Other Separation Equipment

Cyclone Separators, Air Filter, Electrostatic Separator and their Design Consideration

Cyclone Separators

Introduction:
Cyclone separators are mostly used for the removal of suspended dust particles from the air, process gases or liquid stream without use of filers, through vortex separation.

Principles of Operation:

- In a reverse-flow cyclone the gas enters the top chamber tangentially and spirals down to the apex of the conical section.
- The centrifugal force causes the solids move radially to the walls, slide down the walls due to gravity, and are collected at the bottom.
- The clean gas moves up towards the central outlet at the top of the cyclone separator.

Cyclones are suitable for separating particles above about 5 μm diameter; smaller particles, down to about 0.5 μm, can be separated where agglomeration occurs.
The most commonly used design is the reverse-flow cyclone.

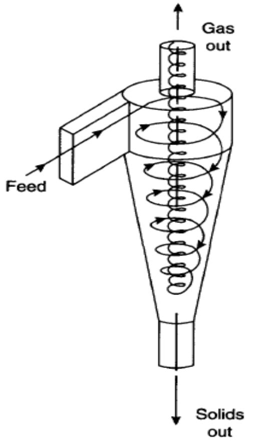
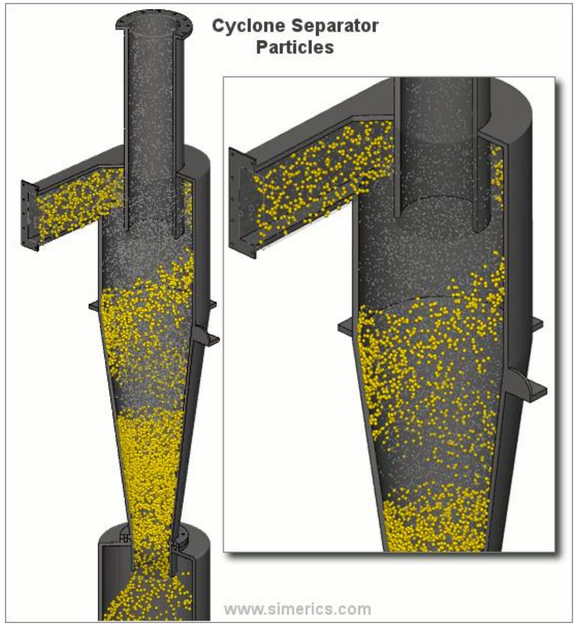


Figure 10.43. Reverse-flow cyclone

(adapted from Coulson Richardson's Chemical Engineering, vol-6, 3rd edition



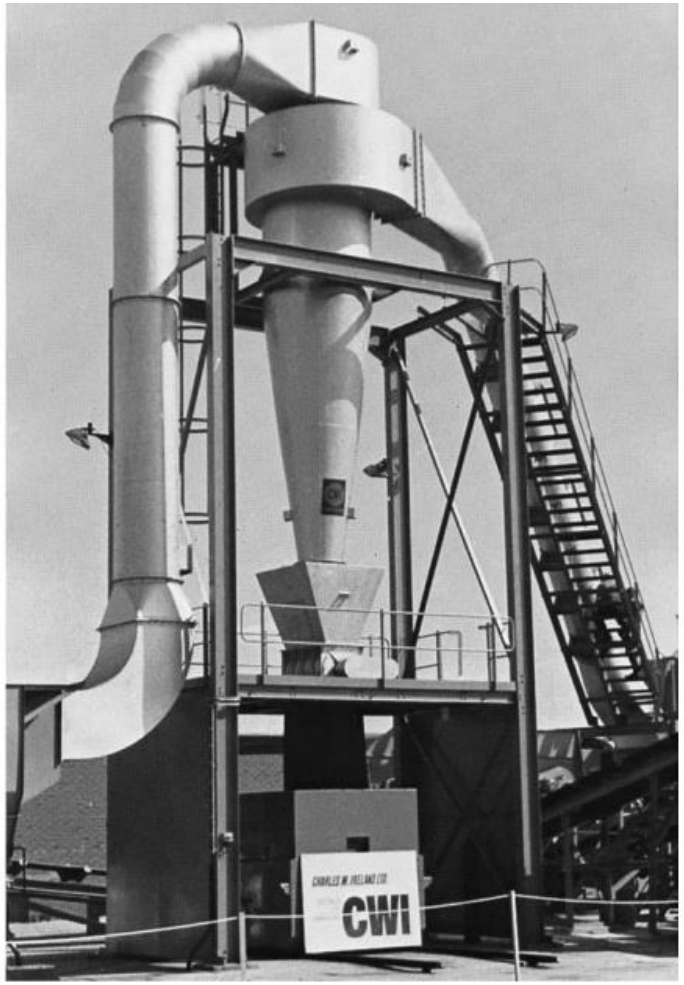


Figure 1.54. Cyclone separator

Industrial cyclone separator (adapted from Coulson Richardson's Chemical Engineering, vol-2, 5th edition

Coulson Richardson's Chemical Engineering, vol-6, 3rd edition
https://skill-lync.com/projects/cyclone-separator-challenge-85

Types of Cyclone Separators

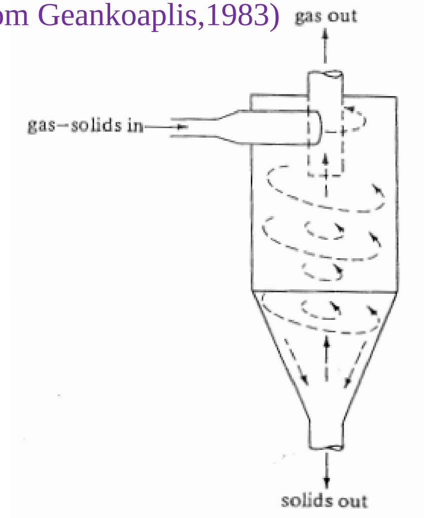
Based on application:

- ❖ Gas-solid cyclone separator
- ❖ Liquid solid cyclone separator (Hydro-cyclone)

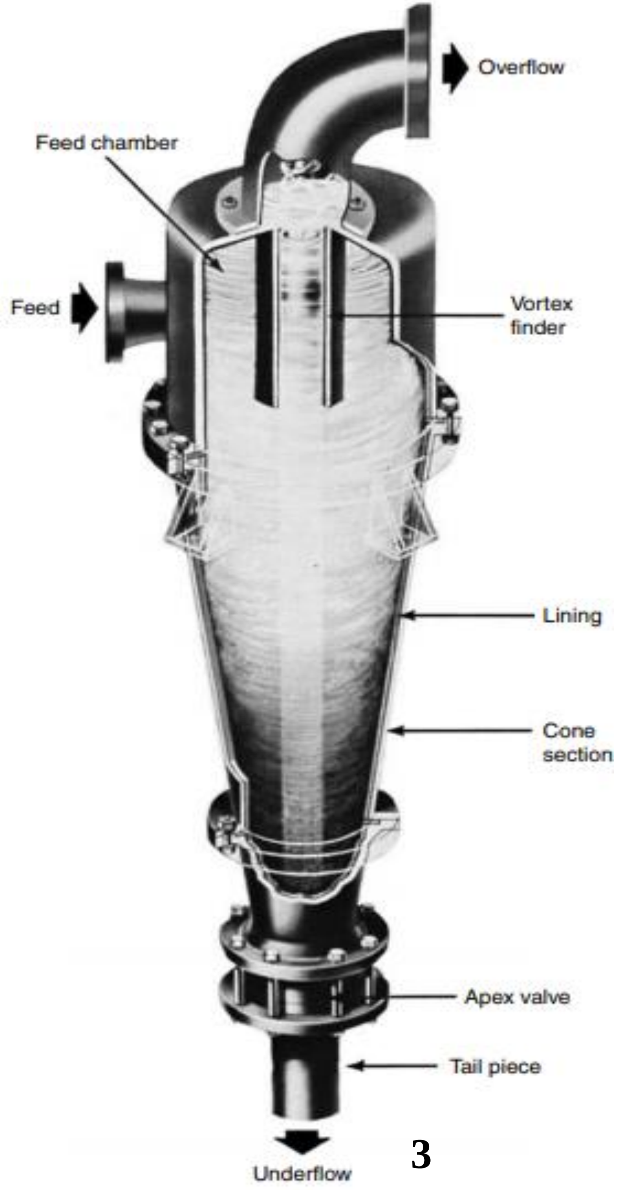
Based on design:

