Efficiency and Pressure Drop of Cyclones Across a Range of Inlet Velocities

W. B. Faulkner, B. W. Shaw

Abstract. *Cyclone separators are widely used in agricultural processing industries as air pollution abatement devices. The Texas A&M Cyclone Design (TCD) method is a simple method for designing cyclones based on an inlet design velocity. The TCD method specifies "ideal" inlet velocities of 975 ± 120 m/min (3200 ± 400 fpm) and 914 ± 120 m/min (3000 ± 400 fpm) for 1D3D and 2D2D cyclones, respectively. There is evidence that higher dust collection efficiencies may be obtained from cyclones using different inlet velocities than those specified as the "ideal" velocity. This article quantifies the inlet velocities at which maximum collection efficiencies are obtained for 1D3D and 2D2D cyclones and the marginal pressure drop associated with reaching these collection efficiencies. It is demonstrated that for large particles, the collection efficiency of six inch diameter 1D3D and 2D2D cyclones is similar for inlet velocities from 10.16 standard m/s (2000 fpm) up to the design velocity, with significantly lower pressure drop at lower inlet velocities.*

Keywords. *Cyclone, 1D3D, 2D2D, Abatement, Inlet velocity, Collection efficiency.*

Cyclones are the most widely used air pollution abatement devices for removing particulate matter from air streams in agricultural processing industries. Relative to other abatement systems, cyclones have low initial costs, maintenance requirements, and energy consumption. Cyclones use centrifugal force to separate particulates from an air stream. A dust-laden air stream enters a cyclone tangentially near the top of the cyclone and flows downward in a spiral. Inertial and centrifugal forces act on the particulates, forcing them to the wall of the cyclone where they slide down the wall to the bottom of the cone and are removed. The air stream spirals to the bottom of the device, where it reverses direction and flows upward and out the top of the cyclone (Cooper and Alley, 2002).

The Lapple cyclone design method, often referred to as the standard cyclone design method, specifies the dimensions of a cyclone based on the barrel diameter. The most commonly used cyclones are the 2D2D (Shepherd and Lapple, 1939) and 1D3D cyclones (Parnell and Davis, 1979). The Ds in the 1D3D and 2D2D designations refer to the diameter of the cyclone barrel, while the numbers preceding the Ds refer to the length of the barrel and cone sections, respectively. A 1D3D cyclone, for instance, has a barrel length equal to the barrel diameter and a cone length equal to three times the barrel diameter. The design parameters for 1D3D and 2D2D cyclones are shown in figure 1.

The Lapple cyclone design method also predicts the efficiency with which particles of a given size will be separated from the air stream. According to the Lapple method, dust collection efficiency increases unconditionally with increased air stream velocity. However, according to Parnell (1996), above a threshold airspeed, the vortex inside a cyclone becomes disturbed and collection efficiencies decline. Furthermore, Parnell (1996) indicates that the Lapple method significantly underestimates collection efficiency.

The efficiency of cyclone systems is a function of the particle size distribution (PSD) of entrained dust and the velocity of the air stream entering the abatement device (Wang et al., 2000). The particle size distribution of most aerosols can be described by a log-normal distribution (Hinds, 1999). While they have historically been considered low-efficiency collectors, recent studies have shown that cyclones can reach efficiencies exceeding 99% for particles larger than five micrometers (Cooper and Alley, 2002).

The Texas A&M Cyclone Design (TCD) method is a simple method for designing cyclones based on an "optimal" inlet velocity. According to the TCD method, the optimal inlet air speed for a 1D3D cyclone is 975 ± 120 m/min (3200 ± 400 fpm) and 914 ± 120 m/min (3000 ± 400 fpm) for 2D2D cyclones under standard conditions (Parnell, 1996). The air stream velocities specified by the TCD method seek to balance the competing desires for high efficiency and low pressure drop through the abatement device. Further testing has indicated that higher efficiencies than those predicted by the TCD method may be achieved by increasing air speed through the cyclone. However, an increase in exit concentrations has been observed for velocities that are significantly higher or lower than the design velocities. This higher collection efficiency is accompanied by increased pressure drop across the cyclone, thus requiring higher energy inputs. There may be times when it is economically beneficial for a processing industry to incur higher energy costs rather than

