

# CONTROL TECHNIQUES

## Module 4

(Control of Particulate matter & Gaseous pollutants – settling chambers, cyclone separators, scrubbers, filters and ESP)

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### **4.1 Introduction**

Everyday about half-a-million tonne of particulates (of sizes  $100\mu\text{m}$  down to  $0.1\mu\text{m}$  and even less) are released into the atmosphere by anthropogenic sources. Micro-scale particles may cause severe effects on man, material and vegetation.

Basically, there are 4 ways available for the control of industrial effluent discharges into atmosphere and thereby controlling the atmospheric pollution.

1. Reduction of pollutants discharge at the source by the application of control equipment
2. Reduction at the source through raw material changes, industrial operational changes or modifications, or replacement of process equipment (for ex., replacing older equipments with newer ones)
3. Dilution of the source discharge by installing taller stacks
4. Dispersion of source locations by adopting proper planning and zoning of industrial areas.

But the most effective ways are reduction at the source by application of control equipment and process control. To remove particulate matter from gases, various types of control equipments are available.

#### **Factors to be considered for the selection of particular equipment -**

1. Quantity of gas to be cleaned and its variation with time
2. Chemical, physical nature and concentration of the particulate matter to be removed
3. Temperature and pressure of the gas stream
4. Nature of the gas (for solubility and corrosive effects)
5. Desired/Required quality of the cleaned gas

#### **Objectives of using control equipments –**

1. Prevention of nuisance
2. Prevention of physical damage to the property
3. Elimination of the health hazards to plant employees and to the population living near the plant
4. Recovery of valuable waste products
5. Minimisation of economic losses through the reduction of plant maintenance
6. Improvement of product quality

### **4.2 Settling Chambers**

The gravitational settling chambers are the simplest of all control equipments. Settling chamber is almost the cheapest device to construct, operate and maintain and serves as a pre-cleaner.

There are two primary types of settling chambers: the expansion chamber and multiple-tray chamber. In the expansion chamber, the velocity of the gas stream is reduced as the gas expands in a large chamber. Reduction in velocity allows larger particles to settle down.

Settling chamber serves as a preliminary screening device usually. Where the mass of larger particles is more, the settling chamber can remove much of the mass of particulate matter, otherwise other control devices would be choked up and their operation will be impaired, leading to frequent cleaning. Thus in majority of particulate control devices, the first unit is a gravity settling chamber.

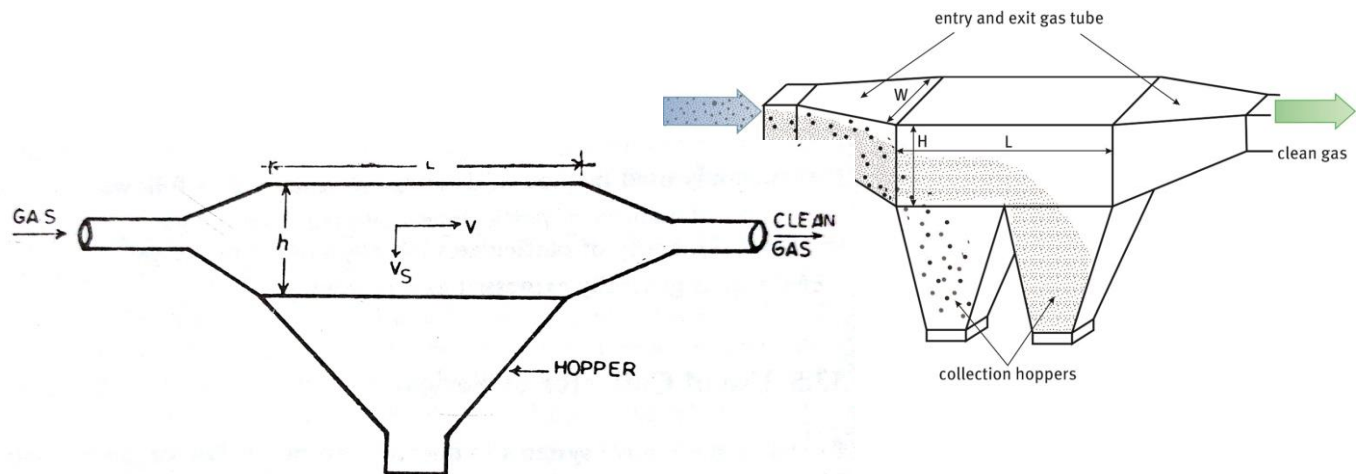
#### 4.2.1 Principle, Construction and Working of settling chambers

##### Principle:

Gravitational force may be employed to remove particulates in settling chambers. Carrier gas velocity is reduced to induce the action of gravity on the particles. For settling operations, Stoke's law is applied. Gravity settling chambers are provided with enlarged areas to minimise horizontal velocities and allow time for the vertical velocity to carry the particulate to the bottom of the tank. Settling chambers are effective for large and/or dense particles.

##### Construction:

The most common type of settling chamber consists of a long box like structure, with an inlet at one end and an outlet at the other end, set horizontally, often on the ground. It can be constructed from brick and concrete. A hopper is provided at the bottom to collect the particulates.



##### Working:

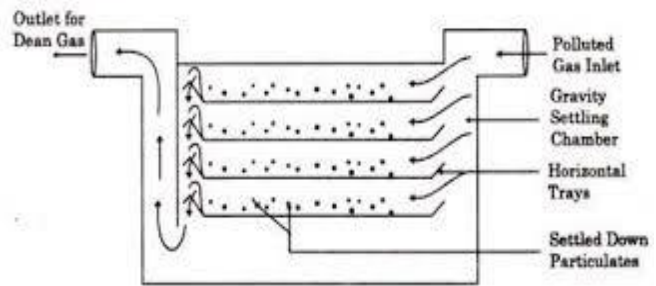
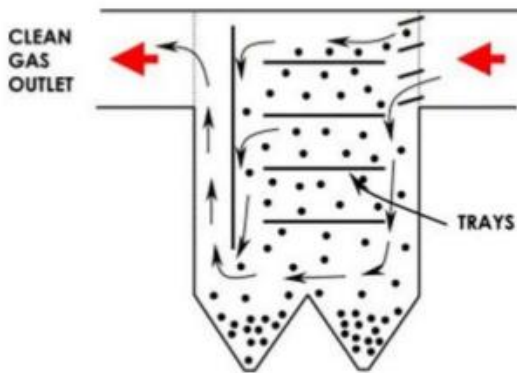
The carrier gas is made to pass inside the chamber through inlet provided at one end, with lower velocities. The solid particulates having higher density than the surrounding gas, settle due to action of gravity on the base of the chamber. The cleaned gas will come out through the outlet provided at another end. The settled out particulates are then collected from the hopper for disposal.

The gas velocity must be sufficiently low (less than about 3m/s to prevent particle re-entrainment, less than 0.5m/s for better results). To minimise turbulence and maintain uniform velocity, curtains, rods and wire mesh screens may be provided in the chamber.

#### 4.2.2 Howard's settling chamber

A multiple-tray settling chamber is referred to as Howard's chamber. A multiple-tray settling chamber consists of a number of thin trays closely spaced within the chamber, which causes the gas flow horizontally between them. Usually the trays are fitted at 1-3cm spacing. The collection efficiency generally improves because the particles have much shorter height to fall down. Efficiency can be improved if the height to be travelled by the particle is reduced. Particles of size 10-15 $\mu$  can be removed by this modified settling chamber. But the use of this modified Howard's chamber is limited due to difficulty in cleaning the closely spaced trays.

## TRAY ARRANGEMENTS



### 4.2.3 Design considerations

Generally, settling chamber design based on laminar flow requires either a large size or large number of trays. Practically, the flow is turbulent rather than laminar.

Consider a settling chamber having dimensions  $L \times W \times H$  and containing 'n' number of trays including bottom surface, assuming laminar conditions.