- ❖ Vertical cyclone separator
- ❖ Horizontal cyclone separator
- ❖ Multiple cyclone separator

Gas-solid cyclone (adapted from Geankoaplis,1983)

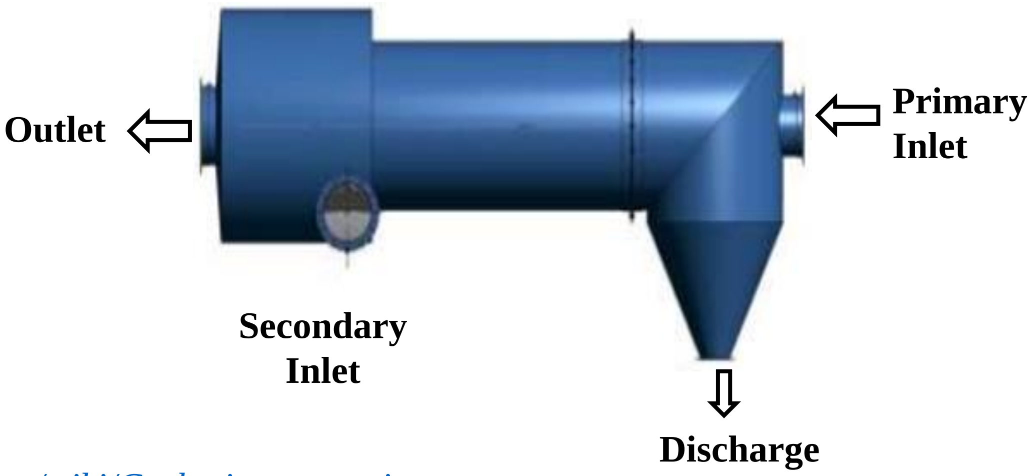


Hydro cyclone (adapted from Coulson Richardson's Chemical Engineering, vol-2, 5th ed.)

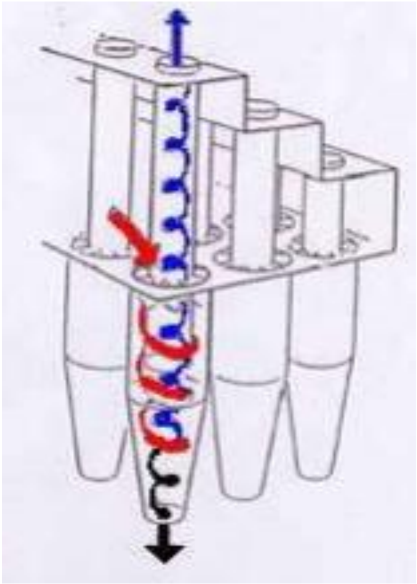


Vertical cyclone

Horizontal cyclone



Multiple cyclone



https://en.wikipedia.org/wiki/Cyclonic_separation

Theory

- It is assumed that particles on entering a cyclone quickly reach their terminal velocities. Particle sizes are usually so small that Stokes's law is considered valid.
- For centrifugal motion, the terminal radial velocity v_{tR} is given by

$$v_{tR} = \frac{\omega^2 r D_p^2 (\rho_p - \rho)}{18\mu}$$

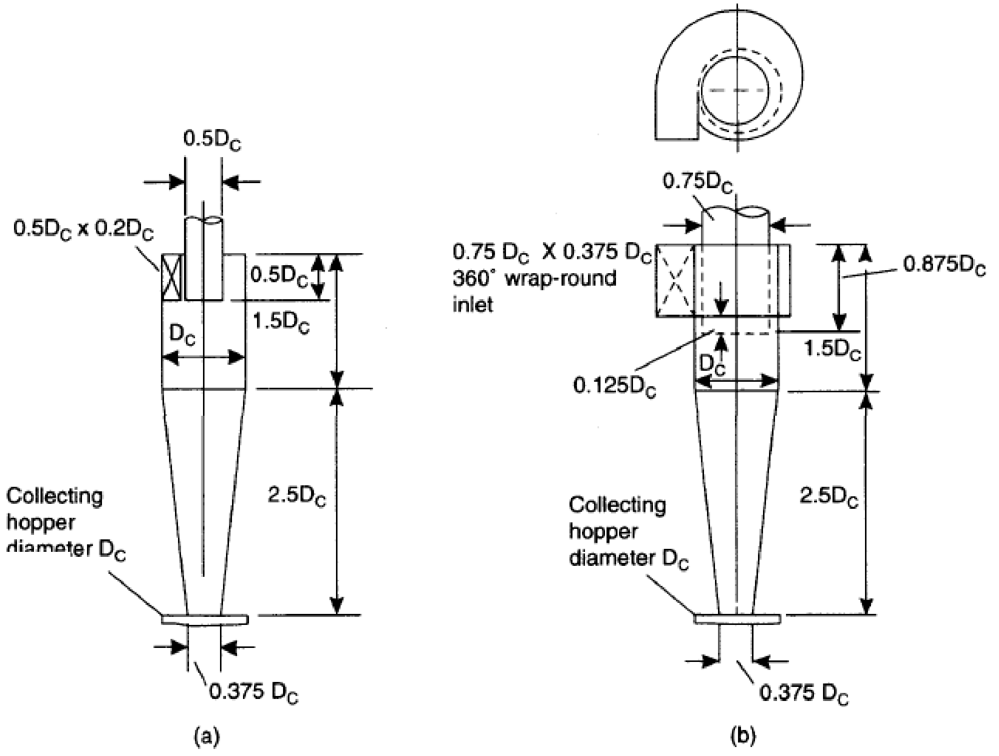
Since $\omega = v_{tan}/r$, where v_{tan} is tangential velocity of the particle at radius r.

$$v_{tR} = \frac{D_p^2 g (\rho_p - \rho)}{18\mu} \frac{v_{tan}^2}{gr} = v_t \frac{v_{tan}^2}{gr}$$

Christie J Geankoplis - Transport processes and unit operations (1993, PTR Prentice Hall)