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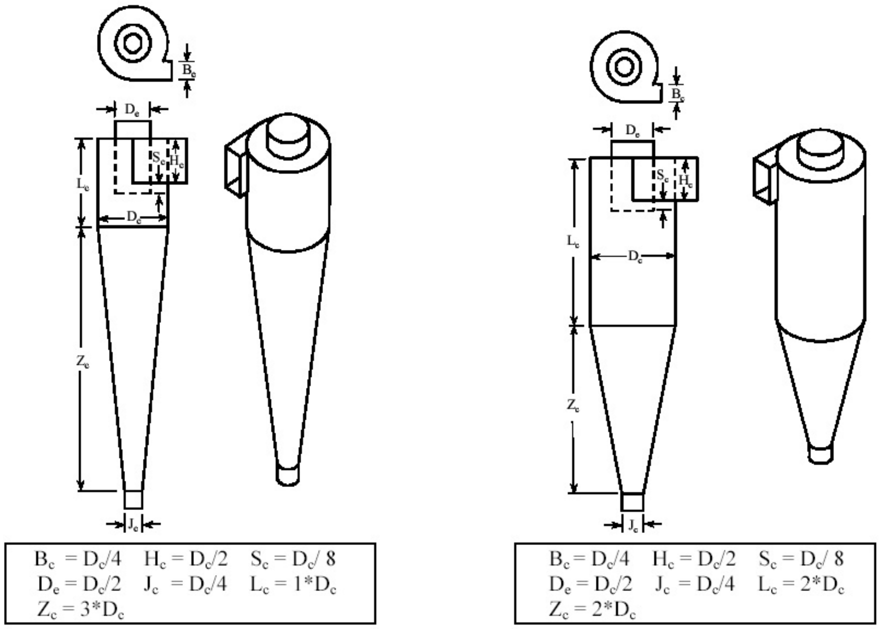

Figure 1. 1D3D and 2D2D cyclone layouts (Wang et al., 2003).

convert to a filter system, the cost of which may be five to ten times higher than that of a cyclonic abatement system (Parnell, 1996).

The objective of the research described in this article is to characterize the collection efficiency and pressure drop associated with 1D3D and 2D2D cyclones across a range of inlet velocities. A secondary objective is to determine the maximum collection efficiency and associated inlet velocity for 1D3D and 2D2D cyclones with varying loading rates of two dust samples. Additionally, the "optimal" inlet velocities specified by the TCD method will be evaluated based on collection efficiency and operating costs, which are a function of both inlet velocity and pressure drop.

MATERIALS AND METHODS

A three-factorial experiment was conducted for both 1D3D and 2D2D cyclones, varying inlet loading concentration, aerosol PSD, and inlet velocity. Commercially available cornstarch and alumina were used as the test dusts in these trials (table 1). Cornstarch was used because the PSD of cornstarch is similar to that of corn dust from grain elevators. Alumina was also used because a second dust with a relatively low mass median diameter (MMD) was desired. A Beckman Coulter Counter Multisizer™ 3 (Beckman Coulter, Miami, Fla.) was used to determine the PSD of each dust. The Coulter Counter is calibrated by the manufacturer annually and by laboratory technicians every 100 runs.

The Coulter Counter measures Equivalent Spherical Diameter (ESD) which is then converted to Aerodynamic Equivalent Diameter (AED) using equation 1:

$$AED = ESD\sqrt{\frac{\rho_p}{\chi}} \qquad (1)$$

where

AED = aerodynamic equivalent diameter

ESD = equivalent spherical diameter

ρ_p = particle density (g/cm^3)

χ = shape factor

The AED of an aerosol particle is the diameter of a unit density sphere (i.e.: density = 1.00 g/cm^3) that would have the same settling velocity as the particle or aerosol in question.

The particle size distribution was described as a log-normal distribution using a MMD and geometric standard deviation (GSD), where MMD is the particle size for which half of the mass is contributed to by particles smaller than the MMD and half by particles larger than the MMD (Hinds, 1999). The GSD is calculated using equation 2:

$$GSD = \sigma_g = \frac{d_{84.1\%}}{d_{50\%}} = \frac{d_{50\%}}{d_{15.9\%}} = \sqrt{\frac{d_{84.1\%}}{d_{15.9\%}}} \qquad (2)$$

where $d_{n\%}$ is the particle size for which n percent of the mass is contributed by particles less than d.

1D3D and 2D2D metal cyclones with a diameter of 0.1524 m (6 in.) were used to conduct experiments with the pull system shown in figure 2.

