DESIGN AND ANALYSIS OF THE BARREL CYCLONE

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Abstract

Cyclones are used as primary particulate abatement devices in many agricultural processes. The goals of this paper are to address the development of design criteria and to compare emission concentrations, pressure drops, and cut points of a new barrel cyclone to traditional 1D3D, 2D2D, 1D3D with a 2D2D inlet, and 1D2D cyclones. Fly ash, corn dust, and high lint cotton gin trash were used to test the performance characteristics. The Texas A&M Cyclone Design Process was used to develop the design parameters for the new barrel cyclone.

Introduction

The Clean Air Act Amendments of 1970 established the National Ambient Air Quality Standards (NAAQS's) to protect the public health by setting the maximum limits for six primary criteria air pollutants. These standards reflect the concentration levels that if exceeded may result in health effects. The six primary criteria pollutants are particulate matter less than 10 microns (PM-10) aerodynamic equivalent diameter (AED), sulfur dioxide, nitrogen dioxide, carbon monoxide, ozone and particulate lead. In the agricultural industry, the primary criteria pollutant emitted as a result of agricultural processes is particulate matter less than 10 microns (Cooper and Alley, 1994).

Cyclone separators are common air pollution abatement devices that separate and collect particulate matter from air streams. They are used extensively in oil mills, grain elevators, feed mills, and cotton gins. A properly designed and constructed cyclone system can be implemented with a low initial cost and minimal operational expense when compared to alternative air pollution abatement strategies (Parnell, 1996). Properly designed, cyclone systems can achieve efficiencies greater than 98%.

Cyclones operate using centrifugal force to separate particulate from the air stream. Air enters tangentially at the top of the barrel and travels downward into the cone forming an outer vortex. The increasing air velocity in the outer vortex results in a centrifugal force on the particles separating them from the air stream. When the air reaches the bottom of the cone, an inner vortex is created reversing direction and exiting out the top as clean air while the particulate falls into the dust collection chamber attached to the bottom of the cyclone.

The two most common cyclones used in the agricultural processing industry, for air pollution control are referred to as the 2D2D designed by Lapple and Shepherd (1939) and the 1D3D cyclone designed by Parnell (1980). Cyclones are comprised of two primary sections, an upper cylindrical section and a lower conical section commonly referred to as the barrel and cone, respectively. The D's in the 2D2D designation refer to the barrel diameter of the cyclone. The numbers preceding the D's relate the length of the barrel and cone sections as a function of barrel diameter. Thus, a 2D2D cyclone has barrel and cone lengths of two times the barrel diameter, whereas the 1D3D cyclone has a barrel length equal to the barrel diameter and cone length of three times the barrel diameter. The inlets of the cyclones are also functions of the barrel diameter and are different for the two cyclones. The width of the inlet for the 2D2D cyclone is 1/4 the barrel diameter and the inlet height is equal to 1/2 the barrel diameter. The 1D3D has an inlet width 1/8 the barrel diameter and a inlet height equal to the barrel diameter.

Simpson and Parnell (1996) introduced a low pressure cyclone designed for use in the cotton industry to separate high lint cotton gin trash. This cyclone, the 1D2D (Figure 1), has an energy consumption of approximately 1/3 of that from either the 1D3D or 2D2D cyclones.

A new cyclone has been developed which was modeled after the 1D2D cyclone. The new cyclone, referred to as the "barrel" cyclone, has a total length of 3D with no cone and utilizes the 1D2D inlet and outlet design. The design inlet velocity for the barrel cyclone is 2400 fpm, similar to that of the 1D2D cyclone. The bottom of the barrel cyclone is connected to a dust collection chamber of length Zc (1.4 Dc) to hold captured particulate matter (Figure 2).

