EFFECT OF AIR DENSITY ON CYCLONE PERFORMANCE AND SYSTEM DESIGN

L. Wang, M. D. Buser, C. B. Parnell, B. W. Shaw

ABSTRACT. *1D3D and 2D2D cyclones were tested at Amarillo, Texas, to evaluate the effect of air density on cyclone performance. Both airflow rate and cyclone inlet velocity change with the change in air density. Two sets of inlet design velocities determined by the different air densities were used for the tests: one set based on the actual airflow, and the other set based on standard airflow. Experimental results indicate that optimal cyclone design velocities, which are 16 m/s (3200 ft/min) of standard air for 1D3D cyclones and 15 m/s (3000 ft/min) of standard air for 2D2D cyclones, should be determined based on standard air density. It is important to consider the air density effect on cyclone performance in the design of cyclone abatement systems. The proposed design velocities should be the basis for sizing cyclones and determining the cyclone pressure drop. The recommended sizes for 1D3D, 2D2D, and 1D2D cyclones are reported in this article.*

Keywords. *Air density, Cyclone, Design velocity, Pressure drop, Sizing cyclone.*

The cyclone, because of its simplicity and low operating cost, is probably the most widely used dust collector in industry. With the growing concern for the environmental effects of particulate pollution, it becomes increasingly important to be able to optimize the design of pollution control systems. As a result, many studies have been made to characterize cyclone performance as affected by design and operational parameters. Unfortunately, there is no information available on the effect of air density on the cyclone inlet design velocity, and consequently on its performance.

The cyclone design procedure outlined in Cooper and Alley (1994) is perceived as a standard method and has been considered by some engineers to be acceptable. However, this design process, hereafter referred to as the classical cyclone design (CCD) process, does not consider the cyclone inlet velocity in developing cyclone dimensions. Previous research at Texas A&M University (TAMU) (Parnell, 1990) indicated that the efficiency of a cyclone increased, and emission concentration decreased, with increasing inlet velocity. But at relatively high inlet velocities, the cyclone efficiency actually began to decrease. A dramatic increase in emission concentration has been observed at velocities higher than a certain threshold level (Parnell, 1996). The level at which the inlet velocities were too high and caused increased emissions was different for each cyclone design. The Texas A&M cyclone design (TCD) process specifies the "ideal" cyclone inlet velocities (design velocities) for different cyclone designs for optimum cyclone performance. The design inlet velocities for 1D3D, 2D2D, and 1D2D cyclones are 16 m/s ±2 m/s (3200 ft/min ±400 ft/min), 15 m/s ±2 m/s (3000 ft/min ±400 ft/min), and 12 m/s ±2 m/s (2400 ft/min ±400 ft/min), respectively. The TCD process allows an engineer to design the cyclone using a cyclone inlet velocity specific for the type of cyclone being considered. However, there is one problem with the CCD and TCD cyclone design processes. None of these cyclone design methods specify whether the cyclone design velocity should be based on the standard air density or actual air density.

Air density is primarily determined by barometric pressure. Barometric pressure is a function of height above sea level. Typically, at 1219 m (4000 ft) above sea level, the air density will be 1.04 kg per dry standard cubic meter, kg/dscm (0.065 lb per dry standard cubic foot, lb/dscf), compared to 1.20 kg/dscm (0.075 lb/dscf) at sea level – the standard air density at 21°C (70°F), 1 atm of barometric pressure, and zero relative humidity. The actual air density can be determined by:

$$\rho_a = \frac{(P_b - \phi \times P_s) MW_{da}}{RT} + \frac{\phi \times P_s \times MW_{wv}}{RT} \qquad (1)$$

where

ρ_a = air density (g/cm^3)
P_b = barometric pressure (atm)
ϕ = relative humidity
P_s = saturated water vapor pressure at dry bulb temperature (atm)
MW_{da} = the molecular weight of dry air (28.96 g/g–mole)
MW_{wv} = the molecular weight of water vapor (18 g/g–mole)
R = ideal gas constant (82.06 atm–cm^3/g–mole–k)
T = dry bulb temperature (K).

The relationships of cyclone airflow rate, inlet velocity, and air densities can be described by equations 2 and 3:

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$$Q_a = \left(\frac{\rho_s}{\rho_a}\right) \times Q_s \qquad (2)$$

where

Q_a = actual airflow rate (m^3/s)
Q_s = standard airflow rate (m^3/s)
ρ_a = actual air density (kg/m^3)
ρ_s = standard air density (1.20 kg/m^3).

$$V_a = \left(\frac{\rho_s}{\rho_a}\right) \times V_s \qquad (3)$$

where

V_a = actual air inlet velocity (m/s)
V_s = standard air inlet velocity (m/s)
ρ_a = actual air density (kg/m^3)
ρ_s = standard air density (1.20 kg/m^3).

A design velocity of 16 m/s (3200 ft/min) based on standard air density (1.20 kg/dscm or 0.075 lb/dscf) would be 19 m/s (3700 ft/min) based on actual air density (1.04 kg/dscm or 0.065 lb/dscf). If the TAMU design process were to be used, then the 19 m/s (3700 ft/min) design velocity would be outside the acceptable range of inlet velocities for 1D3D cyclones (16 m/s ±2 m/s). Which is correct? Should cyclones be designed based on standard air density or actual air density?