A laminar flow element (LFE) (Meriam Instrument Model 50MC2-2, Serial No. 773880-NI, Cleveland, Ohio), calibrated by the manufacturer, was used to determine the flow rate of air through the system, and a voltage controller was used to obtain the desired flow rate. The actual flow rate was corrected for air temperature using a correction factor furnished by the LFE manufacturer.

Table 1. Properties of experimental aerosols.

Aerosol	Particle Density (g/cm^3)	Shape Factor	MMD (AED[a]) (μm)	GSD
Cornstarch	1.5	1.00	17.95	1.41
Alumina	3.9	1.44[b]	9.96	1.42

[a] Aerodynamic equivalent diameter.
[b] Source: (Mark et al., 1985).

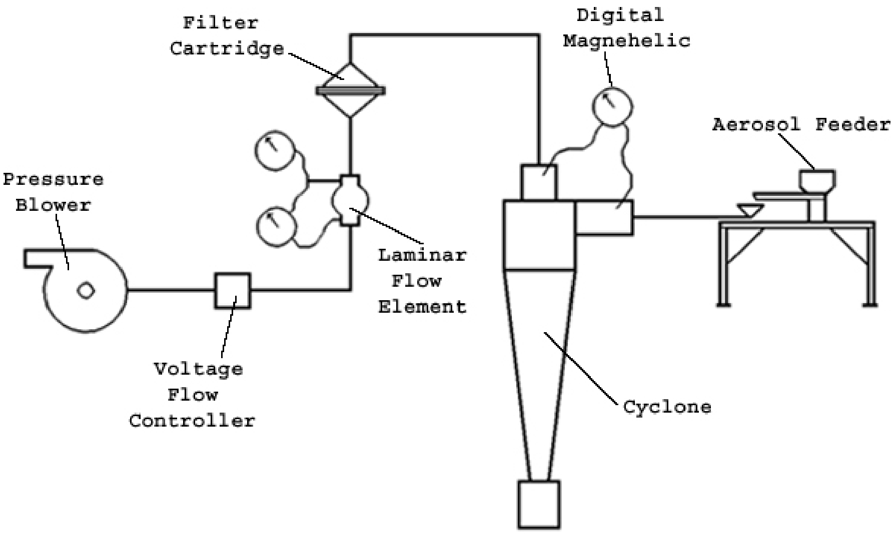

Figure 2. Cyclone testing system.

For each test, the temperature, barometric pressure, and relative humidity were recorded. Wang et al. (2003) demonstrated that for highest efficiency, cyclones should be designed based on inlet velocities of dry-standard air rather than actual conditions. A digital magnehelic (Dwyer Instruments, Series 475 Mark III, Michigan City, Ind.) was used to determine the negative pressure created by the cyclone, filter, and piping upstream of the LFE, and the standard flow rate through the system was calculated. The standard flow rate of air was calculated based on the actual air density and a standard density of 1.20 kg/m^3 (0.075 lb/ft^3) using equation 3:

$$Q_{std} = Q_{act} \frac{\rho_{act}}{\rho_{std}} \tag{3}$$

where
- Q_{std} = flow rate of standard air
- Q_{act} = measured flow rate
- ρ_{act} = measured density of air (kg/m^3)
- ρ_{std} = density of standard air (kg/m^3)

For each trial, a filter was placed in the filter holder and the fan was turned on. When equilibrium at the desired flow rate was reached, a measured mass of the aerosol was fed into the system using a vibratory feeder at a specified rate. The feed rate was controlled by adjusting the frequency of vibration and verified by visual inspection. Test durations were 3 min for glass fiber filters (for gravimetric analysis) and 10 min for Teflon filters (for gravimetric and particle size analysis). Tests were longer for filters used in particle size analysis so that enough dust would accumulate on the filters to run three sets of PSDs. Three minute tests were deemed sufficient for gravimetric analysis because the amount of dust that accumulates on a filter during a 3-min test is larger than the measurement variability of the scale used, and preliminary tests demonstrated that the dust collection efficiency of the cyclone is statistically similar ($\alpha < 0.05$) for 3- and 10-min tests.

