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Design of air cyclones: part I – a review of applicable models

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ABSTRACT

This paper presents a review of the available models used in the design, simulation and optimisation of air cyclones. These models are particularly important in computer-aided design of air cyclones. A review of the models indicates that the key design and simulation parameters of collection efficiency and pressure drop of air cyclone are governed chiefly by the cross sectional areas and lengths of the individual flow channels, operational conditions and physical properties of the feed. Analysis of the models shows that to increase cyclone efficiency, the following is required; decrease the cyclone diameter; decrease the outlet diameter; reduce the cone angle and increase the cyclone length. An increase in capacity can be achieved by increasing the cyclone diameter and length. An increase in pressure drop results in an increase in separation efficiency and a more concentrated underflow. The models reviewed in this study are useful in the design, testing and validation of air cyclones. Computer aided design, simulation and optimisation of processes involving air cyclone can also be carried out using these model

INTRODUCTION

A very significant number of locally used equipment in the small, medium and large scale industries are largely fabricated by road-side artisans or semi-skilled craftsmen with very little knowledge of equipment design. While these efforts deserve commendation and encouragement, such pieces of equipment when in service are either not effective or grossly inefficient.

It has become very essential that proper design of manufacturing processes and process equipment be undertaken by those with the skill and training to do so. It is necessary to have accurate models that depict actual situations taking place in various types of equipment and the complete process.

The mode of operation of air cyclones is based on the use of centrifugal and gravitational forces to separate particles in gaseous streams (Ogawa, 1997). Particles which enter the device with the flowing fluid swirl round the cylindrical parts of the device, impact the walls, fall down the cyclone walls (by gravitational action) and are collected in a hopper.

Cyclones are generally pre-cleaning devices, and have found wide

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applications because they are robust, easy to build and install, have low capital and maintenance cost, and can be adapted to a wide range of operating conditions (Leith, 1984, Koch and Licht, 1980). They are used not only as dust collectors but also in particle sizing, classification and screening. However, cyclones are prone to low efficiencies and high operating costs due to high pressure drop as well as internal erosion/corrosion.

In this paper available models that can be used in the design, simulation and optimisation of air cyclones are reviewed.

CYCLONE DESIGN

Cyclones can be used in three principal areas, namely classification, gas cleaning and product recovery duties. In all these cases, the important parameters that are generally used to evaluate cyclone performance are emission concentrations, collection efficiency as a function of particle size and pressure drop (energy consumption as a function of inlet velocity).

Although the operation of an air gas cyclone is relatively simple, it is however not completely understood, partly as a result of the complicated flow pattern within the cyclone. Notwithstanding the fact that much work exists in the literature on how the cyclone dimensions and its operating conditions affect its performance, current design practice is based partly on theory and partly on empirical models. The design philosophy is based on a standard (or known) cyclone design, which is that cyclone that has the proper geometric relationship between the cyclone diameter, inlet area, vortex finder, apex orifice and sufficient length that provides adequate retention time for particle classification (Svarovsky, 1981). By selecting the standard design, a meaningful scale-up can be performed which leads to reasonably reliable design. There is a choice of several standard or optimum designs that have been developed and tested by different researchers as well as some well-documented commercial cyclones.

As mentioned earlier, the literature on air cyclones is full of studies of the effect of the relative geometrical proportions on pressure drop or capacity and separation efficiency. What follows is a discussion on how these factors affect the performance of an air cyclone.

Cyclone Geometry

Cyclones come in different design geometries. The hypothesis is that different cyclone designs are used for different process streams and dust types for optimum performance. That is, a design geometry selected for a specific application may perform better for one type or size of dust than for another. There are several geometrical configurations of industrial air cyclones that exist today. In fact, as many as seventeen configurations have been reported in the literature. The earlier standard designs are six in number and are grouped into three categories: high efficiency, conventional (or medium efficiency) and high throughput as shown in Fig 1 and Table 1. These designs are:

i Shepherd and Lapple conventional (2D2D)(1939)
ii Stairmand high efficiency (1951)
Iii Stairmand high throngh put (1951)
iv Swift high efficiency (1969)
v Swift conventional (1969)
vi Swift high throughput (1969)