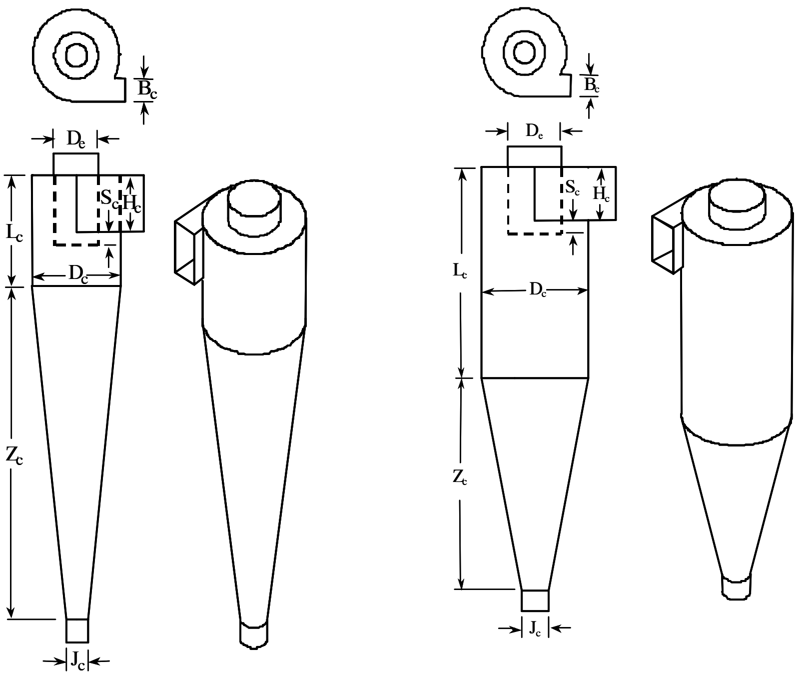
It was hypothesized that cyclone performance and pressure drop would be affected by varying air density. The goal of this research was to quantify the air density effects on cyclone performance, and ultimately, to recommend a cyclone design philosophy based on either actual or standard air density.

EXPERIMENTAL METHOD

Cyclone airflow rate and inlet velocity change with air density. In this research, tests were conducted to evaluate 1D3D and 2D2D cyclone emission concentrations and pressure drops with two sets of inlet design velocities: one set based on actual airflow rate, and the other set based on dry standard airflow rate. All the tests were conducted at Amarillo, Texas, where the altitude is 1128 m (3700 ft) and consequently the air density is relatively low. During the tests, barometric pressure, air temperature, and relative humidity were monitored by a digital weather station (Davis Perception II) to determine the air density by equation 1.

CYCLONES

In the agricultural processing industry, 2D2D and 1D3D cyclones have been used for particulate matter control for many years. The "D" in the 2D2D designation refers to the barrel diameter of the cyclone. The numbers preceding each D relate the length of the barrel and cone sections, respectively. A 2D2D cyclone has barrel and cone lengths of two times the barrel diameter, whereas a 1D3D cyclone has a barrel length equal to the barrel diameter and a cone length of three times the barrel diameter. The configurations of these two cyclone designs are shown in figure 1. Previous research (Wang, 2000) indicated that, compared to other cyclone designs, 1D3D and 2D2D are the most efficient cyclone collectors for fine dust (less than 100 μm). In this research, only fine dust and 1D3D and 2D2D cyclones were used to conduct experiments. Both 1D3D and 2D2D cyclones used in this research were 15 cm (6 in.) in diameter.



1D3D

$B_c = D_c/4$ $J_c = D_c/4$
$D_e = D_c/2$ $S_c = D_c/8$
$H_c = D_c/2$ $L_c = 1 \times D_c$
$Z_c = 3 \times D_c$

2D2D

$B_c = D_c/4$ $J_c = D_c/4$
$D_e = D_c/2$ $S_c = D_c/8$
$H_c = D_c/2$ $L_c = 2 \times D_c$
$Z_c = 2 \times D_c$

Figure 1. 1D3D and 2D2D cyclone configurations.

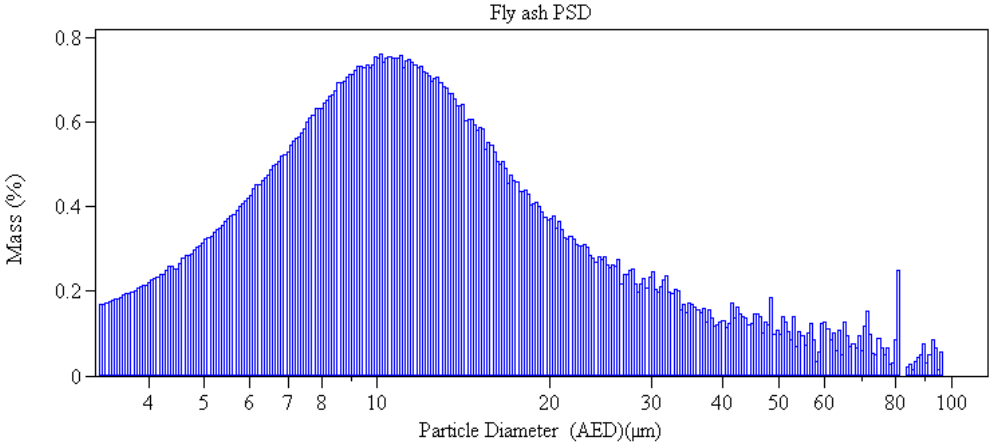


Figure 2. Coulter Counter PSD for fly ash (MMD = 11.34 μm, GSD = 1.82).