The barrel cyclone was developed as a preseparator for a high volume sampler used to measure emission concentration from the grain unloading process at a feed mill. Preliminary calculations using the interim emission factors for feed mills revealed that the sampling system should be able to capture a maximum of one pound of corn dust. Thus, the sampling system was designed to capture 454 grams of corn dust with approximately 452 grams being captured by the barrel cyclone and less than two grams penetrating the cyclone to the filter, requiring an efficiency of 99.6%. Laboratory test results indicated that the sampling system achieved an efficiency greater than 99.6% and would allow the capture of up to one pound of dust.

An initial sampling trip to a feed mill in Texas was used to evaluate the sampling system. One result of this trip was a concern that the outer vortex in the barrel cyclone was continuing through the barrel and into the dust collection

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Reprinted from the *Proceedings of the Beltwide Cotton Conference*
Volume 2:1520-1525 (1997)
National Cotton Council, Memphis TN

chamber. This phenomena could result in reentrainment of the captured dust and increase emission concentrations, especially when capturing as much as one pound of particulate per cyclone. Although each barrel cyclone was able to collect one pound of particulate without overloading the filter it was desirable to design the cyclone to collect more than one pound of dust for future sampling trips. To correct this problem, a vortex inverter (a small cone with a diameter of 0.9 Dc and a 45 degree slope) was placed in the dust collection chamber (Figure 2). The purpose of the vortex inverter was to prevent the possible reentrainment of dust by forcing the outer vortex to turn upward before reaching the dust collection chamber.

Cyclone Design Methods

Texas A&M Cyclone Design (TCD)

The TCD process determines the cyclone diameter (D_c) utilizing an inlet design velocity (V_d). The design velocities for the 1D3D, 2D2D, and 1D2D cyclones are 3200, 3000, and 2400 (fpm), respectively. A dramatic increase in exit concentrations has been observed at velocities significantly higher and lower than the design velocities (Parnell 1996). The inlet area of each cyclone is calculated using Equation 1.

$$A_i = H \times W \qquad \text{(Eq. 1)}$$

where

H = height of inlet (in),
W = width of inlet (in) and
A_i = inlet area (in^2).

For the 1D3D, 2D2D, and 1D2D cyclones, the inlet area equals $D_c^2/8$. Since most cyclones used for agricultural operations are constructed in sheet metal shops, the barrel diameters are limited to even inch increments, i.e. 32", 34", 36", etc. Equation 2 is used to obtain the first estimate of D_c:

$$D_c^2/8 = Q/V_d \qquad \text{(Eq. 2)}$$

where

Q = volume rate of flow entering the cyclone (cfm) and,
V_d = design velocity (fpm).

The pressure drop equation used in the TCD process is:

$$\Delta p = K * (Vp_i + Vp_o) \qquad \text{(Eq. 3)}$$

where

Vp_i = inlet velocity pressure (in w.g.),
Vp_o = outlet velocity pressure (in w.g.), and
K = empirical constant. (K = 5.1, 4.7, 3.4 for 1D3D, 2D2D, and 1D2D cyclones, respectively.)

There are several methods or procedures being used by engineers to design cyclones. The design procedures outlined in the Air Pollution Engineering Manual (AMCA, 1992) and Air Pollution Control - A Design Approach (Cooper and Alley, 1994) are perceived by some engineers as a standard method. However, this design process here-to-fore referred to as Classical Cyclone Design (CCD) has some problems. Primarily, the CCD process under-estimates collection efficiency. As a consequence, many engineers have assumed that cyclones would not suffice to meet the required reduction in emission rates and have used more expensive filtration systems in applications where cyclones would have been sufficient. There is no design inlet velocity associated with the CCD process. The Texas A&M Cyclone Design process (TCD) specifically states that there is a design velocity at which cyclones can achieve the highest collection efficiencies. Using the CCD process an engineer could use any inlet velocity, which may be considerably higher or lower than the TCD design velocity. Furthermore, the CCD process for predicting number of effective turns, through experimental testing, has been proven to be inaccurate. The emission concentrations measured by Simpson (1996) for inlet loadings of 3 and 6 g/m^3 of corn dust were approximately 1/100 of the predicted emission concentrations using the CCD process. If an engineer were to be totally dependent upon the CCD process, there would likely be an overestimation of emission concentration. For these reasons the Texas A&M Cyclone Design process was used as the primary design method in this paper.

