Air pollution

Classification of air pollutants

Air pollutants are classified into two categories of primary pollutants and secondary pollutants.

A. **Primary pollutants** are those that are emitted directly from the sources. A general list of primary air pollutants are:

1- Particulate matter such as ash, smoke, dust, fumes, mist, fog, spray, and aerosol.
2- Inorganic gases such as sulfur dioxide, hydrogen sulfide, nitric acid, ammonia, carbon monoxide, carbon dioxide, and hydrogen fluoride.
3- Olefin and aromatic hydrocarbons.
4- Radioactive compound.

B. Secondary Pollutants are those that are formed in the atmosphere by chemical interactions among primary pollutants and normal atmospheric constituents. Pollutants such as sulfur trioxide, nitrogen dioxide, PAN (peroxyacetyl nitrate), ozone, aldehydes, ketones and various sulfate and nitrate salts.

Particulate matter

Particulate refers to all atmospheric substances that are not gases. They can be suspended droplets or solid particles or mixture of the two. Particulates can be composed of inert or extremely reactive materials ranging in size from 100 µm down to 0.1 µm and less.

Air borne particulate

Air born particles can be classified as:

Dust: It contains particles of the size ranging from 1 to 200 µm. These are formed by natural disintegration of rock and soil or by the mechanical process of grinding and spraying. They have large settling velocities and are removed from the air by gravity and other proce**ss.**

Smoke: It contains fine particles of the size ranging from 0.01 to 1 µm, which are they liquid or solid, and are formed by combustion or by other processes.

Fume: These are solid particles of the size ranging from 0.1 to 1 µm, and are normally released from chemical or metallurgical processes.

Mist: It is made up of liquid droplets generally smaller than 10 µm, which are formed by condensation in the atmosphere or released from industrial operations.

Fog: It is the mist in which the liquid is water.
Aerosol: These included all air-born suspensions either solid or liquid. These are generally smaller than 1 µm.

Air pollution control equipments

The various air pollution control equipments are used to control the air pollution from stationary sources. These equipments are conveniently divided into two types, one type are those which applicable for controlling particulate, and the other that used for controlling gaseous pollutants as shown in Fig.1.

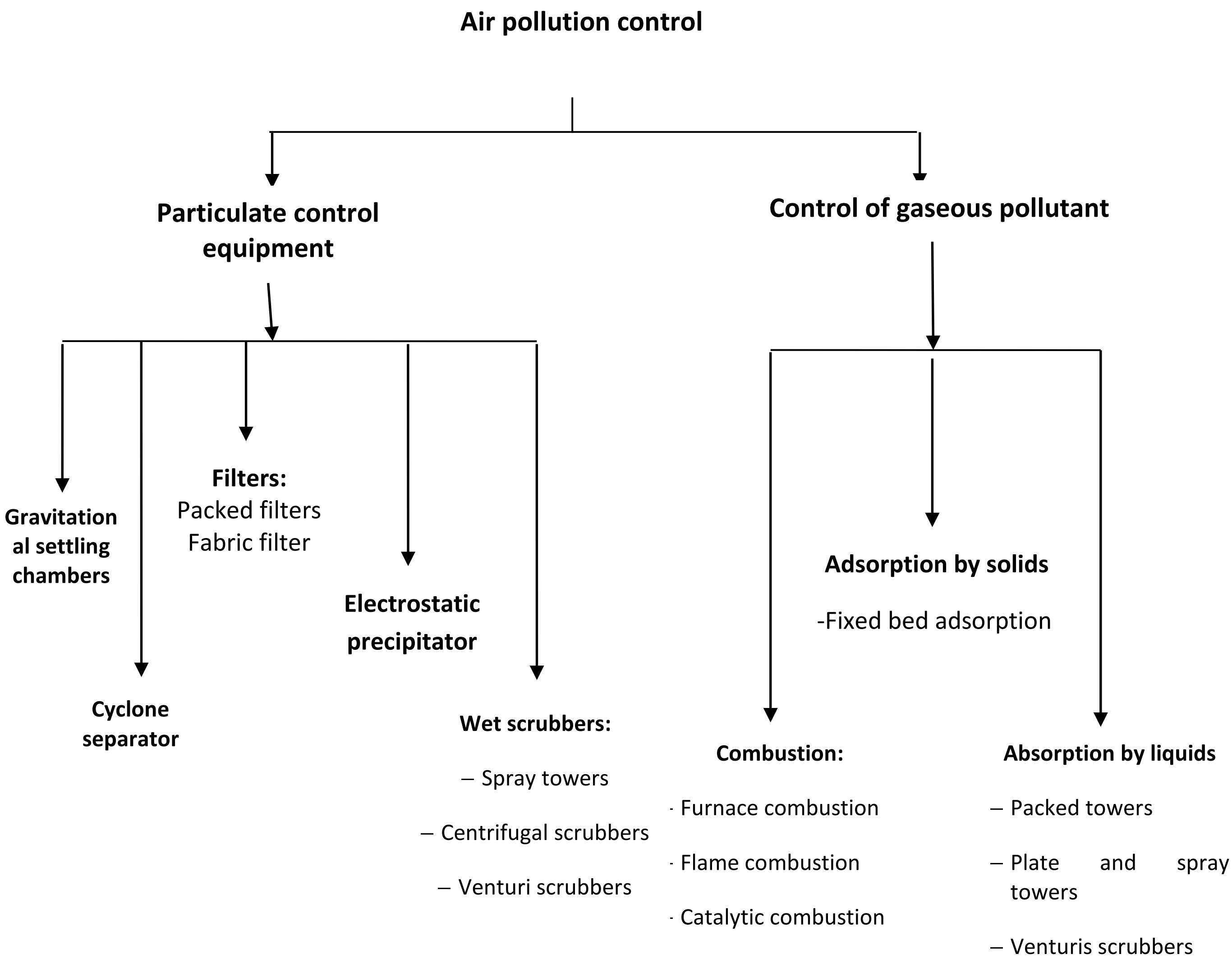


Fig.1. the most commonly equipments deal with air pollution control from stationary sources

Control of Particulate Pollutants

Particulate control equipment

A number of factors must be determined before a proper choice of collection equipment can be made. Among the most important data required are the following:

1- The physical and chemical properties of the particulates.

2- The range of volumetric flow rate of the gas stream.

3- The particulate size and concentration in gas stream.

4- The temperature and pressure of the flow stream.

5- The humidity.

6- The collection efficiency that required for outlet stream.

1- Gravitational settling cambers

Gravitational force may be employed to remove particulate in settling chambers when the settling velocity is greater than about 25 ft/min (13 cm/s).

In general settling chamber equipment is applied to remove of coarse particles larger than 50 µm from gas streams. Settling chambers offer low pressure drop and required simple maintenance, but their efficient is quit small for particles smaller than 50µm. Since most of particles in the gas stream are much smaller sizes than 50 µm, these devices are used as a primarily prior to passing the gas stream through high efficiency devices.

The efficiency of equipment depends on the residence time of the gas in the settling chamber which is related to the velocity of the gas flow and the chamber volume. The simplest form of gravity settling camber is shown in Fig.2.

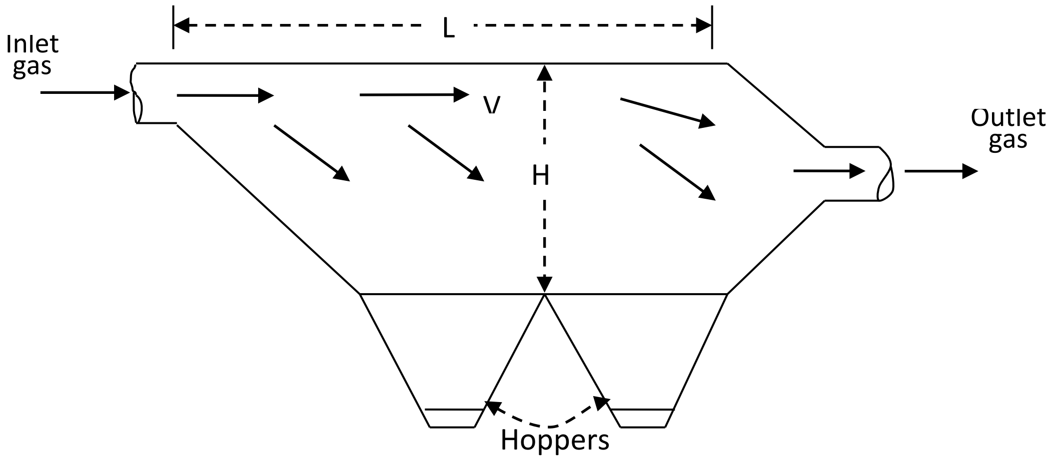


Fig.2. A gravitational settling chamber

1. Settling chamber design (gravity settling)

1.1. Terminal settling velocity

A gravity settler is simply a long chamber through which the contaminated gas passes slowly, allowing time for particles to settle by gravity to the bottom. The important parameter is the terminal or settling velocity of the particle, V_t the terminal velocity is defined as the constant downward speed that a particle attains in a direction parallel to the Earth's gravity field.