Cyclone Design Principles

- Stairmand developed two standard designs for gas-solid cyclones:
  - ➤ High-efficiency cyclone (Figure 10.44a)
  - ➤ High throughput design (Figure 10.44 b)
- The performance curves for these designs, obtained experimentally under standard test conditions, are shown in Figures 10.45a and 10.45ft.
- These curves can be transformed to other cyclone sizes and operating conditions by use of the following scaling equation, for a given separating efficiency:



10.44. Standard cyclone dimension (*a*) High efficiency cyclone (*b*) High gas rate cyclone

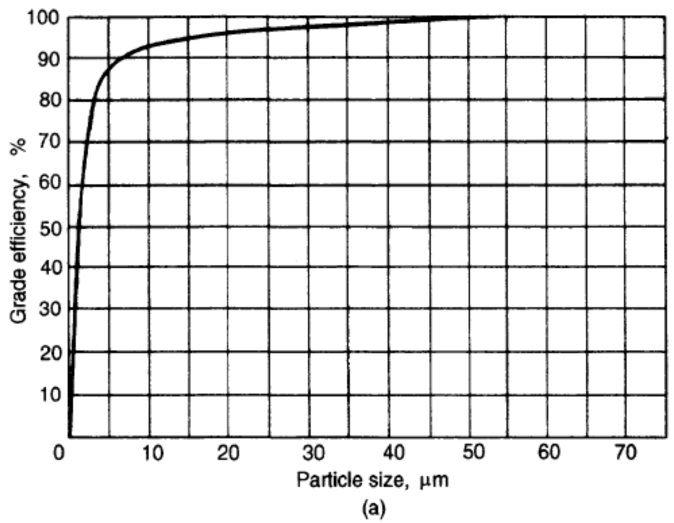


Figure 10.45. Performance curves, standard conditions (*a*) High efficiency cyclone

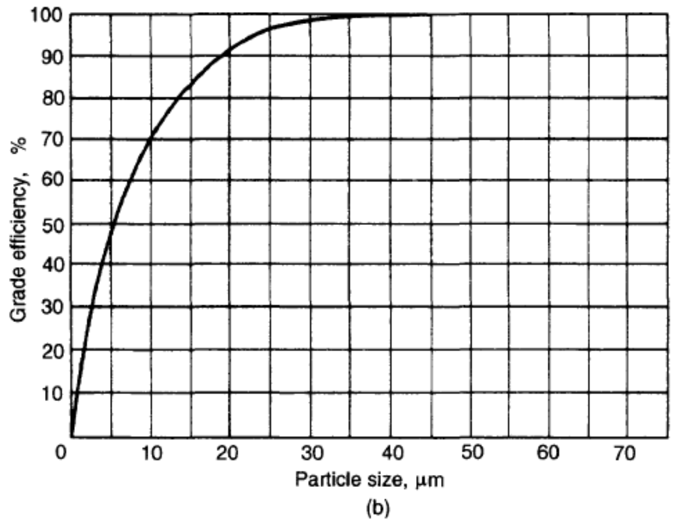


Figure 10.45 (continued). Performance curves, standard conditions (*b*) High gas rate cyclone

Coulson Richardson's Chemical Engineering, vol-6, 3rd edition

Continued…….

- These curves can be transformed to other cyclone sizes and operating conditions by use of the following scaling equation, for a given separating efficiency:

$$d_2 = d_1\left[\left(\frac{D_{c_2}}{D_{c_1}}\right)^3 \times \frac{Q_1}{Q_2} \times \frac{\Delta\rho_1}{\Delta\rho_2} \times \frac{\mu_2}{\mu_1}\right]^{1/2} \qquad \text{.........................(1)}$$

where d_1 = mean diameter of particle separated at the standard conditions, at the chosen separating efficiency, Figures 10.45*a* or 10.45*b*,

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

D_{c_1} = diameter of the standard cyclone = 8 inches (203 mm),

D_{c_2} = diameter of proposed cyclone, mm,

Q_1 = standard flow rate:

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 conditions = 2000 kg/m^3,

$\Delta\rho_2$ = density difference, proposed design,

μ_1 = test fluid viscosity (air at 1 atm, 20°C)

= 0.018 $mN\ s/m^2$,

μ_2 = viscosity, proposed fluid.

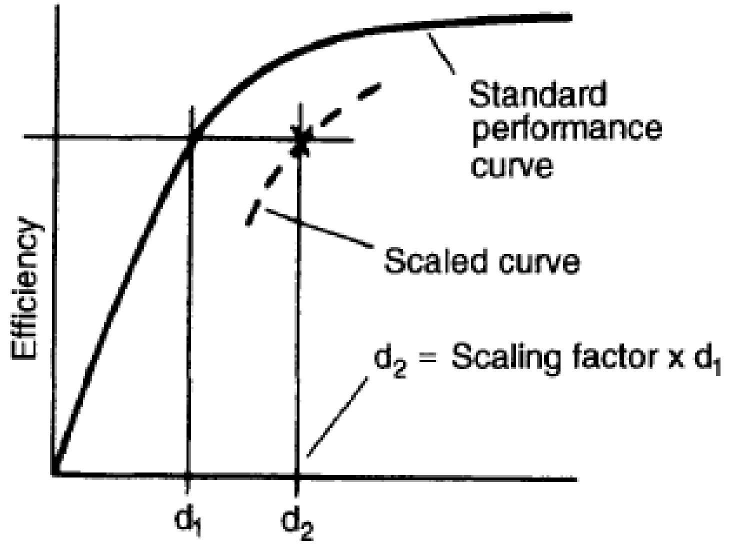


Figure 10.46. Scaled performance curve

- A performance curve for the proposed design can be drawn up from Figures 10.45a or 10.45b by multiplying the grade diameter at, say, each 10 per cent increment of efficiency, by the scaling factor given by equation 1; as shown in Figure 10.46.
- The cyclone should be designed to give an inlet velocity of between 9 and 27 m/s (30 to 90 ft/s); the optimum inlet velocity has been found to be 15 m/s (50 ft/s).

Coulson Richardson's Chemical Engineering, vol-6, 3rd edition

Pressure Drop

- The pressure drop in a cyclone will be due to the entry and exit losses, and friction and kinetic energy losses in the cyclone.
- The empirical equation given by Stairmand (1949) can be used to estimate the pressure drop:

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

where ΔP = cyclone pressure drop, millibars,

ρ_f = 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 centre line of the inlet is tangential, m,

r_e = radius of exit pipe, m,

ϕ = factor from Figure 10.47,

ψ = parameter in Figure 10.47, given by:

$$\psi = f_c \frac{A_s}{A_1}$$

f_c = friction factor, taken as 0.005 for gases,

A_s = surface area of cyclone exposed to the spinning fluid, m^2.

For design purposes this can be taken as equal to the surface area of a cylinder with the same diameter as the cylone and length equal to the total height of the cyclone (barrel plus cone).

A_1 = area of inlet duct, m^2.

