CYCLONE DESIGN FOR AIR POLLUTION ABATEMENT ASSOCIATED WITH AGRICULTURAL OPERATIONS

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Abstract

This paper addresses problems associated with the design of cyclones using what is referred to as the Classical Cyclone Design (CCD) procedure. The primary problem with the CCD process is a gross overestimate of emission concentrations. The Texas A&M Cyclone Design Process (TCD) is presented as an alternative. Measurements of emission concentrations, cut-points and pressure drops are used to compare the two design procedures.

Introduction

Cyclone separators are the most widely used air pollution abatement device in the agricultural processing industry. They are used extensively in oil mills, grain elevators, feed mills, and cotton gins for collecting or separating particulate matter from air streams. Properly designed and constructed cyclones can be operated relatively inexpensively. Typically, cyclones have a relatively low initial cost, maintenance cost and energy consumption compared to other air pollution abatement systems. If they are sized, designed, installed, and operated properly, they will allow a facility to meet state or federal air pollution regulations for particulate matter.

The two most common cyclones used (figure 1) in the agricultural processing industry, for air pollution control, are referred to as the 2D2D or "high efficiency cyclone" 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 referred to as the barrel and a lower conical section referred to as the cone. 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, respectively. 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 a 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 one-fourth the barrel diameter and the height is one-half the barrel diameter. The 1D3D has an inlet width one-eighth the barrel diameter and a height equal to the barrel diameter. The 2D2D cyclone has been the cyclone of choice for many years, but studies conducted on the 1D3D cyclone have shown it to be a more efficient cyclone design for the agricultural processing industry.

Simpson and Parnell (1996) introduced a new low-pressure cyclone which was referred to as a 1D2D (figure 2). This new cyclone has an energy consumption of approximately 1/3 of that expected from either the 1D3D or 2D2D cyclones. A wide range of tests were performed on 1D3D, 2D2D, and 1D2D cyclones as part of this research. One series of tests consisted of measuring the emission concentrations from each cyclone with an inlet loading of 6 g/m^3 of a corn dust fraction that had been sieved to less than 100 micrometers (100 µm). The resulting emission concentrations from these tests were less than 20 mg/m^3 for the 1D3D, 2D2D, and 1D2D cyclones . These results indicate that a properly designed and operated 1D3D, 2D2D, and 1D2D cyclone can have a collection efficiency of more than 99%.

Fines as high as $10,000 a day can be imposed on processing facilities unable to meet emission regulations set by regulatory agencies. The next level of technology above cyclone separators is filtration (baghouses). According to Parnell (1990), the annual cost of operating a filtration system for air pollution control could be 5 to 10 times higher than using cyclone technology. Presently, regulatory agencies expect filtration technology (baghouses) to reduce emission concentrations to 23 mg/m^3 (milligrams per cubic meter) [.01 gr/dscf (grains per dry standard cubic foot)]. Cyclones are expected to achieve an emission concentration of 69 mg/m^3 (.03 gr/dscf) (Parnell 1990). There is a perception among some engineers in regulatory agencies that cyclone systems can not reduce emission rates to levels that will be in compliance with their respective state rules and regulations. As a consequence some agricultural facilities have had to replace their cyclones with filtration systems. As previously stated, the cost of installing and operating filtration systems is significantly higher than cyclone systems.

Cyclone Design Theory

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 severe problems. The primary problem is that the CCD process grossly 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. It is the premise of this paper that properly designed cyclones will allow agricultural operations to

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comply with State Air Pollution Regulatory Agency (SAPRA) rules and regulations.

Classical Cyclone Design (CCD)

There are four equations used in the CCD process. These include calculations of the following:

- number of effective turns (N_e),
- cut-point diameter (d_{pc}),
- cyclone collection efficiency (η_t), and
- pressure drop (δp).

The CCD equation used to calculate the number of effective turns made by the dust laden strands of air moving from the inlet toward the dust outlet prior to the cleaned air reversing direction is as follows:

$$N_e = \frac{1}{H}\left[\frac{L_b + L_c}{2}\right] \qquad \textbf{(Eq. 1)}$$

where;

N_e	=	number of effective turns,
H	=	height of inlet duct,
L_b	=	length of cyclone body, and
L_c	=	length of cyclone cone.

