2006 Beltwide Cotton Conferences, San Antonio, Texas - January 3 - 6, 2006

EFFECTS OF CYCLONE DIAMETER ON PERFORMANCE OF 1D3D AND 2D2D CYCLONES

William Brock Faulkner
Texas A&M University
College Station, TX
Bryan W. Shaw
Texas A&M University
College Station, TX
Michael D. Buser
USDA-ARS Cotton Production and Processing Research Unit
Lubbock, TX

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. This paper describes a system and the experimental design that will be used to empirically determine the relationship between the diameter and performance of 1D3D cyclones. Six, 12, 24, and 36 inch cyclones will be tested using a polydisperse PM with an aerodynamic mass median diameter near ten microns. The mass of PM collected by the cyclones and the mass of PM that penetrates the cyclones and is deposited on a set of filters will be used to determine the collection efficiency of each cyclone. The objective of this research is to develop a model to accurately characterize the change in cyclone performance with changes in cyclone diameter based on empirical data.

Introduction

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. Cyclones are relatively inexpensive to install and operate and have no moving parts, thus minimizing maintenance requirements. An air stream containing PM enters a cyclone tangentially near the top of the cyclone and flows downward in a spiral. Inertial and centrifugal forces move the particulates outward to the wall of the cyclone where the PM slides down to the trash outlet at bottom of the cone section and are removed.

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 (Wang et al., 2000). 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 the cyclone cut point is defined as the particle diameter corresponding to 50% collection efficiency. However, Lapple's approach does not account for the effects of PSD on cyclone performance, documented by Wang et al. (2000). Similarly, Pant et al. (2002) developed an empirical relationship that predicts 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. Barth (1956) developed a model to predict cyclone cut point as a function of volumeric flow rate, effective cyclone length, and inlet velocity. Barth's model was subsequently corrected by Wang, et al (2003) to more closely match experimental data taken using 6 inch diameter 1D3D and 2D2D cyclones.

The Texas A&M Cyclone Design (TCD) method specifies cyclone dimensions based on a the diameter (D_c) of the cyclone barrel (Figure 1). The barrel diameter is selected so that the volumetric flow rate of air (determined by the application) through the inlet cross-section ($D_c/2 \times D_c/4$) results in the TCD design inlet velocity (3200±400 fpm for 1D3D cyclones). 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

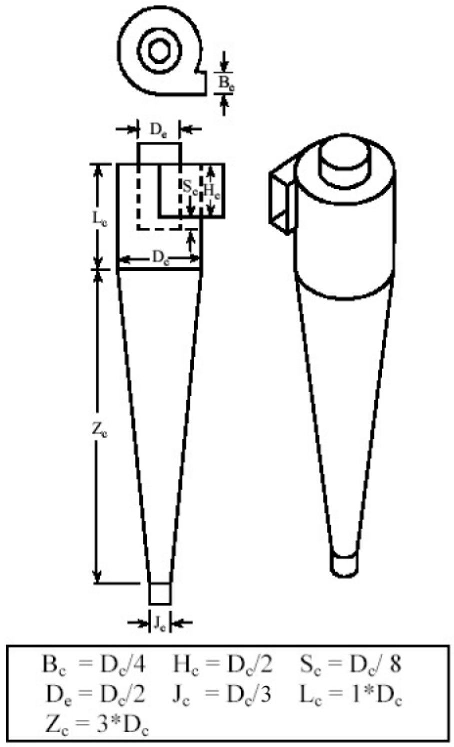

Figure 1. 1D3D cyclone configuration.

Each of the aforementioned models: Lapple (1951), Barth (1956), Pant et al. (2002), and Wang et al. (2003), was used to predict the cut point of 1D3D cyclones ranging in size from 4 to 60 inches in diameter. All models predicted an increase in cut point as cyclone diameter increased. The predicted cut points increase according to the equation:

$$d_{50} = ax^{b} \tag{1}$$

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

The value of *a* ranged from 0.96 to 2.29, and the value of *b* ranged from 0.49 to 0.58, with all R^2 values equal to 1.00.

