4 Cyclones

4.1 Collection Mechanisms

Introduction

Cyclone separators have been used in the world for about 100 years, and are still among the most widely used of all industrial gas-cleaning devices. The main reasons for the widespread use of cyclones are that they are inexpensive to purchase, they have no moving parts, and they can be constructed to withstand harsh operating conditions. Cyclones by themselves are generally not adequate to meet stringent air pollution regulations, but they serve an important purpose for use as precleaners for more expensive final control devices such as baghouses or electrostatic.

Typically, a particulate-laden gas enters tangentially near the top of the cyclone, as shown schematically in Figure 4.1. The gas flow is forced into a downward spiral simply because of the cyclone's shape and the tangential entry. Centrifugal force and inertia cause the particles to move outward, collide with the outer wall, and then slide downward to the bottom of the device. Near the bottom of the cyclone, the gas reverses its downward spiral and moves upward in a smaller, inner spiral. The cleaned gas exits from the top through a "vortex-finder" tube, and the particles exit from the bottom of the cyclone through a pipe sealed by a spring-loaded flapper valve or a rotary valve.

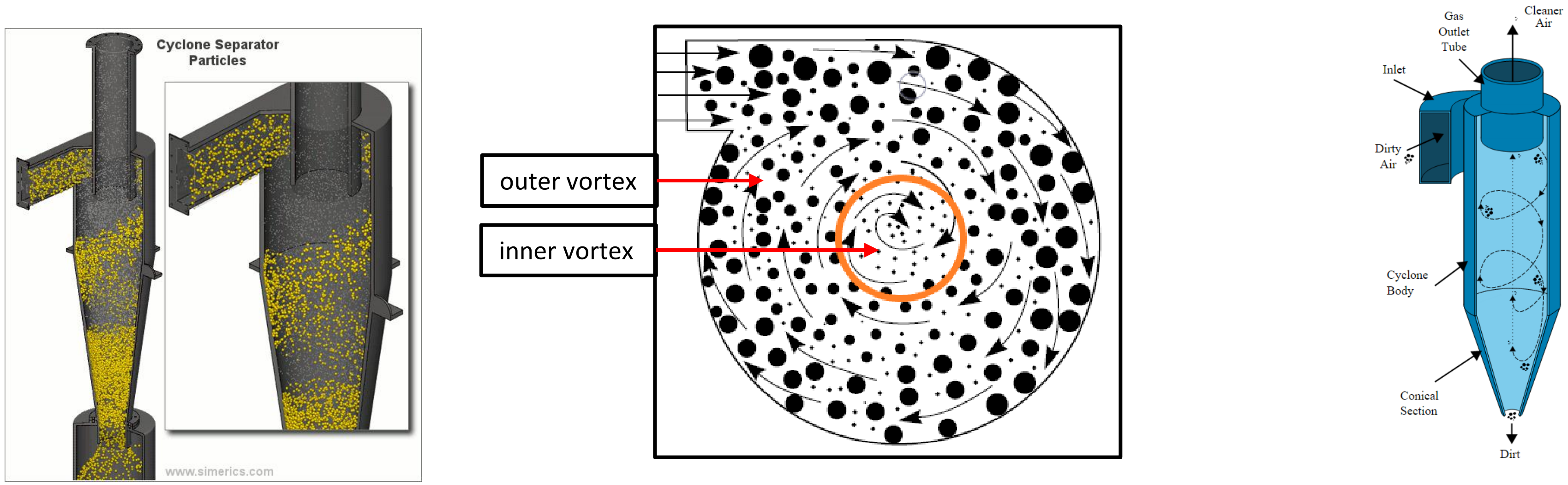

Figure 4.1 Schematic flow diagram of a classical cyclone
From https://www.energyeducation.ca/encyclopedia/Cyclone_separator

Cyclone flow patterns

Measurements of the direction and velocity of gas flow within cyclones are extremely difficult due to the complexity of the flow patterns and the effect of the measuring device on the flow patterns themselves. These flow patterns should be considered a general representation of the movement of gases within the device and not an exact description.