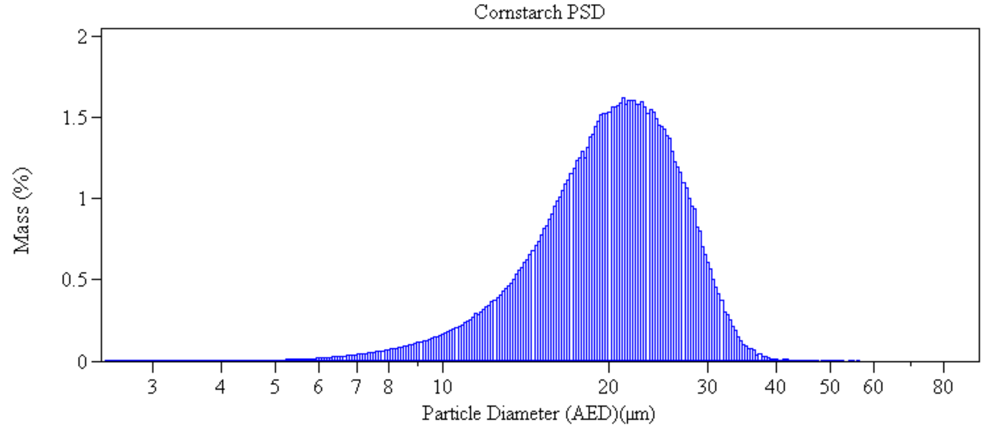


Figure 3. Coulter Counter PSD for cornstarch (MMD = 20.38 μm, GSD = 1.39).

TESTING MATERIAL

Fly ash, cornstarch, screened manure dust, and regular manure dust were used as test materials in this research ("screened manure dust" refers to cattle feedyard dust that has been passed through a screen with 100 μm openings, and "regular manure dust" refers to manure dust from the same source as the screened manure dust with the larger than 100 μm PM included). The particle densities of fly ash, cornstarch, and manure dust were 2.7 g/cm^3, 1.5 g/cm^3, and 1.8 g/cm^3, respectively. Emission concentrations for specific cyclone designs were directly related to the fine dust inlet loadings and the particle size distributions (PSDs) of inlet particulate matter (PM). Tests were conducted with inlet concentrations of the dust at 1 and 2 g/m^3. A Coulter Counter Multisizer 3 (CCM) (Beckman Coulter, Fullerton, Cal.) was used to analyze PSDs of inlet dust and emitted dust on the filters. The CCM is an electronic particle sizer that operates on the resistance principle to measure PSD in electrical liquid suspensions (Hinds, 1999). Figures 2 to 5 show PSDs of the four inlet PM. Mass median diameter (MMD) and geometric standard deviation (GSD) are two parameters that characterize PSDs. The MMD is the aerodynamic equivalent diameter (AED) such that 50% of PM mass is larger or smaller than this diameter. The GSD is defined by the following equation (Cooper and Alley, 1994):

$$\mathrm{GSD} = D_{84.1}/D_{50} = D_{50}/D_{15.9} \tag{4}$$

where

$D_{84.1}$ = diameter such that particles constituting 84.1% of the total mass of particles are smaller than this size

D_{50} = mass median diameter (50% of the total mass of particles are smaller than this size)

$D_{15.9}$ = diameter such that particles constituting 15.9% of the total mass of particles are smaller than this size.

TESTING SYSTEM

The testing system was a pull system, as shown in figure 6. The blowers pull the air from the feeding mechanism directly into a pipe and then to the cyclone. A collection hopper was connected to the bottom of the cyclone dust outlet to store the dust collected by the cyclone. Cleaned air flowed out of the cyclone through the outlet–conveying duct to a filter holder. The filter captured all the dust emitted from the cyclone, and clean air flowed through an orifice meter and the blowers and was discharged into the testing room. A designed airflow rate was maintained by monitoring the pressure drop across the orifice meter during the test. The equipment used in the testing system is listed in table 1, and the relationship between flow rate and pressure drop across the orifice meter is shown by the following equation:

$$Q = 3.478 \times K \times D_o^2 \times \sqrt{\frac{\Delta P}{\rho_a}} \tag{5}$$

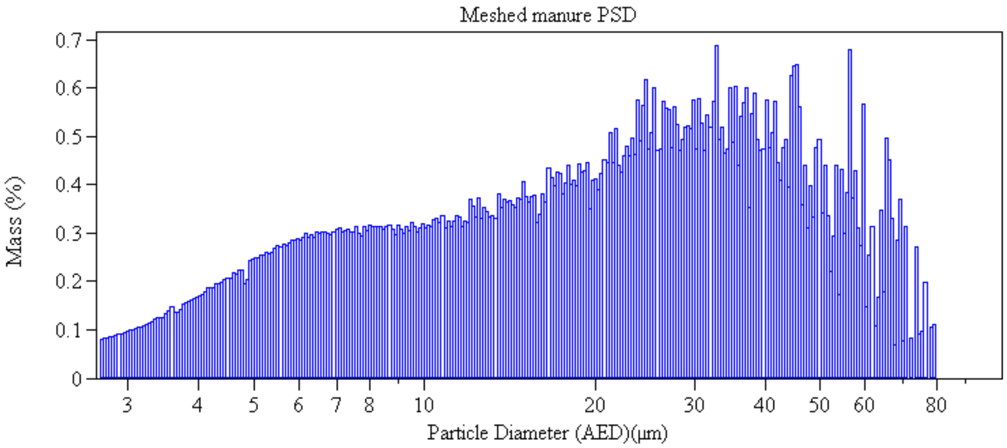


Figure 4. Coulter Counter PSD for screened manure dust (MMD = 20.81 µm, GSD = 3.04).

