cm (in.)	Collection Efficiency[a] (%)
15.24 (6)	99.49^a
30.48 (12)	99.17^a
60.96 (24)	97.86^b
91.44 (36)	94.52^c

[a] Values in a column followed by the same letter are not statistically different ($\alpha = 0.05$) as

determined by Tukey's HSD.

A regression analysis was also conducted to determine the relationship between cyclone diameter and collection efficiency for the conditions tested. A quadratic curve fit was applied using SPSS (fig. 5).

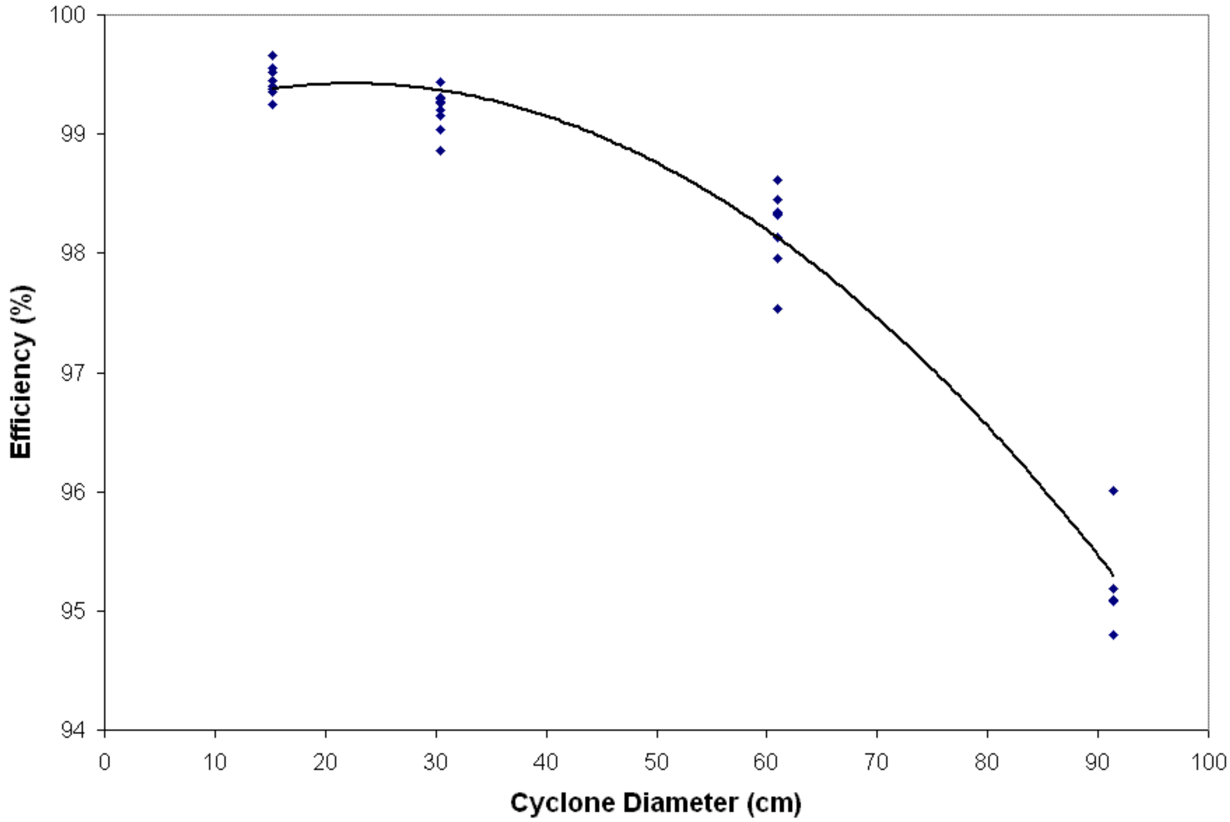

Figure 5. Regression of collection efficiency versus cyclone diameter for conditions tested.

The resulting regression (R^2 = 0.97; α < 0.0005) can be described by equation 12:

$$\eta = -0.0009d^2 + 0.0314d + 99.1587 \tag{12}$$

where: η = cyclone collection efficiency (%) and

d = cyclone diameter (cm).

The regression shown in equation 12 is only applicable for PM with PSDs similar to those used in this experiment. We expect that collection efficiencies of cyclones used in typical agricultural industries such as cotton gins and grain elevators would be higher than those reported here because the PM in the exhaust streams of such operations is significantly larger than that used in these tests.