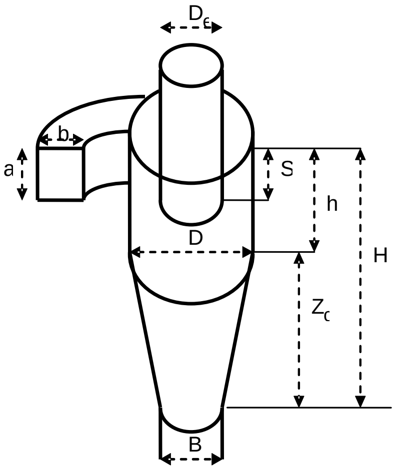

Fig 1 A schematic diagram of the cyclone

i Peterson and Whitby high throughput (1965)
ii Parnell and Davies (1D3D) (1979)
iii Simpson and Parnell (1D2D)(1995)
iv Tullis et al (Barrel) (1997)
v Kenny, Gussman and Meyer (Sharp-cut cyclone, SCC) (2000)
vi Kenny and Thorpe (Very sharp-cut cyclone, VSCC) (2000)
vii StorchT2/160
viii StorchT3/315
ix Tengbergen100-2.5/A370
x Tengbergen50-2.5/B280
xi Musch D

The later designs are modifications of the earlier geometries and are listed chronologically by the name(s) of the designer(s) as follows:

Note that in the above designs D is the cyclone diameter. Also, the lengths of the cylindrical and conical portion of the cyclone are expressed in terms of its diameter (D). For example 2D2D means:

Length of cylindrical part = length of the conical part = 2D . Information on the date of development of the last five geometries was not available but the dimensions are presented in Table 2 along with those of Peterson and Whitby, 1D3D and 1D2D cyclone designs.

Table 1: **Standard dimensions of early cyclone designs**

	Cyclone Type					
	High Efficiency		Conventional		High Throughput	
	(1)	(2)	(3)	(4)	(5)	(6)
Body Diameter, *D/D*	1.0	1.0	1.0	1.0	1.0	1.0
Height of Inlet, a*/D*	0.5	0.44	0.5	0.5	0.75	0.8
Width of Inlet, b/D	0.2	0.21	0.25	0.25	0.375	0.35
Diameter of Gas Exit, D_e/D	0.5	0.4	0.5	0.5	0.75	0.75
Length of Vortex Finder, L*/D*	0.5	0.5	0.625	0.6	0.875	0.85
Length of Body, *h/D*	1.5	1.4	2.0	1.75	1.5	1.7
Length of Cone, Z_c/D	2.5	2.5	2.0	2.0	2.5	2.0
Diameter of Dust Outlet, B*/D*	0.375	0.4	0.25	0.4	0.375	0.4

SOURCES: Columns (1) and (5) = Stairmand, 1951; columns (2), (4) and (6) = Swift, 1969; columns (3) =Shepherd & Lapple, 1939.

Table 2: **Standard Dimensions of New Cyclone Designs.**

	Peterson & Whitby	1D3D	1D2D	Storch T2/160	Storch T3/315	Tengbergen 100-2.5/A370	Tengbergen 50-2.5/B280	MuschD
D/D	1	1	1	1	1	1	1	1
D_e/D	0.5	0.5	0.5	0.48	0.559	0.405	0.536	0.333
S/D	0.583	0.625	0.625	1.063	1.048	0.568	1.07	0.81
h_d/D	1.33	1	2	2.06	2.17	0.649	1.554	0.734
Z_c/D	3.17	3	2	4.875	3.86	2.335	2.87	2.417
a/D	0.583	0.5	0.5	0.8375	0.783	0.486	0.857	0.523
b/D	0.208	0.25	0.25	0.0244	2.83	0.268	0.268	0.143
B/D	0.5	0.25	0.25	0.375	0.434	0.405	0.536	0.547

The most commonly used cyclone designs are the 2D2D (Shepherd and Lapple, 1939), the Stairmand high efficiency (1951) and the 1D3D (Parnell and Davies, 1979). Simpson and Parnell (1995) introduced the 1D2D design as a new low pressure cyclone, for the cotton ginning industry. Tullis et al (1997) also introduced the Barrel cyclone to address the problem of fine particulate matter (PM) that get diverted into the clean air stream and enable them to be collected, for exhausts containing a significant fraction of cotton lint fiber. In comparative terms 1D3D and 2D2D cyclones are best designs for fine dust, 1D2D cyclone is best design for lint fiber/fine dust from gin trash while Barrel cyclone is best design for lint fiber/large trash.