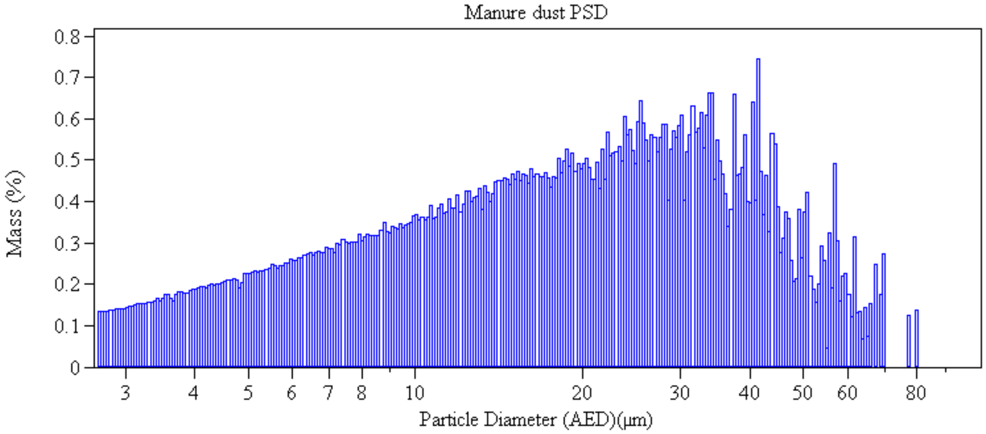


Figure 5. Coulter Counter PSD for regular manure dust (MMD = 18.43 µm, GSD = 2.76).

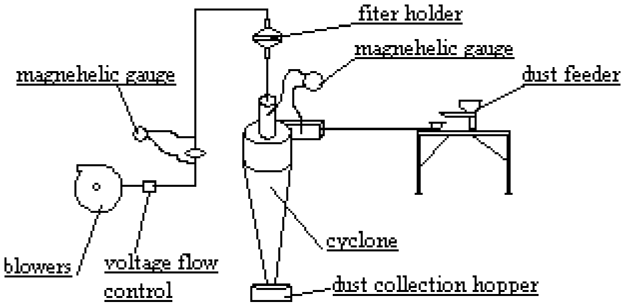


Figure 6. Cyclone testing system.

where

Q = airflow rate through orifice meter (m^3/s)
K = orifice meter coefficient (dimensionless)
D_o = orifice diameter (m)
ΔP = pressure drop across orifice meter (mm H_2O)
ρ_a = air density (kg/m^3).

Testing time was 3 min for each test, and the system was cleaned between tests. The filters were conditioned in an environmental chamber for 24 h at 25°C and 46% relative humidity, as specified by EPA, and weighed with a microbalance (range: 0 to 101 mg, accuracy: ±0.1 mg) that was located in the environmental chamber before and after testing to determine total penetrating weights. The feeding rates and emission concentrations were determined with equations 6 and 7:

Table 1. Equipment used for the testing system.

Equipment	Model and Make	Parameter
Hand–held blowers	Cadillac HP–33, Clements National Co., Chicago, Ill.	1.42 m^3/min, 2989 Pa (50 cfm, 12 in. w.g.)
Orifice meter	Made in house	Range: 0 to 3.11 m^3/min; accuracy: ±0.7% reading. Calibrated with laminar flow element (Meriam Process Technologies, Cleveland, Ohio).
Magnahelic differential pressure gauges	Dwyer Instruments, Michigan City, Ind.	Range: 0 to 1245 Pa (0 to 5 in. w.g.); accuracy: ±24.9 Pa (±0.1 in. w.g.)
Magnetic dust feeder	Syntron F–TO, FMC Technologies, Homer City, Pa.	—
Filter holder	Made in house	20.3 × 25.4 cm (8 × 10 in.)

$$F = L \times Q \tag{6}$$

where

F = feeding rate (g/s)
L = total inlet loading rate (g/m^3)
Q = system airflow rate (m^3/s).

$$EC = \frac{FW_2 - FW_1}{Q \times T} \times 1000 \tag{7}$$

Table 2. Airflow rate of the testing system.

	Diameter of Cyclone	Design Velocity	Airflow Rate of System
1D3D	15 cm	16 m/s	0.05 m^3/s
	(6 in.)	(3200 ft/min)	(100 ft^3/min)
2D2D	15 cm	15 m/s	0.04 m^3/s
	(6 in.)	(3000 ft/min)	(94 ft^3/min)

where

EC = emission concentration (mg/m^3)
FW_1 = pre–weight of filter (g)
FW_2 = post–weight of filter (g)
Q = system airflow rate (m^3/s)
T = testing time for each sample (s).

The airflow rates of the testing system were determined by using the TCD design velocity. Table 2 shows the airflow rate and cyclone inlet velocity. Equations 2 and 3 were used to calculate cyclone airflow rates and inlet velocities based on actual or standard conditions.

The same testing system was used to measure cyclone pressure drops at two inlet velocity treatments. In order to accurately measure the static pressure drop across the cyclones, the static pressure taps were inserted into the air stream such that the static pressure sensing position was in the direction of airflow (fig. 7). The pressure drop measurement was conducted without any dust feeding.

EXPERIMENTAL DESIGN AND DATA ANALYSIS

The tests were conducted as a 4–factorial experiment. The four factors were (1) inlet velocity (optimum design velocity at actual air condition, optimum design velocity at standard air condition), (2) cyclone design (1D3D, 2D2D), (3) inlet PSDs (fly ash, cornstarch, and manure dust), (4) inlet loading rates (1 and 2 g/m^3). Each treatment was based on three repeating observations, for a total of 60 observations. ANOVA tests, using Tukey's Studentized range (HSD) test at 95% confidence interval, were performed on the results.

Equation 8 was used to convert the actual air emission concentration to standard air emission concentration for the comparison:

$$EC_a = \left(\frac{\rho_a}{\rho_s}\right) \times EC_s \qquad (8)$$

where

EC_a = actual air emission concentration (mg/m^3)
EC_s = standard air emission concentration (mg/dscm; dscm = dry standard cubic meter)
ρ_a = actual air density (kg/m^3)
ρ_s = dry standard air density (1.2 kg/m^3).