Objective

The objectives of this paper are to report test results of the barrel cyclone and compare its performance characteristics to those of standard 1D3D (1D3D/s), 2D2D, 1D3D with a 2D2D inlet (1D3D/2) and 1D2D cyclones and define and improve problem areas in the design of the barrel cyclone.

Methods

Vortex Inverter

The vortex inverter was added to the barrel cyclone to minimize the reentrainment of captured dust. It was anticipated that significant reentrainment would occur without the vortex inverter if the sampling system were to capture one pound or more of corn dust. Several vortex inverters with cone diameters of 3 and 4.5 inches (0.7 Dc and 0.9 Dc) were tested having slopes of 30, 45 and 60 degrees. The cone was attached to a piece of 3/8 inch all thread fixed to a plate that attached to the bottom of the dust collection chamber. This allowed the inverter to be adjusted to the desired height. All vortex inverter tests were performed with a particulate loading of 50 grams for five minutes at 52 cfm (52 cfm was the flow rate for the 5 inch barrel cyclone that yielded the design inlet velocity of 2400 fpm). These tests were performed on the same system and with the same filter weighing procedure used for emission concentration testing, described below. Once the tests were performed and the filters post weighed, cyclone efficiencies were determined using Equation 4.

$$E = (TD - FD) / TD \quad \text{(Eq. 4)}$$

where

E = cyclone efficiency,
TD = total inlet loading (g) and,
FD = total filter loading (g).

Cyclone efficiency results from each test were used to determine the optimum size, slope and placement of the vortex inverter.

Emission Concentration Testing

The system used to collect emission concentration data included a cyclone to which a loading tube and exit tube were fixed. Attached to the exit tube was a transition that enclosed a filter to capture particulate that penetrated the cyclone. A centrifugal fan controlled by a variable AC voltage controller pulled air through the entire system and the flow rate was monitored by a laminar flow element located between the transition and the fan (Figure 3). Emission concentrations were determined from the results of tests using fly ash, corn dust, and high lint trash. Determination of emission concentrations was accomplished by capturing particulate that penetrated the cyclone. The filters were weighed before and after each test was performed, and the net weight of dust captured was used to calculate the emission concentration (Eq. 5).

$$EMC = (W / (F \times T)) \times 1000 \quad \text{(Eq. 5)}$$

where

EMC = emission concentration (mg/m^3),
W = weight of dust on filter (g),
F = flowrate (m^3/min) and,
T = length of test (min).

Fly Ash. Tests were conducted using fly ash to determine cut point of the cyclone and emission concentrations. Coulter Counter particle size distributions (PSD's) indicated that approximately 50% of the fly ash had an aerodynamic diameter of ten microns or less (50% PM10). All cyclones were tested four times at their respective design inlet velocities. After each test, filters were post-weighed and emission concentrations were calculated based on the filter loading.

It was anticipated that using fly ash as the test particulate would result in larger variations between emission concentrations of each cyclone facilitating a valid comparison of cyclone performance. The drawback of testing with fly ash is its tendency to adhere to all kinds of surfaces. The adhesion of the fly ash on the inside of the barrel cyclone and its consequent detaching during tests may have caused an increase in emission concentrations. Hence, fly ash may not be the ideal testing material for agricultural air pollution abatement devices.