Kenny, Gussman and Meyer (2000) developed the tangential round-entry Sharp-Cut Cyclone (SCC) to offer size selectivity; that is for sharpness of selectivity curve. Kenny and Thorpe (2000) further modified the SCC design by enlarging the cyclone cone (longer cone, wider base) and decreasing the inlet and outlet tube diameters to obtain the Very Sharp-Cut Cyclone (VSCC). The VSCC body diameter is smaller than the corresponding SCC, to compensate for the effects of these changes in geometry on D_{50}, the diameter of particle collected with 50% efficiency. D_{50} value as low as 2.5µm at a flow rate of 16.67l/min was obtained.

Experimental results have shown that the optimum operating conditions for the cyclones also vary widely from geometry to geometry. For instance the Texas A&M Cyclone Design (TCD) process specified the “ideal” cyclone inlet velocities for the 1D3D, 2D2D and 1D2D cyclones as 975m/min ± 122m/min, 914m/min ± 122m/min and 732m/min ± 122m/min respectively for optimum performance (Wang et al, 2002).

Cyclone Performance

In all cyclones, particulate is separated from the gas stream by means of centrifugal force. Particulate is thrown toward the outside of the spinning column of gas, while the relatively clean gas exhausts from the spinning vortex. The two main factors that affect the performance of any cyclone include:

1. The velocity at which a given particle is moving toward the cyclone wall (where it is theoretically collected).
2. The length of time that is available to move the particle into a region where it will be collected before the gas exits the device. This is known as the cyclone residence time.

The effects of these two factors on cyclone performance are measured primarily by:

1. The pressure drop (energy consumed) in moving the particulate through the cyclone.
2. The fractional or grade efficiency.

Pressure Drop

The energy consumed in a cyclone is most frequently expressed as the pressure drop across the cyclone. The pressure drop across a cyclone or a set of cyclones is usually restricted to less than or equal to 2500Pa (Martinez-Benet and Casal, 1984). Many models have been developed for calculating the pressure drop; some are empirical while the others are theoretical. The most common one is probably (Casal and Martinez-Benet, 1983):

$$\Delta P = \frac{1}{2}\rho_g v_i^{n'} N_H \qquad \textbf{(1)}$$

where ρ_g is gas density; v_i is the inlet velocity; n' is a constant and varies between 1.5 and 2 but is usually taken as 2. N_H is the number of inlet velocity heads and can be calculated from (Ogawa. 1984, Coker, 1993):

$$N_H = K\left(\frac{a.b}{D_e^2}\right) \qquad (2)$$

$$K \begin{cases} = & 16 \text{ for no inlet vane} \\ = & 7.5 \text{ with neutral inlet vane} \end{cases}$$

D_e = vortex finder diameter

a, b = inlet height and width, respectively

N_H can also be calculated from (Casal and Martinez-Benet, 1983):

$$N_H = 11.3\left(\frac{ab}{D_e^2}\right)^2 + 3.33 \qquad (3)$$

Another expression for calculating pressure drop in a cyclone is (Sinnot, 1999; Strauss,1966)

$$\Delta P = \frac{\rho_g}{203}\left\{v_1^2\left[1+2\varphi^2\left(\frac{2[D-b]}{D_e}-1\right)^1\right]+2v_2^2\right\} \qquad (4)$$

where ρ_g = gas density

v_1 = inlet velocity

b = inlet duct width

φ = friction factor

De = Vortex finder diameter

v_2 = exit gas velocity & is given by

$$v_2 = \frac{4Q}{\pi D_e^2} \qquad (5)$$

where Q is the inlet feed flow rate.