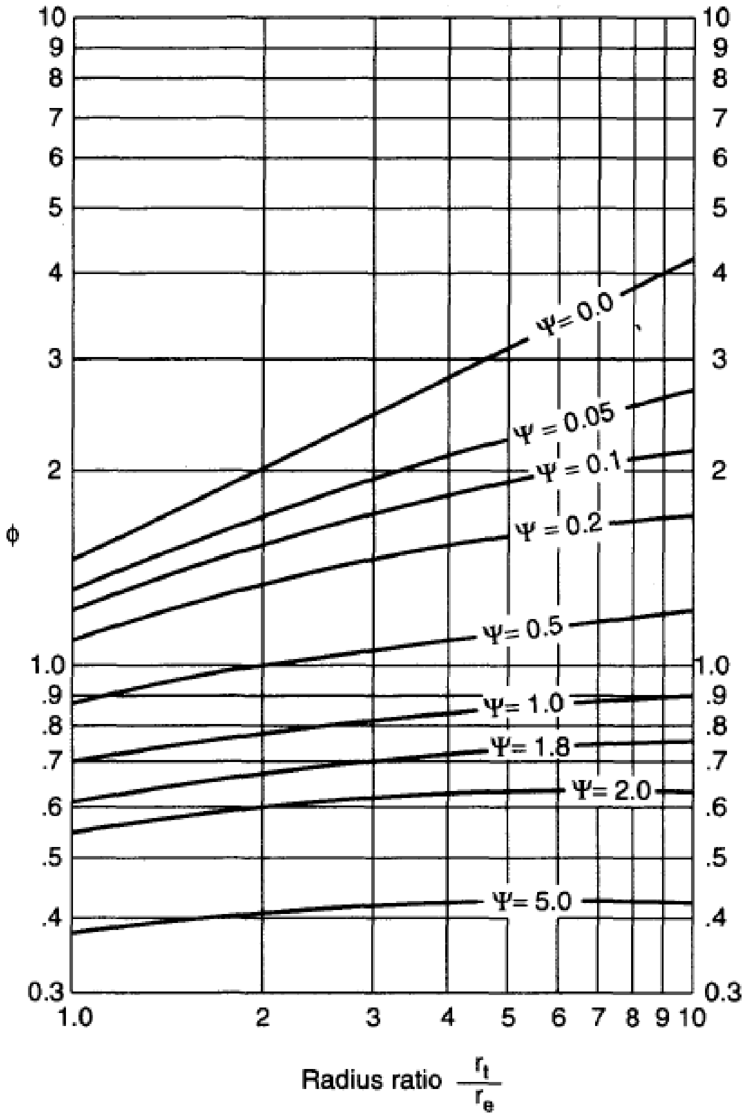


Figure 10.47. Cyclone pressure drop factor

General design procedure

1. Select either the high-efficiency or high-throughput design, depending on the performance required.
2. Obtain an estimate of the particle size distribution of the solids in the stream to be treated.
3. Estimate the number of cyclones needed in parallel.
4. Calculate the cyclone diameter for an inlet velocity of 15 m/s (50 ft/s). Scale the other cyclone dimensions from Figures 10.44a or 10.44b.
5. Calculate the scale-up factor for the transposition of Figures 10.45a or 10.45b.
6. Calculate the cyclone performance and overall efficiency (recovery of solids). If unsatisfactory try a smaller diameter.
7. Calculate the cyclone pressure drop and if required, select a suitable blower.
8. Cost the system and optimize to make the best use of the pressure drop available, or, if a blower is required, to give the lowest operating cost

Coulson Richardson's Chemical Engineering, vol-6, 3rd edition

Design Problem

Example 10.4

Design a cyclone to recover solids from a process gas stream. The anticipated particle size distribution in the inlet gas is given below. The density of the particles is 2500 kg/m^3, and the gas is essentially nitrogen at 150°C. The stream volumetric flow-rate is 4000 m^3/h, and the operation is at atmospheric pressure. An 80 per cent recovery of the solids is required.

Particle size (μm)	50	40	30	20	10	5	2
Percentage by weight less than	90	75	65	55	30	10	4

Solution

As 30 per cent of the particles are below 10 μm the high-efficiency design will be required to give the specified recovery.

$$\text{Flow-rate} = \frac{4000}{3600} = 1.11\ \text{m}^3/\text{s}$$

$$\text{Area of inlet duct, at 15 m/s} = \frac{1.11}{15} = 0.07\ \text{m}^2$$

From Figure 10.44*a*, duct area $= 0.5\ D_c \times 0.2\ D_c$

so, $D_c = 0.84$

This is clearly too large compared with the standard design diameter of 0.203 m.
Try four cyclones in parallel, $D_c = 0.42$ m.

$$\text{Flow-rate per cyclone} = 1000\ \text{m}^3/\text{h}$$

$$\text{Density of gas at 150°C} = \frac{28}{22.4} \times \frac{273}{423} = 0.81\ \text{kg/m}^2,$$

negligible compared with the solids density

$$\text{Viscosity of } N_2 \text{ at 150°C} = 0.023\ \text{cp(mN s/m}^2)$$

From equation 10.8,

$$\text{scaling factor} = \left[\left(\frac{0.42}{0.203}\right)^3 \times \frac{223}{1000} \times \frac{2000}{2500} \times \frac{0.023}{0.018}\right]^{1/2} = \underline{\underline{1.42}}$$

The performance calculations, using this scaling factor and Figure 10.45*a*, are set out in the table below:

Calculated performance of cyclone design, Example 10.4

1 Particle size (μm)	2 Per cent in range	3 Mean particle size ÷ scaling factor	4 Efficiency at scaled size % (Figure 10.46a)	5 Collected $\frac{(2) \times (4)}{100}$
>50	10	35	98	9.8
50–40	15	32	97	14.6
40–30	10	25	96	9.6
30–20	10	18	95	9.5
20–10	25	11	93	23.3
10–5	20	5	86	17.2
5–2	6	3	72	4.3
2–0	4	1	10	0.4
	100		Overall collection efficiency	$\underline{\underline{88.7}}$

The collection efficiencies shown in column 4 of the table were read from Figure 10.45*a* at the scaled particle size, column 3. The overall collection efficiency satisfies the specified solids recovery. The proposed design with dimension in the proportions given in Figure 10.44*a* is shown in Figure 10.48.

Coulson Richardson's Chemical Engineering, vol-6, 3rd edition

Pressure-drop calculation

$$\text{Area of inlet duct, } A_1, = 210 \times 80 = 16{,}800 \text{ mm}^2$$

$$\text{Cyclone surface area, } A_s = \pi 420 \times (630 + 1050)$$

$$= 2.218 \times 10^6 \text{ mm}^2$$

f_c taken as 0.005

$$\psi = \frac{f_c, A_s}{A_1} = \frac{0.005 \times 2.218 \times 10^6}{16{,}800} = 0.66$$

$$\frac{r_t}{r_e} = \frac{(420 - (80/2))}{210} = 1.81$$

From Figure 10.47, $\phi = 0.9$.

$$u_1 = \frac{1000}{3600} \times \frac{10^6}{16{,}800} = 16.5 \text{ m/s}$$

$$\text{Area of exit pipe} = \frac{\pi \times 210^2}{4} = 34{,}636 \text{ mm}^2$$

$$u_2 = \frac{1000}{3600} \times \frac{10^6}{34{,}636} = 8.0 \text{ m/s}$$

From equation 10.6

$$\Delta P = \frac{0.81}{203}[16.5^2[1 + 2 \times 0.9^2(2 \times 1.81 - 1)] + 2 \times 8.0^2]$$

$$= \underline{\underline{6.4 \text{ millibar}}} \quad (67 \text{ mm } H_2O)$$

This pressure drop looks reasonable.