Corn Dust. PSD's performed on a representative sample of the corn dust, sieved to 100 microns or less, indicated that 15% of the corn dust was less than 10 microns (15% PM-10). Corn dust was typical of the type of dust that was anticipated to be sampled. Most agricultural facilities encounter loadings of 1 to 3 g/m^3 (Simpson, 1996), so tests were conducted with inlet concentrations of 3 and 6 g/m^3. Corn dust was used to compare the barrel cyclone with preexisting data on 1D2D, 1D3D/s (standard 1D3D), 1D3D/2 (1D3D with 2D2D inlet) and 2D2D cyclones.

Cotton Gin Trash. Tests were performed with high lint cotton gin trash to simulate loadings typical to cotton gins. All cotton gin trash was air washed through a 100 micron screen to remove fine particles. After the high lint gin trash was air washed it was "spiked" with 10% corn dust sieved to 100 microns or less (high lint trash/fine dust) to quantify fine particle content. A 60 g/m^3 inlet loading corresponds to a cotton ginning system handling 2000 pounds of trash per bale with an assumed air volume rate of flow of 8000 cfm per bale-per-hour (Simpson, 1996). Tests using high lint cotton gin trash were loaded at 30 and 60 g/m^3 to simulate actual cotton gin loadings. The barrel cyclone was tested with high lint cotton gin trash/fine dust to facilitate comparison of results to those of the 1D2D, 1D3D/s, 1D3D/2, and 2D2D cyclones previously tested (Simpson, 1996).

Pressure Drop

The pressure drop testing system consisted of a fan, variac, laminar flow meter, and cyclone. The system was designed so the fan would push air through the laminar flow meter and into the inlet of the cyclone. Air exiting the cyclone was released to the atmosphere (Figure 4) resulting in an exit static pressure equal to zero. Pressure drops were measured using static pressure taps located at the inlet of the cyclone. Pressure drop tests were conducted on all cyclones to test current K values used to calculate pressure drop across a cyclone in the Texas A&M Cyclone Design Process (TCD), and to determine a K value for the barrel cyclone. This system was chosen to obtain consistent values for pressure drops with air only. Three repetitions were recorded at increments of ±200 fpm and ±400 fpm from the design velocity of each cyclone. Ideal K values for each cyclone were obtained using statistical R^2 values.

Cyclone Cut Points

The cut point of a cyclone is defined as the diameter of particle collected with 50% efficiency. Cut points were determined for each cyclone using particle size distributions performed on filters loaded with fly ash. A Coulter Counter Multisizer was used to perform the PSD's on two of the four filters loaded at each inlet velocity. The PSD's were analyzed and fractional efficiencies obtained. Generation of fractional efficiency requires inlet dust concentrations, outlet dust concentrations and PSD's for both inlet and outlet concentrations. The product of an inlet PSD value for a specific particle size range and the inlet total dust concentration yields a total inlet concentration of particles in that size range. The same holds for outlet concentrations. The fractional efficiency for a particle size was determined using Equation 6.

$$FE = 1.0 - (f_o/f_i) \qquad \text{(Eq. 6)}$$

where

FE = fractional efficiency,
f_o = outlet concentration of particles (mg/m^3) , and
f_i = inlet concentration of particles (mg/m^3).

Cut points are expressed in aerodynamic diameter.

Clear Plastic Cyclone

A plexi-glass cyclone was built and modeled after the barrel cyclone. This was done to determine the number of turns that the outer vortex makes before it turns back up toward the exit. Fly ash was loaded to visually monitor the outer vortex. However it was not possible to monitor the inner vortex because of the high separation efficiency of the cyclone. Very fine dust from a combine tertiary filter was loaded in an attempt to view the inner vortex. The glass cyclone was also used to view the amount of cycling lint when loaded with high lint trash without fine dust. The loading of fine dust limits vision due to the attraction of the particles to the cyclone walls caused by static electricity.