The friction factor φ is given by (Strauss, 1966)

$$\varphi = \frac{-\sqrt{\frac{D_e}{2(D-b)}} + \sqrt{\frac{D_e}{2(D-b)} + \frac{4GA}{ab}}}{2GA/ab} \qquad (6)$$

where G= friction constant (= 0.005 for gas cyclones)

a, b = cross sectional area of inlet duct (a >b)

A = surface area of cyclone exposed to gas

This surface area is given by

$$A = \pi D^2(\alpha_1 + \alpha_2) \qquad (7)$$

α_1 = length ratio (S/D) for cylindrical portion of cyclone

α_2 = length ratio ((H – h)/D) for vertical cone portion of cyclone

The main factors that affect pressure drop in a cyclone are its geometry, the gas flow rate, gas density and dust loading (Hoffman et al, 1995).

Gas flow rate: With all other conditions remaining constant, pressure drop will increase exponentially with the gas flow rate according to the equation

$$\Delta P_2 = \Delta P_1\left(\frac{Q_2}{Q_1}\right)^{C_1} \qquad (8)$$

where ΔP_2 = new cyclone pressure drop

ΔP_1 = original cyclone pressure drop

Q_2 = new cyclone flow rate

Q_1 = original cyclone flow rate

For most cyclones, the exponent C_1 varies between 1.9 and 2.3 and is best determined by actual measurements on a cyclone from a given family. (Two cyclones are of the same family if they represent scaled versions of each other.) Thus as the flow rate (velocity) increases, so does the pressure drop.

Gas density: Pressure drop is directly proportional to gas density as shown below

$$\Delta P_2 = \Delta P_1 \left(\frac{Q_2}{Q_1}\right)^{C_1} \left(\frac{\rho_{g2}}{\rho_{g1}}\right) \qquad (9)$$

where ρ_{g2} = new gas density
ρ_{g1} = original gas density

Dust loading: Cyclone pressure drop decreases with increased dust loading, and vice versa (Comas et al, 1991). Numerous empirical measurements have shown the dust loading effect to be:

$$\Delta P_2 = \Delta P_1 C_2 \qquad (10)$$

$$C_2 = \begin{cases} 1 & \text{if } W < 1.249\text{g/m}^3 \\ 0.96 - 0.4722\ln\frac{W}{2.288} & \text{if } 1.249 < W < 12220.06\text{g/m}^3 \\ 0.55 & \text{if } W > 12220.06\text{g/m}^3 \end{cases} \qquad (11)$$

where
ΔP_1 = pressure drop at W =0
ΔP_2 = pressure drop at specified dust loads
W = dust loading {g/m^3}

The general equation for cyclone pressure drop incorporating all of the effects then becomes

$$\Delta P_2 = C_2 \Delta P_1 \left(\frac{Q_2}{Q_1}\right)^{C_1} \left(\frac{\rho_{g2}}{\rho_{g1}}\right) \qquad (12)$$

where ΔP_1 is the original pressure drop at W = 0.

Cyclone fractional efficiency

The fractional efficiency curve of a cyclone measures the performance of a cyclone as it relates to particulate removal. Cyclones collect aerodynamically larger particles (i.e., those with higher terminal velocities) more readily than smaller ones. The fractional or grade efficiency curve is the continuous curve that shows the removal efficiency of a cyclone as a function of particle size. A fractional efficiency curve will generally appear as S-shaped when plotted on normal scales and will be asymptotic toward 0 and 100 percent efficiencies but never actually attaining either value. Fractional efficiency curves are usually represented either graphically or in tabular form.

In cyclone applications where total collection efficiency is important, extreme care is needed to measure accurately the characteristics of the particulate that is to be collected, especially the particle size distribution. This is necessary for accurate determination of the fractional efficiency curve. Having determined the fractional efficiency curve for a given cyclone, the new fractional efficiency curve for any other member of that family of cyclones may be determined by applying the following equation

$$d_2 = K'd_1 \qquad (13)$$

where d_2 = new particle size
d_1 = original particle size and
K' = fractional efficiency curve shift constant computed as

$$K' = \left[\left(\frac{D_2}{D_1}\right)^3 \left(\frac{Q_1}{Q_2}\right)\left(\frac{\rho_1}{\rho_2}\right)\left(\frac{\mu_2}{\mu_1}\right)\right]^{0.5} \qquad (14)$$

where ρ = particle density
μ =viscosity of the fluid

and the subscripts 1 and 2 refer to original condition and new condition, respectively.