If the particle is settling in a fluid at its terminal velocity, three forces acting on it: drag, buoyancy, gravity force, as shown in Fig.8. The terminal settling velocity of the particles is found from forces balance as:

$$F_g = F_D + F_B$$

where

F_g = gravity force (secondary Newton law) = $m_p g$

F_D = drag force = $F_D = \frac{\rho_g V_t^2 A C_D}{2}$

F_B = buoyancy force = $F_B = m_p \left(\frac{\rho_g}{\rho_p} \right) g$

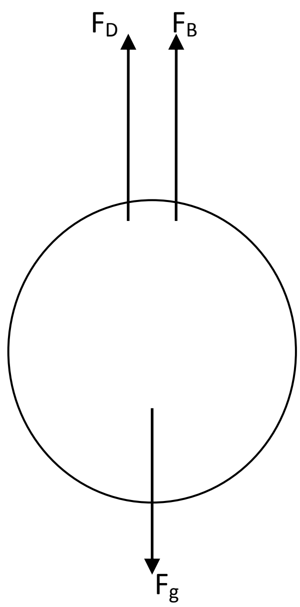


Fig.10. the forces acting on a particle in a fluid

m_p = mass of particle = $\rho_p V_p$

g = gravitational acceleration, m^2/s

ρ_p = particle density, kg/m^3

ρ_g = gas density, kg/m^3

C_D = drag coefficient

V_t = terminal velocity, m/s

A = frontal cross sectional area, m^2

V_p = volume of particle, m^3

Substituting the overall balance then becomes

$$m_p g = \frac{\rho_g V_t^2 A C_D}{2} + \left(\frac{\rho_g}{\rho_p}\right) g$$

The general solution to the equation, in term of V_t, is

$$V_t = \sqrt{\frac{2 m_p g(\rho_p - \rho_g)}{\rho_p \rho_g A C_D}}$$

for spherical particle

$$V_t = \sqrt{\frac{4 g d_p(\rho_p - \rho_g)}{3 C_D \rho_g}}$$

(1)

where

$$V_p = \frac{\pi}{6} d_p^3, \qquad A = \frac{\pi}{4} d_p^2, \qquad m = \rho_p V_p$$

where

d_p = particle diameter, m

Eq.1 is the general equation for the terminal settling velocity

where C_D is the drag coefficient which is related to the particles Reynolds number,

Where $\mathrm{Re}_p = \dfrac{\rho_g V_t d_p}{\mu_g}$

The general drag coefficient for spherical particles may be represented by three relationships.

In Stocks law region, laminar flow around the particle

❖ $C_D = \dfrac{24}{\mathrm{Re}_p}$ for $\mathrm{Re}_p < 0.1$ (2)

In transition region, (1< Re < 1000) this region between the Stokes law region and turbulent region

❖ $C_D = \dfrac{18.5}{\mathrm{Re}_p^{0.6}}$ for $0.1 \le \mathrm{Re}_p \le 1000$ (3)

In the turbulent region, (Re_p < 1000), the drag force becomes almost constant with the value of 0.45,

❖ $C_D = 0.445$ for $\mathrm{Re} > 1000$
(4)

The drag coefficient can be calculating within the required range of Reynolds number and then substituted in the Eq(1) to determine the terminal velocity as:

1. Substituting Eq.(2) into Eq.,(1), we can calculate the terminal settling velocity in the Stokes region:

$$V_t = \frac{g d_p^2 (\rho_p - \rho_g)}{18 \mu_g} \quad (5)$$

2. Substituting Eq.(3) into Eq.(1) we can calculate the terminal settling velocity In the transition region.

$$V_t = 0.153\frac{g^{0.71}d_p^{1.14}(\rho_p - \rho_g)^{0.71}}{\rho_g^{0.29}\mu^{0.43}} \qquad (6)$$

3. Substituting Eq.(4) into Eq.(1), we can calculate the terminal settling velocity in the turbulent region:

$$V_t = 1.73\left[\frac{gd_p(\rho_p - \rho_g)}{\rho_g}\right]^{1/2} \qquad (7)$$

It is difficult to estimate Reynolds number and then to estimate which C_D correlation used to calculate terminal velocity, V_t, because V_t is presented in Reynolds number and C_D equations. Therefore the following equation is used to provide a convenient correlation using K, as

$$K = d_p\left[\frac{g(\rho_p - \rho_g)\rho_g}{\mu_g^2}\right]^{1/3} \qquad (8)$$

If the size of particles is known, K value can be calculated from Eq.8:

If $K < 3.3$ then Stokes region applied to estimate V_t, Eq.5.

If $3.3 \leq K \leq 43.6$ then transition region applied to estimate V_t, Eq.6.

If K value > 43.6 then turbulent region applied to estimate V_t, Eq.7

1.2. Retention time, τ

Additional parameter in design of settling chamber hydrodynamic is retention time, τ, where

$$\tau = \frac{V}{Q} = \frac{L * W * H}{W * H * u} = \frac{L}{u} \qquad (9)$$

Where:-

V = the volume of the settling chamber, m^3

Q = the volumetric flow of gas stream, m^3/s

u = linear gas velocity, m/s

L, W, H = chamber length, width, and height respectively, m

1.3. Chamber efficiency, η

$$\eta = \frac{V_t L}{Hu} \qquad (10)$$

For most air pollution applications, Stock's law Eq.5 is appropriate substituting in Eq.10 as

$$\eta = \frac{d_p^2 g(\rho_p - \rho_g)L}{18\mu_g Hu} \qquad (11)$$

With 100% efficiency (η =1), Eq.11 becomes

$$d_{p,\min} = \sqrt{\frac{18\mu_g Hu}{g(\rho_p - \rho_g)L}} \qquad (12a)$$

Or

$$d_{p,\min} = \sqrt{\frac{18\mu_g Q}{g(\rho_p - \rho_g)WL}} \qquad (12b)$$

Eq.12.a & b is to determine the minimum particle size $d_{p,min}$ can removed with 100% efficiency (completely removed).

Design of settling chamber

To design a settling chamber the following equations seems to be useful as a guide:

$$WL = \frac{18\mu_g Q}{g\rho_p d_p^2} \quad (13)$$

$$WH = \frac{Q}{u} \quad (14)$$

where

Q = volumetric flow rate of the gas stream

W = width of settling chamber

H = height of settling chamber

L = Length of settling chamber

u = linear gas velocity, as a design rule of thumb must be below 10 ft/s (30 m/s).

The minimum height of the chamber (H) should be 1 m for cleaning.

Note Eq. 13 estimated from Eq.11 assuming η = 1 for design purpose

Ex.1: Three different-sized fly ash particles settle through air. You are asked to calculate the particle terminal velocity and determine how far each will fall in 30 s. Assume that the particles are spherical. Data are provided below:

Fly ash particle diameters = 0.4, 40, 400 μm

The density of air = 0.0569 lb/ft^3

Specific gravity of fly ash = 2.31

The viscosity of air is = 1.41×10^{-5} lb/(ft . s)

Solu: The particle density is calculated using the specific gravity given:

$$\rho_p = (2.31)(62.4)$$
$$= 144.14 \ lb/ft^3$$

The value of K for each fly ash particle size setting in air may be calculated. **Note** that $\rho_p - \rho_{gas} = \rho_p$.

- For a d_p of 0.4 μm:

$$K = d_p \left[\frac{g(\rho_p)\rho_g}{\mu_g^2} \right]^{1/3}$$

$= (0.4*10^{-6}*3.281)\ [(32.2)(144.14)(0.0569) / (1.41*10^{-5})^2]^{1/3}$

$= 0.0144 < 3.3$ stokes low range

- For a d_p of 40 μm:

$K = (40*10^{-6}*3.281)\ [(32.2)(144.14)(0.0569) / (1.41*10^{-5})^2]^{1/3}$

$= 1.44 < 3.3$ stokes low range

- For a d_p of 400 μm:

$K = (400*10^{-6}*3.281)\ [(32.2)(144.14)(0.0569) / (1.41*10^{-5})^2]^{1/3}$

$= 14.4$ $3.3 \le 3.3 \le 43.6$ intermediate range

Velocity calculation:

- For a d_p of 0.4 μm:

$$V_t = \frac{g d_p^2 (\rho_p)}{18 \mu_g}$$

$V_t = (32.2)\ (0.4\times10^{-6} \times3.281)^2\ (144.14) / 18\ (1.41 \times 10^{-5}$

$= 3.15\times10^{-6}$ ft/s

- For a d_p of 40 μm:

$V_t = (32.2)\ (40\times10^{-6} \times3.281)^2\ (144.14) / 18\ (1.41 \times 10^{-5})$

$= 0.315$ ft/s

- For a d_p of 400 μm:

$$V_t = 0.153 \frac{g^{0.71} d_p^{1.14} (\rho_p)^{0.71}}{\rho_g^{0.29} \mu^{0.43}}$$

$V_t = 0.153 \; [(32.2)^{0.71}(400\times10^{-6} \times3.281)^{1.14}(144.14)^{0.71} \,/\, (0.0569)^{0.43}(1.41\times 10^{-5})^{0.29}]$

$= 8.9$ ft/s

The distance that the fly ash particles will fall in 30 s may also be calculated using

d = v t , d: distance

- For a d_p of 0.4 μm:

Distance = 3.15×10^{-6} ft/s ×30 sec. = 0.945×10^{-4} ft

- For a d_p of 40 μm:

Distance = 0.315 ft/s ×30 sec. = 9.45 ft

- For a d_p of 400 μm:

Distance = 8.9× ft/s ×30 sec. = 267 ft

Effect of Plates on Efficiency

Ex. 1: A monodispersed aerosol 1.099 μm in diameter passes through a gravity settler 20 cm wide , 50 cm long with 18 plates and channel thickness of 0.124 cm. The gas flow rate is 8.6 L/min, and it is observed that it operates at an efficiency of 64.9%. How many plates would be required to have the unit operate at 80% efficiency?