Between tests the system was run for 3 min to clear any residual dust out of the system. During each trial, the mass of dust entrained in the system and the test duration were measured and used in conjunction with the volumetric flow rate through the system to determine the loading concentration according to equation 4:

$$C = \frac{m_{in}}{Q \times t} \tag{4}$$

where
- C = inlet loading concentration (g/m^3)
- m_{in} = mass of dust entrained in the system (g)
- Q = system flow rate (m^3/s)
- t = test duration (s)

The pressure drop across the cyclone and the laminar flow element were measured using digital magnehelics with a 0.01-kPa resolution (Dwyer Instruments, Series 475 Mark III, Michigan City, Ind.). Teflon filters (with 2-µm pore size) were used for replications requiring PSD analysis because of the lower background particle count as compared to glass fiber filters. The background particle count quantifies the number of particles within the size range of interest which are generated from analysis of a blank (unused) filter and are detected during particle size analysis. Evaluation of blank glass fiber filters by Buser (2004) indicated a background concentration of 12,388 particles in 500 µL of electrolyte, while 2-µm Teflon filters yielded only 58 particles in an equal amount of electrolyte. Glass fiber filters were used for the remaining replications requiring only gravimetric analysis as they require less fan power and are significantly less expensive than Teflon filters.

Particle size distributions of the aerosol emitted from the cyclone were obtained by placing ten 1.6-cm diameter samples containing particulates cut from random locations on a given filter into a lithium-chloride methanol electrolyte solution and placing this combination into an ultrasonic bath for 3 min. The solution was then filtered through a 100-µm screen to remove large particles. The strained electrolyte/particulate solution was injected into a beaker of electrolyte until a 6% to 7% concentration of dust in the electrolyte was obtained (Herber, 1988). For every PSD analysis in this article, three replications of three runs each were conducted for all filters and the average used as the reported PSD. Each run measured approximately 300,000 particles.

Initial experiments were conducted for the 1D3D cyclone at nominal inlet velocities of 10.16, 16.26, and 20.32 m/s (2000, 3200, and 4000 fpm), at loading rates of 1 and 2 g/m^3, and PSDs analyzed using the Coulter Counter. Loading rates were selected to approximate the loading expected in a process stream at a cotton gin and/or grain elevator. For each combination of inlet velocity and loading rate there were five replications (one using a Teflon filter and four using glass fiber filters). By conducting experiments at inlet velocities lower than, equal to, and higher than the design velocity specified by Parnell (1996), we established the magnitude of change expected. This allowed for appropriate inlet velocities to be selected for testing. Similar initial tests were conducted for the 2D2D cyclone at inlet velocities of 10.16, 15.24, and 20.32 m/s (2000, 3000, and 4000 fpm) at loading rates of 1 and 2 g/m^3.

For both cyclones, subsequent similar tests were run with 1- and 2-g/m^3 loading rates at inlet velocities ranging from 10.16 m/s (2000 fpm) at standard conditions, corresponding to the lowest recommended conveying velocity for seed cotton (Baker et al., 1994), to 20.32 m/s (4000 fpm), 2.04 m/s (400 fpm) above the maximum design velocity of the 1D3D cyclone according to the TCD method.

For gravimetric tests, filters were weighed before and after each trial using a 10-µg resolution scale (AG245, Mettler Toledo, Greifensee Switzerland). In order to reduce uncertainty associated with filter weights, three pre-weights and three post-weights were taken and the averages were used to determine the amount of dust collected on the filter.

The efficiency of cyclonic separation was calculated for each test using the equation 5:

$$\eta = 1 - \frac{\Delta m_{filter}}{m_{in}} \tag{5}$$

where

η = cyclone efficiency

Δm_{filter} = post-weight of the filter minus the pre-weight of the filter (g)

m_{in} = mass of dust entrained in the system (g)

An analysis of variance test was conducted on the collection efficiencies of all treatments, and the MMDs and GSDs of all Teflon filters for each treatment. A post hoc Tukey's HSD procedure was conducted to analyze the data. The null hypotheses tested (α = 0.05) were that the collection efficiencies of each treatment were equal and the MMD and GSD of emitted aerosols were equal.