Effect of Dust Loading

As dust loading increases, so does collection efficiency. An empirical adjustment factor Z for dust loading should be applied to the fractional efficiency curve after the K' coefficient has been used to shift the curve for all conditions except dust loading. The generalized equation for applying Z is

$$E_{d_2} = 100 - Z\left(100 - E_{d_1}\right) \qquad (15)$$

Where E_{d2} = new efficiency at particle size d_2
E_{d1} = original efficiency at particle size d_1

$$Z = \left[2.095 \left(\frac{W}{2.288} \right)^{0.0197} - 1.09 \right] \tag{16}$$

The cyclone models discussed above can be used with a high degree of accuracy and confidence if the original fractional efficiency curve was determined accurately. However it is difficult and expensive to properly determine fractional efficiency curves. Hence most engineers and cyclone manufacturers opt for the use of theoretically-based mathematical models to generate fractional efficiency curves rather than the much more accurate empirical method.

Theoretical determination of fractional efficiency curves

There exists a vast array of literature concerning methods of predicting cyclone fractional efficiencies utilizing generalized methods. We discuss some of the well-known equations below:

The Leith and Licht Equation: One of the best theoretical approaches was presented by Leith and Licht (1972), which also compared other previous methods of calculating fractional efficiencies. Their expression for cyclone fractional efficiency is

$$\eta_i = 1 - \exp\left\{ -2 \left[\frac{G' \tau_i Q}{D^3} (n+1) \right]^{\frac{1}{2(n+1)}} \right\} \tag{17}$$

where Q is the gas volumetric flow rate and τ_i is called relaxation time which is given by

$$\tau_i = \frac{\rho_p \, d_{pi}^2}{18\mu} \tag{18}$$

where d_{pi} and ρ_p are the particle diameter and density, respectively and μ the gas viscosity.

The exponent n, normally called the vortex index, can be estimated as a function of the cyclone diameter and of gas temperature (in Kelvin, K) by the following expression:

$$n = 1 - \left[1 - \frac{(39.3701 D_c)^{0.14}}{2.5} \right] \left[\frac{T}{294.44} \right]^{0.3} \tag{19}$$

The effect of cyclone configuration on separation efficiency is considered using factor G', given by

$$G' = \frac{8 K_c}{K_a^2 K_b^2} \tag{20}$$

where

$$K_a = \frac{a}{D} \tag{21}$$

$$K_b = \frac{b}{D} \tag{22}$$

$$K_c = \frac{(2V_s + v_{nl,H})}{2D^3} \tag{23}$$

The annular volume above the exit duct up to the middle of the gas entrance duct, V_s, is given by

$$V_s = \frac{\left[\pi \left(S - \frac{a}{2} \right) \left(D^2 - D_e^2 \right) \right]}{4} \tag{24}$$

The natural length of the vortex can be estimated by (Alexander, 1949)

$$l = 2.3 D_e \left(\frac{D^2}{ab} \right)^{\frac{1}{3}} \tag{25}$$

For $l < (H - S)$, volume V_{nl}, which is the volume of the region that includes the natural length of the vortex excluding the central core, can be estimated by

$$V_{nl} = \frac{\pi D^2}{4}(h - S) + \left(\frac{\pi D^2}{4} \right) \left(\frac{1 + S - h}{3} \right) \left(1 + \frac{d_n}{D} + \frac{d_n{}^2}{D^2} \right) - \frac{\pi D_e^2 l}{4} \tag{26}$$

where the diameter of the central core, d_n is defined by

$$d_n = D - (D - B) \left[\frac{S + 1 - h}{H - h} \right] \tag{27}$$

For $l > (H - S)$, volume V_H, which is the volume of the gas below the gas exit duct excluding the core, can be calculated by

$$V_H = \frac{\pi D^2}{4}(h - S) + \left(\frac{\pi D^2}{4} \right) \left(\frac{H - h}{3} \right) \left(1 + \frac{B}{D} + \frac{B^2}{D^2} \right) - \frac{\pi D_e^2 (H - S)}{4} \tag{28}$$

The natural length, which is the length of the inner vortex core, is also referred to as the effective length (Wang, et. al. 2002). This length does not necessarily reach the bottom of the cyclone (Leith and Mehta, 1973). When the effective length is shorter than the cyclone physical length, the space between the bottom of the vortex and the bottom of the cyclone will not be used for particle collection. On the other hand, if the effective length is longer than the cyclone physical length, the vortex will extend beyond the bottom of the cyclone, and a dust re-entrainment problem will occur (Wang, et. al. 2002). According to Hoffman et al (1995), vortex length increases with an increase in gas velocity for a fixed cyclone geometry. Therefore, besides increasing the centrifugal force, an increase in gas velocity also increases the effective collection area in the cyclone and both effects result in an appreciable improvement in collection efficiency (Santana et. al (2001).