Solution: The volumetric flow is

q1 = 8.6 L/min ×(min/60 s) ×(1000 cm^3/L) ×(1/19) channels

= 7.544 cm^3/channel .s :

The settling velocity can be calculated from Equation

$E_1 = v_t \, BL / q_1$

$V_t = E_1 \, q_1 / BL$

$= [(7.544 \text{ cm}^3/\text{s})(0.649)] / [(20\text{cm})(50\text{cm})] = 4.896 \times 10^{-3}$ cm/s

At $E_2 = 0.8$, the new volumetric flow is

$q_2 = v_t BL / E_2$

$= [(4.896 \times 10^{-3} \text{ cm/s}) (20\text{cm}) (50\text{cm})] / (0.8)$

$= 6.12 \text{ cm}^3/\text{channel .s}$

Then, the number of channels necessary is

Number of channels = q_1 / q_2

$= [7.544 \text{ cm}^3/\text{channel .s} \times 19 \text{ channel}] / 6.12 \text{ cm}^3/\text{channel .s}$

= 23.42 say 24

Penetration:

Penetration is define as. An extremely convenient efficiency-related term employed in particulate control calculations is the penetration P. By definition:

$P = 100 - E$; percent basis

$P = 1 - E$; fractional basis

Note that there is a 10-fold increase in P as E goes from 99.9% to 99%. For a multiple series of n collectors, the overall penetration is simply given by

$P = P_1P_2 - - - - - P_n$

For particulate control, penetrations and/or efficiencies can be related to individual size ranges. The overall efficiency (or penetration) is then given by the contribution from each size range, obtained from the summation of the product of mass fraction and efficiency for each size range.

$E = E_1w_1 + E_2w_2 + - - - - - - E_nw_n$

Exa. 1: The inlet and outlet loading of a particulate in an air control device have been measured experimentally to be 2.7 and 0.036 gr/ft^3 , respectively. Calculate the efficiency of the unit.

Solution:

$$E = [(2.7-0.036) / 2.7] \times 100$$
$$= (0.9867) \times 100$$
$$= 98.67\%$$

Efficiency of TwoCo ntrol Devices in Series

Exa. 2: Two particulate air pollution control devices operate in series with collection efficiencies of 90% and 99.5%, respectively. Calculate the overall efficiency of the two units.

Solution: This problem is best solved by noting the overall penetration given by the product of the penetration for each device:

$$P = P_1 P_2; \qquad \text{fractional basis}$$

According to the data given

$$P_1 = 1 – 0.9$$
$$= 0.1$$

and

$$P_2 = 1 – 0.995$$
$$= 0.005$$

Therefore

$$P = (0.1)(0.005)$$
$$= 0.0005; \quad \text{fractional basis}$$
$$= 0.05; \quad \text{percent basis}$$

Finally

$$E = 100 - P$$
$$= 100 – 0.05$$
$$= 99.95\%$$

CYCLONES

2- Cyclone separators

Cyclone separators are the most popular and effective devices used for separation particulates from gas stream. Cyclone separators utilize a centrifugal force generated by spinning gas stream to separate the particulates from the carrier gas. The centrifugal force on particles in a spinning gas stream is much greater than gravity; therefore, cyclones are effective in the removal of much smaller particles than gravitational settling chambers, and required much less space to handle the same gas volumes.

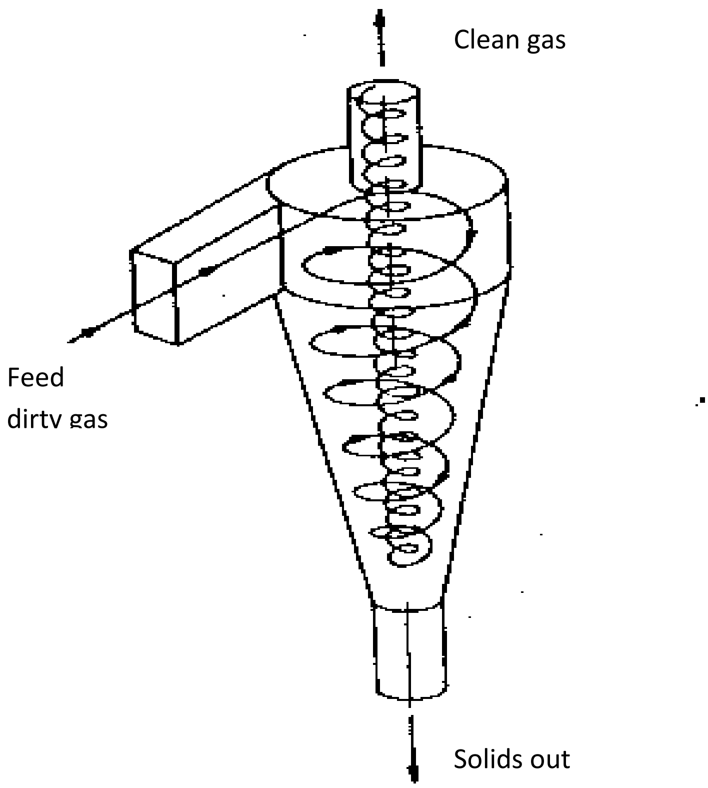


Fig.3. Reverse flow cyclone

The most commonly used design is the reverse flow cyclone, see Fig.3. The dirty gas flows tangentially into the cyclone at the top, and spiral down near the outer radius and then back upward in the center core, in a second smaller diameter spiral, and exit at the top through a central vertical pipe. The particle moves radials to the walls, slide down the walls, and are collected at the bottom.

Objects moving in circular paths tend to move away from the center of their motion. The object moves outward as if a force is pushing it out. This force is known as centrifugal force.

$$F= \rho_p d^3_p\ v^2_p / r$$

Where
ρ_p = particle density, lb/ft^3 (kg/m^3)
d_p = particle diameter, inches (μm)

v_p = particle tangential velocity, ft/s (m/s)
r = radius of the circular path, ft (m)

Three important parameters can be used to characterize cyclone performance:

d_{pc} = cut diameter

ΔP = pressure drop

E = overall collection efficiency

Cut Diameter:
The cut diameter is defined as the size (diameter) of particles collected with 50% efficiency

$$d_{pc} = [\ 9\mu B_c / 2\pi N v_i\ (\rho_p - \rho_g)]^{0.5}$$

where

d_{pc} or $[d_p]_{cut}$ = cut diameter
μ = viscosity, lb/ft . s (Pa . s)
N = effective number of turns (5–10 for the common cyclone)
v_i = inlet gas velocity, ft/s (m/s)
ρ_p = particle density, lb/ft^3 (kg/m^3)
ρ_g = gas density, lb/ft^3 (kg/m^3)
B_c = inlet width, ft (m)

$E = 1/ 1+ (d_{pc} / d_p)^2$ ………… Theodore–DePaola equation for the collection efficiency

Critical size : Is referred to as the smallest particle size that is collected at 100% efficiency by a cyclone.

Note: that an increase in the number of turns, inlet velocity, or the particle density will decrease the cut size as one would expect. A decrease in viscosity will decrease the drag force opposing the centrifugal force and therefore also reduce the cut size (i.e., smaller particles will be collected).

Pressure Drop

The pressure drop across a cyclone is an important parameter to the purchaser of such equipment. Increased pressure drop means greater costs for power to move an exhaust gas through the control device. With cyclones, an increase in pressure drop usually means that there will be an improvement in collection efficiency (one exception to this is the use of pressure recovery devices attached to the exit tube; these reduce the pressure drop but do not adversely affect collection efficiency).

