Cyclones

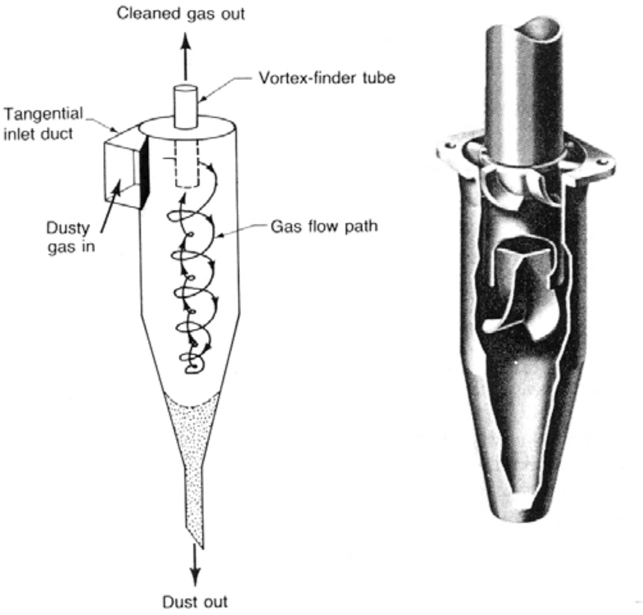
(Adapted from *Air Pollution Control* by C. D. Cooper & F.C . Alley, 1986)

1. Introduction

Cyclone separators have been used in the United States for about 100 years, and are still one of the most widely used of all industrial gas-cleaning devices. The main reasons for the wide-spread 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.

Typically, a particulate-laden gas enters tangentially near the top of the cyclone, as shown schematically in Figure 1. The gas flow is forced into a downward spiral simply because of the cyclone's shape and the tangential entry. Another type of cyclone (a vane-axial cyclone – see right panel of Figure 1) employs an axial inlet with fixed turning vanes to achieve a spiraling flow. 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 rotary valve.

Figure 1

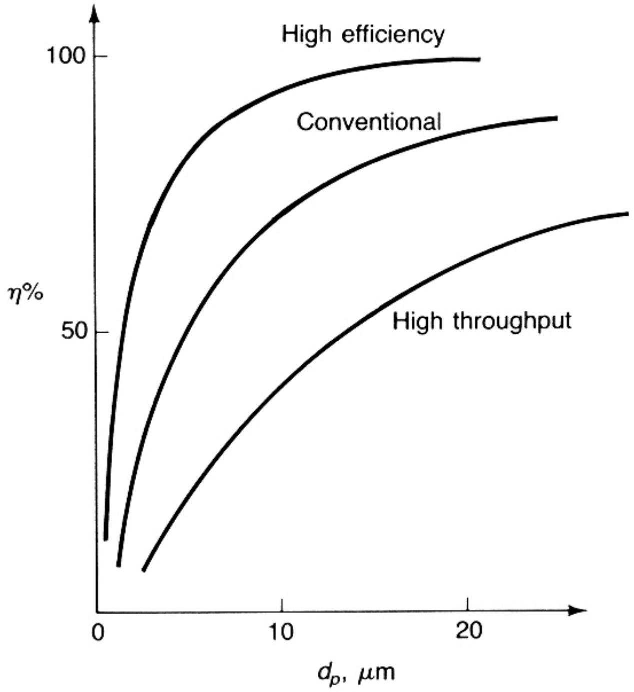


Cyclones by themselves are generally not adequate to meet stringent air pollution regulations, but they serve an important purpose. Their low capital cost and their maintenance-free operation make them ideal for use as precleaners for more expensive final control devices such as baghouses or electrostatic precipitators. In addition to use for pollution control work, cyclones are used extensively in process industries; for example, they are used for recovering and recycling certain catalysts in petroleum refineries and for recovering freeze-dried coffee in food processing plants.

In the past, cyclones have often been regarded as low-efficiency collectors. However, efficiency varies greatly with particle size and cyclone design. During the past two decades, advanced design work has greatly improved cyclone performance. Current literature from some of the cyclone manufacturers advertises cyclone that have efficiencies greater than 98% for particles larger than 5 microns, and others that routinely achieve efficiencies of 90% for particles larger than 15 – 20 microns.

In general, operating costs increase with efficiency (higher efficiency requires higher inflow pressure), and three categories of cyclones are available: high efficiency, conventional, and high throughput. Generalized efficiency curves for these three types of cyclones are presented in Figure 2.