Test Results

Results from Vortex Inverter Testing

The height of the inverter in the collection chamber had little effect on efficiency, but there was a slight decrease in the pressure drop across the cyclone as it was positioned higher. The larger diameter inverters tended to reduce the pressure drop and increase efficiency when compared to the smaller inverters. A vortex inverter with a diameter of 4.5 inches (0.9 Dc) and a 45 degree slope was chosen. The inverter was placed at a height of 7 inches (1.4 Dc) above the base of the dust collection chamber with the tip located at the base of the barrel cyclone. This position was chosen to allow sufficient space for dust to fall between the vortex inverter and the barrel, to maximize the volume of the dust collection chamber, and to maximize efficiency. Average test results are shown in Table 1.

Comparison of Average Emission Concentrations

Results from testing with fly ash loaded at 5 g/m^3 for 3 minutes are shown in Table 2. Emission concentrations were slightly lower with increasing inlet velocity for all cyclones except the 1D3D/s, which had emission concentrations with lower magnitudes of difference.

Figure 5 illustrates the average emission concentrations of the five cyclones with inlet loadings of fly ash at 5g/m^3 with inlet velocities of V_d plus 400, Vd minus 400, and design velocity (V_d). The results show that 1D3D/s and 2D2D cyclones had similar emission concentrations at the design velocity, but the 2D2D was slightly lower at V_d plus 400, and slightly higher at V_d minus 400. The 1D3D/2 obtained higher overall emission concentrations than the 1D3D/s and 2D2D, but was lower overall than the barrel cyclone. The barrel cyclone had emission concentrations higher than the 1D3D/2 and had significantly lower emission concentrations than the 1D2D.

Results from testing corn dust with a loading of 6 g/m^3 on the barrel cyclone were compared with previous results (Simpson, 1996) for 1D3D/s, 2D2D, 1D3D/2, and 1D2D cyclones. The 1D3D/2 had the best results of all cyclones. The 1D3D/s had significantly lower emission concentrations than the 2D2D. The 2D2D had lower emission concentrations than the barrel and the barrel was a small improvement over the 1D2D. The results are shown graphically in Figure 6.

Emission Concentration results from high lint gin trash/fine dust tests on the barrel cyclone are compared with previous emission concentration data for the 1D2D, 1D3D/s, 2D2D, 1D3D/2 cyclones (Simpson, 1996). The 1D2D and barrel cyclones had the lowest emission concentrations of all five cyclones. The barrel cyclone had significant decrease in emission concentration at the 30 g/m^3 loading rate, when compared to the 1D2D.

Comparison of Pressure Drop Results

It was concluded from pressure drop test results that K values used in the TCD process needed slight modification. Original K values for the 1D3D, 2D2D, and 1D2D cyclones were 5.1, 4.7, and 3.4 respectively. To obtain new K values the cyclones were tested and actual pressure drop values were determined. Individual K values for each test were calculated using measured static pressure drop at the corresponding inlet velocity. For a conservative measure, the largest K value was then used to recalculate pressure drops. The optimum K value was determined by choosing the one with the statistical R^2 value that indicated the highest correlation between pressure drop and inlet velocity. These were defined as the new K value. The 1D3D/s and 2D2D cyclones needed more repetitions with different K values to obtain one value that accurately represented the actual pressure drop readings. The K value for the 1D3D/2 had previously been the same as the 1D3D/s, but test results indicate that it should have a different K value. The new K values for the cyclones are shown in Table 3.

Comparison of Cut Point Results

Cyclone cut points were determined using fractional efficiencies. The 1D3D/s, 2D2D, and 1D3D/2 cyclones had the same cut point for all three test velocities. The barrel cyclone had a higher cut point at the design velocity than at the other two inlet velocities. The 1D2D had increased cut points at design velocity and V_d plus 400, but a lower cut point at V_d minus 400. Table 4 shows cut point results for each cyclone at the three test velocities.