The criterion for laminar flow is that Reynold's number, which is based on hydraulic diameter, should be less than 2300. The hydraulic diameter for flow passage between the trays is given by

$$D_h = \frac{2W \Delta H}{W + \Delta H} \text{ ----- 4.1}$$

The Reynold's number,  $R_e = \frac{VD_h \rho}{\mu} \text{ ----- 4.2}$

Velocity inside the chamber can be given by,  $V = \frac{Q}{nW \Delta H} \text{ ----- 4.3}$

Substituting eq. 4.1 & 4.3 in eq. 4.2,

$$R_e = \frac{2Q\rho}{n\mu(W + \Delta H)} \text{ ----- 4.4}$$

If thickness of the thin trays is neglected, the space between the trays is  $\Delta H = \frac{H}{n}$

Then eq. 4.4 becomes

$$R_e = \frac{2Q\rho}{\mu(nW + H)} \text{ ----- 4.5}$$

A particle entering the chamber at the top will be collected by the chamber, if its settling time is the same (or less than) the time the gas takes to pass through the chamber (from inlet to outlet).

For laminar conditions ( $Re < 2300$ ) within the trays, particles of size  $dp$  will settle to a height of  $h$  with settling velocity  $V_s$  in time  $t$ . Thus  $t = \text{distance/velocity} = h/V_s$

During the same time the particles are transported horizontally a distance  $L$ , with horizontal velocity of the gas stream  $V$ . Thus  $t = L/V$ .

Equating these two,  $h/V_s = L/V$

$$V_s = \frac{hV}{L} \text{ ----- 4.6}$$

Height through which the particulates travel before settling down,  $h = \frac{V_s \cdot L}{V}$

$$\text{Efficiency, } \eta = \frac{h}{\Delta H} = \frac{L V_s}{V \Delta H} = \frac{L V_s n}{V H} = \frac{n W L V_s}{Q} \text{----- 4.7}$$

The Vs can be calculated using Stoke's law

$$V_s = \frac{g \cdot (d_p)^2 \cdot (\rho_p - \rho)}{18\mu} \text{----- 4.8}$$

Where,  $d_p$  = diameter of the particle

$g$  = acceleration due to gravity

$\rho_p$  = density of the particles

$\rho$  = density of the gas

$\mu$  = viscosity of the gas

From eq. 4.6 and 4.7,

$$dp = \sqrt{\frac{18Vh\mu}{Lg(\rho_p - \rho)}} \text{----- 4.9}$$

$$\text{And also } dp = \sqrt{\frac{18\mu Q}{WLg(\rho_p - \rho)}} \text{----- 4.10 (another formula)}$$

If the flow is turbulent, the collection efficiency can be given by

$$\eta = 1 - e^{\left[\frac{n L W V_s}{Q}\right]} \text{----- 4.11}$$

#### 4.2.4 Advantages and disadvantages of settling chambers

##### Advantages

1. Low initial costs
2. Simple construction, no moving parts
3. Low maintenance costs
4. Low pressure drop
5. Dry and continuous disposal of solid particles
6. Excellent reliability
7. It can be constructed out of almost any material

##### Disadvantages

1. Large space requirements
2. Unable to handle sticky and tacky particles
3. Trays in Howards chamber may warp during high temperature operations
4. Only larger particulates can be collected ( $>40\mu$ )

##### Problem 4.1:

Calculate the settling velocity of fog with a particle size of  $1\mu\text{m}$ .

Soln: Given  $d_p = 1 \times 10^{-6} \text{m}$

Assume  $\rho$ =density of air=1.2 Kg/m<sup>3</sup>

$\rho_p$ =density of particle i.e., fog=1000 Kg/m<sup>3</sup> ,  $\rho \ll \rho_p$

$\mu$  = viscosity of the medium i. e. , air =  $1.8 \times 10^{-5}$  Kg/m . sec

$$\begin{aligned}\text{Eq. 4.8 } V_s &= \frac{g \cdot (d_p)^2 \cdot (\rho_p - \rho)}{18\mu} \\ V_s &= \frac{9.81 \times (1 \times 10^{-6})^2 \times (1000 - 1.2)}{18 \times 1.8 \times 10^{-5}} \\ \therefore V_s &= 3 \times 10^{-5} \text{ m/sec}\end{aligned}$$

Stoke's law is applicable only if  $Re < 1$

$$\begin{aligned}\text{Eq. 4.2 } Re &= \frac{VD\rho}{\mu} \\ Re &= \frac{3 \times 10^{-5} \times 1 \times 10^{-6} \times 1.2}{1.8 \times 10^{-5}} \\ \therefore Re &= 0.000002\end{aligned}$$

Hence Stoke's law is applicable hence settling velocity is  $3 \times 10^{-5}$  m/sec

**(NOTE:** This value is very very less. That is why fog appears to float in air. Particles with  $< 0.1\mu$  are affected by Brownian motion. They collide with the surrounding particles, they combine and then finally settle down)

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**Problem 4.2:**

Calculate minimum size of the particle that will be removed with 100% efficiency from a settling chamber of size 8m×4m×1.5m designed for a flow rate of 6 m<sup>3</sup>/sec at 75 °C.

Soln: Given L= 8m, W= 4m, H= 1.5m

$$\begin{aligned}\text{Eq. 4.9, } dp &= \sqrt{\frac{18Vh\mu}{Lg(\rho_p - \rho)}} \\ V &= \frac{Q}{c/s \text{ Area}} = \frac{Q}{WH} = \frac{6}{4 \times 1.5} = 1.0 \text{ m/sec}\end{aligned}$$

Assume  $\mu$  at 75°C =  $2.1 \times 10^{-5}$  Kg/m .sec and  $\rho_p$  = 2650 Kg/m<sup>3</sup>, neglecting  $\rho$  as  $\rho \ll \rho_p$

$$\begin{aligned}dp &= \sqrt{\frac{18 \times 1.0 \times 2.1 \times 10^{-5} \times 1.5}{8 \times 9.81 (2650)}} \\ dp &= 5.22 \times 10^{-5} \text{ m} \\ dp &= 52.2 \mu\text{m}\end{aligned}$$

**Problem 4.3:**

Find the length of the simple gravity collector required to remove 90% of 50 $\mu$ m diameter particles of density 2.0g/cc. The bulk gas velocity is 0.5m/s and the chamber is 3m in height. Calculate the length if two trays are used for same efficiency.

Soln: Given  $\eta = 0.9$ ,  $d_p = 50\mu\text{m} = 50 \times 10^{-6}\text{m}$   
 $H = 3\text{m}$ ,  $V = 0.5\text{m/sec}$

Assume  $\rho = 1.2\text{ Kg/m}^3$ ,  $\rho_p = 2000\text{Kg/m}^3$ , Neglect  $\rho$  as  $\rho \ll \rho_p$

$$V_s = \frac{g \cdot (d_p)^2 \cdot (\rho_p - \rho)}{18\mu}$$

$$V_s = \frac{9.81 \times (50 \times 10^{-6})^2 \times (2000)}{18 \times 1.8 \times 10^{-5}}$$

$$V_s = 0.15\text{m/sec}$$

$$\text{Efficiency, Eq. 4.7, } \eta = \frac{h}{\Delta H} = \frac{L V_s}{V \Delta H} = \frac{L V_s n}{V H}$$

here number of trays 'n' is 1, considering bottom floor as one tray

$$L = \frac{\eta V H}{V_s n}$$

$$L = \frac{0.9 \times 0.50 \times 3}{0.15 \times 1} = 9\text{m}$$

If two trays are installed and considering bottom floor as one tray,  
 $\Delta H = H/n = 3/3 = 1\text{m}$ , this is the new effective height of the chamber

Thus length of the chamber with 2 trays =  $L = \frac{\eta V \Delta H}{V_s} = 9/3 = 3\text{m}$

**Problem 4.4:**

A multi-tray settling chamber handles 6 m<sup>3</sup>/sec of air at 20 °C. There are 8 trays including the bottom surface spaced 0.25m apart. The chamber is 4m long and 1m wide. For particles of density 2000 Kg/m<sup>3</sup> and sizes a) 70 and b) 25 $\mu$ m, calculate residence time (t), the distance settled (h) and the efficiency of collection ( $\eta$ ). Is the tray spacing sufficient to collect all the particles of each size? Assume Laminar flow. What will be the efficiency if the flow regime is turbulent in each case?