The most popular of the empirical pressure drop equations has the form

$$\Delta P = K_c \rho v_i^2 \qquad \text{; consistent units}$$

where K_c = a proportionality factor vary from 0.013 to 0.024, with 0.024 the normal.
v_i = inlet velocity.
ρ = gas density.

Type of cyclones

Three types of cyclones:

1- Conventional cyclones
   It is applied to remove of particles of 25 μm or larger with an efficiency greater than 90%.

2- High efficiency cyclones
   The inlet gas velocity is higher, thereby importing a higher centrifugal force. These types are effective with particle sizes down 5 μm.

3- High volume cyclones
   Particle size are generally larger than 50 μm are collected with great efficiency. They can handle larger flow.

Fig.4 shows typical curves for several types of equipment with their fraction collection efficiency as a function of particle size

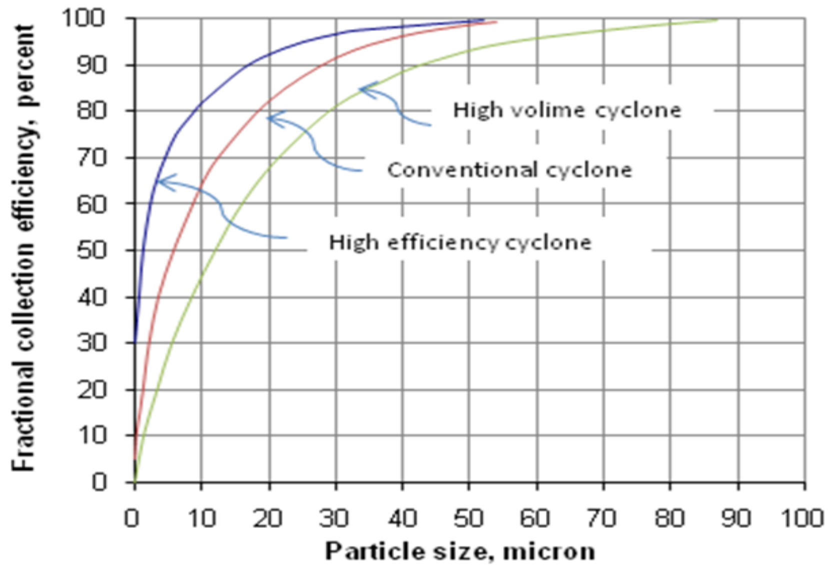


Fig.4. the fractional collection efficiency as a function of particle size for several types of cyclones.

Operation and Maintenance, and Improving Performance:

There are many operating variables in cyclone performance. These include characteristics of both the gas and the particles. Gas operating variables include temperature, pressure, and composition. Dust characteristics include size, size distribution, shape, density, and concentration.

As the temperature of a gas increases, its density decreases while its viscosity increases. Since the gas density is negligible compared to the particle density, this has no direct effect on efficiency. A higher temperature will increase the inlet velocity, increasing the particle velocity toward the wall. However, the increasing viscosity decreases the particle velocity toward the wall. The net effect of this is that within the normal operating range of 40–7008F the collection efficiency is essentially constant. As the temperature rises above 10008F, the viscosity effect dominates, causing a decrease in efficiency. The gas composition can also affect gas viscosity and density.

Collection efficiency in a cyclone is primarily determined by the pressure drop and/ or the inlet velocity. The pressure drop can be increased or decreased by varying the diameter of the cyclone body or by varying the volumetric flow rate per tube. These features must be designed into the system. If the cyclone is operated at a lower volumetric flow rate, dampers should be used so that the gas velocity will be increased. Since cyclones have no moving parts, fine tuning them is very difficult. Spiral vanes are used in axial entry cyclones, allowing some control of volumetric flow rate by moving a vane in and out of a constricted opening in the collector element. When fully in, maximum rotation is induced, resulting in greater centrifugal action.

Changes in Performance Characteristics

Cyclone and Process Design Changes	**Pressure Drop**	**Efficiency**	**Cost**
Increase cyclone size (D_c)	Decreases	Decreases	Increases
Lengthen cylinder (L_c)	Decreases	Decreases	Increases
Lengthen cone (Z_c)	Decreases	Increases	Increases
Increase exit tube diameter (D_e)	Decreases	Decreases	Increases
Increase inlet area maintaining velocity	Increases	Decreases	Decreases
Increase velocity	Increases	Increases	Operating costs higher
Increase temperature (maintaining velocity)	Decreases	Decreases	No change
Increased dust concentration	Decreases for large increases	Increases	No change
Increasing particle size and/or density	No change	Increases	No change

Example. 1:

As a graduate student you have been assigned the task of studying certain process factors in an operation in Sa˜o Paulo, Brazil that employs three cyclones in series to treat catalyst-laden gas at 25 ^{o}C and 1 atm. The inlet loading to the cyclone series is 8.24 gr/ft^3, and the volumetric flow rate is 1,000,000 acfm. The efficiency of the cyclones are 93%, 84% and 73%, respectively. Calculate the following:

(a) Daily mass of catalyst collected (lb/day).
(b) Daily mass of catalyst discharged to the atmosphere.

(c) Whether it would be economical to add an additional cyclone (efficiency = 52%) costing an additional $300,000 per year. (The cost of the catalyst is $0.75 per pound.)
(d) Outlet loading from the proposed fourth cyclone if the operation is based on 300 days per year.

Solution: The mass rate entering, m_i, is

m_i = $(10^6 \text{ ft}^3/\text{ min}) (60 \text{ min/hr})(24 \text{ hr/day}) (8.24 \text{ gr/ft}^3) (1 \text{ lb/7000 gr})$

= 1,695,086 lb/day

The mass rate collected m_c is

m_c = 1,695,086 (0.93) + (0.84)[1,695,086 (1- 0.93)] + 0.73[1,695,086(1-0.93)(1- 0.84)]

= 1,689,960 lb/day

Thus the mass discharge rate $\dot{m}_d$ is

m_d = 1,695,086 - 1,689,960 = 5126 lb/day

With a fourth cyclone, the additional mass collected $\dot{m}_4$, is

m_4 = 5126 (0.52) = 2666 lb/day
and 5126 - 2666 = 2460 lb/day is discharged.

The savings S is

S = (2666 lb/day)($0.75 /lb)(300 day/year)
= $600,000 per year

Since the cyclone costs $300,000 annually, purchase it.

The outlet loading (OL) is

OL = $(2460 \text{ lb/day})(1 \text{ day/24 h}) (1\text{h /60 min}) (1 \text{ min }/10^6 \text{ ft}^3)(7000 \text{ gr/ lb})$

= 0.012 gr/ ft^3

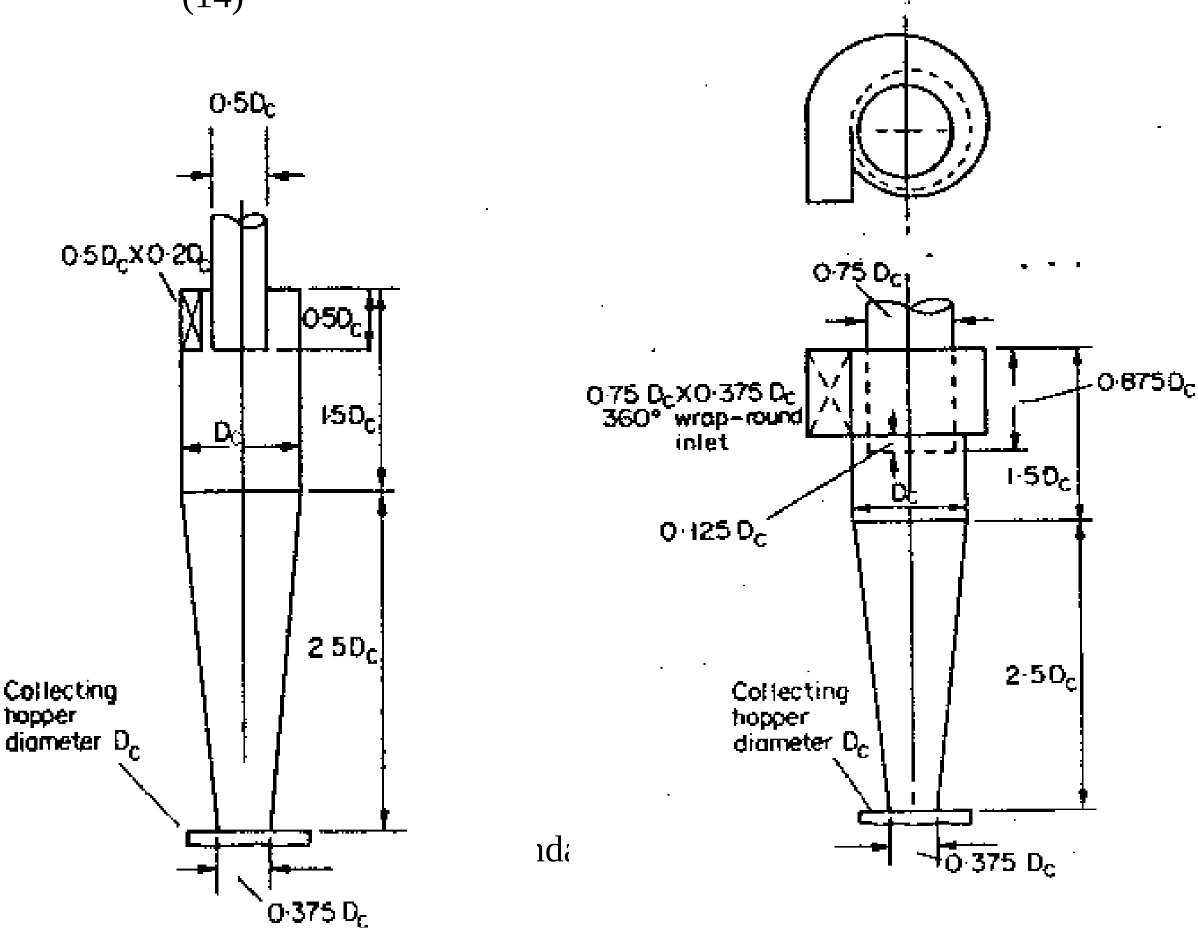
2. Centrifugal separators (Cyclone separators)design