Figure 2



Note: Efficiency versus size curves present broad generalizations, not exact relationships.

Advantages of cyclones are:

1. Low capital cost
2. Ability to operate at high temperatures
3. Low maintenance requirements because there are no moving parts.

Disadvantages of cyclones are:

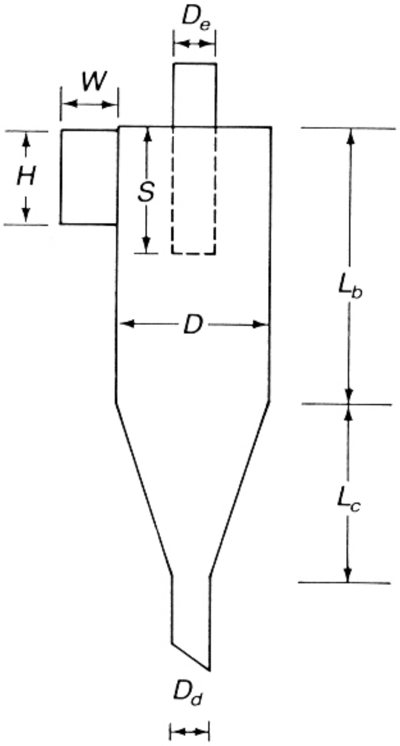
1. Low efficiencies (especially for very small particles)
2. High operating costs (owing to power required to overcome pressure drop).

Table 1 Standard 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

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

Figure 3



Source: Lapple, 1951

Standard Cyclone Dimensions

Extensive work has been done to determine in what manner dimensions of cyclones affect performance. In some classic work that is 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" cyclones were born. Table 1 summarizes the dimensions of standard cyclones of the three types mentioned previously. Figure 3 illustrates the various dimensions used in Table 1.

2. Theory

Collection Efficiency

A very simple model can be used to determine the effects of both cyclone design and operation on collection efficiency. In this model, gas spins through a number of revolutions N_e in the outer vortex. The value of N_e can be approximated by

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

where

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

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

$$\Delta t = \pi D\, N_e / V_i$$

where

Δt = time spent by gas during spiraling descent (sec)
D = cyclone body diameter (m or ft)
V_i = gas inlet velocity (m/s or ft/s) = Q/WH
Q = volumetric inflow (m^3/s or ft^3/s)
W = width of inlet (m or ft).

The maximum radial distance traveled by any particle is the width of the inlet duct *W*. The centrifugal force quickly accelerates the particle to its terminal velocity in the outward (radial) direction, with the opposing drag force equaling the centrifugal force. The terminal velocity that will just allow a particle initially at distance *W* away from the wall to be collected in time Δt is

$$V_t = W/\Delta t$$

where V_t = particle terminal velocity in the radial direction (m/s or ft/s).

The particle terminal velocity is a function of particle size. Assuming Stokes regime flow (drag force = $3\pi\mu d_p V_t$) and spherical particles subjected to a centrifugal force (mv^2/r, with m = mass of particle in excess of mass of gas displaced, $v = V_i$ of inlet flow, and $r = D/2$), we obtain

$$V_t = \frac{(\rho_p - \rho_g)\, d_p^2 V_i^2}{9\mu D}$$

where

V_t = terminal velocity (m/s or ft/s)
d_p = diameter of the particle (m or ft)
ρ_p = density of the particle (kg/m^3)
ρ_g = gas density (kg/m^3)
μ = gas viscosity (kg/m.s).

Substitution of the 2nd equation into the 3rd eliminates Δt. Then, setting the two expressions for V_t equal to each other and rearranging to solve for particle diameter, we obtain

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

It is worth noting that in this expression, 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.

Note that the units must be consistent in all equations. One consistent set is m for d_p, R and W; m/s for V_i and V_t; kg/m.s for μ; and kg/m^3 for ρ_p and ρ_g. An equivalent set in English units is ft for d_p,R and W; ft/sec for V_i and V_t; lb$_m$/ft.sec for μ; and lb$_m$/ft^3 for ρ_p and ρ_g.