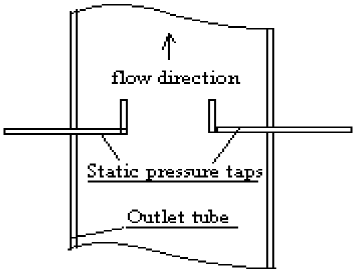


Figure 7. Static pressure taps in the cyclone outlet tube.

Besides the emission concentration, another important parameter to characterize cyclone performance is cyclone fractional efficiency. Cyclone fractional efficiency curves were developed based on the cyclone inlet concentration (feeding rate), inlet PSD (measured by CCM), emission concentration, and the PSD of PM emitted (on the filter, measured by CCM). The inlet and outlet concentrations for various size ranges were calculated using inlet and outlet PM 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:

$$\eta_j = (1 - Conc_{outj}/Conc_{inj}) \qquad (9)$$

where

η_j = fractional efficiency of jth size range
$Conc_{outj}$ = outlet concentration of jth size range
$Conc_{inj}$ = inlet concentration of jth size range.

A cyclone fractional efficiency curve (FEC) can be represented by a cumulative lognormal distribution. This FEC distribution is defined by the cut–point (D_{50}) and sharpness–of–cut (the slope of the FEC) (Wang et al., 2002). The cut–point of a cyclone is the aerodynamic equivalent diameter (AED) of the particles 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:

$$\text{slope} = D_{84.1}/D_{50} = D_{50}/D_{15.9} \qquad (10)$$

where

$D_{84.1}$ = diameter of particles collected with 84.1% efficiency
D_{50} = diameter of particles collected with 50% efficiency
$D_{15.9}$ = diameter of particles collected with 15.9% efficiency.

TEST RESULTS AND DISCUSSION

EMISSION CONCENTRATION MEASUREMENTS

Tables 3 and 4 contain the average emission concentrations for the tests conducted on the 1D3D and 2D2D cyclones. The null hypothesis for the 1D3D cyclone design was that there was no difference in emission concentrations for inlet velocities of 16 actual m/s (3200 afpm) versus 16 standard m/s (3200 sfpm or 3800 afpm); at an air density of 1.02 kg/m^3 (0.0635 lb/ft^3), the 16 standard m/s (3200 sfpm) velocity corresponds to 19 actual m/s (3800 afpm). For comparison purposes, all the emission concentrations were converted from mg per actual cubic meter (mg/acm) into mg per dry standard cubic meter (mg/dscm). The statistical analyses indicated that the cyclone emission concentrations were highly dependent on cyclone design, inlet loading rates, PSDs of inlet PM, as well as air density. The following observations were noted:

- For the fly ash tests, the average emission concentrations were significantly higher for both 1D3D and 2D2D cyclones for inlet velocities of 16 and 15 actual m/s (3200 and 3000 afpm) compared to 16 and 15 standard m/s (3200 and 3000 sfpm). For an air density of 1.02 kg/m^3

(0.0635 lb/ft^3), 16 standard m/s (3200 sfpm) is equivalent to 19 actual m/s (3800 afpm), and 19 m/s (3800 afpm) is outside of the TCD ideal design velocity range of 16 ± 2 m/s (3200 ±400 fpm) for the 1D3D cyclones. One would assume that higher emissions would occur at 19 m/s (3800 afpm). However, the measured data did not support this assumption. Experimental results indicate that the optimum design velocity for the 1D3D cyclone is 16 standard m/s (3200 sfpm), not 16 actual m/s (3200 afpm). The same observations were made for the 2D2D cyclone. With an air density of 1.01 kg/m^3 (0.063 lb/ft^3), 15 standard m/s (3000 sfpm) inlet velocity is equivalent to 18 actual m/s (3600 afpm), and 18 actual m/s (3600 afpm) is also outside of the TCD ideal design velocity range of 15 ±2 m/s (3000 ±400 fpm) for the 2D2D cyclones. Again, the experimental data indicate that the optimum design velocity for the 2D2D cyclone should be 15 standard m/s (3000 sfpm), not 15 actual m/s (3000 afpm).

- For agricultural dust with larger MMD, such as cornstarch and manure dust, the trend of decreasing emission concentration for 1D3D and 2D2D cyclones was observed when the inlet design velocity was based on standard air density. However, the differences in the emission concentrations for inlet velocities based on actual versus standard air densities were not statistically significant.
- Among the four test dusts, the rankings from the smallest to the largest MMDs are as follows: (1) fly ash, (2) regular manure, (3) cornstarch, and (4) screened manure (figs. 2 to 5). The test results suggest that as the MMD of the PM decreases, the differences in emission concentrations resulting from inlet velocities based on standard versus actual air densities will increase (tables 3 and 4).
- The results from both 1D3D and 2D2D cyclones also indicate that higher inlet loading rates increased the differences in the emission concentration with different inlet velocity treatments. This implies that the effect of air density is increased as cyclone inlet loadings increase.

The emission concentrations associated with inlet and outlet PSDs were also used to calculate cyclone fractional efficiencies and to develop cyclone fractional efficiency curves. The methodology used to develop fractional efficiency curves is similar to the one developed by Wang et al. (2002). It includes the following three steps:

1. Obtain PSDs of inlet (original dust) and outlet PM (dust on the filter) using the CCM.
2. Calculate the fractional efficiency curves using inlet and outlet concentrations and the PSDs.
3. Obtain the "best–fit" lognormal distribution for the fractional efficiency curves obtained above.

Table 3. Average emission concentrations[a] from 1D3D and 2D2D cyclones with fly ash and corn starch.