Overall gas motion within a cyclone consists of **two vortices**: an **outer vortex** moving downwards and an **inner vortex** flowing upwards and out the gas exit duct. The **boundary** between the outer and inner vortices, called the **cyclone core**, is the cyclindrical extension of the gas exit duct shown by the dotted lines in Figure 4.2. Values assumed for diameter of the inner core have ranged from 0.5 to 1.0 times the diameter of the gas exit duct. The length of the inner core is, by Barth's (1956)definition, the distance from the bottom of the gas outlet to the base of the cyclone, H_t-S(Figure 4.3). Dirgo and Leith (1985) reinterpreted core length to be the distance from the bottom of the gas outlet to the intersection of the cylindrical core with the cone wall, a distance that can be less than (H_t-S) if core diameter is greater than B.

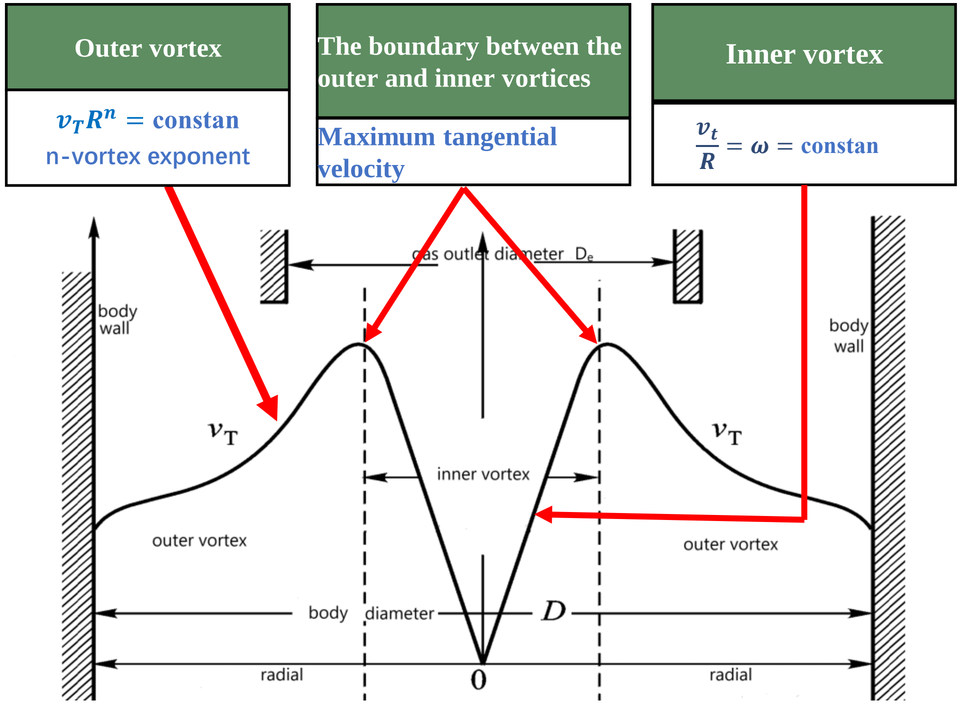

Figure 4.2 Relative variation of tangential velocity

Alexander (1949)proposed that cyclones have a "natural length" that depends on inlet and outlet dimensions but is independent of gas flow. In the outer vortex tangential gas velocity increases with decreasing radius to reach a maximum at the radius of the central core. In the inner vortex the tangential gas velocity decreases with decreasing radius as rotation of a solid body. The maximum tangential velocity within a cyclone can greatly exceed the cyclone inlet velocity (ter Linden,1949).

4.2 Collection Efficiency

The difficulty in accurately predicting cyclone fractional efficiency curves from theoretical models is caused by the extremely complicated flow patterns created within a cyclone. A very simple model can be used to determine the effects of both cyclone design and operation on collection efficiency. In this model, the gas spins through a number of revolutions N_e in the outer vortex. The value of N_e can be approximated by

$$N_e = \frac{1}{H}\left[L_b + \frac{L_c}{2}\right] \qquad (4.1)$$

where

N_e = number of effective turns; H = height of inlet duct, m ; L_b = length of cyclone body, m ; L_c = length (vertical) of cyclone cone, m.