2.1. Cyclone design

Two standard designs for gas-solid cyclones; (a) high-efficiency cyclone, Fig.11a and (b) high gas flow rate cyclone, Fig.12b. The performance curves for the high efficiency cyclone and high gas rate cyclone are shown in Fig.12 a and b These curves can be transformed to other cyclone sizes and operating conditions by use the following scaling equation for a given separating efficiency:

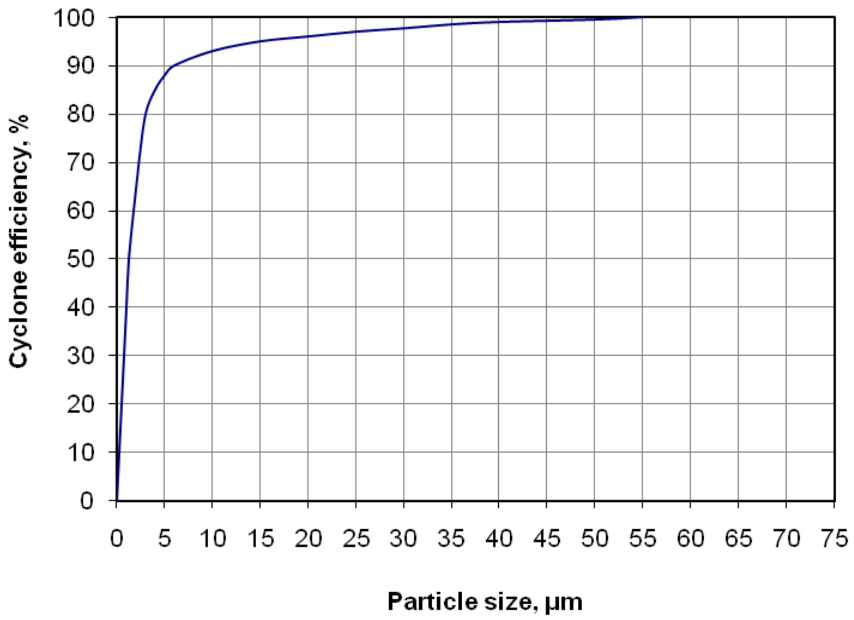
$$d_2 = d_1 \left[\left(\frac{D_{C2}}{D_{C1}} \right)^3 \times \frac{Q_1}{Q_2} \times \frac{\Delta\rho_1}{\Delta\rho_2} \times \frac{\mu_2}{\mu_1} \right]$$

(14)

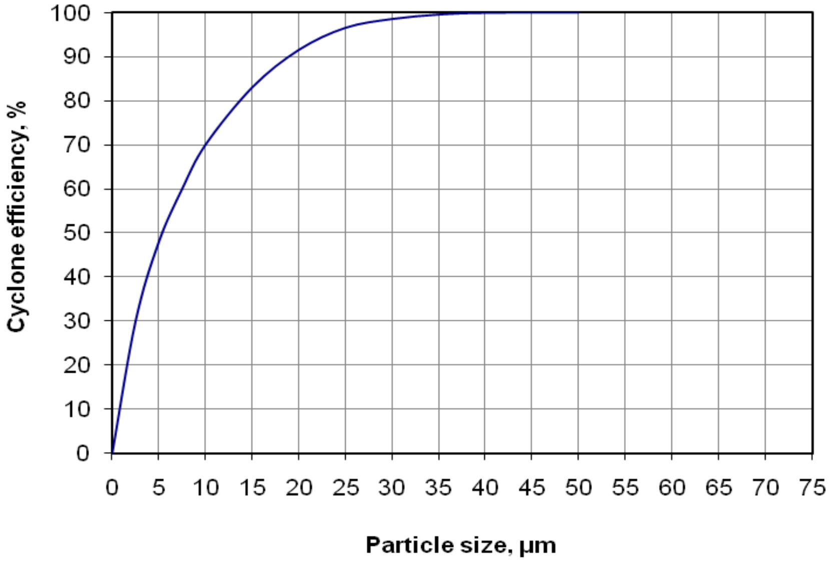


(a) High efficiency cyclone

(b) High gas rate cyclone



(a) High efficiency Cyclone



(b) High gas rate cyclone

Fig.12. Performance curves, standard conditions

Where:-

d_1= mean diameter of particle separated at standard condition, at chosen separation efficiency, Fig.13.

d_2 = mean diameter of particle separated in proposed design, at the same separation efficiency.

D_{C1} = diameter of standard cyclone = 8 inches (203 mm).

D_{C2} =diameter proposed cyclone, mm

Q_1 = standard flow rate, m^3/h.

for high efficiency design = 223 m^3/h.

for high throughput design = 669 m^3/h.

Q_2 = proposed flow rate, m^3/h.

$\Delta\rho_1$ = solid-fluid density difference in standard condition = 2000 kg/m^3.

$\Delta\rho_2$ = solid-fluid density difference, proposed design.

μ_1 = fluid viscosity (air at 1 atm, 20 °C = 0.018 mNs/m^2.

μ_2 = fluid viscosity, proposed design.

Hint

Cyclones should be designed to give an inlet velocity of between 9 and 27 m/s (30-90 ft/s). The optimum velocity has been found to be 15 m/s (50 ft/s).

2.2. Cyclone pressure drop

the pressure drop in cyclone will be due to the entry and exit losses, and friction and kinetic energy losses in the cyclone. The empirical equation can be used to estimate the pressure drop:

$$\Delta p = \frac{\rho_g}{203}\left\{u_1^2\left[1+2\phi^2\left(\frac{2r_t}{r_e}-1\right)+2u_2^2\right]\right\} \tag{14}$$

where

Δp = cyclone pressure drop, millibars.

ρ_g = gas density, kg/m^3.

u_1 = inlet duct velocity, m/s.

u_2 = exit duct velocity, m/s.

r_t = radius of circle to which the center line of the inlet is tangential, m

r_e = radius of exit pipe, m

ϕ =fraction from Fig.13.

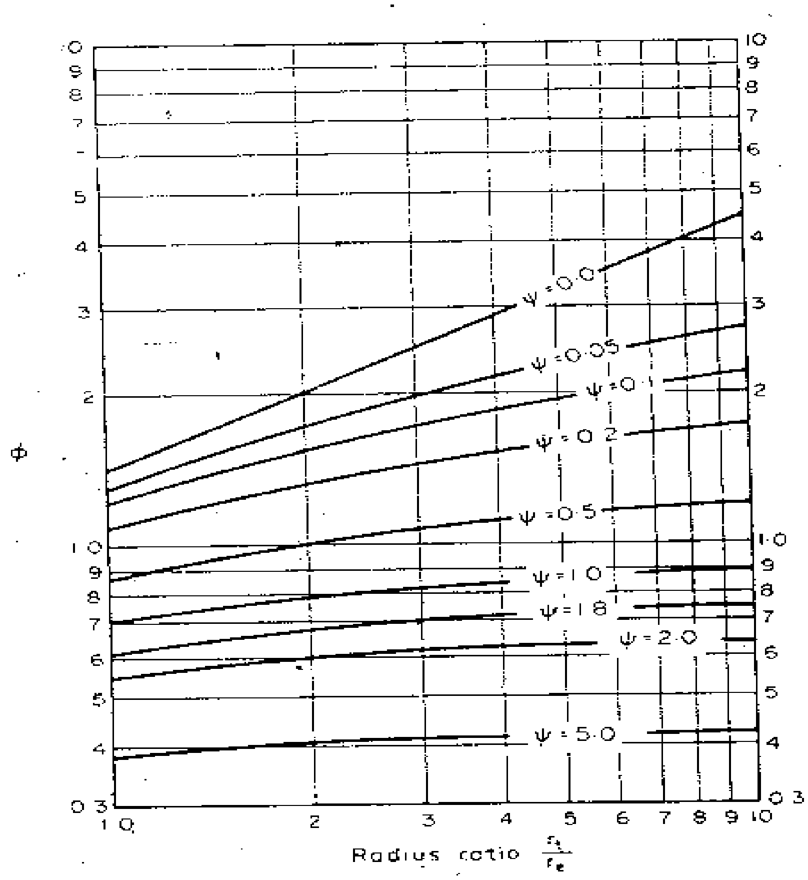


Fig.13. Cyclone pressure drop factor

Ψ = parameter in Fig.14..

$$\psi = f_C \frac{A_S}{A_1}$$

where

f_C = fraction factor, taken as 0.005 for gas.