Inlet Velocity (V_{in}, m/s)	Actual Air Density (kg/m^3)	Inlet Loading[b] Fly Ash 1 g/m^3	Fly Ash 2 g/m^3	Corn Starch 1 g/m^3	Corn Starch 2 g/m^3
1D3D					
16 actual air	1.02	50	93	7a	18b
16 standard air	1.02	42	73	6a	17b
2D2D					
15 actual air	1.02	57a	109	9b	20c
15 standard air	1.01	51a	96	8b	18c

[a] Emission concentration = mg/dscm (dscm = cubic meter of dry standard air).

[b] Three tests were performed for each condition. Means followed by the same letter are not significantly different at the 0.05 level.

Table 4. Average emission concentration[a] from 1D3D cyclone with manure dust.

Inlet Velocity (V_{in}, m/s)	Actual Air Density (kg/m^3)	Inlet Loading[b] Screened Manure 2 g/m^3	Regular Manure 2 g/m^3
16 actual air	1.01	75c	50
16 standard air	1.01	74c	43

[a] Emission concentration = mg/dscm (dscm = cubic meter of dry standard air).

[b] Three tests were performed for each condition. Means followed by the same letter are not significantly different at the 0.05 level.

Statistical analyses were also conducted on the cyclone cut–points and slopes. Table 5 lists the average cut–points and slopes for the 1D3D and 2D2D cyclones with fly ash. For the 1D3D cyclone, the cut–points are significantly different with different inlet velocity treatments and two inlet loading rates. However, for the 2D2D cyclone, the cut–points are not significantly different with different inlet velocity treatments. Air density effect on the 1D3D cyclone cut–point is greater than on the 2D2D cyclone cut–point.

PRESSURE DROP MEASUREMENT

Table 6 lists the pressure drop test results. Parnell (1990) reported that pressure drops for 1D3D and 2D2D cyclones operating at design velocities were 1145 and 921 Pa (4.6 and 3.7 in. w.g.). However, the experimental data (table 6) indicate that cyclone pressure drop is highly dependent on air density. Only when 1D3D and 2D2D cyclones operate at their respective design velocities of standard air will their pressure drops be around the previous reported value, i.e., 1145 Pa (4.6 in. w.g.) for 1D3D, and 921 Pa (3.7 in. w.g.) for 2D2D. It is important that air density be considered in the design of cyclone systems.

CYCLONE SYSTEM DESIGN – SIZING CYCLONES

The first step in designing a cyclone abatement system is to size the cyclone. Cyclone size and configuration depend on the cyclone design velocity and the volume of air to be

Table 5. 1D3D and 2D2D cyclones cut–point and slope with fly ash.

Inlet Velocity (V_{in}, m/s)	Actual Air Density (kg/m^3)	Inlet Loading[a] 1 g/m^3 Cut Point (µm)	1 g/m^3 Slope	2 g/m^3 Cut Point (µm)	2 g/m^3 Slope
1D3D					
16 actual air	1.02	3.9	1.29a	4.1	1.24
16 standard air	1.02	3.4	1.43a	3.6	1.35
2D2D					
15 actual air	1.02	4.2a	1.23b	4.2a	1.26b
15 standard air	1.01	4.0a	1.30b	4.0a	1.28b

[a] Three tests were performed for each condition. Means followed by the same letter are not significantly different at the 0.05 level.

handled. The following equation (Parnell, 1996) can be used to size 1D3D or 2D2D cyclones:

$$D_c = \sqrt{\frac{8 \times Q}{V_{in}}} \qquad (11)$$

where

D_c = cyclone diameter (m)
Q = airflow rate into cyclone (dscm/s; dscm = cubic meter of dry standard air)
V_{in} = cyclone design inlet velocity (m/s of dry standard air, or dsmps):

Table 6. Cyclone pressure drop measurements.

Inlet Velocity (V_{in}, m/s)	Actual Air Density (kg/m^3)	Cyclone Pressure Drop[a]
1D3D		ΔP_{1D3D} (Pa)
16 actual air	1.02	755
16 standard air	1.02	1238
2D2D		ΔP_{2D2D} (Pa)
15 actual air	1.02	580
15 standard air	1.01	827

[a] Five tests were performed for each condition.

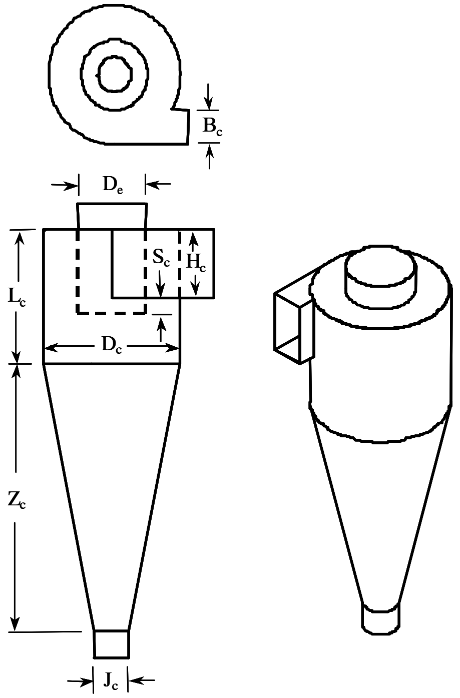
Table 7. Recommended sizes for 1D3D cyclones.