Another simplified model of a given particle's path through a cyclone was used such that 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 2:

$$\int_0^d E = Fdx \tag{2}$$

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 3:

$$L_b = N_b \pi D_c \tag{3}$$

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_c = 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 4:

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

where: $V_{t,c}$ = tangential velocity at time t in the cyclone cone (m/s),
D_c = 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 was calculated.

The distance traveled in the axial direction at time t can be found using equation 5, assuming that Z is equal to zero when t is equal to zero.

$$Z = \int_0^t \frac{4D_c * V_{in}}{(Z + 4D_c)\pi} t \tag{5}$$

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

Integrating the centrifugal force over the distance traveled (eq. 2), 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 laminar flow model, and it implies that, given fixed geometric proportions and inlet velocity, the cut point of a cyclone should not be a function of cyclone diameter.

The cut points of a 1D3D cyclone operating with an inlet velocity of 3200 fpm that are predicted by each of the models mentioned above are shown in Figure 2.

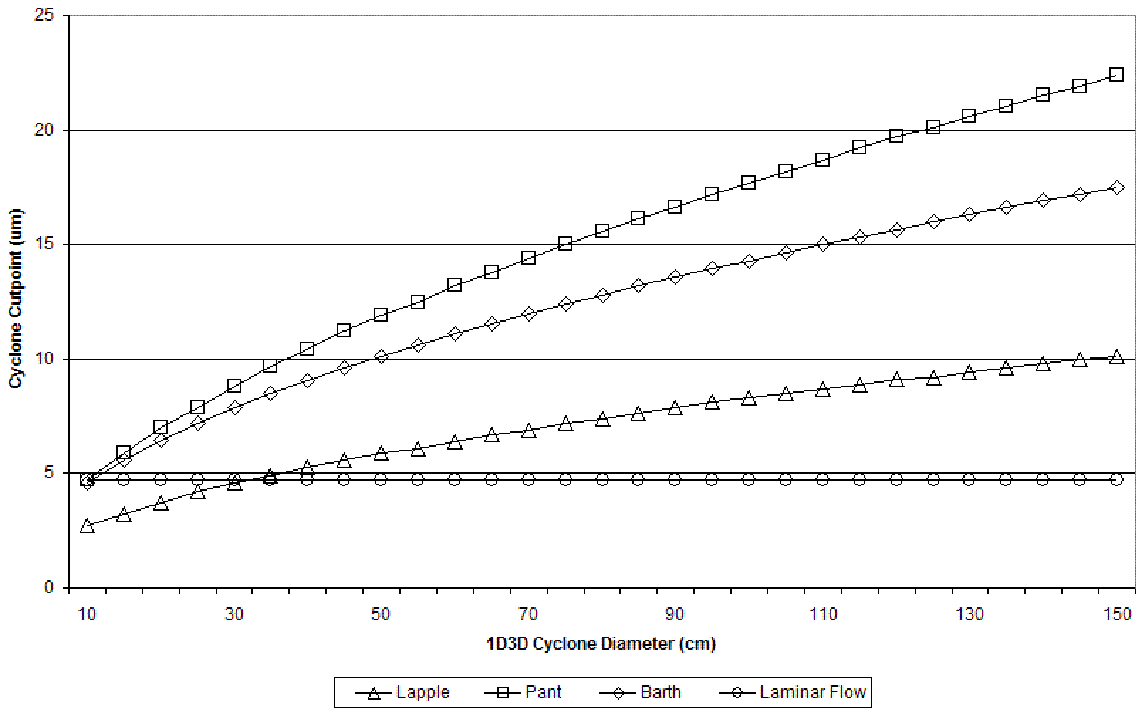

Figure 2. 1D3D cyclone cut point models.

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 a dust with a consistent PSD, the total collection efficiency of a cyclone will increase as its 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 develop a model to accurately characterize the change is cyclone performance with changes in cyclone diameter based on empirical data. This paper describes the experimental design that will be used to determine the change in cyclone performance with changes in cyclone diameter.

Methods

To determine the relationship between cyclone barrel diameter and cut point, four 1D3D cyclones (6-, 12-, 24- and 36-inch diameter) will be evaluated based on collection efficiency. The system used for testing is shown in Figure 3.