Clear Plastic Cyclone Results

The path of the outer vortex could be viewed and the number of turns counted when loaded with fly ash. With the tip of the vortex inverter at the base of the barrel the number of effective turns was 2.5. The inverter was adjusted to a height where the base of the inverter was 1/2 inch below the base of the barrel. This increased the number of turns to 3, which, theoretically, should increase the efficiency. Fine dust from a combine filter was loaded into the glass cyclone. With light loadings the inner vortex could not be seen, due to the small amount of penetration through the cyclone. Heavy loadings clouded the surface of the cyclone restricting vision. The dynamics of the inner vortex were unable to be viewed. The most significant results were concluded from the cotton gin trash tests. The plastic cyclone was loaded heavily with high lint cotton gin trash to determine if lint was circulating in the cyclone. When lint circulates in the conical section of a cyclone it causes dust to be reentrained, which increases penetration through the cyclone. There was no lint circulation observed in the plastic cyclone after heavy loadings (> 100 g/m^3) of high lint cotton gin trash.

Results and Conclusions

1. Placing a vortex inverter in the barrel cyclone reduces emission concentrations. Further testing needs to be done to find the optimum size and placement of the vortex inverter for different material types.

2. The barrel cyclone had higher emission concentrations than all cyclones, except for the 1D2D, using fly ash (50% PM-10), but had near the same emission concentrations as 1D3D/s, 1D3D/2, and 2D2D cyclones when tested with corn dust (15% PM-10).

3. The lowest emission concentrations were obtained by the barrel cyclone when loaded with high lint cotton gin trash at 30 g/m^3. At 60 g/m^3 loadings, 1D2D and barrel cyclones obtained the same emission concentrations.
4. The barrel is equal to or better than the 1D2D at separating high lint cotton gin trash/ fine dust.

5. No lint circulation was observed in the glass cyclone with greater than 100 g/m^3 inlet loading rates of high lint cotton gin trash.

6. The emission concentrations of the barrel cyclone are not significantly different at ±600 fpm from the design velocity. This allows the barrel cyclone to be applied to many different situations.

7. Pressure drop across the barrel cyclone can be determined using the TCD pressure drop equation with a K value of 3.1.

8. New K values were determined for 1D3D/s, 2D2D, 1D3D/2, and 1D2D cyclones. They are 5.3, 4.7, 5.1 and 3.4 respectively.

9. Pressure drop across the barrel cyclone was significantly lower than 1D3D/s, 2D2D, 1D3D/2 and 1D2D cyclones. The barrel cyclone had the lowest pressure drop allowing it to be used with axial flow fans.

10. The barrel cyclone has a simpler design and lower construction cost than traditional cyclones.

Acknowledgment

The authors would like to thank the Texas Agricultural Experiment Station, the National Cattleman's Beef Association, and the Cotton Foundation for their support of this research.

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Table 1: Average efficiencies from vortex inverter tests.

Cone Diameter (inches)	Cone Angle (degrees)	Cone Height (inches)	Cyclone Efficiency (%)	Standard Deviation
4.5	45	5	99.72	0.1131
4.5	45	6	99.66	0.0707
4.5	45	7	99.72	0.0283
4.5	45	8	99.70	0.0990
no cone	N/A	N/A	99.26	0.0283

Table 2: Average emission concentrations from fly ash tests in mg/m^3 with standard deviations.

V_{IN}	1D3D/s	SD	2D2D	SD	1D3D/2	SD	Barrel	SD	1D2D	SD
V_D+400	172	2.99	162	8.58	176	4.03	195	1.71	244	7.53
V_D	181	5.91	188	12.2	192	9.71	208	5.32	266	4.55
V_D-400	180	9.32	201	7.41	209	13.1	236	1.41	296	8.85

Table 3: New K values for pressure drop across the cyclone equation in TCD.