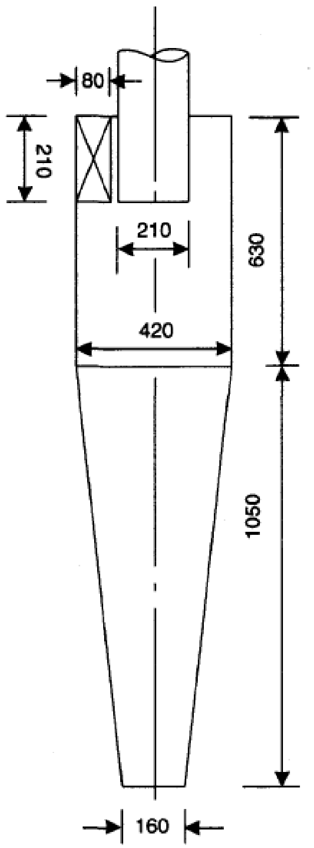


Figure 10.48. Proposed cyclone design, all dimensions mm

Hydrocyclone Separators

Introduction:

- A hydro-cyclone is a device to classify, separate or sort particles in a liquid suspension based on the ratio of their centripetal force to fluid resistance.
- This ratio is high for dense (where separation by density is required) and coarse (where separation by size is required) particles, and low for light and fine particles.

Operating theory:

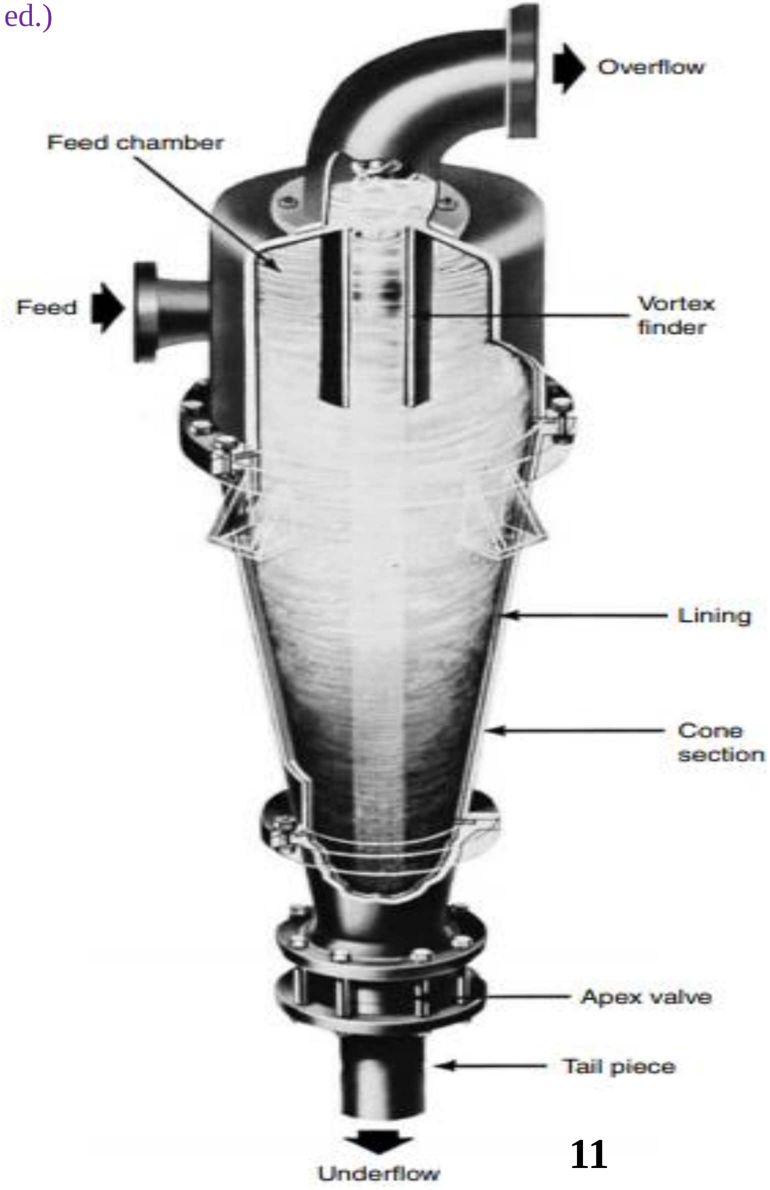
- The fluid is injected into the near the top of the cylindrical section of hydro-cyclone in such a way as to create the vortex and, depending upon the relative densities of the two phases, the centrifugal acceleration will cause the dispersed phase to move away from or towards the central core of the vortex.
- Overflow is removed through a centrally located offtake pipe at the top.

Applications:

- Separating particles (suspended in a liquid of lower density) by size or density, or more generally, by terminal falling velocity;
- The removal of suspended solids from a liquid;
- Separating immiscible liquids of different densities;
- Dewatering of suspensions to give a more concentrated product;
- Breaking down liquid–liquid or gas–liquid dispersions; and
- The removal of dissolved gases from liquids.

Coulson Richardson's Chemical Engineering, vol-2, 5th edition

Hydro cyclone (adapted from Coulson Richardson's Chemical Engineering, vol-2, 5th ed.)