The cut-point of a cyclone is the Aerodynamic Equivalent Diameter (AED) of the particle collected with 50% efficiency. As the cut-point diameter increases, the cyclone collection efficiency decreases. The CCD equation used to calculate the cut-point of a cyclone is as follows:

$$d_{pc} = \sqrt{\frac{9\mu W}{2\pi N_e V_i(\rho_p - \rho_g)}} \qquad \textbf{(Eq. 2)}$$

where

d_{pc}	=	cut-point diameter,
μ	=	gas viscosity,
W	=	inlet duct width,
N_e	=	number of effective turns,
V_i	=	inlet velocity,
ρ_p	=	particle density, and
ρ_g	=	gas density.

The CCD equation used to calculate collection efficiency of any particle size range (Cooper and Alley, 1990) is as follows:

$$\eta_j = \frac{1}{1+\left(\frac{d_{pc}}{\bar{d}_{pj}}\right)^2}, \quad \eta_j \le 1 \qquad \textbf{(Eq. 3)}$$

where

η_j	=	collection efficiency for the j[th] particle size range, and
$\bar{d}_{pj}$	=	characteristic diameter (midpoint) of the j[th] particle size range.
d_{pc}	=	cut-point diameter

The overall collection efficiency of a cyclone and subsequent penetration for the CCD process can be calculated with equations 4 and 5.

$$\eta_t = \Sigma \eta_j m_j \qquad \textbf{(Eq. 4)}$$

where

η_t	=	overall collection efficiency, and
m_j	=	mass fraction of particulate in size range j.

$$P_t = 1 - \eta_t \qquad \textbf{(Eq. 5)}$$

where

P_t	=	overall penetration of cyclone.

The CCD process for calculating pressure drop across a cyclone uses the following two equations:

$$H_v = K{*}H{*}W/D_e^2 \qquad \textbf{(Eq. 6)}$$

where

H_v	=	number of inlet velocity heads,
H	=	height of cyclone inlet,
W	=	width of cyclone inlet,
D_e	=	diameter of gas exit, and
K	=	empirical coefficient ranging from 12 to 18.

$$\delta p = H_v * Vp_i \qquad \textbf{(Eq. 7)}$$

where

δp = pressure drop across the cyclone,

and

Vp_i = inlet velocity pressure.

Texas A&M Cyclone Design (TCD)

The Texas A&M Cyclone Design (TCD) process is simpler by comparison. The basis for the TCD process is the determination of D_c (cyclone size) utilizing an inlet design velocity (V_d). The premise of this design process is that every cyclone has ideal inlet velocity (V_d). This premise is in contradiction with the implication of the CCD process that the cyclone efficiency will continue to increase with increasing inlet velocities. We have observed a dramatic increase in exit concentrations at velocities higher than the design velocities. **The design velocities for the 1D3D, 2D2D, and 1D2D cyclones are 3200, 3000, and 2400, respectively.**

The inlet area of each cyclone is calculated with equation 8:

$$A_i = H * W \qquad \textbf{(Eq. 8)}$$

where

H	=	height of inlet, and
W	=	width of inlet.

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 9 is used to obtain the first estimate of D_c:

$$D_c^2 = Q/V_d \qquad \textbf{(Eq. 9)}$$

where

Q = volume rate of flow entering the cyclone.

The pressure drop equation used in the TCD process is different:

$$\delta p = K*(Vp_i + Vp_o) \qquad \textbf{(Eq. 10)}$$

where

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

Sample Design

Given: Q = 4,000 scfm,
inlet loading = C_i = 6 g/m^3 of fine corn dust (<100 µm), and
Particle Size Distribution (PSD) - Table 1.

Determine the following using the CCD and TCD process for a 1D3D, 2D2D and 1D2D cyclone:

(a) d_{pc}
(b) n_t
(c) emission concentration (C_o)
(d) pressure drop (δp)

In this sample design, the TCD process was used to size the cyclones to facilitate a comparison. The appropriate cyclone diameters for the 1D3D, 2D2D and 1D2D cyclones are 38", 40" and 44", respectively. The respective inlet velocities were 3191 feet per minute (fpm), 2880 fpm, and 2380 fpm. The CCD procedure includes the following calculations:

(1) N_e - Eq. 1,
(2) d_{pc} - Eq. 2,
(3) n_j - Eq. 3,
(4) n_t - Eq. 4,
(5) P_t - Eq. 5,
(6) Emission concentration = (P_t * C_i)/100, and
(7) δp.