	Using 1 Cyclone		Using 2 Cyclones		Using 3 Cyclones		Using 4 Cyclones	
Air Volume, dscm/s[a] (dscf/min)[b]	D_c, m (in.)	Approx. Height, m (ft)	D_c, m (in.)	Approx. Height, m (ft)	D_c, m (in.)	Approx. Height, m (ft)	D_c, m (in.)	Approx. Height, m (ft)
0.7 (1,500)	0.6 (24)	0.2 (8)	—	—	—	—	—	—
1.0 (2,000)	0.7 (28)	0.3 (9)	0.5 (20)	0.2 (7)	—	—	—	—
1.2 (2,500)	0.8 (30)	0.3 (10)	0.6 (22)	0.2 (8)	—	—	—	—
1.4 (3,000)	0.8 (32)	0.3 (11)	0.6 (24)	0.2 (8)	0.5 (20)	0.2 (7)	—	—
1.9 (4,000)	1.0 (38)	0.3 (13)	0.7 (26)	0.2 (9)	0.6 (22)	0.2 (8)	0.5 (20)	0.2 (7)
2.4 (5,000)	1.1 (42)	0.4 (14)	0.8 (30)	0.3 (10)	0.6 (24)	0.2 (8)	0.6 (22)	0.2 (8)
2.8 (6,000)	1.2 (46)	0.4 (16)	0.8 (32)	0.3 (11)	0.7 (28)	0.3 (10)	0.6 (24)	0.2 (8)
3.3 (7,000)	—	—	0.9 (36)	0.3 (12)	0.8 (30)	0.3 (10)	0.7 (26)	0.2 (9)
3.8 (8,000)	—	—	1.0 (38)	0.3 (13)	0.8 (32)	0.3 (11)	0.7 (28)	0.3 (10)
4.3 (9,000)	—	—	1.0 (40)	0.4 (14)	0.8 (32)	0.3 (11)	0.7 (28)	0.3 (10)
4.7 (10,000)	—	—	1.1 (42)	0.4 (14)	0.9 (34)	0.3 (12)	0.8 (30)	0.3 (10)
5.2 (11,000)	—	—	1.1 (44)	0.4 (15)	0.9 (36)	0.3 (12)	0.8 (32)	0.3 (11)
5.7 (12,000)	—	—	1.2 (46)	0.4 (16)	1.0 (38)	0.3 (13)	0.8 (32)	0.3 (11)
6.6 (14,000)	—	—	—	—	1.1 (42)	0.4 (14)	0.9 (36)	0.3 (12)
7.6 (16,000)	—	—	—	—	1.1 (44)	0.4 (15)	1.0 (38)	0.3 (13)
8.5 (18,000)	—	—	—	—	1.2 (46)	0.4 (16)	1.0 (40)	0.4 (14)
9.4 (20,000)	—	—	—	—	—	—	1.1 (42)	0.4 (14)
10.4 (22,000)	—	—	—	—	—	—	1.1 (44)	0.4 (15)
11.3 (24,000)	—	—	—	—	—	—	1.2 (46)	0.4 (16)

[a] dscm = cubic meter of dry standard air.
[b] dscf = cubic foot of dry standard air.

Table 8. Recommended sizes for 2D2D cyclones.

	Using 1 Cyclone		Using 2 Cyclones		Using 3 Cyclones		Using 4 Cyclones	
Air Volume, dscm/s[a] (dscf/min)[b]	D_c, m (in.)	Approx. Height, m (ft)	D_c, m (in.)	Approx. Height, m (ft)	D_c, m (in.)	Approx. Height, m(ft)	D_c, m (in.)	Approx. Height, m (ft)
0.7 (1,500)	0.6 (24)	0.2 (8)	—	—	—	—	—	—
1.0 (2,000)	0.7 (28)	0.3 (10)	0.5 (20)	0.2 (7)	—	—	—	—
1.2 (2,500)	0.8 (30)	0.3 (10)	0.6 (22)	0.2 (8)	—	—	—	—
1.4 (3,000)	09 (34)	0.3 (12)	0.6 (24)	0.2 (8)	0.5 (20)	0.2 (7)	—	—
1.9 (4,000)	1.0 (40)	0.4 (14)	0.7 (28)	0.3 (10)	0.6 (22)	0.2 (8)	0.5 (20)	0.2 (7)
2.4 (5,000)	1.1 (44)	0.4 (15)	0.8 (30)	0.3 (10)	0.7 (26)	0.2 (9)	0.6 (22)	0.2 (8)
2.8 (6,000)	1.2 (48)	0.4(16)	0.9 (34)	0.3 (12)	0.7 (28)	0.3 (10)	0.6 (24)	0.2 (8)
3.3 (7,000)	—	—	0.9 (36)	0.3 (12)	0.8 (30)	0.3 (10)	0.7 (26)	0.2 (9)
3.8 (8,000)	—	—	1.0 (40)	0.4 (14)	0.8 (32)	0.3 (11)	0.7 (28)	0.3 (10)
4.3 (9,000)	—	—	1.1 (42)	0.4 (14)	0.9 (34)	0.3 (12)	0.8 (30)	0.3 (10)
4.7 (10,000)	—	—	1.1 (44)	0.4 (15)	0.9 (36)	0.3 (12)	0.8 (30)	0.3 (10)
5.2 (11,000)	—	—	1.2 (46)	0.4 (16)	1.0 (38)	0.3 (13)	0.8 (32)	0.3 (11)
5.7 (12,000)	—	—	1.2 (48)	0.4 (16)	1.0 (40)	0.4 (14)	0.9 (34)	0.3 (12)
6.6 (14,000)	—	—	—	—	1.1 (42)	0.4 (14)	0.9 (36)	0.3 (12)
7.6 (16,000)	—	—	—	—	1.2 (46)	0.4 (16)	1.0 (40)	0.4 (14)
8.5 (18,000)	—	—	—	—	1.2 (48)	0.4 (16)	1.1 (42)	0.4 (14)
9.4 (20,000)	—	—	—	—	—	—	1.1 (44)	0.4 (15)
10.4 (22,000)	—	—	—	—	—	—	1.2 (46)	0.4 (16)
11.3 (24,000)	—	—	—	—	—	—	1.2 (48)	0.4 (16)



1D2D

$B_c = D_c/4$
$J_c = D_c/2$
$D_e = D_c/1.6$
$S_c = D_c/8$
$H_c = D_c/2$
$L_c = 1 \times D_c$
$Z_c = 2 \times D_c$

Figure 8. 1D2D cyclone configuration.