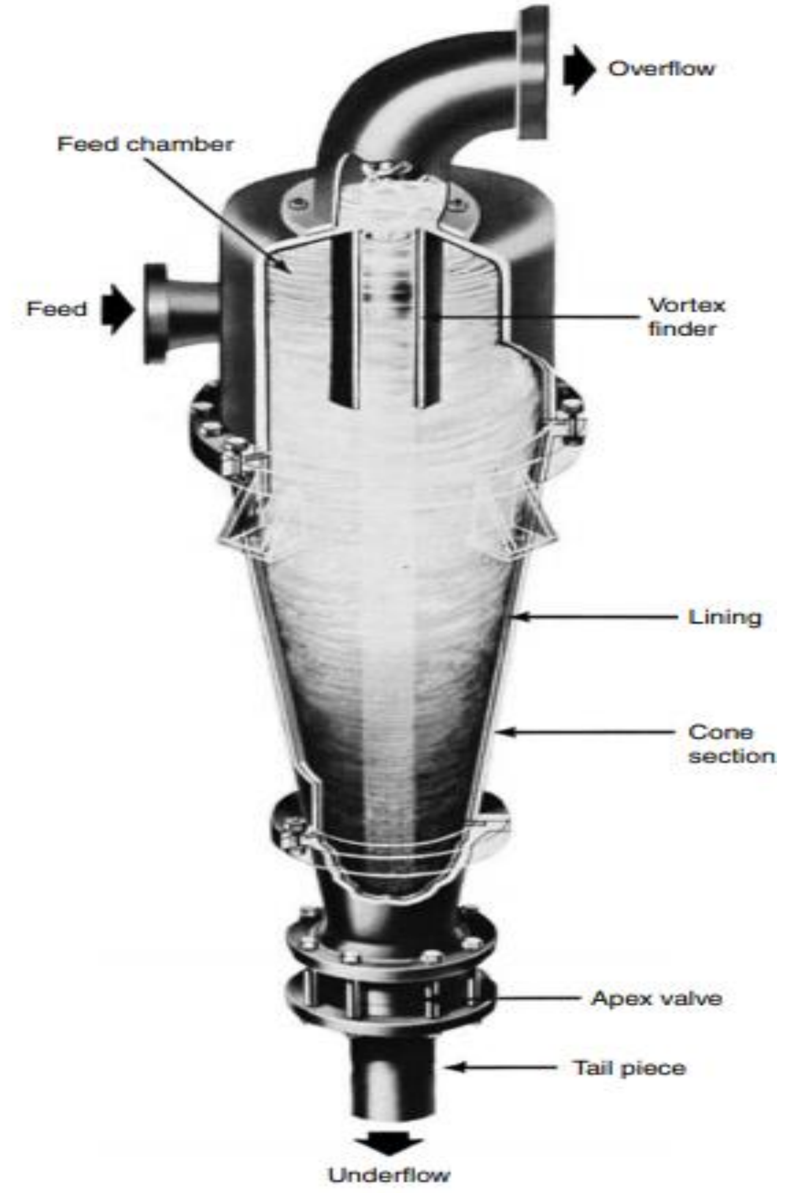


Working Principle of Hydrocyclone

https://youtu.be/vDzKG93WidM

Design Considerations

- Hydrocyclones are 20–500 mm in diameter, with the smaller units giving a much better separation.
- Typical values of length to diameter ratios range from about 5 to 20.
- Generally, hydrocyclone are not effective in removing particles smaller than about 2–3 μm.
- Because separating power is greatest in hydro-cyclones of small diameter, the cut size being approximately proportional to the diameter of the cylindrical shell raised to the power of 1.5.
- In general, the performance of the hydrocyclone is improved by increasing the operating pressure, and the principal control variable is the size of the orifice on the underflow discharge.

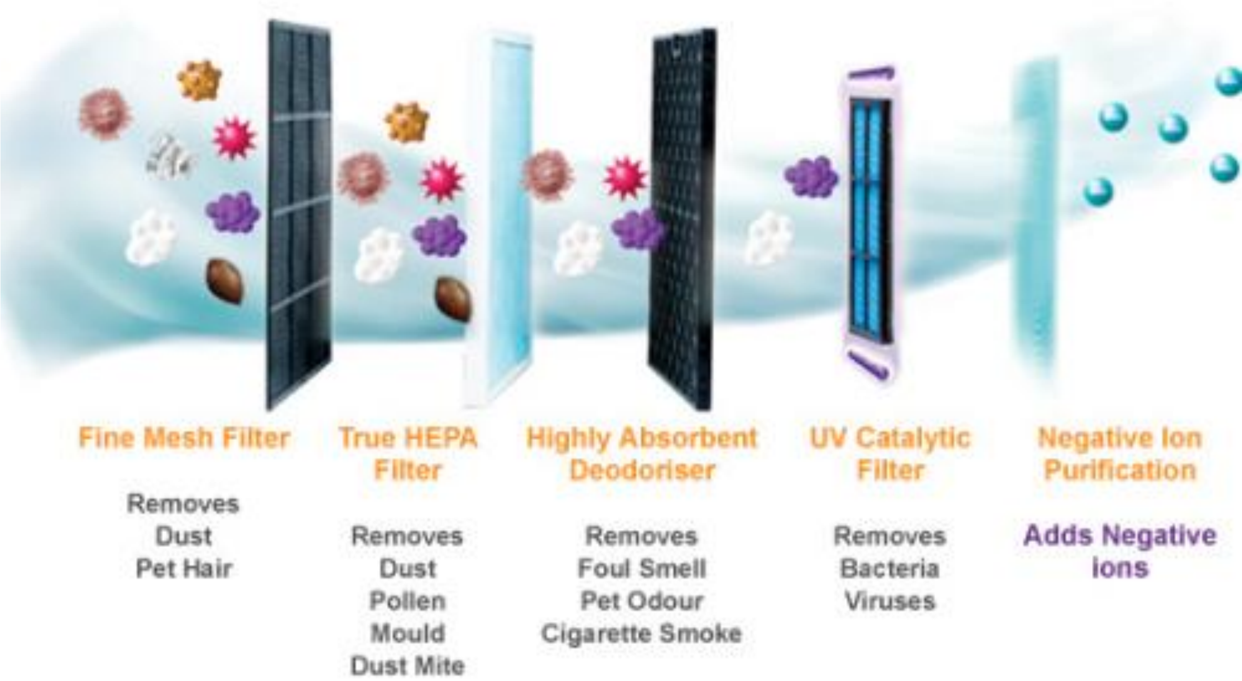


Coulson Richardson's Chemical Engineering, vol-2, 5th edition

Air Filter

Introduction:

- Air filter is a device composed of fibrous materials to removes solid particulates such as dust, pollen, mould, and bacteria from the air.
- Air filters are used in applications where air quality is important, notably in building ventilation systems.
- The requirements of air filtration differ from those of process gas filtration mainly in that the quantity of dust to be removed will be lower, typically less than 10 mg/m^3 (~5 grains per 1000 ft^3); and also in that there is no requirement to recover the material collected.



Types of air filter:

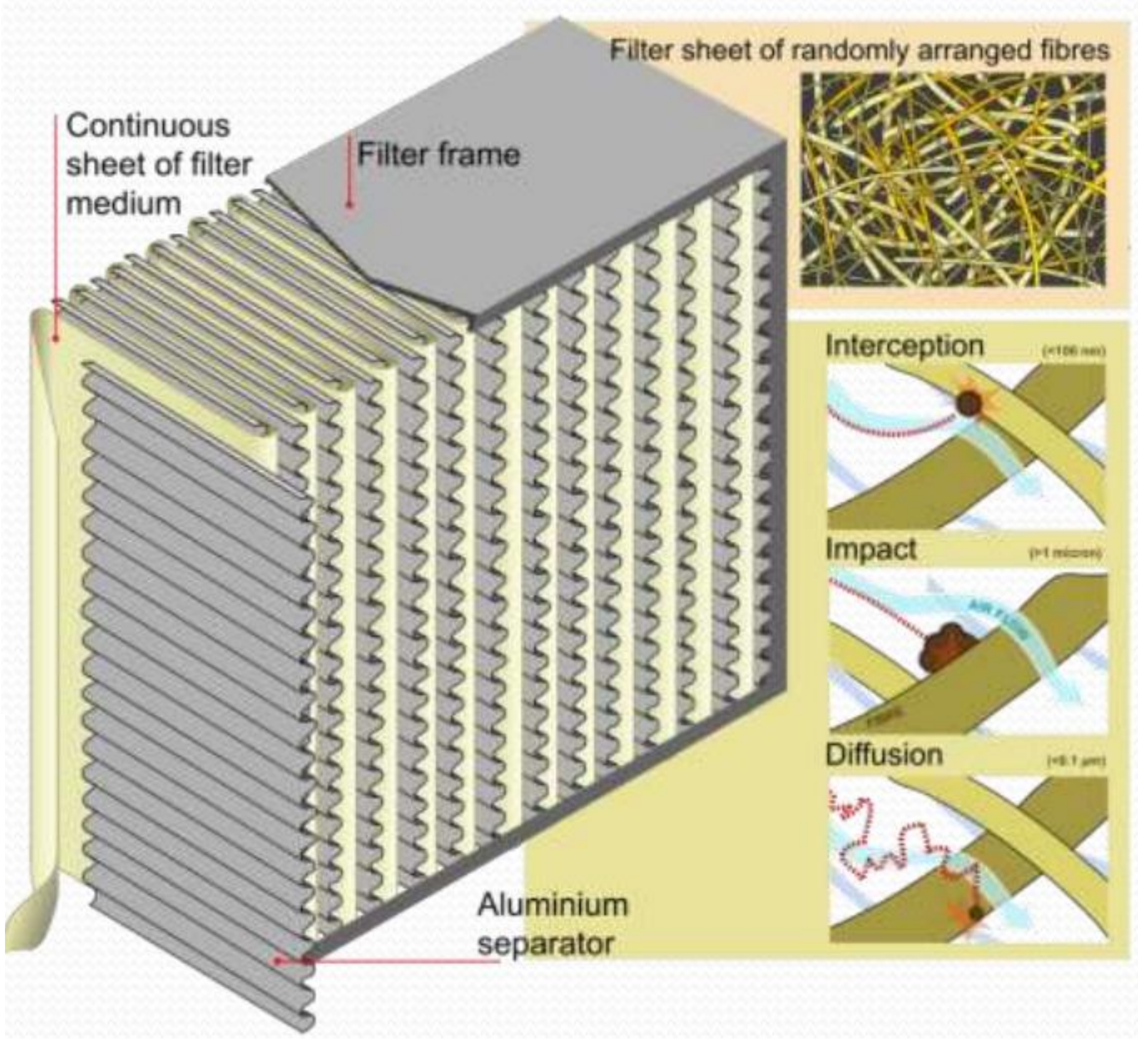
- ➢ Ionic Air Filters
- ➢ HEPA Filter
- ➢ Carbon Air Filters
- ➢ UV Light Air Filter