A_S = surface area of cyclone expose to the spinning fluid, m^2.

For design purpose this can be taken as equal to the surface area of a cylinder with the same diameter as the cyclone.

A_1 = area of inlet duct, m^2.

2.3. Cyclone efficiency

The efficiency of cyclone can be estimated by using the concept of a cut diameter, cut diameter can be defined as the particle diameter at which 50% of particle are removed by cyclone:

$$d_{p_{50}} = \left[\frac{9\mu_g b}{2\pi N V_g \left(\rho_p - \rho_g\right)} \right]^{1/2} \tag{15}$$

where

μ_g = gas viscosity, kg/m.s.

b = cyclone inlet width, m.

N = effective number of outer turn in the cyclone(normally about 4).

V_g = inlet gas velocity, m/s.

ρ_p = particle density, , kg/m^3.

ρ_p = gas density, kg/m^3.

The cut diameter can be used to establish the collection efficiency for any other diameter particle, d_p, as shown in Fig.14.

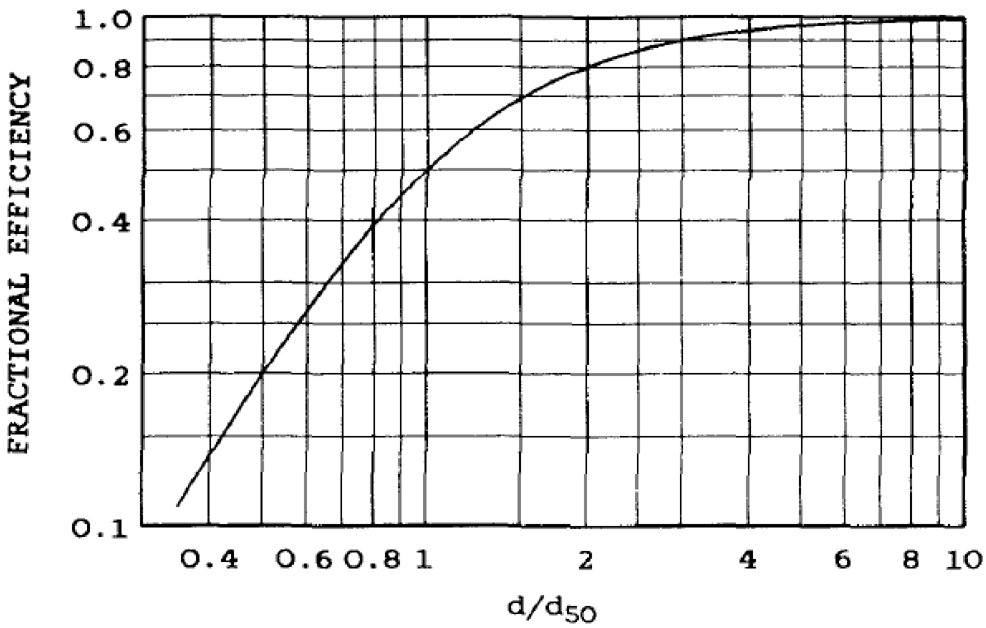


Fig.14. Cyclone efficiency versus particle-size ratio

3- Fabric filter (Baghouses)

Filtration is one of the oldest and most widely used methods of separating particulate from a carrier gas. A filter generally is a porous structure which tends to retain the particulate as the carrier gas passes through the void of filter, and allowing clean gas to pass out.

The fabric filter consists of several tubular bags or an envelope, called a baghouse, hanged in such a manner that the collected particle fall into a hopper. The dirty gas enters the bag at the bottom and passes through the fabric filter, while the particulate is deposited on the inside of the bag and passes out from their side to be finely released out of the filter system as a clean gas. Fig.5 shows a typical baghouse.

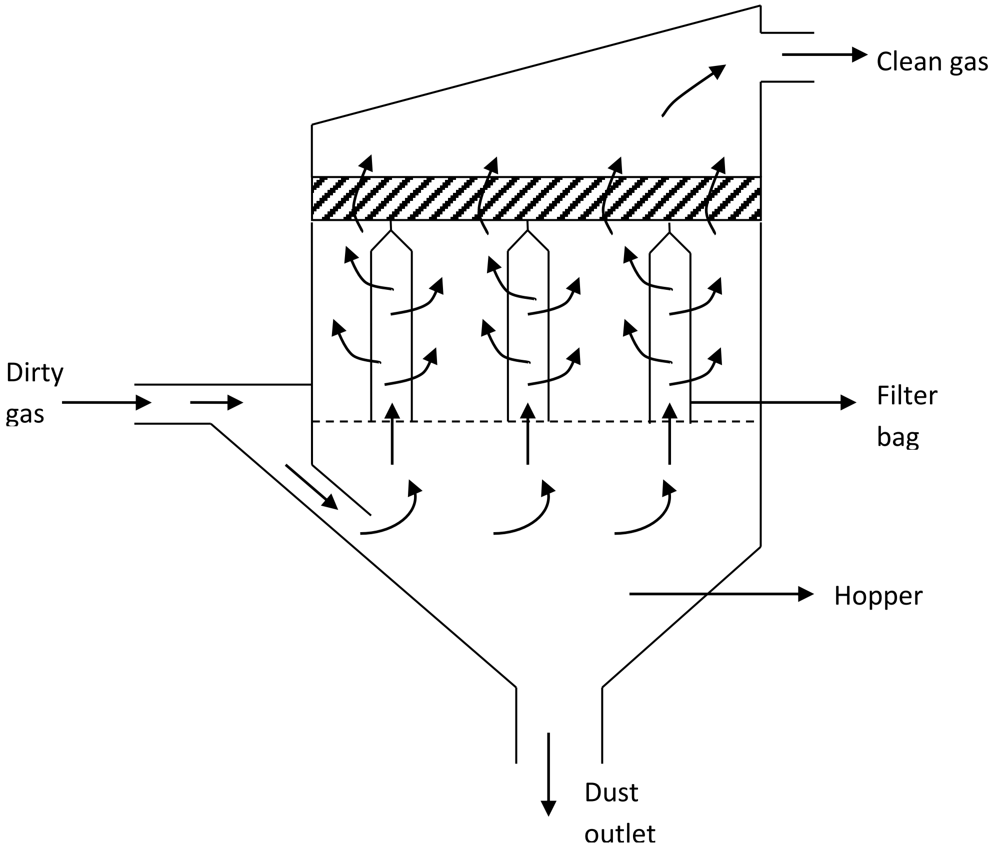


Fig.5. Typical bag house

The advantages of fabric filter

1- High collection efficiency over broad range of particle size.

2- Retention of finest particles.

3- Relatively low pressure drops.

4- Collection of particulates in dry form.

The main disadvantages of fabric filter

1- Their large size.
2- High construction costs.
3- Hydroscopic material cannot be handling.

Ex.1:
The dimensions of a bag in a filter unit are 8 inches in diameter and 15 feet long. Calculate the filtering area of the bag. The filtering unit consists of 40 such bags and is to treat 480,000 ft^3/hr of gas from an open-hearth furnace. Calculate the "effective" filtration velocity in feet per minute . Also calculate the mass of particles collected daily assuming that the inlet loading is 3.1 gr/ft^3 and the unit operates at 100 % collection efficiency.

Solution: Assume once again the bag to be cylindrical in shape with diameter D and height H. The total area of the bag is (including the flat top)

$$A = A_{\text{curved surface}} + A_{\text{flat top}}$$

$$= \pi DH + \pi D^2/4$$

$$= \pi\,(8/12)\,(15) + \pi\,(8/12)^2 / 4$$

$$= 31.43 + 0.34$$

$$= 31.77\ ft^2$$

The total area for 40 bags is

$$A = (40)\,(31.77) = 1271\ ft^2$$

The filter velocity is then

$$v = q / A$$

$$= (480{,}000=60) / 1271$$

$$= 6.30\ ft/min$$

The mass collected daily is

$$m = c_i \times q$$

$$= (480{,}000)\,(24)\,(3.1) / 7000$$

$$= 5102\ lb/day$$

Note once again that 7000 gr = 1 lb.