3. Design Considerations

Collection Efficiency

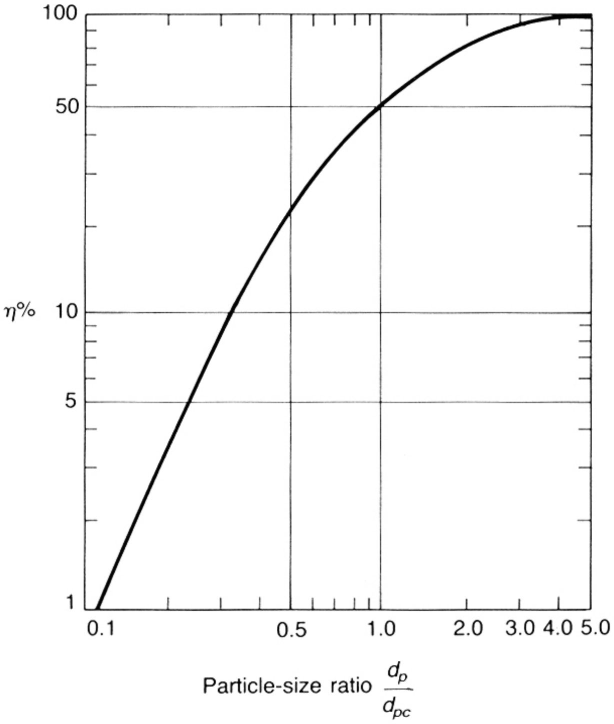
From the preceding equation, we see that, in theory, the smallest diameter of particles collected with 100% efficiency is directly related to gas viscosity and inlet duct width, and inversely related to the number of effective turns, inlet gas velocity, and density difference between the particles and the gas. In practice, collection efficiency does, in fact, depend on these parameters. However, the model has a major flaw: It predicts that *all* particles larger than d_p will be collected with 100% efficiency, which is incorrect.

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

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

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

Figure 4. Particle collection efficiency versus particle size ratio for standard conventional cyclones



Note the similarity between the last two equations. (The only difference is a factor 2 in the denominator.) Lapple then developed a general curve for standard conventional cyclones to predict the collection efficiency for any particle size (Figure 4). If the size distribution of particles is known, the overall collection efficiency of a cyclone can be predicted by using Figure 4. Theodore and DePaola (1980) have fitted an algebraic equation to Figure 4, 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

$$\eta_j = \frac{1}{1 + \left(d_{pc} / d_{pj}\right)^2}$$

where

η_j = collection efficiency of particles in the *j*th size range ($0 < \eta_j < 1$)
d_{pj} = characteristic diameter of the *j*th particle size range (in μm).

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

$$\eta = \frac{\sum \eta_j m_j}{M}$$

where

η = overall collection efficiency ($0 < \eta < 1$)
m_j = mass of particles in the *j*th size range
M = total mass of particles.

The use of the previous equations is illustrated in application below.

Application

Consider a conventional cyclone of standard proportions as described by Lapple [column (3) of Table 1], with a body diameter of 1.0 m. 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
x	1.0

First, we calculate d_{pc} . For this, we take the gas viscosity equal to 0.075 kg/m.hr and the gas density as 1.01 kg/m^3.(both at 350 K). The inlet velocity is

$$V_i = \frac{150\,m^3}{\min} \times \frac{1}{(0.5m)(0.25m)} = \frac{1200m}{\min}.$$

For a Lapple standard cyclone, N_e = 6 and

$$d_{pc} = \left[\frac{9\left(0.075\frac{kg}{m\ hr}\right)(0.25m)}{2\pi(6)\left(1200\frac{m}{\min}\right)\left(60\frac{\min}{hr}\right)\left[(1600-1)\frac{kg}{m^3}\right]} \right]^{1/2}$$

$$d_{pc} = 6.26\ 10^{-6}\,m = 6.3\mu m.$$

Next, we determine the collection efficiency for each size range from Figure 4 or the accompanying equation. The arithmetic midpoint of the range is often used as the characteristic particle size. It is convenient to proceed with the construction of a table, as follows.

j	Size Range, μm	d_{pj}, μ m	d_{pj} / d_{pc}	η_j	$\frac{m_j}{M}$,%	Mass Percent Collected $\eta_j \frac{m_j}{M}$, %
1	0 – 2	1	0.159	0.025	1.0	0.02
2	2 – 4	3	0.476	0.185	9.0	1.66
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	2.06	0.81	30.0	24.3
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
						67.6%

Finally, as shown in the table,

$$\eta_o = \sum_{j=1}^{8} \frac{\eta_j m_j}{M} = 67.6\%$$

The overall collection efficiency of this cyclone for this particular air-particulate mixture is approximately 68%, or 0.68.