A lognormal curve was used to describe the PSD data from each exposed Teflon filter. These characteristic lognormal distributions were subsequently used to determine the fractional efficiency curve (FEC) of the cyclone for each test. A fractional efficiency curve describes the efficiency with which a cyclone separates particles of a given size from the entering aerosol mixture. The cyclone collection efficiency for a given size range was determined using equation 6:

$$\eta_j = \frac{m_{in} \times f_{in,j} - m_{filter} \times f_{filter,j}}{m_{in} \times f_{in,j}} \tag{6}$$

where

η_j = fractional collection efficiency of jth size range

m_{in} = mass of dust entrained in the entering air stream

$f_{in,j}$ = fraction of dust entering the cyclone in the jth size range

m_{filter} = mass of dust deposited on the filter

$f_{filter,j}$ = fraction of dust deposited on the filter in the jth size range

The size distribution of the fractional collection efficiency is the difference between two lognormal distributions (the PSD of dust entrained in the air stream and the PSD of dust collected on the filter) and can also be described using a lognormal distribution. The size range at which 50% of the particles are collected is known as the cyclone cut point. The slope of the cyclone collection efficiency curve is described by equation 7:

$$Slope = \frac{d_{84.1\%}}{d_{50\%}} = \frac{d_{50\%}}{d_{15.9\%}} = \sqrt{\frac{d_{84.1\%}}{d_{15.9\%}}} \tag{7}$$

where $d_{n\%}$ is the particle size for which n percent of the particles are collected by the cyclone.

Results and Discussion

Using fractional efficiency curves, characteristics were determined for the 0.154-m (6-in.) cyclones used in these experiments (table 2). As expected, the measured cut points of both cyclones were proportional to the MMD of the experimental aerosol.

Collection Efficiency

For both the 1D3D and 2D2D cyclones and for both dusts at all tested inlet velocities, no significant difference was detected in cyclone collection efficiency between the inlet loading rates of 1 and 2 g/m^3.

For tests in which cornstarch was used as the test aerosol, no significant difference in cyclone efficiency was detected for either the 1D3D (fig. 3) or 2D2D (fig. 4) cyclones for inlet velocities ranging from 10.16 to 20.32 m/s (2000 to 4000 fpm). However, for tests in which alumina was used as the test aerosol, significant differences were detected in the collection efficiencies of both the 1D3D and 2D2D cyclone.

Tests of the 1D3D cyclone with alumina (fig. 3) showed that for all inlet velocities between 10.16 and 15.75 m/s (2000 and 3100 fpm), collection efficiencies were not statistically different. However, for inlet velocities greater than 17.27 m/s (3400 fpm), cyclone collection efficiency was significantly lower than that found at 15.24 m/s (3000 fpm).

Tests of the 2D2D cyclone with alumina (fig. 4) showed that the collection efficiency at 17.78 m/s (3500 fpm) was statistically lower than at 15.24 m/s (3000 fpm), at which the highest collection efficiency was observed. However, collection efficiencies were not statistically different for all inlet velocities between 10.16 and 15.24 m/s (2000 and 3000 fpm). The standard deviation of measured collection efficiencies increased as inlet velocity increased above 16.26 m/s (3200 fpm) for the 1D3D cyclone and 15.24 m/s (3000 fpm) for the 2D2D cyclone.

Table 2. Cyclone characteristics.

	Cornstarch			Alumina		
Cyclone	d_{50}	Slope	MMD/d_{50}	d_{50}	Slope	MMD/d_{50}
1D3D	4.7	1.10	3.8	2.67	1.11	3.7
2D2D	5.0	1.11	3.6	2.49	1.13	4.0