4- Electrostatic precipitators, (ESP)

Electrostatic precipitator is a physical process by which particles suspended in gas stream are discharged electrically and, under the influence of the electrical field, separated from the gas stream. A typical wire and pipe precipitator is shown in Fig.6.

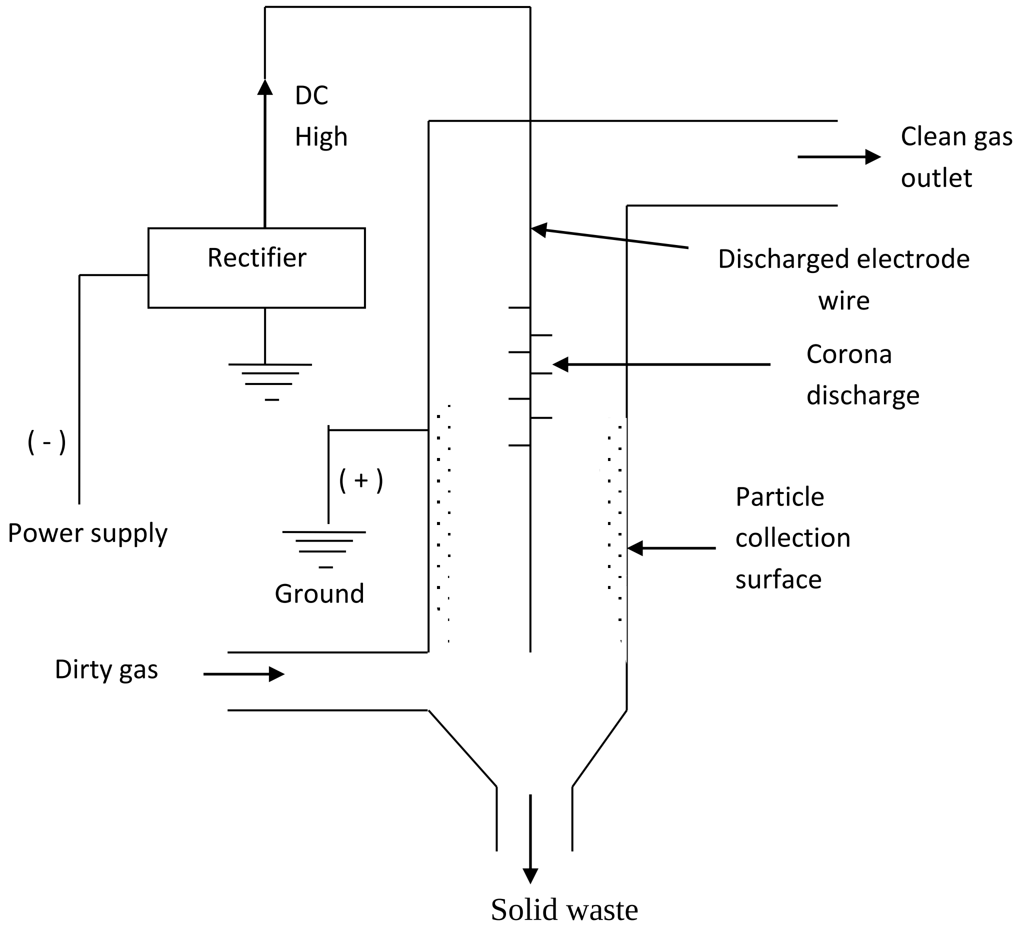


Fig.6. Electrostatic precipitators

The ESP system consists of a positively charged (grounded) collecting surface and a high-voltage discharge electrode wire (negative electrode) suspended axially in the tube. At a very DC a corona discharge occurs close to the negative electrode, setting up an electric field between the wire electrodes and the collecting surface electrode. Electrons are released at the wire electrode in a corona discharge. As the particle-laden gas enters near the bottom and flows upward, these electrons attach themselves to particles to charge them. The charge particles are derived by the electric field toward the grounded surface of tube; on the surface the particles lose their charge and collection occur.

Advantages of electrostatic precipitators

1- Pressure drop and hence power requirement is small compare to that of other devices.
2- High collection efficiencies very small particles can be collected wet and dry.
3- Can handle both gas and mists for high volume flows.
4- Low energy consumption.
5- Ability to operate with relatively high temperature gases.

Disadvantages of electrostatic precipitators

1- Relatively high initial cost and large space requirement.
2- It is necessary to safeguard operating person from high voltage.
3- Collection efficiency can deteriorate (تتدهور) gradually.

5- Wet scrubbers

Wet scrubber is one of the particulate control equipment in which water is used to capture particulate dust. The resulting the solids are removed from the gas stream by water as slurry. The principle mechanism involved impact (impingement) of the dust particles and water droplet in order to achieve good contact time.

-The advantages of wet scrubbers

1- Simultaneously removal of gases and particulate.
2- Can effectively remove fine particulate, both liquid and solid, ranging from 0.1-20 μ from gas stream.
3- Equipment occupies only a moderate amount of space compared to dry collectors such as bag house.

-The disadvantages of wet scrubbers

1- Relatively high energy costs.
2- Problem of wet sludge disposal.
3- Corrosion problems
4- The wet sludge causes water pollution and there is need to treatment method to remove particles from the water.
5- Very small particles (sub-micron sizes) may not capture.

The major types of wet scrubbers are:

1- Spray scrubbers
2- centrifugal scrubbers
3- Venture scrubbers

1-Spray scrubbers

The simplest type of wet scrubbers is a spray tower in which the polluted gas flows upward and water droplet is sprayed downward by means of spray nozzles located across the flow passage. The particle from the polluted gas is colliding with water droplet and the water droplet contaminated with this particle. If the gas flow rate is relatively slow, the contaminated water droplets will settle by gravity to the bottom of the tower as slurry. A mist eliminator is usually placed at the top of the tower to remove both excess clean water droplet and dirty droplets which are very small that cannot be settled and thus carried upward by the gas flow.

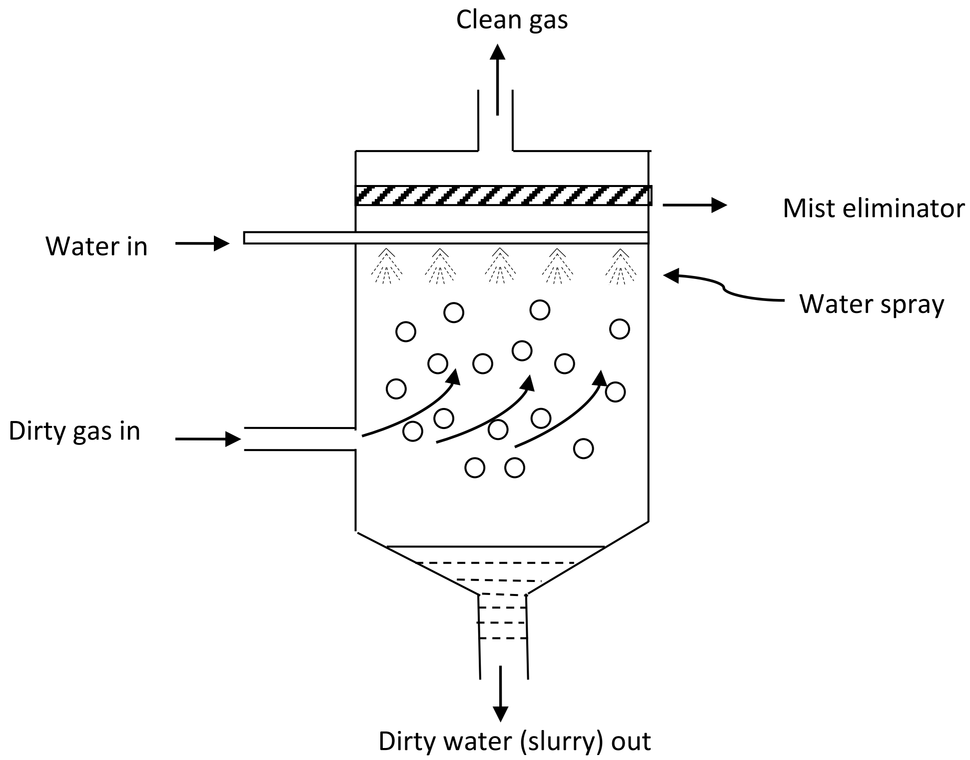


Fig.7. Sketch of a spray tower scrubber

High pressure spray produce small droplet with more surface area per mass of water used. The effectiveness spray towers ranges from 95% for 5 μm particles 99% for 25μm particles.

Spray tower is a counter current flow and may be circular or rectangular spray tower as shown in Fig.7.