To be collected, particles must strike the wall within the amount of time that the gas travels in the outer vortex. The gas residence time in the outer vortex is

$$\Delta t = 2\pi R N_e / V_i \qquad (4.2)$$

where

Δt= gas residence time; R=cyclone body radius; V_i= gas inlet velocity.

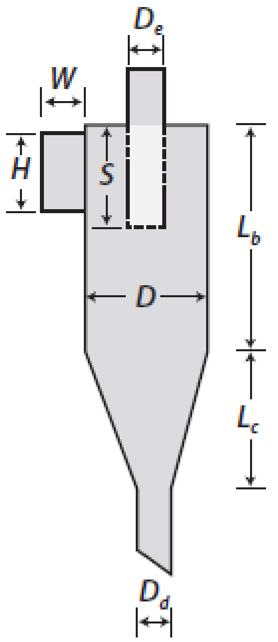

Figure 4.3 Cyclone dimensions

The maximum radial distance traveled by any particle is the width of the inlet duct W. Assume that centrifugal force quickly accelerates the particle to its terminal velocity in the outward (radial) direction. Terminal velocity is achieved when the opposing drag force equals the centrifugal force. The terminal velocity that will just allow a particle to be collected in time Δt is

$$V_t = W/\Delta t \qquad (4.3)$$

where V_t = particle terminal velocity in the radial direction.

Assuming Stokes regime flow and spherical particles under a centrifugal force, we obtain

$$V_t = \frac{\rho_p d_p^2 V_i^2}{18\mu R} \qquad (4.4)$$

where

V_t = terminal velocity, m/s; d_p = diameter of the particle, m; ρ_p = density of the particle, kg/m^3; μ = gas viscosity, kg/m · s.

Substitution of Eq. (4.2) into Eq. (4.3) eliminates Δt. Then, setting Eq. (4.3) equal to Eq. (4.4) to eliminate V_t and rearranging to solve for particle diameter, we obtain

$$d_p = \left[\frac{9\mu W}{\pi N_e V_i \rho_p}\right]^{1/2} \qquad (4.5)$$

Theoretically, d_p is the size of the smallest particle that will be collected if it starts at the inside edge of the inlet duct. Thus, in theory, all particles of size d_p or larger should be collected with 100% efficiency.

From Eq. (4.5), we can see that, in theory, the smallest diameter of particles collected with 100% efficiency is directly related to gas viscosity and inlet duct width, and inversely related to number of effective turns, inlet gas velocity, and particles density. In practice, collection efficiency does, in fact, depend on these parameters. However, the model leading to Eq. (4.5) has a major flaw: it predicts that all particles larger than d_p will be collected with 100% efficiency, which is not correct.

The semi-empirical relationship developed by Lapple (1951) to calculate a " 50% cut diameter," d_{pc}, which is the diameter of particles collected with 50% efficiency, is

$$d_{pc} = \left[\frac{9\mu W}{2\pi N_e V_i \rho_p}\right]^{1/2} \qquad (4.6)$$

where d_{pc} = diameter of particle collected with 50% efficiency.

Note the similarity between Eqs. (4.5) and (4.6). Lapple then developed a general curve for classical conventional cyclones, from which we can predict the collection efficiency for any particle size (see Figure 4.5). If the size distribution of particles is known, the overall collection efficiency of a cyclone can be predicted by using Figure 4.5. Theodore and DePaola (1980) have fitted an algebraic equation to Figure 4.5 , which makes Lapple's approach more precise and more convenient for application to computers. The efficiency of collection of any size of particle is given by