Table 2 illustrates a tabular approach of performing calculations 3 -5. Tables 3-5 are the results of the CCD process and recent measured results (Simpson, 1996).

Observations

The following was noted from the results of the CCD process:

(1) Properly designed cyclones are more efficient collectors than would be predicted using the CCD process.

(2) The CCD process for predicting number of effective turns (Eq. 1) is inaccurate. (We have measured 6 turns for the 1D3D compared to the 2.5 turns obtained from equation 1.)

(3) There is no design inlet velocity associated with the CCD process. Hence, an engineer could use any inlet velocity which may be considerably higher or lower than the TCD design velocity. (We have observed a significant increase in emission concentrations for inlet velocities higher and lower than the V_d.)

(4) The emission concentrations measured (Simpson, 1996) for inlet loadings of 3 g/m^3 and 6 g/m^3 were approximately 1/100 of the predicted emission concentrations using the CCD process (Tables 4 and 5). If an engineer were to be totally dependent upon the CCD process, it would be likely that his or her recommendation would be that filtration technology would be required.

(5) The PM10 fraction of corn dust is less than 15% (Table 1).

(6) The measured and calculated cut points were comparable (Table 4). It is possible that a correction in N_e will improve CCD calculations of d_{pc}.

(7) The CCD method of calculating δp (Eq. 7) allows for significant error if K were allowed to range from 12 to 18. A K value of 14 in equation 7 compares favorably with the TCD method calculating pressure drop (Eq. 10) for the 1D3D and 2D2D cyclones. However, the result of using the CCD pressure drop model (Equations 6 and 7) for the 1D2D cyclone will not be accurate. The TCD method will provide more accurate results for estimating pressure drop.

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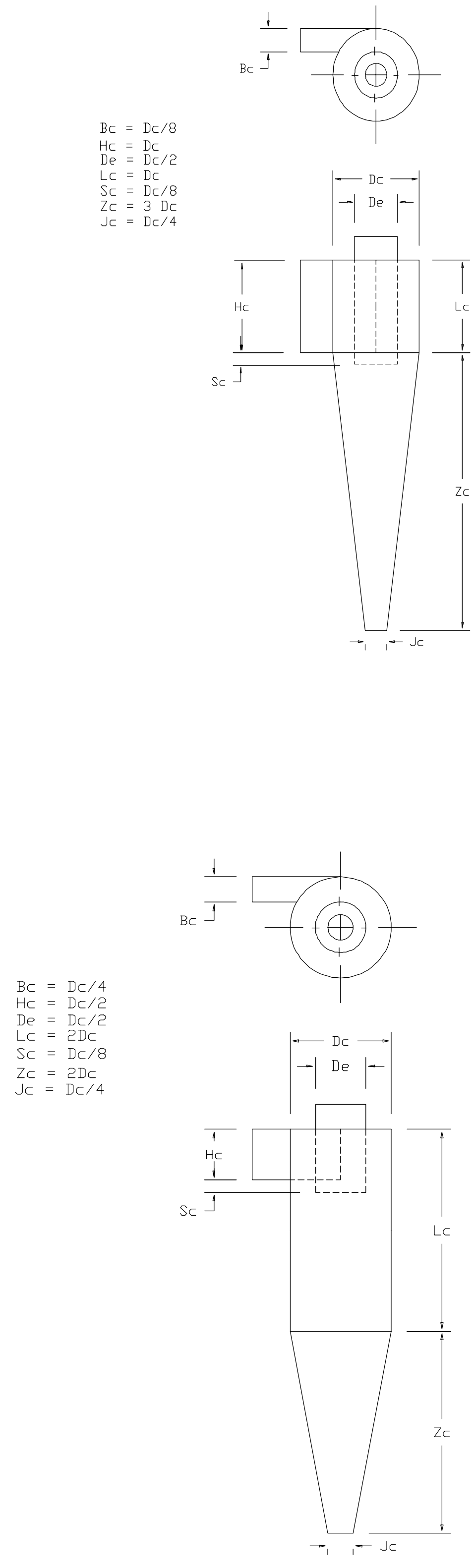