2-Centrifugal scrubbers

Fig.8. shows centrifugal scrubber. The polluted gas introduced tangentially into the lower portion of the vertical cylinder. Water drops are injected from multiple nozzles, which throw the water radially outward across the flow gas stream. These droplets are caught in the spinning gas stream and are thrown upward towards the wall by centrifugal force. During their motion the, the droplets collide with particles and capture them. The scrubbing liquid along with the particles flows down the wall to the bottom of the scrubber and exits as slurry. The cleaned gas exists through a demister and is processed for the removal of any entrained water droplets.

The collection efficiency for the particles smaller than those recovered in spray towers can be increased through the use of centrifugal scrubbers. Commercial scrubbers have operating efficiency of 97% or better for particles larger than 1 μm.

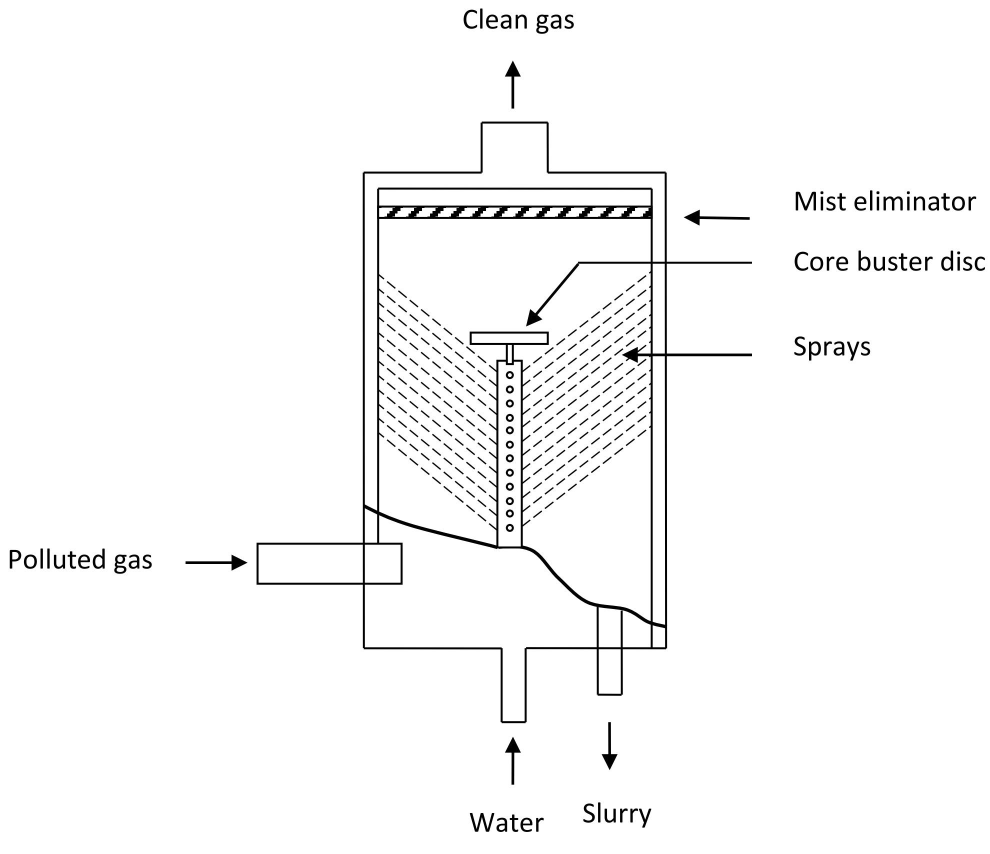


Fig.8. Centrifugal Scrubber, tangential entry

3-Venture scrubbers

A venturi is a rectangular or circular flow channel which converges to a narrow throat section and diverges back to its original cross section area. The narrow throat causes acceleration of the velocity of the gas to a high level in the venturi section. Fig.5. shows a vertical downward venturi with throat injection. A bank of nozzles on either side of throat injects water into high velocity gas stream. The high velocity gas assist in atomizing the liquid injected into the gas. The drops collide with dust particles in the gas to form dust-water agglomerates. The gas-liquid mixture is then directed to a separation device such as cyclone separator where the droplets carrying the particulates are separated from the gas stream. Venturi scrubbers offer high performance collection of fine particles usually smaller than 2 to 3 μm. They are suitable when the particulate matter is sticky, flammable or highly corrosive.

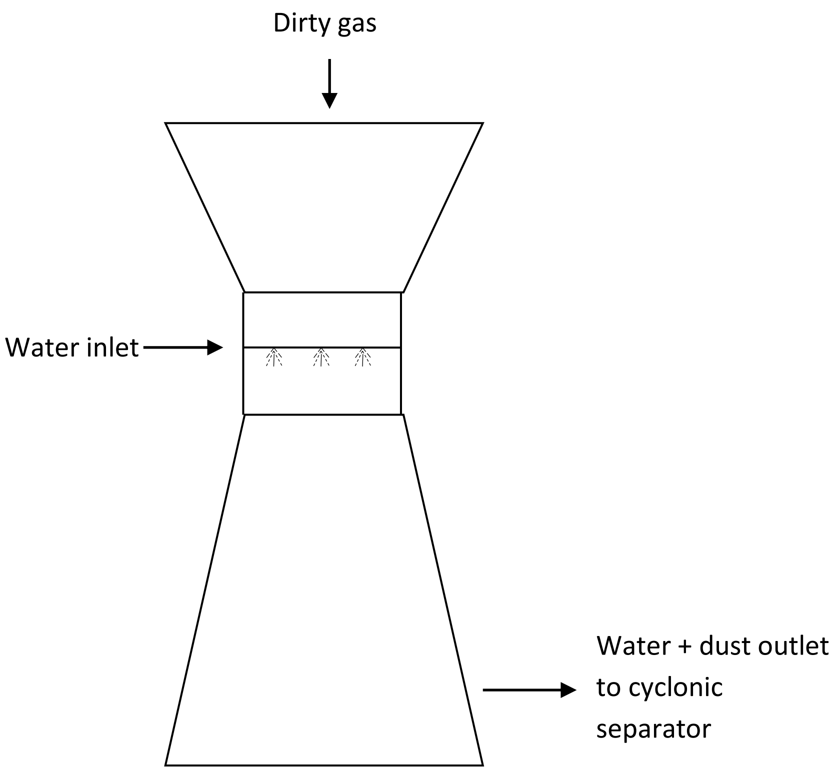


Fig.9. Vertical downward venturi scrubber with throat injection

Collection efficiency:
One of the more popular and widely used collection efficiency equations is that originally suggested by Johnstone.

$$E = 1 - e^{-kR(\psi)0.5} \qquad (11.5)$$

Where:

E = efficiency (fractional)

Ψ= inertial impaction parameter (dimensionless)

R = liquid-to-gas ratio (gal/1000 acf or gpm/1000 acfm)

k = correlation coefficient, the value of which depends on the system geometry and operating conditions (typically 0.1–0.2 acf/gal)

Calculations on a Venturi Scrubber
Exa. 1: A venturi scrubber is being designed to remove particulates from a gas stream. The maximum gas flow rate of 30,000 acfm has a loading of 4.8 gr/ft^3. Neglect the Cunningham correction factor. The Johnstone coefficient (k) for this system is 0.15. The proposed water flow rate is 180 gal/min, ψ= 24.56 and the gas velocity is 250 ft/s.
(a) What is the efficiency of the proposed system?
(b) Determine the pressure drop for. Assume Equation (11.5) to apply.
(c) Determine the daily mass of dust collected and discharged.
(d) What is the discharge loading?

Solution:
(a) The ratio of liquid-to-gas flow rate is given by

$$R = (180) / (30{,}000)$$
$$= 6.0 \text{ gal} / 1000 \text{ acf}$$
$$= 6.0 \text{ gpm} / 1000 \text{ acfm}$$

$$E = 1 - e^{-kR(\psi)0.5}$$

$$= 1 - e^{-(0.15)(6)\,(24.56)0.5}$$

$$= 0.9884 = 98.84\%$$

(b) The pressure drops are given by

$$\Delta P = 5 \times 10^{-5} v^2_t R \qquad \text{(where } v_t \text{ is the gas velocity)}$$
$$= (5 \times 10^{-5})(250)^2(6) = 18.75 \text{ in}H_2O$$

(c) The total daily loading (TDL) is

$$TDL = (4.8 gr/ft^3)(30,000)(60)(24) / 7000$$
$$= 29,600 \text{ lb/day}$$
$$= 14.81 \text{ tons/day} \quad (\text{ton} = 2000 \text{ lb})$$

For v = 250 ft/s:

$$\text{Dust collected} = (0.9884)(29,600)$$
$$= 29,256 \text{ lb/day}$$
$$\text{Dust discharged} = 344 \text{ lb/day}$$

(d) The discharge loading (DL) is

$$DL = (4.8)(1 - E)$$
$$= (4.8)(1 – 0.9884)$$
$$= 0.056 \text{ gr/ ft}^3$$