The use of Equation (17) to predict collection efficiency has been shown by Santana et al (2001) to be restricted to a narrow range of G', the configuration factor, and fails in the prediction of cyclone efficiency for large variations in cyclone configuration. They observed experimentally a decrease in G, in contrast to an inverse tendency predicted by the theoretical correlation. Other models that are available to predict fractional efficiency include the Barth model, the Dietz model and the Mothes and Loffler model.

Empirical Equations for Fractional Efficiency Curves

In cases where experimental data are available, attempts have been made to fit the data into equations. Such is the case for Stairmand high efficiency (HE) and high throughput (HT) fractional efficiency curves. Equations for the two types of cyclones have been derived by Gerrard et al (1976) and take the following form:

Stairmand High Efficiency:

$$\eta = 1 - \exp - (d^{0.42}) \qquad (29)$$

Stairmand High Throughput:

$$\eta = 1 - \exp - (0.115d) \qquad (30)$$

where d = particle size and η is the fractional efficiency.

The Licht Model (Leith and Licht, 1972): Licht also developed a model that was based on the assumption of turbulent flow with lateral mixing. The following equations apply:

$$\mathrm{D}_{50} = \left(\frac{0.693}{\mathrm{A}}\right)^{\mathrm{n}+1} \qquad (31)$$

where n is vortex exponent and A is a pre-factor that is determined according to the following equation

$$\mathrm{A} = 2\left(\frac{\mathrm{KQ}\rho_{\mathrm{p}}(\mathrm{n}+1)}{18\mu D^3}\right)^{\frac{1}{2(\mathrm{n}+1)}} \qquad (32)$$

where K is a configuration factor, Q is air flow rate and D is cyclone body diameter. The fractional efficiency for other particle sizes can then be calculated as

$$\eta_i = 1 - \exp\left[-0.693\left(\frac{d_{pi}}{D_{50}}\right)^{\frac{1}{n+1}}\right] \qquad (33)$$

The overall efficiency for the entire particle size distribution can then be determined as

$$\eta = \sum n_i f_i \qquad (34)$$

where f_i is the fraction of the size range.

The configuration factor, K, along with other parameters, is listed in Table 3 for some standard configurations of industrial cyclones.

Table 3 Parameters of some standard industrial Cyclones

		High Efficiency		Medium Efficiency	General Purpose	
Symbol	Description	Stairmand	Swift	Shephard & Lapple	Swift	Peterson & Whitby
D	Body diameter	1	1	1	1	1
a	Inlet height	0.5	0.44	0.5	0.5	0.583
b	Inlet width	0.2	0.21	0.25	0.25	0.208
S	Gas Outlet length	0.5	0.5	0.625	0.60.5	0.53
D_e	Gas outlet diameter	0.5	0.4	0.5	1.75	0.5
h	Cylinder height	1.5	1.4	2	3.75	1.33
H	Overall height	4	3.9	4	0.4	3.17
B	Dust outlet diameter	0.375	0.4	0.25	381.8	0.5
K	Configuration number	551.3	699.2	402.9	8	342.3
N_H	Inlet velocity head	6.4	9.24	8	3.65	7.76
surf	Surface parameter	3.67	3.57	3.78	13.1	3.2
K/N_Hsurf		23.5	21.2	13.3		13.8

Total Collection Efficiency

In normal industrial application the user has no real concern for the fractional efficiency of the cyclone but rather the total collection efficiency of that particular application. The total collection efficiency can be obtained easily once the fractional efficiency curve of the cyclone and the particle size distribution of the dust are known. If the fractional efficiency curve can be described as a mathematical function of the particle size f(d), and the particle size distribution as a function of the particle size g(d), then the total collection efficiency E_T is described as (Hoffman et al, 1995):

$$E_T = 100 \int_{d=0}^{\partial=\infty} \left[\frac{\partial g\,(d)}{\partial y} \quad f(d)\, \partial d \right] \qquad (35)$$