Soln: Given  $Q = 6\text{ m}^3/\text{s}$ ,  $n=8$ ,  $\Delta H=0.25\text{m}$   
 $L=4\text{m}$ ,  $W=1\text{m}$ ,  $\rho_p=2000\text{ Kg/m}^3$

a) For 70 $\mu$ m

$$\text{From Eq. 4.7, } V = \frac{Q}{n W \Delta H} = \frac{6}{8 \times 1 \times 0.25} = 3\text{ m/s}$$

$$V_s = \frac{g \cdot (d_p)^2 \cdot (\rho_p - \rho)}{18\mu} \quad \text{Neglect } \rho \text{ as } \rho \ll \rho_p$$

$$V_s = \frac{9.81 \times (70 \times 10^{-6})^2 \times (2000)}{18 \times 1.8 \times 10^{-5}}$$

$$V_s = 0.295 \text{ m/s}$$

$$\text{Residence time } t = \frac{\text{distance (length)}}{\text{velocity}} = \frac{4}{3} = 1.33 \text{ sec}$$

For laminar flow conditions,  $h/V_s = L/V$

$$\text{Distance settled, } h = \frac{L V_s}{V} = \frac{4 \times 0.295}{3} = 0.393 \text{ m}$$

$$\text{Efficiency, Eq. 4.7} \quad \eta = \frac{h}{\Delta H} = \frac{L V_s}{V \Delta H} = \frac{4 \times 0.295}{3 \times 0.25} = 1.57 \cong 100\%$$

(**NOTE:** When  $h > \Delta H$ , ( $0.393 > 0.25$ ) all particles of that size or larger will be collected).

b) For  $25 \mu\text{m}$

Residence time will be same, as all the dimensions are same as before.

$$V_s = \frac{g \cdot (d_p)^2 \cdot (\rho_p - \rho)}{18\mu} \quad \text{Neglect } \rho \text{ as } \rho \ll \rho_p$$

$$V_s = \frac{9.81 \times (25 \times 10^{-6})^2 \times (2000)}{18 \times 1.80 \times 10^{-5}}$$

$$V_s = 0.037 \text{ m/s}$$

$$\text{Distance settled, } h = \frac{L V_s}{V} = \frac{4 \times 0.037}{3} = 0.05 \text{ m}$$

$$\eta = \frac{h}{\Delta H} = \frac{L V_s}{V \Delta H} = \frac{4 \times 0.037}{3 \times 0.25} = 20\%$$

c) If the flow regime is turbulent

$$\begin{aligned} \text{Efficiency for } 70 \mu\text{m, Eq. 4.11, } \eta &= 1 - e^{\left[ \frac{n L W V_s}{Q} \right]} \\ \eta &= 1 - e^{\left[ \frac{-8 \times 1 \times 4 \times 0.295}{6} \right]} = 79.2\% \end{aligned}$$

$$\begin{aligned} \text{Efficiency for } 25 \mu\text{m, Eq. 4.10, } \eta &= 1 - e^{\left[ \frac{n L W V_s}{Q} \right]} \\ \eta &= 1 - e^{\left[ \frac{-8 \times 1 \times 4 \times 0.037}{6} \right]} = 18\% \end{aligned}$$

(**NOTE:**  $V_s$  can also be calculated by the empirical formula ( $V_s = 30000 \cdot \rho_p \cdot dp^2$ ))

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#### Problem 4.7:

Design a gravity settler to remove all the iron particulates from a dust-laden gas stream with the data given as:

$dp = 35 \mu$  uniform

$$Q = 3.6 \text{ m}^3/\text{s}$$

$$\rho_p = 7.62 \text{ g/cc}$$

Soln: Collection area required can be obtained from Eq. 4.10,

$$dp^2 = \frac{18\mu Q}{WLg(\rho_p - \rho)}$$

$$WL = \frac{18\mu Q}{dp^2 g(\rho_p - \rho)}$$

$$WL = \frac{18 \times 1.8 \times 10^{-5} \times 3.6}{(35 \times 10^{-6})^2 \times 9.81 \times 7620} \text{ Neglect } \rho, \text{ as } \rho \ll \rho_p$$

$$WL = 12.8 \text{ m}^2$$

Assuming an inlet velocity of 3m/sec, the c/s area is,  $WH = \frac{Q}{V} = \frac{3.6}{3} = 1.2 \text{ m}^2$

Based on minimum height required for cleaning purposes, H is usually 1m, then

$$W \times 1 = 1.2 \text{ m}^2$$

$$W = 1.2 \text{ m}$$

$$WL = 12.8 \text{ m}^2$$

$$L = \frac{12.8}{1.2} = 10.6 \text{ m}$$

But for economic considerations, We can take  $L=W$ ,

$$WL = L^2 = 12.8 \text{ m}^2$$

$$W = L = 3.5 \text{ m}$$

$$H = 1 \text{ m}$$

$$\text{And in this case, } V = \frac{Q}{WH} = \frac{3.6}{3.5 \times 1} = 1 \text{ m/s}$$

### 4.3 Cyclone Separators

Cyclone separators are the most common separating devices called as centrifugal or inertial separators because of the use of centrifugal force or action for the separation process. A cyclone collector can be defined as “a structure without any moving parts in which the velocity of an inlet gas stream is transformed into a confined vortex from which centrifugal forces tend to drive the suspended particles to the wall of the cyclone body”.

It depends upon centrifugal force instead of gravity to separate the particles from the gas stream. Because the centrifugal force generated can be several times greater than the gravitational force, particles that can be removed in centrifugal collectors are much smaller than those that can be removed in gravity settling chambers.

During cyclonic separation, carrier gas rotational velocity (velocity of vortex flow inside cyclone) may exceed several times the average inlet velocity.

#### 4.3.1 Principle, Construction and Working of Cyclone Separators



**Principle:**

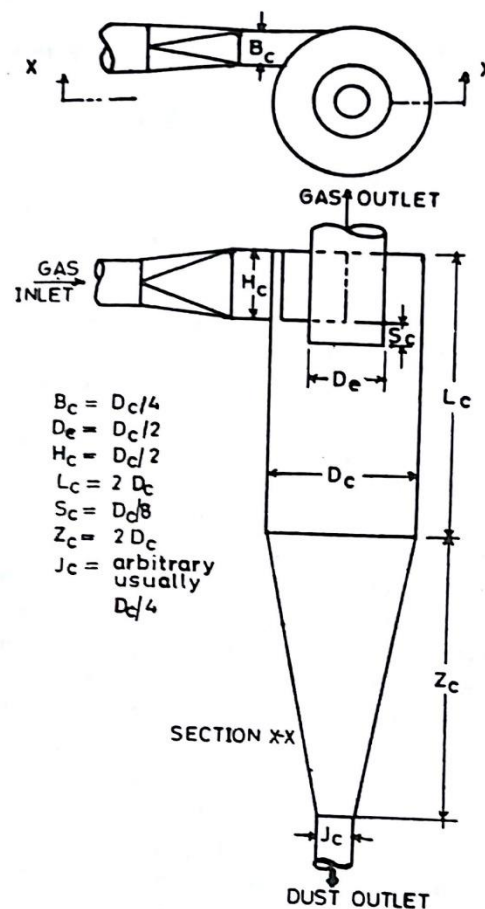
Centrifugal force separates the particulates from the gas stream instead of gravitational force. Velocity of an inlet gas stream is transformed into a confined vortex from which centrifugal forces tend to drive the suspended particles to the wall of the cyclone body.