Coulson Richardson's Chemical Engineering, vol-6, 3rd edition.
https://www.thomasnet.com/articles/instruments-controls/air-filters-different-types/

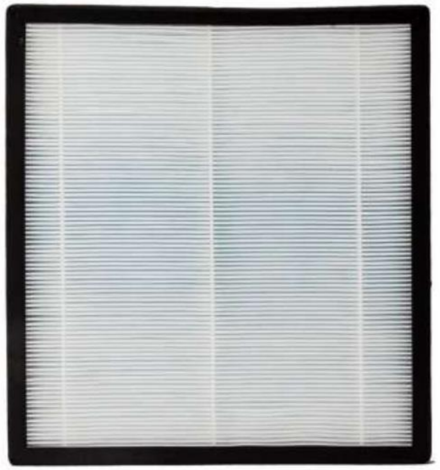
High Efficiency Particulate Air (HEPA) Filter

Introduction:

- ➢ This type of air filter can remove at least 99.97% of dust, pollen, mold, bacteria and any airborne particles with a size of 0.3 micrometers (µm).
- ➢ HEPA filter is constructed of borosilicate microfibers in the form of pleated sheet to increase the overall filtration surface area.
- ➢ The pleats are separated by serrated aluminum baffles or stitched fabric ribbons, which direct airflow through the filter.
- ➢ This combination of pleated sheets and baffles acts as filtration medium.



- Human Hair
- Household dust and lint
- Pollen
- Pet dander
- Smoke
- Viruses and Bacteria

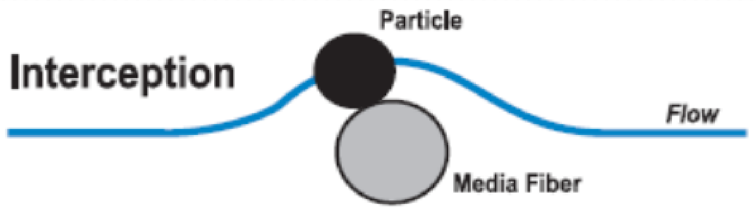


https://en.wikipedia.org/wiki/HEPA

Mechanism of filtration

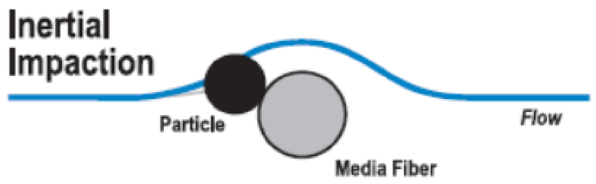
1. Interception :

- ✓ In order to be intercepted, a particle must come within a distance from a fiber of one radius of itself. Thus, the particle makes contact with the fiber and becomes attached.
- ✓ The interception mechanism can be contrasted with the impaction mechanism in that a particle which is intercepted is smaller and its inertia is not strong enough to cause the particle to continue in a straight line



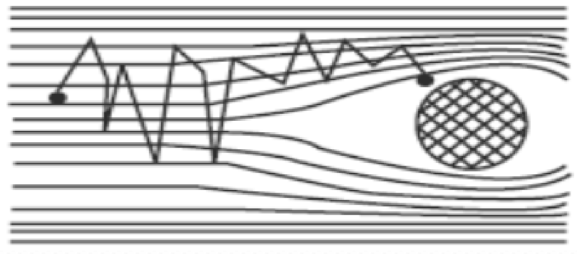
2. Inertial Impaction :

- ✓ larger particles are filtered due to the impaction mechanism.
- ✓ Larger particles have higher mass and are harder to turn than smaller particles due to inertia.
- ✓ Because of this inertial effect, the particles continue to travel in a somewhat straight line even though the airstream is turning to move past the fiber.
- ✓ Once the particle comes in contact with the fiber, it becomes attached and is "filtered" from the airstream



3. Diffusion:

- ✓ Very small particles come in contact with fibers due to diffusive effects.
- ✓ The particles collide with air molecules and are "pushed around." This effect is called Brownian motion.
- ✓ Because of Brownian motion, small particles don't precisely follow the airstream, but instead "vibrate" or move erratically.



https://en.wikipedia.org/wiki/HEPA

Air Filter – Overall Design

1. Fine Mesh Filter (Washable):

Traps large particles such as dust and pet hair at the beginning of the purifying process. This also helps to prolong the lifespan of the subsequent filters.

2. Two-in-one Formaldehyde & Granular Activated Carbon Filter

Neutralizes odors such as cigarette smoke, pet and cooking odors. It also adsorbs Volatile Organic Compounds (VOCs) in the air which are gas chemicals released by many household products such as paints, adhesives and sprays.

3. True HEPA Filter (treated with Titanium Dioxide and Anti-Microbial Sanitized® Silver*)

Removes 99.97% of harmful particles even those as small as 0.3 microns. The additional coat of Sanitized® Silver, eradicates germs and provides lasting anti-microbial hygiene protection.

4. UV Light

Inactivates viruses, bacteria, mold and fungi instead of simply trapping them. Photocatalytic oxidation is achieved when UV light activates the Titanium Dioxide (TiO_2) coated on the True HEPA filter, which produces powerful bioactive hydroxyl radicals (OH·). These strong oxidizers break apart chemical bonds in these harmful bacteria and viruses, effectively destroying them.

5. Active ionizer with ion cluster technology

Breaks down and inactivates airborne microbes by the positive and negative ions released into the air, further enhancing the air purification process.

https://www.osim.com.my/ualpine-smart-air-purifier-my.html

Major application of air filters

- **Automotive** — Air filters are required for many of the processes in the production of automobiles, including HEPA air filtration for paint application, fluid filtration for coatings, solvents, oils and deionized water, and molecular filtration for breathing air supply and VOC abatement.