In practice it is common to perform the above equation as a series calculation, since the integral of the product of f(d)dg(d) is not apparent or readily known. Hence in such cases the generalized form of the calculation of total collection efficiency is

$$E_T = \sum_{d=0}^{d=\infty} \left\{ \left[g(d)_{N+1} - g(d)_N \right] f \left[\frac{(d)_N + (d)_{N+1}}{2} \right] \right\} .100 \qquad (36)$$

FACTORS THAT AFFECT CYCLONE DESIGN

Body Diameter

The cyclone body diameter is one of the most widely employed parameters in cyclone design. Other physical dimensions of a cyclone are usually quoted in geometric proportions to the body diameter. If all the other factors are the same, there will be less centrifugal force on particles travelling around a large-radius circle than a small-radius one. An increase in diameter decreases the centrifugal force on a particle, which in turn causes a decrease in the velocity with which a given particle moves toward the wall of a cyclone where it is theoretically captured. An opposite effect is noticed when the body diameter is decreased. Note that the effect of diameter on fractional efficiency curve is given by Equation 13.

From the foregoing, one can conclude that within a given family of cyclones, it is possible to achieve higher particulate collection efficiencies with multiple cyclones in parallel as against a single larger cyclone. However, such a conclusion cannot be reached when comparing cyclones of different geometries (different families). The practical use of cyclone models as relating to body diameter provides a reliable and useful tool for shifting the fractional efficiency curve from a known efficiency curve to that of a different member (larger or smaller) of the same family.

Inlet velocity

In general, the higher the inlet velocity, the greater the centrifugal force on the particles, which will subsequently cause them to move toward the wall of the cyclone at greater velocity. This effect of inlet velocity on the collection efficiency is described by the shift (increase) in the fractional efficiency curve, as higher velocity means higher flow rate, which increases the efficiency. However, the pressure drop (energy consumption) increases exponentially with increased inlet velocity. Moreover, when collecting abrasive particulate the rate of erosion will usually increase with increased inlet velocity. A frequent rule of thumb is that the rate of erosion will increase by a factor of 8 if the velocity doubles. In general care should be taken when inlet velocities exceed 100 to 120 ft/s (30 to 37m/s). An optimum value is about 15m/s, while the inlet velocity is usually restricted to between 15m/s and 30m/s.

However, according to Wang et al (2002), there exist ideal inlet velocities (design velocities) for different cyclone designs to optimize performance. The authors compiled a rather extensive table for different flow rates, different cyclone configurations and different number of cyclones in parallel. A small extract is quoted below.

Cyclone configuration	Design velocity, m/min (fpm)
1D3D	975 ± 122 (3200 ± 400)
2D2D	914 ± 122 (3000 ± 400)
1D2D	732 ± 122 (2400 ± 400)

Gas Viscosity

The viscosity of the feed gas is of great significance in cyclone design and operation. Since viscosity is a measure of the resistance of a gas or liquid to movement, viscosity relates directly to the drag forces placed on the object and the subsequent speed that the object will reach in moving through the gas under some driving force. This effect has been described by Stoke's law, from which it could be seen that the terminal velocity is inversely proportional to the gas viscosity. Since viscosity increases with temperature for gases, there is a shift of the fractional efficiency curve toward lower collection efficiency at high temperatures. The converse is equally true at lower temperatures. Gas viscosity is a measured property and requires to be known for cyclone design.

Particle density

The density of the particulate directly affects the speed with which any given particle travels through a gas while being acted upon by some force. As the particle density increases, so does the velocity at which it travels through the gas, causing an increase in cyclone collection efficiency. A decrease in particle density also decreases the collection efficiency. As with gas viscosity, particle density is not a factor within the control of the designer.

Dust Loading

It has been well known that collection efficiency increases with increased dust loading. Although research in this area is ongoing, it seems one of the most significant mechanisms causing increased fractional efficiencies with increased dust loading is particle agglomeration. As dust loading increases, there is also increased probability of collision between particles and subsequent increase in particle agglomeration.