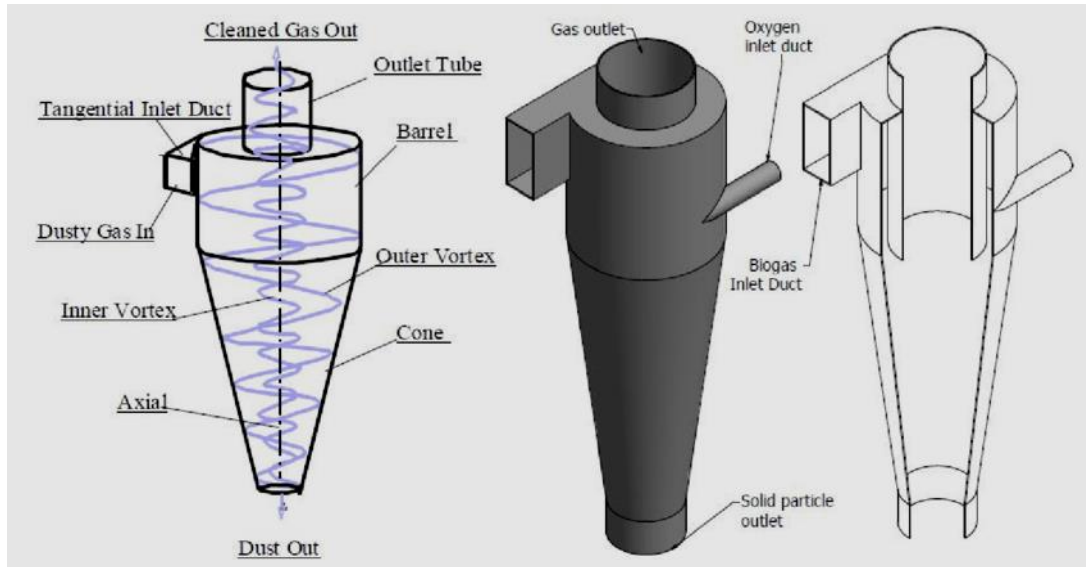
**Construction:**

Generally a cyclone separator consists of a vertically placed cylinder, an inverted conical base attached to the bottom of the cylinder, a dust hopper too collect the dust and an inlet from where the dirty gas enters the cyclone. Outlet for clean gas is provided in the centre at the top. All the parts of the cyclone are designed as per the standard set of dimensions as shown in the figure.

**Working:**

The dirty gas consisting of particulates is made to enter the cyclone with higher velocities through inlet, tangentially to the cylinder. The gas path generally follows a double vortex. First, the gas spirals downwards along the wall of the cylinder and continues through conical portion and reaches the bottom. Then, second, the gas stream moves upwards in a narrower inner spiral, concentric with the first and comes out from the cyclone through the outlet pipe. Due to the rapid spiralling movement of the gas, the particles are thrown to the wall by the centrifugal force and then they fall to the bottom of the body by gravity. They are collected in a storage hopper.





#### 4.3.2 Design considerations:

##### 1. A set of sizes of various parts of the cyclone

Diameter of the cyclone cylinder =  $D_c$ , Diameter of the gas exit  $D_e = D_c/2$ ,

Length of cylinder  $L_c = 2 D_c$ , Length of the cone  $Z_c = 2 D_c$ ,

Height of the entrance/inlet  $H_c = D_c/2$ , Width of the entrance/inlet  $B_c = D_c/4$ ,

Diameter of dust exit  $J_c = D_c/4$

##### 2. Separation factor

In a cyclone, the initial separating force is the radial component of the centrifugal force and is a function of tangential velocity. The centrifugal force  $F_c$  is given by,

$$F_c = \frac{m V_0^2}{R}$$

$$\text{Separation factor } S = \frac{V_0^2}{g R}$$

Higher the separation factor, the better is the performance of the cyclone.

##### 3. Efficiency

$$\eta = \frac{1}{1 + \left(\frac{d_{pc}}{d_p}\right)^2}$$

##### 4. Cut size

Cut size ( $d_{pc}$ ) is the size of those particles that are collected with 50% efficiency. Collection efficiency will be greater than 50% for the particles larger than  $d_{pc}$ . Collection efficiency will be less for smaller particles.

The extremely smaller particles than  $d_{PC}$  may be collected in very less quantity or they may not be collected. Thus  $d_{PC}$  is the diameter of the smallest particle which can be theoretically completely separated from the gas stream.

$$d_{PC} = \sqrt{\frac{9 \mu B_c}{2\pi V_i N_t (\rho_p - \rho)}}$$

### 5. Number of cyclones

If  $Q$  is total volumetric flow, then  $Q = VA$

$A$  is total area of cyclone including of all cyclones

$V$  is inlet velocity

Then  $Q = VA = V_i B_c H_c n$

$$\text{Number of cyclones (n)} = \frac{Q}{V_i B_c H_c}$$

### 6. Number of turns

Number of turns made by inlet gas  
in main outer vortex inside the cyclone

$$N_t = 1.5 \times \frac{L_c}{H_c}$$

Or

$$N_t = \frac{1}{H_c} \left[ L_c + \frac{Z_c}{2} \right]$$

### 4.3.3 Operating Problems

There are 3 important operating problems associated with cyclones. They are erosion, corrosion and material build-up.

**Erosion:** Heavy, hard, sharp-edged particles, in a high concentration, moving at high velocity in the cyclone, continuously scrape against the wall and can erode the metallic surface. Therefore suitable body material is used.

**Corrosion:** This problem occurs if the cyclone operates at lower temperatures and when reactive gases are present. The best solution to any corrosion problem in a cyclone is to maintain the temperature above the dew point. If the gas and dust are corrosive at low temperatures then perhaps the only alternative is to use a stainless alloy.

**Build-up of dust cake:** It occurs most frequently on the cyclone walls. It can be removed periodically and scrapped.

### 4.3.4 Advantages and Disadvantages of Cyclone separators

#### Advantages

1. Low initial cost
2. Simple construction and operation
3. Low pressure drop
4. Low maintenance requirements
5. It has no moving parts
6. Continuous disposal of solid particulates

7. They can be constructed of any material

### Disadvantages

1. Low collection efficiency for particulates below 5-10 $\mu$
2. Equipment is subject to severe abrasive deterioration
3. Decreasing collection efficiency for decreasing particulate concentration.

### 4.3.5 Applications

Cyclones are used widely for control of particulates in industrial operations such as cement manufacture, feed & grain processing, food and beverage processing, mineral processing, paper and textile industry, and wood working industries.

Cyclones are also used to separate dust in disintegration operations, such as rock crushing, ore handling and sand conditioning in industries. They are also used in the recovery of catalyst dusts in the petroleum industry, and in the reduction of fly ash emissions.

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#### Problem 4.8:

Calculate number of cyclones required to treat a flow of 60m<sup>3</sup>/sec with an inlet velocity of 15m/s. The diameter of cyclone is 1.8m.

Soln: Given Q= 60m<sup>3</sup>/sec, Dc = 1.8m, Vi = 15m/s

$$B_c = D_c/4 = 1.8/4 = 0.45\text{m}$$

$$H_c = D_c/2 = 1.8/2 = 0.9\text{m}$$

$$\text{Number of cyclones (n)} = \frac{Q}{V_i B_c H_c}$$

$$n = \frac{60}{15 \times 0.45 \times 0.9}$$

$$n = 9.876 \cong 10 \text{ No's}$$

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#### Problem 4.9:

Calculate collection efficiency for a gas flow rate of 7 m<sup>3</sup>/sec, particle density of 1500 Kg/m<sup>3</sup> and diameter of 10 $\mu$ , if a multiple cyclone (64 cyclones each of diameter 24cm) is used instead of single large unit.

Soln: Given Q = 7m<sup>3</sup>/sec, Dc = 24cm = 0.24m,  $\rho_p$ =1500 Kg/m<sup>3</sup>, dp = 10 $\mu$

$$B_c = D_c/4 = 0.24/4 = 0.06\text{m}$$

$$H_c = D_c/2 = 0.24/2 = 0.12\text{m}$$

$$\text{Area of inlet of one cyclone} = B_c H_c = 0.06 \times 0.12 = 7.2 \times 10^{-3} \text{ m}^2$$

$$\text{Area of all the inlets} = 64 \times 7.2 \times 10^{-3} = 0.45 \text{ m}^2$$

$$\text{Inlet velocity } V_i = Q/A = 7/0.45 = 15 \text{ m/s}$$

Assuming  $N_t = 5$  and  $\mu @ 20^\circ\text{C} = 1.81 \times 10^{-5} \text{ Kg/m} \cdot \text{sec}$

$$(d_{PC})^2 = \frac{9 \mu Bc}{2\pi V_i N_t (\rho_p - \rho)}$$

$$(d_{PC})^2 = \frac{9 \times 1.81 \times 10^{-5} \times 0.06}{2\pi \times 15 \times 5 (1500)}$$

$$(d_{PC})^2 = 1.3827 \times 10^{-11}$$

$$d_{PC} = 3.7185 \times 10^{-6} \text{ m} = 3.72 \mu$$

Efficiency,

$$\eta = \frac{1}{1 + \left(\frac{d_{PC}}{d_p}\right)^2}$$

$$\eta = \frac{1}{1 + \left(\frac{3.72}{10}\right)^2}$$

$$\eta = 0.878 = 87.8\%$$

**Note:** If you want you can neglect  $\rho$  as  $\rho \ll \rho_p$

Or simply take it as  $1.2 \text{ Kg/m}^3$

#### Problem 4.10:

A cyclone has an inlet width of 15cm and the shortest length of 25cm with diameter of 0.5m, operates at 5 effective turns. The gas temperature is 345 K and inlet velocity is 20m/s. The average particle size is  $10\mu$  with particle density  $1.2 \text{ g/cc}$ , the viscosity of the gas at 345 K is  $0.745 \text{ Kg/m} \cdot \text{h}$ . Determine cut diameter and separation factor. Is this a high efficiency cyclone?