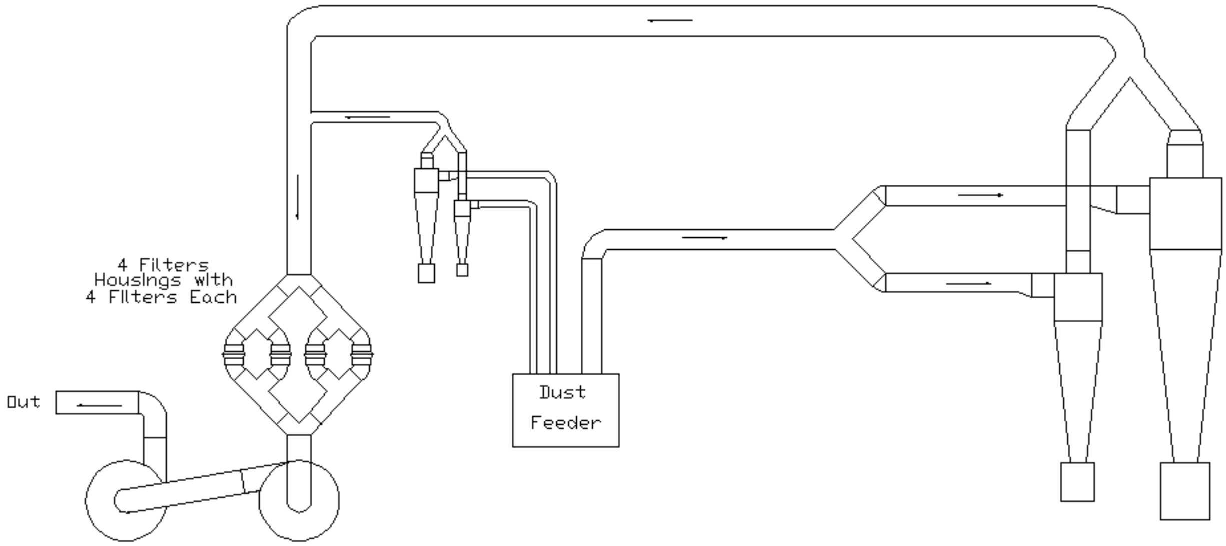

Figure 3. Schematic of cyclone testing system.

According to the Texas A&M Cyclone Design method, 1D3D cyclones should be operated with an inlet velocity of 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 actual or standard terms. Therefore, where possible, tests will be conducted using both actual and standard inlet velocities. The standard flow rate of air is calculated based upon a standard air density of 0.075 lb/ft^3 using equation 6:

$$Q_{std} = Q_{act} \frac{\rho_{act}}{\rho_{std}} \qquad (6)$$

where: Q_{std} = flow rate of standard air,
Q_{act} = measured flow rate,
ρ_{act} = measured density of air (lb/ft^3), and
ρ_{std} = density of standard air (lb/ft^3).

Due to the limitations of the fans used in these experiments, it is not possible to test the 36 inch cyclone using standard inlet velocities.

Before each test, the system will be run with no filters for several minutes to clean out any residual PM in the ducts. Microalumina (mass median diameter [MMD] = 10.3-µm aerodynamic equivalent diameter [AED] and geometric standard deviation [GSD] = 1.40, Figure 3) will be fed into the cyclone at a rate of 3 g/m^3. An AccuFeeder vibratory screw feeder (VibraScrew, Inc.; Totowa, NJ) will be used to meter the PM into the system, and the feed rate will be verified by weighing the feeder before and after each test to the nearest 0.01 lb.