$$\eta_j = \frac{1}{1+\left(d_{pc}/\bar{d}_{p_j}\right)^2} \qquad (4.7)$$

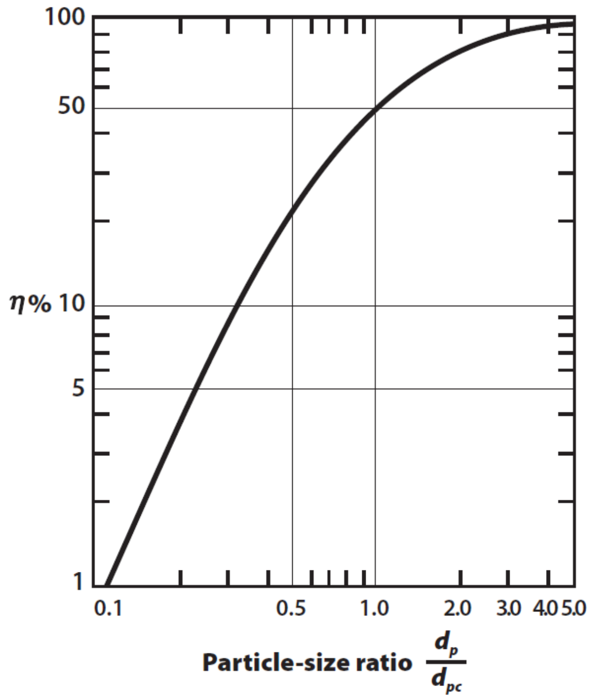

Figure 4.4 Particle collection efficiency versus particle size ratio for classical conventional cyclones.

where η_j = collection efficiency for the j th particle size range; $\bar{d}_{pj}$ = characteristic diameter of the j th particle size range;

The overall efficiency of the cyclone is a weighted average of the collection efficiencies for the various size ranges; that is,

$$\eta_o = \sum \eta_j m_j \qquad (4.8)$$

where η_o = overall collection efficiency; m_j = mass fraction of particles in the j th size range.

Example 4.1

Consider a conventional cyclone with a body diameter of 1.0 m, inlet height of 0.5m,inlet width 0.25m,Diameter of outlet 0.5m . For air with a flow rate of 150 m^3/min at $T = 350$ K and 1 atm , containing particles with a density of 1600 kg/m^3 and a size distribution as given below, calculate the overall collection efficiency.

Particle Size Range, μm	Mass Percent in Size Range
0 – 2	1.0
2 – 4	9.0
4 – 6	10.0
6 – 10	30.0
10 – 18	30.0
18 – 30	14.0
30 – 50	5.0
50 – 100	1.0

Solution

First, we calculate d_{pc} from Eq. (4.6). From Appendix B, Table B. 2, the viscosity is 0.05lbm/ft · h, converting units SI 0.075kg/m ·h. The inlet velocity is the volumetric flow divided by the inlet area (H × W) :

$$V_i = \frac{150\ \mathrm{m^3}}{\mathrm{min}} \times \frac{1}{(0.5\ \mathrm{m})(0.25\ \mathrm{m})} \times 60\mathrm{min} = 72000\ \mathrm{m/h}$$

For a Lapple standard cyclone, $N_e = 6$ from Eq. (4.1).

$$d_{pc} = \left[\frac{9\left(0.075\frac{\mathrm{kg}}{\mathrm{m\cdot h}}\right)(0.25\ \mathrm{m})}{2\pi \times 6 \times 72000\frac{\mathrm{m}}{\mathrm{h}} \times 1600\frac{\mathrm{kg}}{\mathrm{m^3}}}\right]^{1/2} = \left(\frac{0.16875}{4340736000}\right)^{\frac{1}{2}}$$

$$d_{pc} = 6.25 \times 10^{-6}\ \mathrm{m} = 6.3\mu\mathrm{m}$$

Next, we determine the collection efficiency for each size range from Eq. (4.7). The arithmetic midpoint of the range is often used as the characteristic particle size. It is convenient to construct the following table.

j	Size Range, μm	$\overline{d}_{pj}, \mu$m	$\overline{d}_{pj}/d_{pc}$	η_j	m_j, %	Percent Collected $\eta_j m_j$, %
1	0 – 2	1	0.159	0.02	1.0	0.02
2	2 – 4	3	0.476	0.18	9.0	1.62
3	4 – 6	5	0.794	0.39	10.0	3.9
4	6 – 10	8	1.27	0.62	30.0	18.6
5	10 – 18	14	2.22	0.83	30.0	24.9
6	18 – 30	24	3.81	0.94	14.0	13.2
7	30 – 50	40	6.35	0.98	5.0	4.9
8	50 – 100	75	11.9	0.99	1.0	1.0
						68.1

Finally, as shown in the table,

$$\eta_o = \sum_{j=1}^{8} \eta_j m_j = 68.1\%$$

The overall collection efficiency of this cyclone for this particular air/ particulate mixture is approximately 68.1%.