Soln:

Given  $Bc = 15\text{cm} = 0.15\text{m}$ ,  $Lc = 25\text{cm} = 0.25\text{m}$ ,  $Dc = 0.5\text{m}$ ,  $N_t = 5$ ,  $d_p = 10\mu$ ,  $V_i = 20\text{m/s}$ ,  
 $\rho_p = 1.2\text{g/cc} = 1.2 \times 10^3 = 1200 \text{ Kg/m}^3$ ,  $\mu = 0.745 \text{ Kg/m} \cdot \text{h}$

$$1\text{Pa} \cdot \text{s} = 3600 \text{ Kg/m} \cdot \text{h} \text{ then } \mu = \frac{0.745}{3600} = 2.069 \times 10^{-4} \text{ Pa} \cdot \text{s}$$

Take  $\rho = 1.2 \text{ Kg/m}^3$

$$(d_{PC})^2 = \frac{9 \mu Bc}{2\pi V_i N_t (\rho_p - \rho)}$$

$$(d_{PC})^2 = \frac{9 \times 2.069 \times 10^{-4} \times 0.15}{2\pi \times 20 \times 5 (1200 - 1.2)}$$

$$(d_{PC})^2 = 3.708 \times 10^{-10}$$

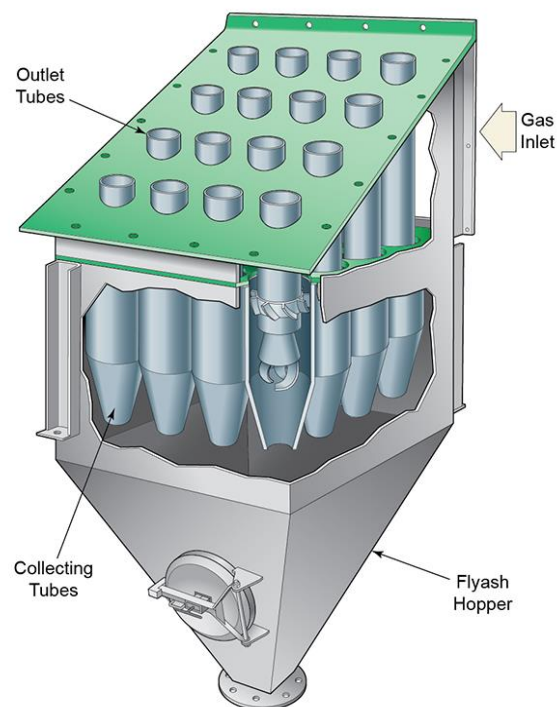
$$d_{PC} = 1.92 \times 10^{-5} \text{ m} = 19.25\mu$$

$$\text{Separation factor } S = \frac{V_0^2}{g R}$$

$$S = \frac{20^2}{9.81 \times 0.25} = 163.09$$

$d_{PC} > d_p$   
then the cyclone is highly efficient

### Multiple cyclone separator unit



## 4.4 Fabric Filters

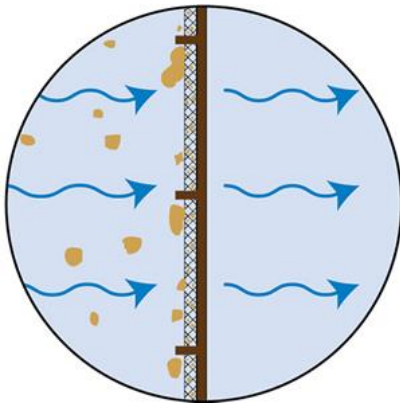
One of the oldest and most widely used methods of separating particulates from carrier gas is 'Filtration'. A filter is generally a porous structure composed of granular or fibrous material which tends to retain the particulates and allows the gas to pass through the voids of the filter. The filter is constructed of any material compatible with the carrier gas and particulates and may be arranged in 1) fabric or cloth filters 2) fibrous or deep bed filters.

In fabric/cloth filters, the filter is made of cloth material arranged in the form of tubular bags or cloth envelops and is suitable for dust content of the order of  $1\text{g}/\text{m}^3$ . They are capable of removing dust particles as small as  $0.5\mu$ . In case of deep bed filters, the filter is made of fibrous material like mats of wool, cellulose etc. Deep bed filters have large void spaces of 97-99% of total volume and collection of particulates takes place in the interstices of the bed, and is suitable for light dust contents of the order of  $1\text{mg}/\text{m}^3$ .

### 4.4.1 Principle, construction and working of Fabric filter or Bag house filter

#### Principal

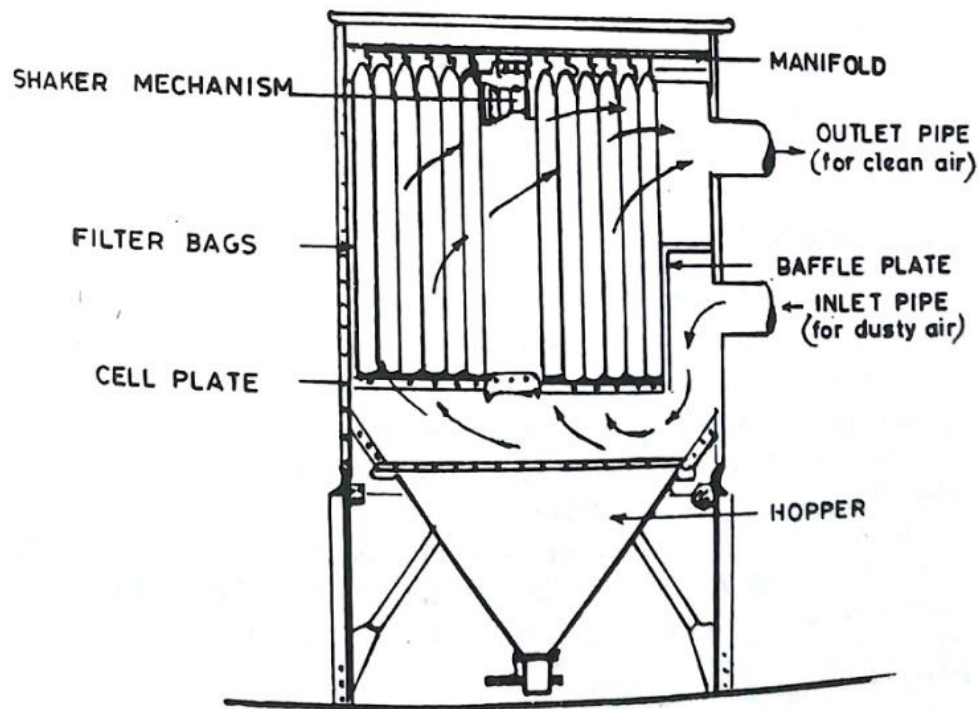
Separation of particulates from carrier gas stream is simply like sieving as the small pores of the fabrics retain the larger particles and allow only gas to pass through them. Basically, initial deposition of the particulates on the filter media takes place through interception and impingement of the particles on the fabric fibres. A pre-coat or the dust cake will be formed on the filter media within a minute or two. This dust cake/dust layer/pre-coat becomes itself a filtering media to retain more number of particles. The fabric fibres just act like matrix to support the dust cake/pre-coat. Efficiency will be comparatively low during the formation of pre-coat but efficiency increases after the formation of pre-coat.