Model Evaluation

The cyclone collection efficiency predicted by the aforementioned mathematical models when collecting PM with the same PSD (MMD of 10.3-µm AED and GSD of 1.40) as the microalumina used in this test as are shown in figure 6 (assuming the cyclone fractional efficiency curve has a constant slope of 1.4). The results of the Pant and Barth models under-predict cyclone collection efficiency when barrel diameter is greater that 15-cm, with the under-prediction growing more severe as barrel diameter increases. Furthermore, the energy dissipation model does not account for changes in cyclone collection efficiency with cyclone barrel diameter. The Lapple model follows the trend indicated by the results of empirical testing, but it still over-predicts the collection efficiency for the parameters tested.

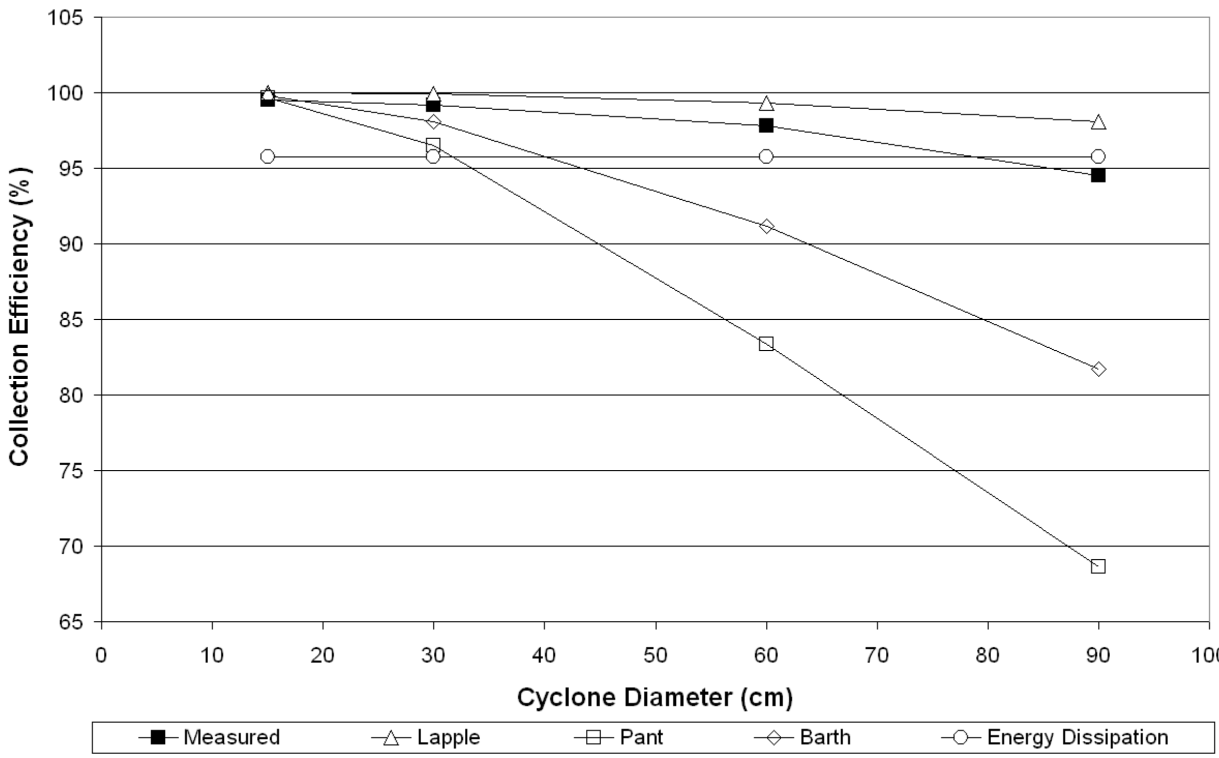

Figure 6. Modeled versus measured collection efficiencies.

Conclusions

The collection efficiency of the 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. The collection efficiency decreased non-linearly as cyclone diameter increased, 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 mathematical models analyzed in this study accurately predicted the performance of the 1D3D cyclones. The Lapple model slightly over-predicted measured performance, while the Pant and Barth models under-predicted collection efficiency, becoming less accurate as cyclone barrel diameter increased.

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, the data from this study will be used to develop a new mathematical model to relate cut point to cyclone diameter. 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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