Cyclone Geometry

This is the greatest single variable that the designer can use to affect the final efficiency of the device. We have already discussed the effect of body diameter in the same cyclone family. There is an infinite number of geometries within each of several basic cyclone styles, and variations in cyclone geometry can provide for significant improvements in collection efficiency at equal or lower energy consumption. In general it can be concluded that the following guidelines apply to cyclone design.

H/D ratio

The length-to-diameter ratio, H/D is the total cyclone height (cylinder length + cone vertical length) divided by the diameter of the cyclone body. Generally, with all other factors constant, cyclone performance improves with increased H/D ratios. Normally this ratio is between 3 and 6 for high efficiency cyclones, with 4 being the most common value. H/D value should rarely be below 2 if there is any concern whatsoever with cyclone performance. There is also minimal gain in using H/D ratios above 6.

Outlet Pipe Diameter

The smaller the bottom end of the outlet pipe, the higher the cyclone pressure drop and collection efficiency. Holding all others factors constant, reducing the diameter of the outlet pipe, also reduces the axial (vertical) velocity components within the cyclone, and increases the residence time. Pressure drop will increase with increases in outlet velocity (decreases in outlet pipe diameter).

Outlet Pipe Length

For any cyclone there is an optimum outlet pipe length. If the outlet pipe length is altered from its optimum, there will be an increased pressure drop and reduced collection efficiency. In general, the outlet pipe should extend below the bottom of the inlet by 10 to 60 percent of the inlet height. Significant losses of efficiency on both small and large diameter particles may occur by short circuiting of the gas flow if the outlet pipe does not extend below the inlet floor. Beyond the optimum length, collection efficiency will decrease while the pressure drop increases.

Cone Shape

The cyclone cone serves the purpose of reducing the cyclone vortex at the material discharge making it possible to disengage the particulate to an area where it will not be substantially re-entrained. The smaller the cone discharge, the lower the turbulence beneath the cyclone and subsequent re-entrainment, and vice versa.

As a minimum, the discharge diameter of the cyclone dust and/or dipleg should be sized as

$$B = \left[3.5\left(2450\frac{M}{\rho_g}\right)^{0.4}\right] \text{ in cm} \qquad (37)$$

where B = discharge pipe diameter of cone, cm
M = solids mass flow rate, kg/s
ρ_g = solid bulk density, kg/m^3

Summary of Effects

The effect of the variation of the above parameters on cyclone efficiency is summarized in Table 4.

Table 4 Effect of Parameter Change on Cyclone Efficiency

Parameter	Change	Effect	Reason
Vortex finder diameter	Increase	Decrease Efficiency	More likely to suck particles up
Pressure drop	Increase	Increase efficiency	Flow rate increases
Particle size	Increase	Increase efficiency	More likely for particle to migrate to exterior wall
Dust outlet diameter	Increase	Prevents overload and in extreme cases decreases efficiency	Causes flushing of particle and gas
Gas viscosity	Increase	Decrease Efficiency	Harder for particles to settle
Cyclone diameter	Increase	Decrease Efficiency	Decrease gravitational forces
Particle concentration	Increase	Decrease Efficiency	Decrease gravitational forces
Feed inlet area	Increase	Decrease Efficiency	More feed enters at less pressure
Gas/Particle density difference	Increase in density	Increase efficiency	More likely for particles to migrate to opposing spirals in cyclone
Cyclone length	Increase	Increase efficiency	Residence time increase

CONCLUSION

Various models for the design and simulation of air cyclones have been presented and analysed. These models are necessary ingredients for the computer aided design of air cyclones. A review of the models indicates that the key design and simulation parameters of collection efficiency and the pressure drop of air cyclones are governed chiefly by the cross sectional areas and lengths of the individual flow channels, operational conditions and physical properties of the feed. A preliminary analysis of the models shows that to increase cyclone efficiency, the following is required; decrease the cyclone diameter; decrease the outlet diameter; reduce the cone angle and increase the cyclone length. An increase in capacity can be achieved by increasing the cyclone diameter and length. An increase in the pressure drop results in an increase in separation efficiency and a more concentrated underflow. The models presented in this study will come in handy in the design, testing and validation of air cyclones. Computer aided design, simulation and optimisation of processes involving air cyclone can be carried with the application of these models.

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