#### Construction:

The most common type of fabric filter consists of tube shaped fabric bags. A bag house consists of numerous vertical bags of 120-400mm diameter and 2-10m long. The upper ends are closed and lower ends are open. The bags are suspended and attached to a manifold/shaking mechanism. The hopper at the bottom serves as a collector for the dust. A baffle plate is provided in front of the inlet.





#### Working:

The gas entering the house through inlet pipe strikes the baffle plate which causes the large particles to fall into a hopper due to gravity. The carrier gas then flows upward into the tubes with velocity of 0.4-1m/min and passes outward through the fabric leaving the particulate matter as a dust cake on inside walls of the bags. Efficiency during the formation of pre-coat is low, but efficiency increases after the formation of pre-coat. Once the pre-coat is formed, it acts as a filtering media which helps in further removal particulates. The clean gas comes out through the outlet.

The accumulation of dust on inside of the bags, increases air resistance therefore filter bags have to be cleaned periodically.

#### 4.4.2 Factors affecting efficiency

1. **Excessive filter ratios** – ‘Filter ratio’ is defined as the ratio of the carrier gas volume to gross filter area, per minute flow of the gas. Excessive filter ratio lowers the removal efficiency and results in bag wear. Therefore low filter ratios are recommended for high concentration of particulate matter.

Filter ratio = Gas volume per minute flow/ Gross filter area

Gas volume per minute of flow = Volume/Time = Discharge (Q)

And we know that Discharge (Q) = c/s Area (A) x Velocity (V)

Thus Filter ratio = AV/Gross filter area

Here filter ratio is directly proportional to velocity. If the velocity increases, filter ratio increases. High velocities cause escaping of particulates through pores of filter media that decreases the efficiency. Thus low filter ratios are recommended.

2. **Improper selection of filter media** leads to lower removal efficiency and higher maintenance costs. While selecting filter media for bag house, we must consider the characteristics and



properties of carrier gas and dust particles such as temperature resistance of the material, resistance to chemical attack, abrasion resistance, carrier gas temperature, carrier gas composition, gas flow rate, size & shape of the dust particles and its concentration.

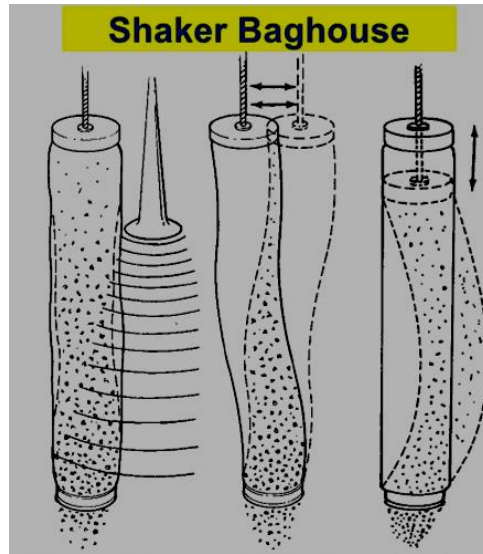
#### 4.4.3 Operating problems in fabric filters

1. **Cleaning:** Periodic cleaning of bags is an important problem. After few hours of operation, the formation of heavy dust layer blocks the passage of air. Thus the carrier gas no longer pass through the bag. Then the bags have to be cleaned by rapping, shaking, by reverse air flow or by pulse jet.
2. **Rupture of cloth:** While cleaning the filter, the greatest problem that may be seen in cloth filters is rupture of cloth. It is often difficult to find out the ruptures and it leads to replacement of the cloth.
3. **Temperature:** Fabric filters will not perform properly if temperature overload occurs. Generally, the filters are designed for about 250°C to 300°C. The temperature related problem occurs when carrier gas contains a reactive gas such as SO<sub>2</sub> which can form an acid if the temperature in the bag house falls below the dew point. This can be prevented having the bag house fairly insulated. Sometimes an auxiliary heater is used in winter season so that temperature does not fall below dew point.
4. **Bleeding:** Bleeding is the escape of fine particles through fabric. Bleeding occurs if fabric weave is too open or if the superficial filtration velocity (Filter ratio) is too high. Generally, only very fine particles may escape through fabrics and they only cause human health hazards. The solution to bleeding is to use double layered thick woven fabrics.
5. **Humidity:** Humidity control is a common and an important problem especially if a hygroscopic dust is involved. Hygroscopic dusts are those readily attract water from its surroundings through either absorption or adsorption. Cleaning will become difficult in such cases. This problem can be overcome by taking suitable precautions.
6. **Chemical attack:** Another problem associated with fabric filters is possibility of chemical attack due to corrosive chemicals such as SO<sub>2</sub> present in the carrier gas. Acid/alkali resistant filter cloths are to be used in such cases.

#### 4.4.4 Filter cleaning methods

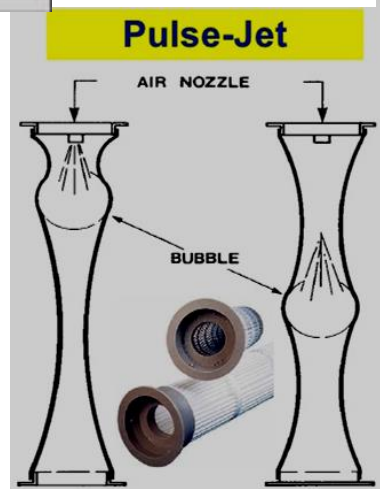
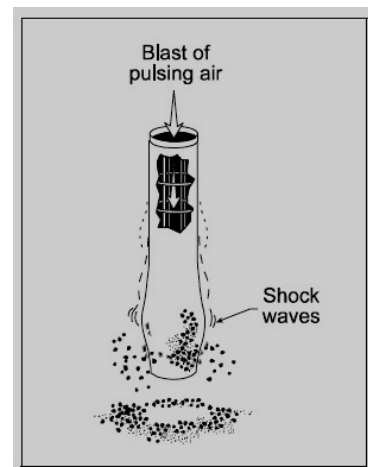
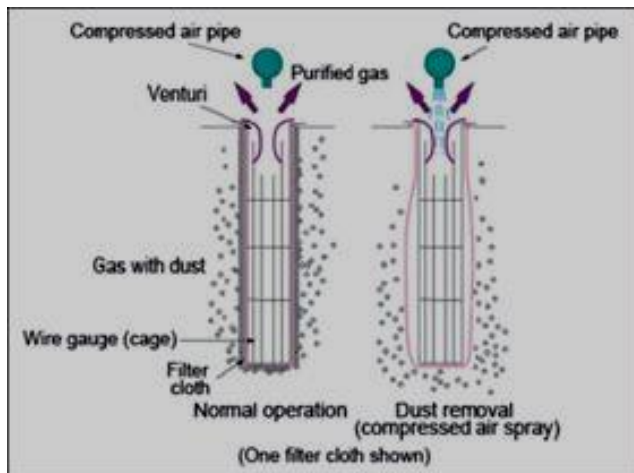
Filter cleaning can be done by the following methods.

1. **Shaking:** The shaking mechanism is the oldest one, the number of bags suspended in the bag house and attached to a shaking manifold are shaken manually or mechanically. Shaker cleaners hold the top of the bag still and shake the entire tube sheath, vibrations produced by the shaker loosens the dust cake. The dust will fall down into the hopper at the bottom. This method is not used for sticky dusts because the forces needed to remove the collected dust would cause tearing and ripping in the bags quickly. For cleaning by this method, the filtration process has to be stopped for some time and specified duration should be provided for cleaning.
2. **Reverse air flow:** The filter is cleaned by a high velocity air jet which is discharged in reverse to normal flow direction to the filter. Blow rings around the each bag are used to pass the air jet. As the blow ring traverses outside of the filter tube, the air jet passes through the fabric in backward direction and removes dust cake continuously from the filter surface. The main advantage of the this method are 1) No need of shutting down of filtration process blow rings are a continuous cleaning mechanism 2) The cloth resistance can be maintained. But the disadvantage is that blow rings are mechanical linkages and are individual attachments for each bag, resulting in increased maintenance costs.