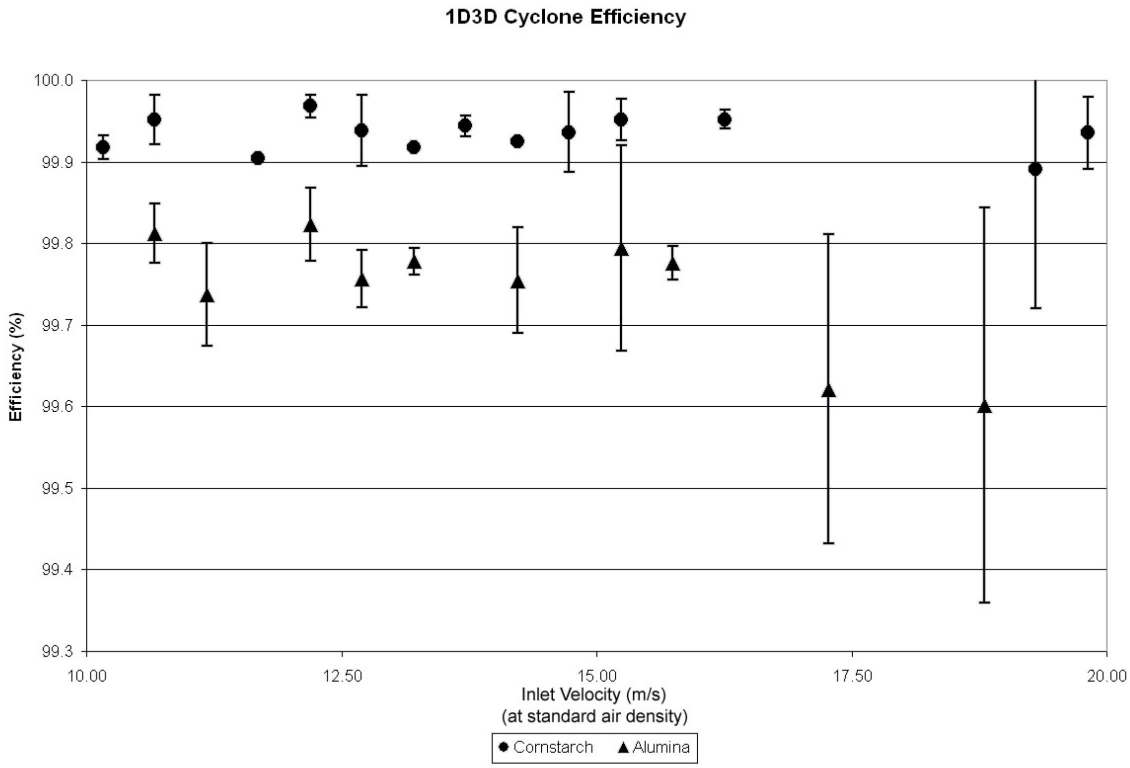

Figure 3. Collection efficiencies with 95% confidence intervals of the 1D3D cyclone for all replications at each inlet velocity and inlet loading rate combination.

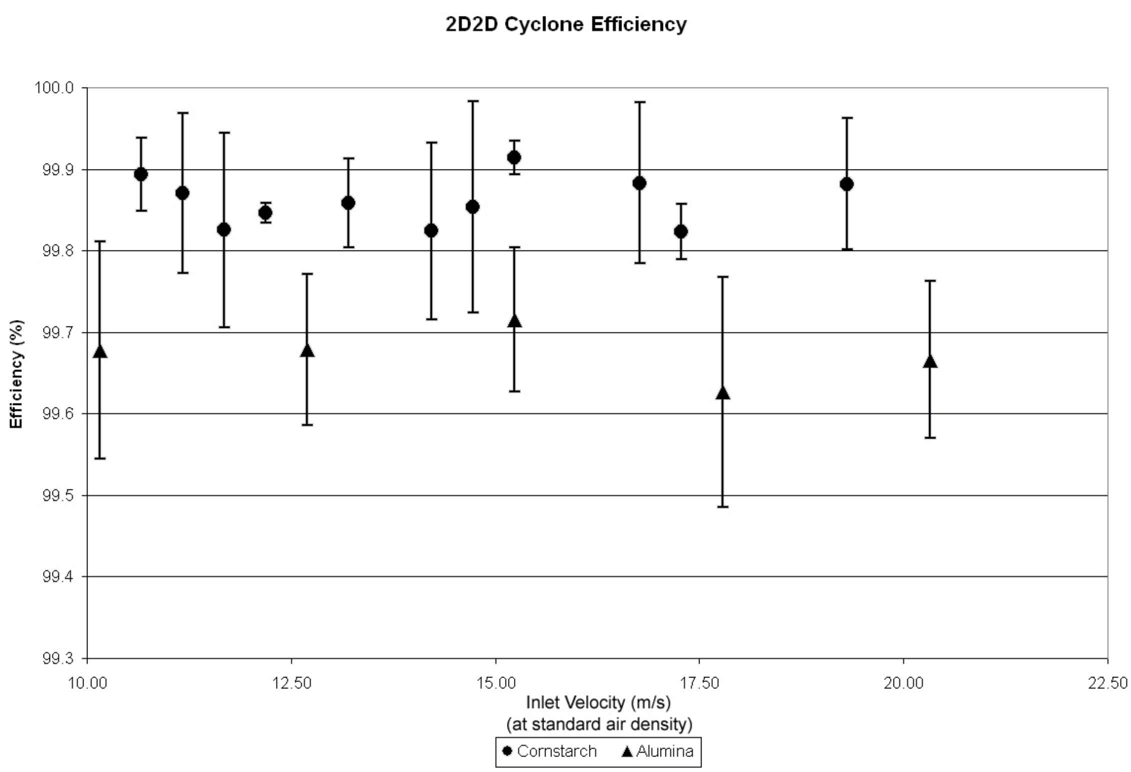

Figure 4. Collection efficiencies with 95% confidence intervals of the 2D2D cyclone for all replications at each inlet velocity and inlet loading rate combination.