4.3 Pressure Drop

Although several pressure drop models exist, the approach of Shepherd and Lapple is the simplest to use and its accuracy is comparable to that of the other methods. The Shepherd and Lapple equation is

$$H_v = K\frac{HW}{D_e^2} \qquad (4.9)$$

where H_v = pressure drop, expressed in number of inlet velocity heads; K= a constant that depends on cyclone configuration and operating conditions.

Theoretically, K can vary considerably, but for air pollution work with standard tangential-entry cyclones, values of K are in the range of 12 to 18 (Caplan 1962). Licht (1984) recommends that K simply be set equal to 16 , and states that, although more complicated methods are available, none are superior to Eq. (4.10).

The number of inlet velocity heads calculated from Eq. (4.10) can be converted to a static pressure drop as follows:

$$\Delta P = \frac{1}{2}\rho_g V_i^2 H_v \qquad (4.10)$$

where ΔP =pressure drop, Pa; ρ_g=gas density, kg/m^3; V_i =inlet gas velocity, m/s.

Cyclone pressure drops range from about 0.5 to 10 velocity heads (250 to 4000 Pa or 1 to 16 inches of water). Once the pressure drop has been calculated, the fluid power requirement can be obtained as

$$\dot{w}_f = Q\Delta P \qquad (4.11)$$

where $\dot{w}_f$ = work input rate into the fluid (fluid power), W;Q = volumetric flow rate, m^3/s.

Example 4.2

For the cyclone of Example 4.1, assume a K value of 15 and calculate

(a)the cyclone pressure drop in kPa , and

(b) the fluid power consumed in the cyclone in kW .

Solution

From Appendix B, Table B. 2 the density of air is 1.01 kg/m^3

(a)

$$H_v = K\frac{HW}{D_e^2} = 15 \times \frac{(0.5)(0.25)}{(0.5)^2} = 7.5$$

$$V_i = \frac{1200\ \text{m}}{\text{min}} \times \frac{1\ \text{min}}{60\ \text{s}} = 20\ \text{m/s}$$

$$\Delta P = \frac{1}{2}\rho_g V_i^2 H_v = \frac{1}{2} \times 1.01\frac{\text{kg}}{\text{m}^3} \times 20^2\frac{\text{m}^2}{\text{s}^2} \times \frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2} \times 7.5$$

$$= 1515\ \text{N/m}^2 = 1.515\text{kPa}$$

(b)

$$\dot{w}_f = Q\Delta P = \frac{150\ \text{m}^3}{\text{min}} \times 1515\ \text{N/m}^2 \times \frac{1\ \text{min}}{60\ \text{s}}$$

$$\dot{w}_f = 3788\frac{\text{N}\cdot\text{m}}{\text{s}} = 3788\ \text{J/s} = 3.788\ \text{kW}$$

4.4 Design

Cyclone Dimensions

Extensive work has been done to determine in what manner dimensions of cyclones affect performance. In two classic studies, which are still used today, Shepherd and Lapple (1939,1940) determined "optimum" dimensions for cyclones. All dimensions were related to the body diameter of the cyclone so that their results could be applied generally.

Subsequent investigators reported similar work, and the so-called standard or classical cyclones were born. Table 4.1 summarizes the dimensions of classical cyclones of the three types mentioned previously. Figure 4.4 illustrates the various dimensions used in Table 4.1.

When designing a cyclone, we use a trial-and-error procedure in which we first choose a body diameter, and then calculate d_{pc} and the efficiency. If the efficiency is too low, we choose a smaller body diameter and iterate. If the efficiency is acceptable, we check the pressure drop constraint. If the ΔP is too high, we must either choose a different type of cyclone, or split the flow of gas between two cyclones in parallel. The design procedure is illustrated in Example 4.3.