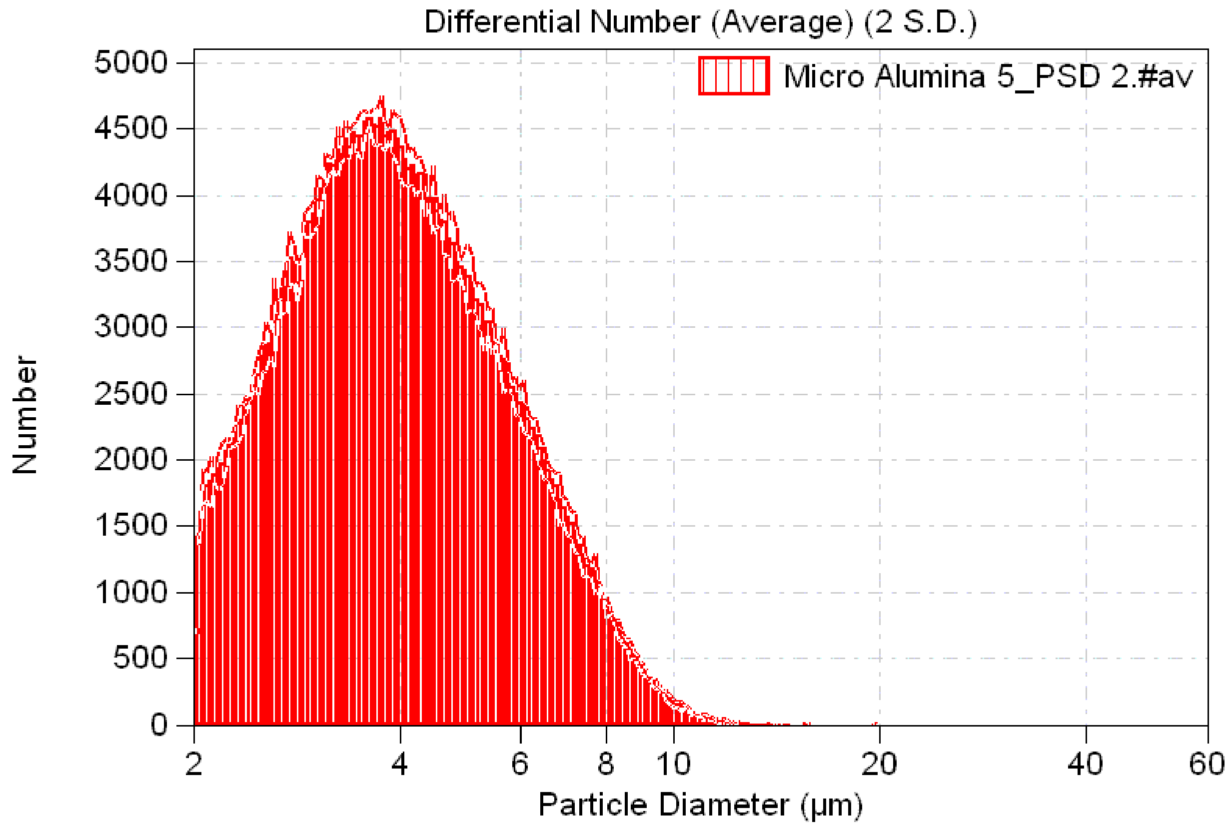

Figure 4. Particle size distribution of microalumina (in equivalent spherical diameter).

Tests will be conducted for 30 minutes for the 6, 12, and 24 inch diameter cyclones in order to obtain sufficient loading on the filters for gravimetric and PSD analysis. 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 36 inch diameter cyclone will be limited because the static pressure drop across the filters increases rapidly as the PM that penetrates the cyclone is deposited on the filter. The 36 inch diameter cyclone tests will be run until the system flow rate falls to such a point that the cyclone inlet velocity is 2800 afpm. Baffles on the exhaust side of the fans (after the filters) will be used to adjust the system flow rate to compensate for reduced flow that occurs as the filters are loaded.

The PM captured by the cyclone will be collected in a sealed container, and, for each run, the mass of PM collected will be determined using an A&D model HP-20K scale with a 0.1 g resolution. PM that penetrates the cyclone will be collected on 16 – 8x10" glass fiber filters. The filters will be conditioned for a minimum of 48 hours in an environmental chamber at 70°F and 35% relative humidity. The filters will be weighed before and after the test runs to determine the mass of PM that penetrates the cyclone. Each filter will be weighed to the nearest 10µg three times before and after the test using an AG-285 (Mettler Toledo) scale. If the standard deviation of the three runs exceeds 50 micrograms then the filters will be re-weighed. If the standard deviation of the filter weights is within tolerance, the three weights will be averaged.