V_{in} = 16 m/s (3200 dsfpm) for 1D3D
V_{in} = 15 m/s (3000 dsfpm) for 2D2D.

Equations 2 and 3 can be used to calculate the standard airflow rate (Q) and standard air inlet velocity (V_{in}). Tables 7 and 8 list the recommended sizes for 1D3D and 2D2D cyclones. They are similar to the tables reported by Parnell (1990). This research supports the practice of sizing cyclones based on the standard air volume flow rate.

Simpson and Parnell (1995) introduced a new low–pressure cyclone, called the 1D2D cyclone (fig. 8), for the cotton ginning industry to solve the cycling–lint problem. The 1D2D cyclone is a better design for high–lint content trash compared with 1D3D and 2D2D cyclones (Wang et al., 1999). The design velocity for 1D2D cyclone is 12 m/s (2400 fpm) (Simpson, 1996). Based on this research, the recommended sizes for the 1D2D cyclone are listed in table 9.

CONCLUSION

The performance of 1D3D and 2D2D cyclones is highly dependent on the inlet air velocity and air density. Proposed cyclone design inlet velocities are:

- 16 m/s (3200 ft/min) with air density at standard condition for 1D3D cyclones.
- 15 m/s (3000 ft/min) with air density at standard condition for 2D2D cyclones.

It is important to consider the air density effect on the cyclone performance in the design of cyclone abatement systems. TCD ideal design velocity for 1D3D, 2D2D, and 1D2D cyclones should be the ideal inlet velocity of standard air, not the ideal inlet velocity of actual air. In designing cyclone abatement systems, the proposed design velocity should be the basis for sizing the cyclone and determining the cyclone pressure drop. The recommended sizes for 1D3D, 2D2D, and 1D2D cyclones are reported in this article.

Table 9. Recommended sizes for the 1D2D cyclone.

	Using 1 Cyclone		Using 2 Cyclones		Using 3 Cyclones		Using 4 Cyclones	
Air Volume, dscm/s[a] (dscf/min)[b]	D_c, m (in.)	Approx. Height, m (ft)	D_c, m (in.)	Approx. Height, m (ft)	D_c, m (in.)	Approx. Height, m (ft)	D_c, m (in.)	Approx. Height, m (ft)
0.7 (1,500)	0.7 (26)	0.2 (7)	—	—	—	—	—	—
1.0 (2,000)	0.8 (30)	0.2 (8)	0.6 (22)	0.2 (6)	—	—	—	—
1.2 (2,500)	0.9 (34)	0.2 (9)	0.6 (24)	0.2 (6)	—	—	—	—
1.4 (3,000)	1.0 (38)	0.3 (10)	0.7 (26)	0.2 (7)	0.6 (22)	0.2 (6)	—	—
1.9 (4,000)	1.1 (44)	0.3 (11)	0.8 (30)	0.2 (8)	0.7 (26)	0.2 (7)	0.6 (22)	0.2 (6)
2.4 (5,000)	1.2 (48)	0.3 (12)	0.9 (34)	0.2 (9)	0.7 (28)	0.2 (7)	0.6 (24)	0.2 (6)
2.8 (6,000)	1.4 (54)	0.4 (14)	1.0 (38)	0.3 (10)	0.8 (30)	0.2 (8)	0.7 (26)	0.2 (7)
3.3 (7,000)	—	—	1.0 (40)	0.3 (10)	0.9 (34)	0.2 (9)	0.7 (28)	0.2 (7)
3.8 (8,000)	—	—	1.1 (44)	0.3 (11)	0.9 (36)	0.2 (9)	0.8 (30)	0.2 (8)
4.3 (9,000)	—	—	1.2 (46)	0.3 (12)	1.0 (38)	0.3 (10)	0.8 (32)	0.2 (8)
4.7 (10,000)	—	—	1.2 (48)	0.3 (12)	1.0 (40)	0.3 (10)	0.9 (34)	0.2 (9)
5.2 (11,000)	—	—	1.3 (52)	0.3 (13)	1.1 (42)	0.3 (11)	0.9 (36)	0.2 (9)
5.7 (12,000)	—	—	1.4 (54)	0.4(14)	1.1 (44)	0.3 (11)	1.0 (38)	0.3 (10)
6.6 (14,000)	—	—	—	—	1.2 (48)	0.3 (12)	1.0 (40)	0.3 (10)
7.6 (16,000)	—	—	—	—	1.3 (50)	0.3 (13)	1.1 (44)	0.3 (11)
8.5 (18,000)	—	—	–	—	1.4 (54)	0.4 (14)	1.2 (46)	0.3 (12)
9.4 (20,000)	—	—	–	—	—	—	1.2 (48)	0.3 (12)
10.4 (22,000)	—	—	—	—	—	—	1.3 (52)	0.3 (13)
11.3 (24,000)	—	—	—	—	—	—	1.4 (54)	0.4 (14)

[a] dscm = cubic meter of dry standard air.
[b] dscf = cubic foot of dry standard air.

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NOMENCLATURE

AED = aerodynamic equivalent diameter
CCD = classical cyclone design
CCM = Coulter Counter Multisizer
GSD = geometric standard deviation
MMD = mass median diameter
PM = particulate matter
PSD = particle size distribution
TAMU = Texas A&M University
TCD = Texas A&M cyclone design