Table 4.1 Classical Cyclone Dimensions

	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, H/D	0.5	0.44	0.5	0.5	0.75	0.8
Width of Inlet, W/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, S/D	0.5	0.5	0.625	0.6	0.875	0.85
Length of Body, L_b/D	1.5	1.4	2.0	1.75	1.5	1.7
Length of Cone, L_c/D	2.5	2.5	2.0	2.0	2.5	2.0
Diameter of Dust Outlet, D_d/D	0.375	0.4	0.25	0.4	0.375	0.4

Note: Columns (1) and (5) adapted from Stairmand, 1951; columns (2), (4), and (6) adapted from Swift, 1969; column (3) adapted from Lapple, 1951.

Example 4.3

Design a conventional Lapple cyclone to function as a precleaner on a gas stream that flows at 120 m^3/min. The cyclone must achieve a minimum overall efficiency of 70% for the following particulate distribution, with a maximum allowable ΔP of 3000 Pa . The particulate density is 1500 kg/m^3, the gas density is 1.0 kg/m^3, and the gas viscosity is 0.07 $kg/m \cdot h$. Specify your final choice of body diameter, overall cyclone efficiency, inlet gas velocity, and pressure drop. (Assume $K = 14$)

Size Range, μm	Mass Percent in Size Range
$0 - 2$	2.0
$2 - 4$	18.0
$4 - 10$	30.0
$10 - 20$	30.0
$20 - 40$	15.0
$40 - 100$	4.0
> 100	1.0

This trial-and-error solution is easily achieved using a spreadsheet. Note that many of the variables in Eqs. (4.1), (4.6), (4.7), and (4.8) are functions of one key parameter-the cyclone body diameter, D. Set up the spreadsheet with all calculations based on the cell where we input body diameter. Then, all that needs to be done is to input different values of D until a feasible solution is obtained.

By a feasible solution, we mean one that meets all the listed constraints-in this case, an efficiency greater than or equal to 70% and a pressure drop less than or equal to 3000 Pa . Often, the solution can be optimized somewhat depending on whether a smaller pressure drop or larger efficiency is more important.

Since the problem specifies a conventional Lapple cyclone, choose a type 3 cyclone from Table 4.1; the dimensional relationships are:

$$H = 0.5D \qquad W = 0.25D \qquad D_e = 0.5D \qquad L_b = 2D \qquad L_c = 2D$$

Other formulas to be coded into the spreadsheet are:

$$V_i = Q/(HW)$$

and Eqs. (4.1), (4.6), (4.7), (4.8), (4.9), and (4.10). We must also remember to include conversion factors (such as 60 min/h) to make the units work, especially in Eq. (4.6).

Once the spreadsheet is built, start simply by entering a value of D, say 1.0 m . If the efficiency is too low, then choose a smaller D. If the pressure drop is too high, then choose a larger D. Keep trying values of D until a feasible solution is obtained. If it turns out that a feasible solution does not exist, one or more constraints must be relaxed, or a different type of cyclone must be chosen.

A spreadsheet to solve this problem is displayed in Figure 4.7. Using this spreadsheet, four values of D were entered and the following results were obtained:

D, m	η, %	ΔP, Pa	ΔP, in. H_2O
1.0	61.8	896	3.6
0.9	66.5	1366	5.5
0.8	71.4	2188	8.8
0.7	76.5	3732	15.0

Other Considerations

When a large volume of gas must be treated, a single cyclone might be impractical. Several cyclones can be used in parallel; one form of parallel cyclones is the multiple-tube cyclone shown in Figure 4.6. Reasonably high efficiencies (90% for 5 - to 10 -micron particles) are obtained by the small diameter (15 to 60 cm) tubes.

Using cyclones in series increases overall efficiency, but at the cost of a significant increase in pressure drop. Furthermore, since most of the larger particles are removed in the first cyclone, the second cyclone usually has a lower overall efficiency than the first. Scroll-shaped entrances and modified inlet areas have been used to achieve higher efficiencies.

Cyclones by themselves are generally not adequate to meet stringent air pollution regulations, but Their low capital cost and their nearly maintenance-free operation make them ideal for use as precleaners for more expensive final control devices such as baghouses or electrostatic precipitator.