Cyclone	V_{IN} (fpm)	K_{OLD}	ΔP_{ACT} (“wg)	K_{TEST}	K_{NEW}	ΔP_{NEW} (“wg)	R^2
1D3D/s	2800	5.1	3.5	5.1	5.3	3.6	1
	3000		4	5.07		4.2	
	3200		4.8	5.35		4.8	
	3400		5.3	5.23		5.4	
	3600		5.8	5.11		6	
1D3D/2	2800	5.1	3.7	5.39	5.6	3.8	0.9983
	3000		4.3	5.45		4.4	
	3200		5	5.57		5	
	3400		5.7	5.7		5.7	
	3600		6.3	5.55		6.4	
Barrel	2000	none	0.9	3.10	3.1	0.9	0.9941
	2200		1.1	3.13		1.1	
	2400		1.3	3.10		1.3	
	2600		1.5	3.05		1.5	
	2800		1.8	3.16		1.8	
1D2D	2000	3.4	1.2	4.13	4.7	1.4	0.9961
	2200		1.5	1.26		1.7	
	2400		1.9	4.54		2	
	2600		2.2	4.68		2.3	
	2800		2.5	4.74		2.7	
2D2D	2600	4.7	2.9	4.9	5.1	3	0.9976
	2800		3.4	4.51		3.5	
	3000		3.9	4.19		4	
	3200		4.7	4.01		4.6	
	3400		5.1	3.75		5.2	

Table 4: Cut point results determined from filters exposed from fly ash tests.

Cyclone	V_{IN} (fpm)	Cut-point (mm)
1D3D/s	2800	3.3
	3200	3.3
	3600	3.3
2D2D	2600	3.5
	3000	3.5
	3400	3.5
1D3D/2	2800	3.5
	3200	3.5
	3600	3.5
Barrel	2000	3.4
	2400	3.6
	2800	3.4
1D2D	2000	3.6
	2400	3.7
	2800	3.7

Bc = Dc / 4
Hc = Dc / 2
De = Dc / 1.6
Lc = Dc
Sc = 5 Dc / 8
Zc = 2 Dc
Jc = Dc / 2

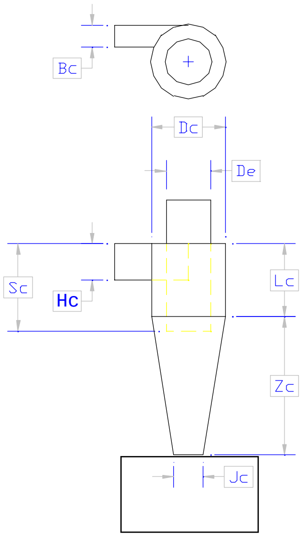

Figure 1: Configuration of 1D2D Cyclone

Bc = Dc / 4
Hc = Dc / 2
De = Dc / 1.6
Lc = 3 Dc
Sc = 5 Dc / 8
Zc = 1.4 Dc
Jc = 1.3 Dc
Dv = 0.9 Dc