- **Bio-pharmaceutical** — Bio-pharmaceutical research and manufacturing involves the maintenance of sterile environments to eliminate exposure of products to viable and non-viable contamination. Air filtration plays an important role in this growing industry.

- **Microelectronics** — The manufacture of microelectronic devices, including microchips and LCD displays, requires extremely clean environments for successful research and development and for manufacturing commercial products. The use of ULPA filters and chemical filters is common in this industry.

- **Museums** — Air filtration, including particulate and molecular or chemical filtration, plays an important role in the conservation of museum artifacts. Contaminants in the air can deteriorate the materials which compose items in the collections.

http://www.airfiltersinc.com/applications

Electrostatic Separators

Introduction:

- Electrostatic separation depends on differences in the electrical properties (electrical conductivity) of the materials to be treated.
- Electromagnetic forces can be used to separate non-magnetic materials from other non-magnetic materials as well.
- Electrostatic forces are generated by the action of an electric field on a charged particle.

Operating theory:

In a typical process the material particles pass through a high-voltage electric field as it is fed on to a revolving drum, which is at earth potential (Figure 10.8). Those particles that acquire a charge adhere to the drum surface and are carried further around the drum before being discharged.

Factors affecting the process:

1. Intensity of electric field
2. Particle size
3. Relative humidity
4. Temperature of the particle/bed
5. Inter-electrode distance

Applications: Electrostatic separation is used successfully for beneficiation of wide range of minerals. Some examples are

1. Beach sand beneficiation
2. Beneficiation of coal

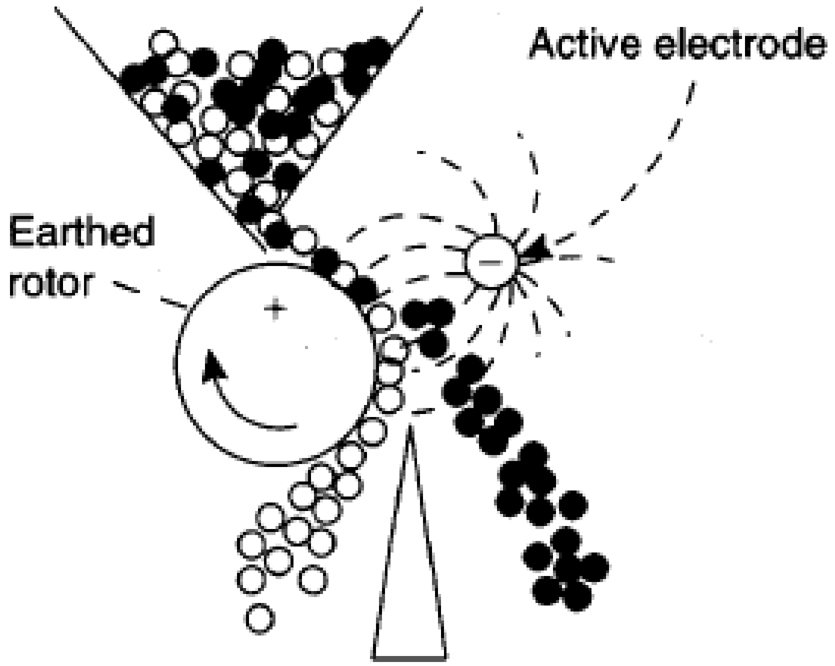


Figure 10.8. Electrostatic separator

Coulson Richardson's Chemical Engineering, vol-6, 3rd edition.
http://eprints.nmlindia.org/5886/1/Chap_8.PDF

Electrostatic Separation Equipment

Generally, two types of equipment are used for separation.

1. Drum type electrostatic separation unit

- This equipment consists of a rotating drum made of mild steel or some other conducting material, which is earthed through its support bearings as shown below in the Figure 8.
- An electrode assembly, comprising of a brass tube in front of which is supported a length of fine wire, spans the complete length of the roll, and is supplied with a fully rectified DC supply of up to 50 kV, usually of negative polarity.
- The voltage supplied to the assembly should be such that ionization of the air takes place. This can often be seen as a visible corona discharge.
- Arcing between the electrode and the roll must be avoided as it destroys the ionization. When ionization occurs, the minerals receive a spray discharge of electricity, which gives the poor conductors a high surface charge, causing them to be attracted to and pinned to the rotor surface.
- The particles of relatively high conductivity do not become charged as rapidly since the charge rapidly dissipates through the particles to the earthed rotor. These particles of higher conductivity follow a path, when leaving the rotor, approximating to the one, which they would assume if there was no charging effect at all.

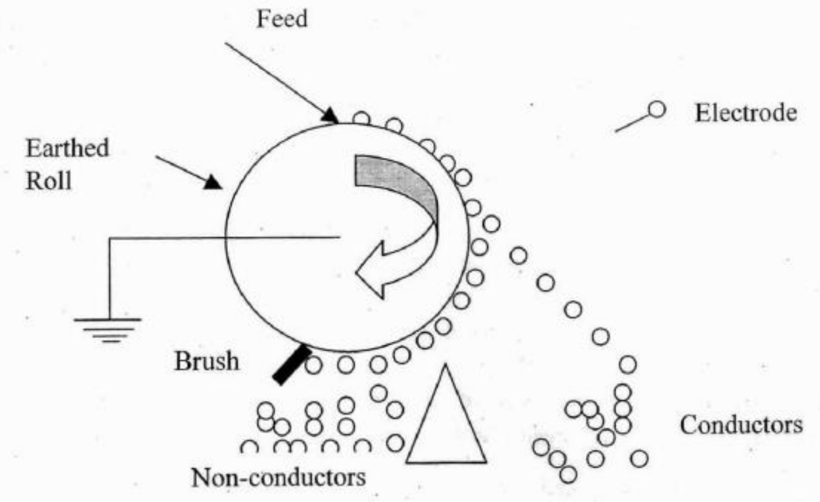


Fig. 8 : Principle of Electrostatic Separation

2. Plate type electrostatic separation unit

- A plate or screen type electrostatic separator is also used for separation. This type of equipment mainly consists of an oval type, high voltage electrode, which induces the electric field.
- The material is fed through a sloping, grounded plate under gravity. The electrostatic field is effectively shorted through the conducting particles, which are lifted towards the charged electrode in order to decrease the energy of the system.

http://eprints.nmlindia.org/5886/1/Chap_8.PDF

Advantages & Disadvantages

Advantages:

1. The electrostatic forces work on the particles to be separated only; they do not affect the medium in which the particles are located.

2. The trajectories of the particles under the influence of the electric field follow the electric field lines. The electric field lines may be shaped to suit the particular application.

3. The direction of electrostatic forces may be reversed by either changing the polarity of the charge or the direction of the external electrostatic field.

4. The electrostatic forces may be arranged to work in combination with other forces such as gravitational or centrifugal forces.

5. The electrostatic separation forces are independent of the substrate of the material on which the surface electric charge is generated. They are determined solely by the product of electric field and charge.

- The electrostatic forces do not differentiate between magnetic and non-magnetic materials. The charged magnetic particle placed in an electric field will be subjected to forces practically equal to those acting on a similar particle made out of nonmagnetic material and charged with the same charge.

Disadvantages:

1. Limitation of maximum mass that it can effectively work upon

2. The size of the material to be separated should be very small which leads to the increase of comminution cost

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