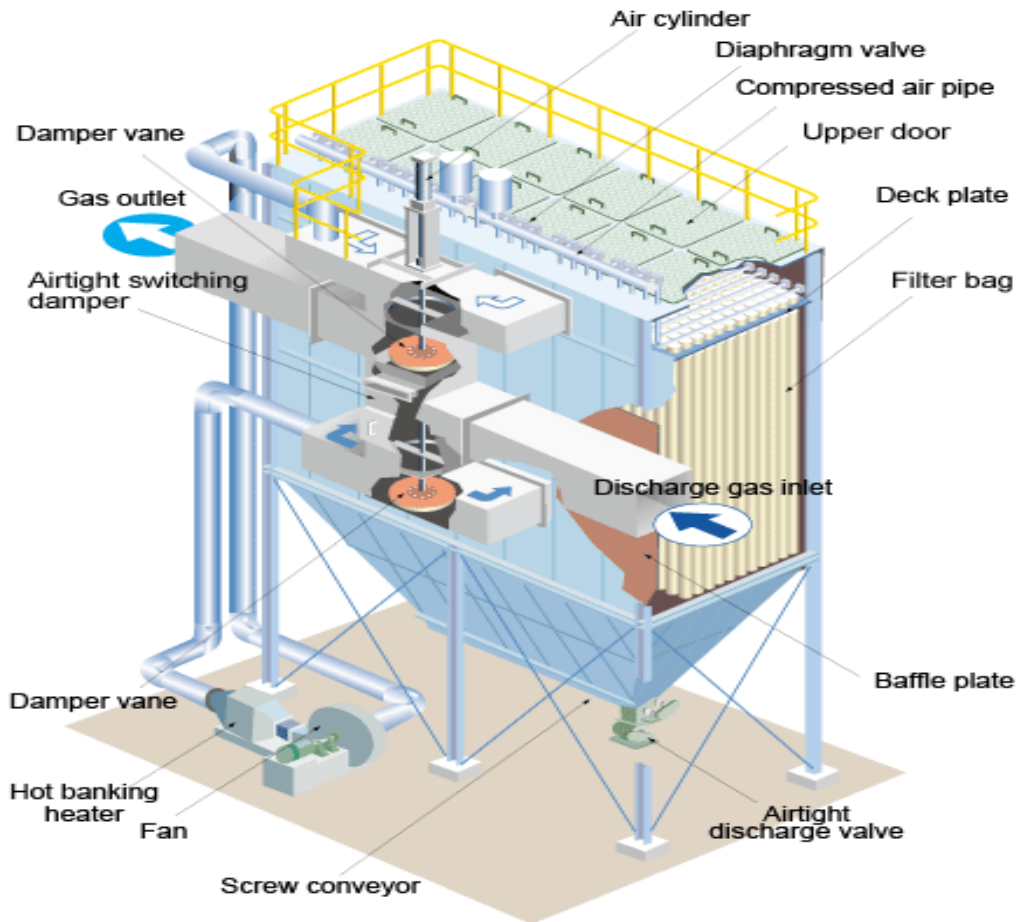


3. **Pulse jet:** Here, a jet of high pressure air is blasted inside periodically. When the compressed high pressure air is blasted, the bag will be inflated (swelled out or stretched out). This inflation of bag causes the dust cake to loosen from the surface and then the dust cake falls down. The advantage of this method is, there are no moving parts and also duration of cleaning is not important.

In general, while selecting particular cleaning method, we have to consider the cleaning mechanism, frequency of cleaning required, duration of cleaning and any undesirable effects on the bags.



### An industrial unit of Bag House



#### 4.4.5 Advantages and Disadvantages of fabric filters

##### Advantages

1. High collection efficiency for particulates of all sizes.
2. Simple construction and operation
3. Nominal power consumption
4. Dry disposal of collected material

##### Disadvantages

1. Operation limits are induced if carrier gas temperature and humidity are high.
2. High maintenance and fabric replacement costs
3. Large size of the equipment
4. Problems in handling dusts which may abrade, corrode, or blind the cloths.

**Problems 4.11:**

A fabric filter is to be constructed using bags of 0.3m in diameter and 6m long. The bag house is to receive 800m<sup>3</sup>/min of carrier gas. Determine the number of bags required if the superficial filtration velocity is 2m/min.

Soln:

Given Q = 800m<sup>3</sup>/min, L = 6m,

Superficial filtering velocity = 2m/min (i.e., 2m<sup>3</sup>/m<sup>2</sup>/min)

$$\therefore \text{cloth area required for filtering} = \frac{800}{2} \left[ \because Q=AV \Rightarrow A = \frac{Q}{V} \right] \\ = 400\text{m}^2$$

Area of each bag, A =  $\pi D L$

$$A = \pi \times 0.3 \times 6$$

$$A = 5.65\text{m}^2$$

$$\therefore \text{Total number of bags} = \frac{\text{Total area of cloth}}{\text{Area of each bag}} = \frac{400}{5.65} = 70.79 \cong 72 \text{ bags}$$

**Note:** Here we can take 71 number of bags, but we cannot fix bags in a bag house in rows perfectly with odd numbers. If we assume 72 numbers, then for example, 72 bags can be fixed in 6 rows each of 12.

**Problem 4.12:**

A bag house filter having 20 compartments, 360 bags per compartment and each bag of diameter 11m and bag length 30m, with gas flow rate of 12,00,000m<sup>3</sup>/min. Calculate the gross and net air to cloth ratios. Assume that 2 compartments are out of service when calculating the net air-cloth ratio.

Soln:

Given D= 11m, L= 30m, Q= 12,00,000 m<sup>3</sup>/min

$$\frac{\text{Air}}{\text{Cloth}} = \frac{\text{Flow rate}}{\text{Fabric area}} = \text{Filter ratio}$$

Total number of bags in the bag house = 360 x 20 = 7200

Area of each bag, A =  $\pi D L$

$$A = \pi \times 11 \times 30$$

$$A = 1036.72\text{m}^2$$

$$\text{Total number of bags} = \frac{\text{Total area of cloth}}{\text{Area of each bag}}$$

Total cloth area = Total number of bags  $\times$  Area of each bag

$$\text{Total cloth area} = 7200 \times 1036.72 = 7.46 \times 10^6 \text{m}^2$$

$$\text{Gross Filter ratio} = \frac{\text{Flow rate}}{\text{Gross cloth area}} = \frac{1200000}{7.46 \times 10^6} = 0.160$$

If two compartments are out of service,

Total number of bags in the bag house =  $360 \times 18 = 6480$

Total cloth area = *Total number of bags*  $\times$  *Area of each bag*

$$\text{Total cloth area} = 6480 \times 1036.72 = 6.717 \times 10^6 \text{ m}^2$$

$$\text{Net Filter ratio} = \frac{\text{Flow rate}}{\text{Net cloth area}} = \frac{1200000}{6.717 \times 10^6} = 0.178$$

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## 4.5 Scrubbers/Wet collectors

We know that nature cleanses herself up to considerable extent. Just consider that in an atmosphere, the particulate matter is suspended in the air. When it rains in that atmosphere, what happens? When it rains, all the dust particulates will be washed away from the atmosphere and they are carried along with the rain water. Every water droplet of the rain hits the dust particle and it tends the particle to settle down. That's why we all experience the fresh air sensation after every rain. The same principle is used in the scrubbers.

Scrubbers are the devices which utilize a liquid to assist in removal of particulates from the carrier gas stream. Generally water is used as the scrubbing liquid. The scrubbers are basically cheap to install but costly to operate. The particles larger than  $0.2\mu$  can be collected from high efficient scrubbers.

### 4.5.1 Collection Mechanism

The four major steps are involved in collecting particles by wet collectors.

- 1) Transport – the particles must be moved to the vicinity of the water droplets which are usually 10-1000 times larger than particulates.
- 2) Collision- the particles must collide with the droplet.
- 3) Adhesion – when the particles collide with the droplets, they will be adhered (stuck) to the water droplets.

Interception - when they hit the droplets, the water droplets act as baffles/barriers which disallow the particles to move further, thus particles will experience a loss of velocity and then can be collected separately.