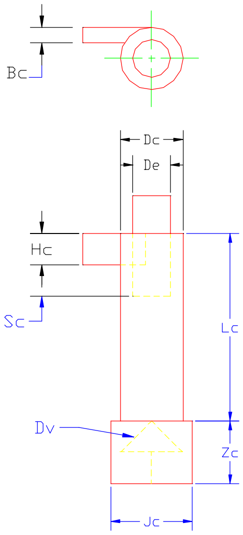

Figure 2: Configuration of Barrel Cyclone

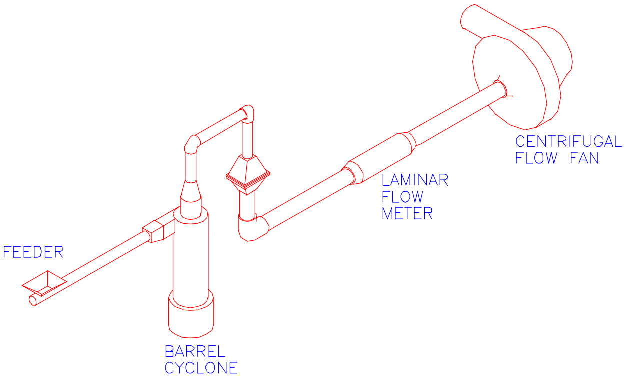

Figure 3: Emission Concentration Testing System

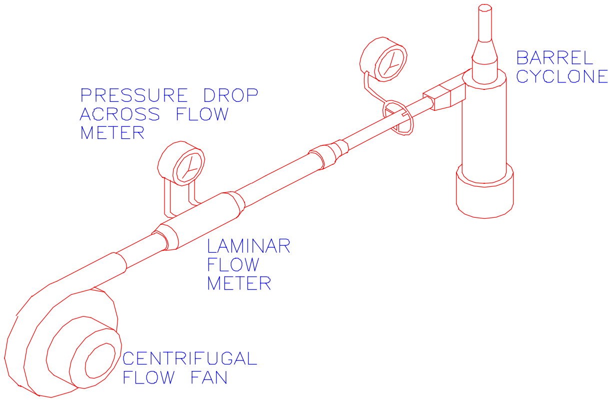

Figure 4: System to Measure Pressure Drop Across Cyclones

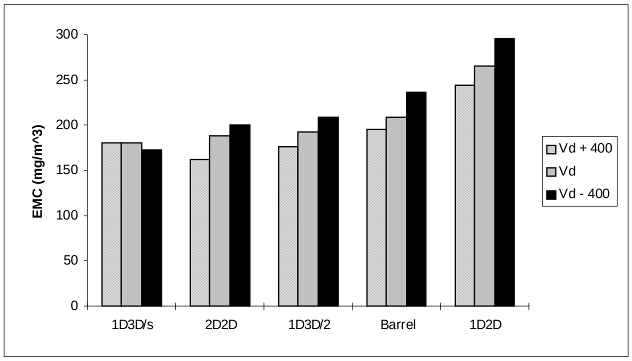

Figure 5: Average emission concentrations (mg/m^3) with inlet loadings of 5 mg/m^3 with fly ash at design velocity and plus and minus 400 fpm from design velocity for all cyclones.

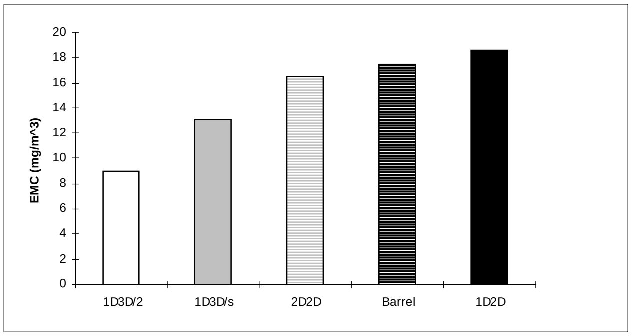

Figure 6: Average emission concentrations for corn dust at inlet loadings of 6 g/m^3 with all cyclones at design velocity.

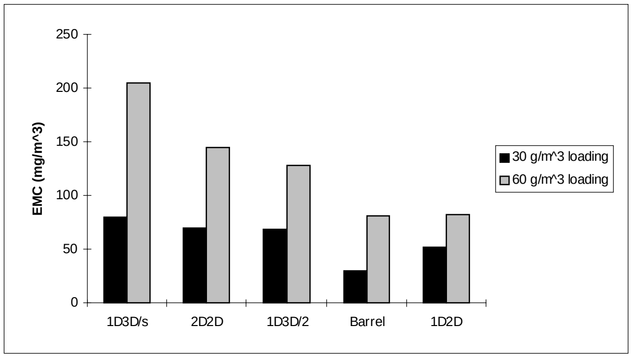

Figure 7: Average emission concentrations of 1D3D/s, 2D2D, 1D3D/2, 1D2D and barrel cyclones using high lint gin trash/fine dust with inlet loadings of 30 and 60 g/m^3 at design velocity.