The collection efficiency of cyclonic separators is a function of the aerosol PSD and the inlet velocity of the air stream. These results showed that the collection efficiency was not impacted by loading rate for the loading rates used (less than or equal to 2 g/m^3). All treatments demonstrated collection efficiencies above 99%, regardless of the inlet velocity, cyclone, or aerosol being tested.

For aerosols with a MMD greater than 3.5 times larger than the cut point of the cyclone and GSD less than or equal to 1.42, collection efficiencies equal to those obtained using the TCD design inlet velocity may be obtained at lower inlet velocities. However, above the TCD design inlet velocity, the variability of collection efficiency increases. This increased variability is due to increased turbulence and disruption of the vortex within the cyclone. Further research is needed to determine the lowest MMD to cut point ratio for which this relationship holds.

Pressure Drop

The pressure drop across the cyclone is directly related to the fan power required to operate a cyclonic abatement device. Therefore, it is important that the pressure drop associated with each inlet velocity be measured so that an estimate of the operating cost at each inlet velocity may be obtained. The pressure drops for each replication as measured across the 1D3D and 2D2D cyclones are shown in figures 5 and 6, respectively.

As expected, the pressure drop through both the 1D3D and 2D2D cyclones increased as inlet velocity increased (figs. 5 and 6). However, the experimentally observed pressure drop was higher than that predicted by the TCD method for both cyclones. Given the wide range over which collection efficiencies were equal, it is desirable to operate at the lowest flow rate possible for which the collection efficiency of the cyclone is acceptable in order to reduce operating costs of the abatement device.

Based on the TCD method, 1D3D and 2D2D cyclones should operate at inlet velocities of 975 ± 120 m/min (3200 ± 400 fpm) and 914 ± 120 m/min (3000 ± 400 fpm), respectively. The results of this research indicate that collection efficiencies similar to those obtained at the TCD design inlet velocity may be obtained at lower inlet velocities when separating aerosols with MMDs that are much larger than the cyclone cut point. This reduction in inlet velocity is accompanied by a reduction in the pressure drop across the cyclone, resulting in lower required energy requirements. The potential energy savings that result from operating a 0.457 m (18 in.) 1D3D and 2D2D cyclone below the TCD design inlet velocity are shown in table 3. These figures represent the energy savings only through the cyclone and disregard the remainder of the system.

Conclusions

When separating large aerosols from process air streams, cyclones may be operated at inlet velocities well below the TCD design specifications. The results of this research show that agricultural processing industries such as cotton gins and grain elevators can operate cyclones at lower inlet velocities

Table 3. Potential energy savings.

Cyclone	Inlet Velocity (m/s)	Flow Rate (m^3/s)	Pressure Drop (kPa)	Energy (kW)	% Energy Use v. TCD[a] (%)
1D3D	16.26	0.0425	1.03	0.44	100
	13.21	0.0345	0.62	0.22	49
	10.16	0.0265	0.32	0.09	20
2D2D	15.24	0.0398	1.18	0.47	100
	12.70	0.0332	0.73	0.24	52
	10.16	0.0265	0.41	0.10	23

[a] TCD = Texas A&M Cyclone Design.