Tests will be conducted in a randomized block design with replication as the blocking factor. All 11 tests in Table 1 will be run, in random order, within each block. The blocks will be replicated five times for a total of 55 runs. Within each block, blanks will be run for all cyclones in which the cyclones will be operated as previously described, except no PM will be fed. The purpose of the blanks is to correct for the residual PM in the system from previous run that may have dislodged and then collected on the filters. Blanks will be run for 30 minutes for the 6, 12, and 24 inch diameter cyclones. For the 36 inch cyclone, the blank test will be run for the same duration as the test with PM in the same block. The mass of PM collected on the filters and in the trash barrels during the blank tests will be used as a background concentration for the equivalent size cyclone tests in the same block.

Table 1. Summary of treatments tested within each block.

Cyclone Diameter (in)	Inlet Velocity	Loading Rate
6	3200 actual fpm (afpm)	0 g/m^3 (blank)
6	3200 afpm	3 g/m^3
6	3200 standard fpm (sfpm)	3g/m^3
12	3200 afpm	0 g/m^3 (blank)
12	3200 afpm	3 g/m^3
12	3200 afpm	3g/m^3
24	3200 afpm	0 g/m^3 (blank)
24	3200 afpm	3 g/m^3
24	3200 afpm	3g/m^3
36	3200 afpm	0 g/m^3 (blank)
36	3200 afpm	3 g/m^3

The collection efficiency of the cyclone will be calculated for each trial using equation 7:

$$\eta = \frac{m_{trash}}{m_{trash} + m_{filter}} x100\% \quad (7)$$

where

η = collection efficiency of the cyclone (%)
m_{trash} = mass of PM collected in the trash bin of the cyclone (g)
m_{filter} = mass of PM collected on the filter (g)

Static pressures will be measured throughout the system during testing to ensure that the system functions properly and to monitor the static pressure loss associated with different cyclone sizes.

Results

As the gravimetric and PSD analyses have not been completed at this time, the results will be presented at a later time.

Because tests of the 36 inch cyclones will last less than two minutes compared to the 30 minute tests used for the 6, 12, and 24 inch cyclones, no statistical comparison will be made between the 36 inch and any other cyclone. For this reason, statistical analyses will be conducted for the 6, 12, and 24 inch cyclones, but only trends will be discussed in relation to the results of the 36 inch cyclone.

An analysis of variance test will be conducted on the collection efficiencies of all treatments. A post hoc Tukey's HSD procedure will be used with a null hypothesis ($\alpha = 0.05$) that the collection efficiency of each treatment is equal.

Conclusions

Several mathematical models have been proposed to predict the performance of cyclone abatement systems for separating PM from air streams. Four of these models were used to determine the cut point of 1D3D cyclones operating at 3200 fpm, and the results diverged significantly as cyclone diameter increased. This paper describes the design of a system to test the collection efficiency of 6, 12, 24, and 36 inch 1D3D cyclones operated with similar inlet velocities in order to empirically determine the change in cyclone performance with cyclone size. A proper understanding of the relationship between cyclone diameter and performance is important for the design of air pollution abatement systems such as those at cotton gins.

References

Barth, W. 1956. *Design and layout of the cyclone separator on the basis of new investigations.* Brenn. Warme Kraft 8:1-9.

Lapple, C.E. 1951. Processes use many collector types. *Chemical Engineering* 58(5).

Pant, K., C.T. Crowe, and P. Irving. 2002. On the design of miniature cyclones for the collection of bioaerosols. *Powder Technology* 125(2-3): 260-265.

Parnell, C. B. 1996. Cyclone design for air pollution abatement associated with agricultural operations. *Proc. of the 1996 Beltwide Cotton Production Conferences*. Nashville, Tenn.: National Cotton Council.

Wang, L., C.B. Parnell and B.W. Shaw. 2000. 1D2D, 1D3D, 2D2D cyclone fractional efficiency curves for fine dust. In *Proceedings of the 2000 Beltwide Cotton Conferences*. San Antonio, TX: National Cotton Council.

Wang, L., C.B. Parnell and B.W. Shaw. 2001. *A new theoretical approach for predicting number of turns and cyclone pressure drop*. Paper Number 014009. St. Joseph, Mich.: ASAE.

Wang, L., C.B. Parnell, B.W. Shaw, and R.E. Lacey. 2003. *Analysis of cyclone collection efficiency*. Paper Number 034114. St. Joseph, Mich.: ASAE.