Figure 1: Configuration of 1D3D and 2D2d Cyclones

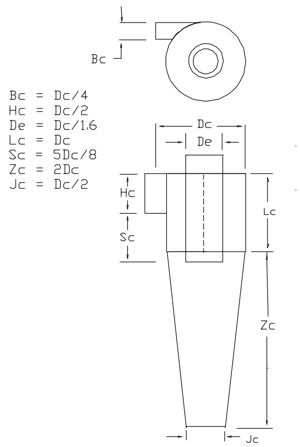

Figure 2: Configuration of 1D2D Cyclone

Table 1. Mass fraction versus Particle Size determined with a Coulter Multisizer II in the Processing Laboratory of the Department of Agricultural Engineering, Texas A&M University.

Particle Size Range* (µm)	Mass Percent in Size Range (%)
0-2.5	0.05
2.5-10	11.2
10-15	33.8
15-20	34.0
20-30	17.3
30-100	3.6

* Aerodynamic Equivalent Diameter (AED) - The Coulter Counter Multisizer PSD results are reported as percent volumes versus Equivalent Spherical Diameter (ESD). To convert AED, the following equation was used:

$$AED = \frac{ESD}{\sqrt{\rho_p}}$$

Corn dust will typically have a ρ_p of 1.4 g/m^3. The assumption was made that particle density is constant for different particle size ranges to convert from percent volume to percent mass.
Note: Only 11.3% of this dust is PM_{10}.

Table 2. Sample Calculations to determine overall efficiency (η_t) for a 38-inch diameter 1D3D cyclone with a dpc of 7.49 µm and the particle size distribution given in Table 1.

Particle Size	Size Range	dp_j	dp_j/dpc	η_j	m_j	$\eta_j m_j$
	(µm)	(µm)		(%)		
1	0-2.5	1.25	0.167	0.03	0.1	0.003
2	2.5-10	6.25	0.84	0.70	11.2	7.8
3	10-15	12.5	1.67	0.74	33.8	24.9
4	15-20	17.5	2.34	0.85	34	28.8
5	20-30	25	3.34	0.92	17.3	15.9
6	30-100	65	8.7	0.99	3.6	3.6
					100	η_t = 81%

$P_t = 1 - \eta_t = 29\%$
Emission Concentration = P_t/100 x 6,000 mg/m^3 = 1140 mg/m^3
Using Equations 6 and 7 and a K = 14, the pressure drop was calculated to be 4.44 inches wg.

Table 3. Results of the CCD process for Case I: 38-inch diameter 1D3D cyclone, Case II: 40-inch diameter 2D2D cyclone and Case III: 44-inch diameter 1D2D cyclone, abating a 4000 cfm exhaust with an inlet loading of 6 g/m^3 of fine corn dust.

Cyclones	N_e (turns)	dpc (µm)	η_t (%)	Co (mg/m^3)	δP (K = 14) (inches wg)
1D3D	2.5	7.49	81	1140	4.4
2D2D	6	7.34	78	1310	3.6
1D2D	4	10.4	66	2020	2.5

Table 4. Measured versus calculated cut points and emission concentrations at an inlet loading of 3 g/m^3 of fine corn dust.

Cyclones	Measured*		Calculated (CCD)	
	dpc (µm)	Co (mg/m^3)	dpc (µm)	Co (mg/m^3)
1D3D	6.2	5	7.5	570
2D2D	6.6	7.1	6.0	655
1D2D	6.2	8.0	10.4	1010

*Simpson, 1996

Table 5. Measured versus calculated cut points and emission concentrations at air inlet loading of 6 g/m^3 of fine corn dust.

Cyclones	Measured*		Calculated (CCD)	
	dpc (µm)	Co (mg/m^3)	dpc (µm)	Co (mg/m^3)
1D3D	6.8	13.1	7.5	1140
2D2D	6.4	16.5	6.0	1310
1D2D	7.8	18.6	10.4	2020

*Simpson, 1996