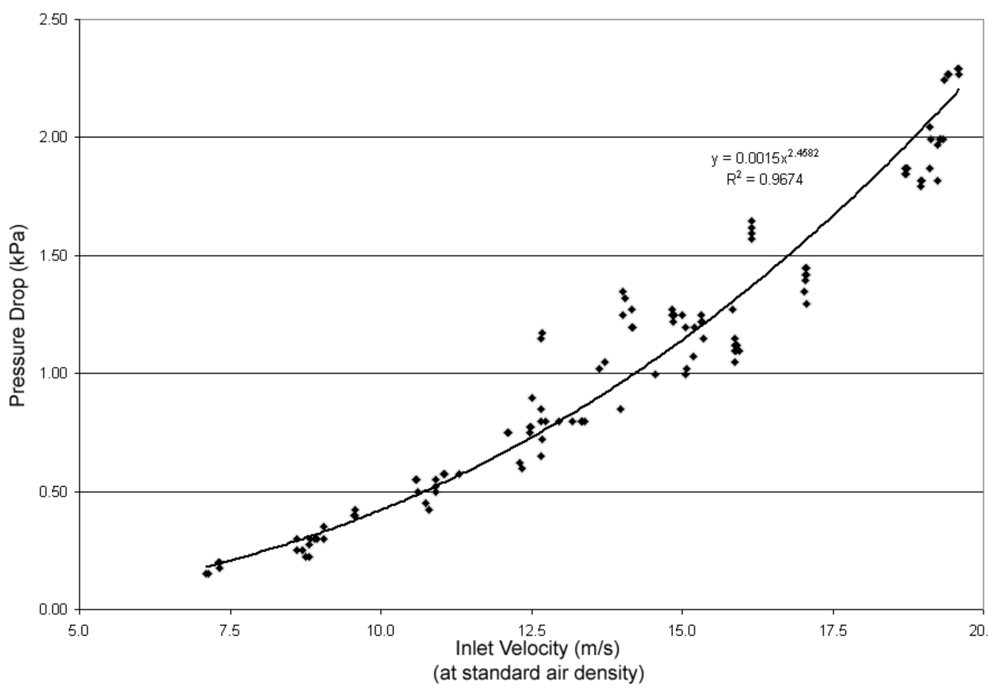

Figure 5. Pressure drop measured across the 1D3D cyclone for all replications at each inlet velocity.

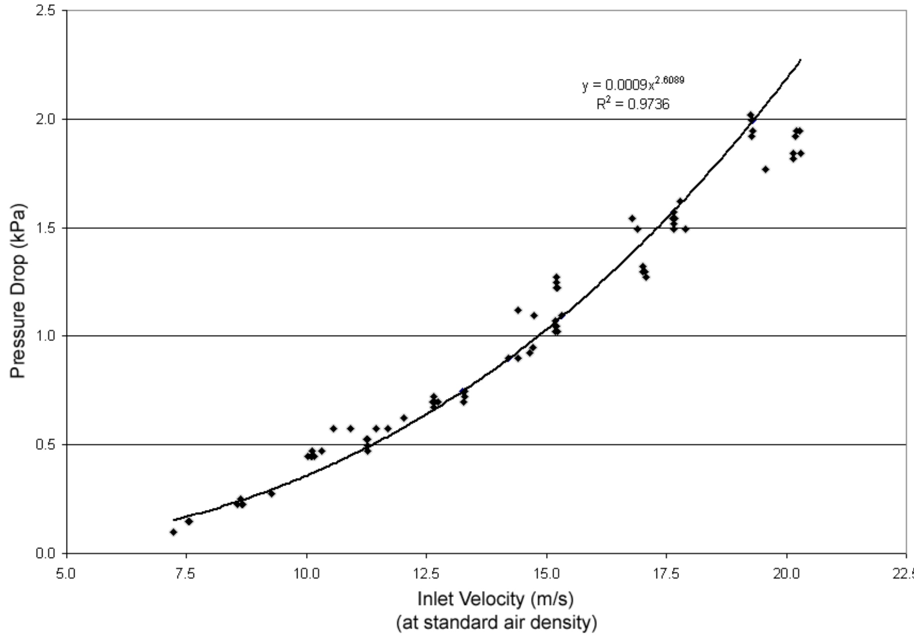

Figure 6. Pressure drop measured across the 2D2D cyclone for all replications at each inlet velocity.

and easily obtain collection efficiencies equal to those predicted by the TCD method. These findings make it much less critical for these industries to maintain the narrow window of flow rates specified by the TCD method in order to be in regulatory compliance with federal and state permit guidelines. All treatments demonstrated collection efficiencies above 99% for the tested aerosols, regardless of the inlet velocity or cyclone. Further research is needed to determine how the results of these tests may be scaled to larger diameter cyclones.

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NOMENCLATURE

FEC = Fractional efficiency curve
GSD = Geometric standard deviation
LFE = Laminar flow element
MMD = Mass median diameter
PSD = Particle size distribution
TCD = Texas A&M cyclone design.