Condensation – Condensation of the liquid medium vapours on the particulates increases the size and weight of particles. Thus, it helps in easy removal of the particulate matter.

- 4) Precipitation – the particles are precipitated to the bottom of the scrubber containing dust particles. It means removal of the droplets containing the dust particle from the gas phase.

### 4.5.2 Types of scrubbers

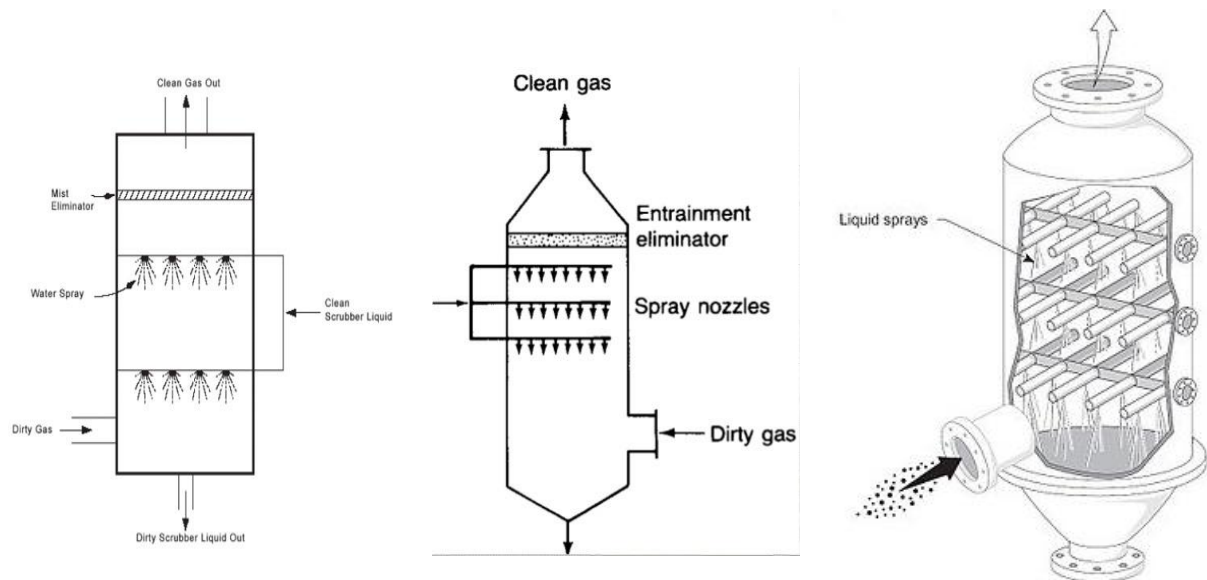
Following are the most commonly used types of scrubbers.

- 1) Spray towers
- 2) Venturi scrubber
- 3) Cyclone scrubber
- 4) Packed scrubber
- 5) Mechanical scrubber

#### 4.5.2.1 Spray Towers

A Spray tower is the simplest type of wet scrubber into which water is introduced by means of spray nozzles. A simple spray tower is shown in figure. A spray tower can be either round or rectangular, in which gas is passed, counter-current to falling liquid drops from spray nozzles. The particle collection can be done by the mechanism of adhesion and interception.

Spray towers cause very little pressure loss (energy) and can handle large volume of gases. The towers effectively remove particles  $>10\mu\text{m}$ . The maximum efficiency occurs if droplets have a diameter of  $800\mu\text{m}$  (0.8mm). The efficiency of a spray tower depends upon the droplet size, flow velocity of the gases, velocity of liquids etc. Effectiveness of the spray tower varies with the size of particles. It is 94% for  $5\mu\text{m}$  particles to 99% for  $25\mu\text{m}$  particles.



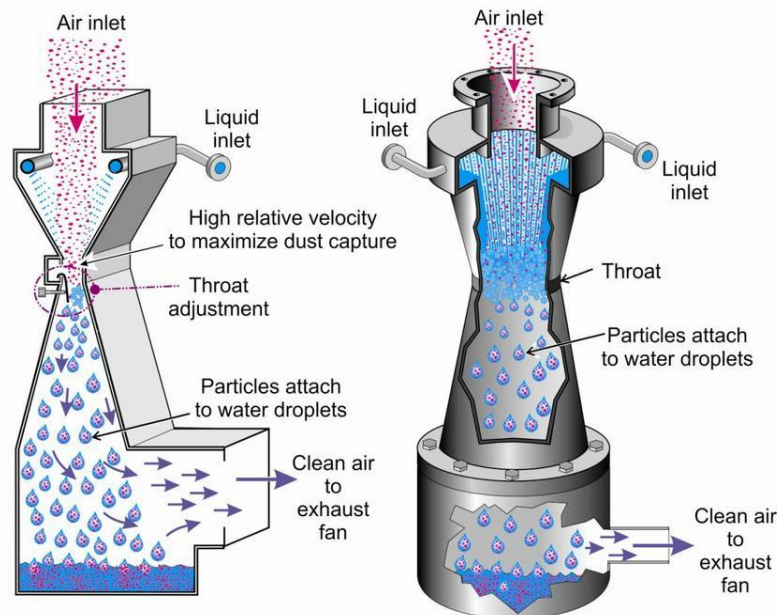
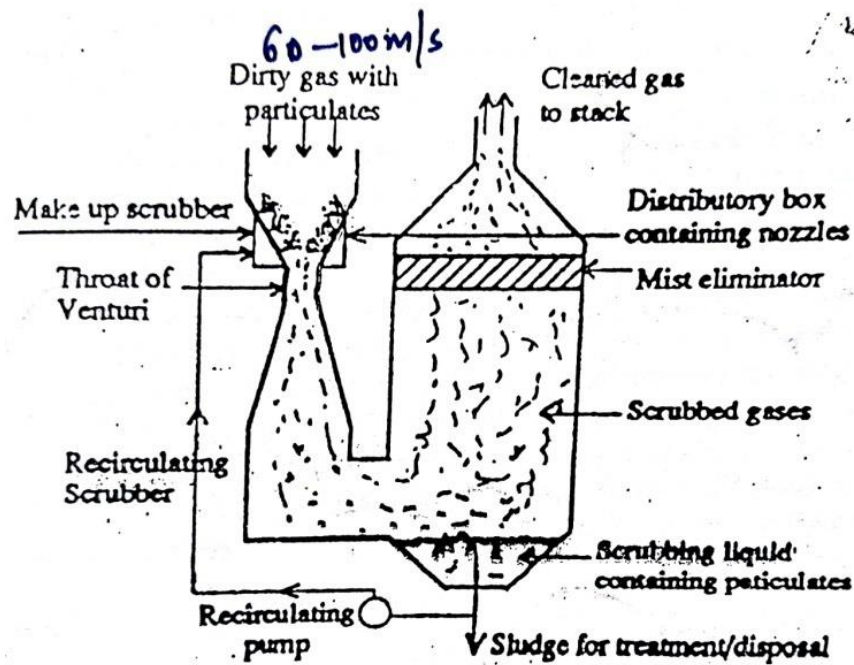
#### 4.5.2.2 Venturi scrubbers

Venturi scrubbers are called as high performance scrubbers. These are high energy wet scrubbers with high efficiency collection of particles ( $0.5\text{--}5\mu\text{m}$ ). These are suitable for submicron particulates associated with smoke, fume and also highly corrosive matter. Venturi scrubbers have converging and diverging sections. The high performance of the venturi scrubber is achieved by accelerating the gas stream to very high velocities ( $60\text{--}100\text{m/s}$ ). Due to high speed action, the feed liquid is atomised (i.e., liquid layers broken into number of droplets) with uniform fashion in the throat of the venturi. In the throat section, several low pressure spray nozzles are mounted as shown in the figure.

The droplets accelerate in the throat section and due to the velocity difference between the particles and the droplets the particles are impacted against the slow moving droplets. Slurry is sent to the collection tank and the cleaned gas is continuously passed out. The principle collection mechanism is inertial impaction (collision and adhesion).

The application of venturi scrubber is more oftenly used in Kraft mill furnaces, metallurgical furnaces, sulphuric acid concentrators etc for removing mists and dusts from gases.

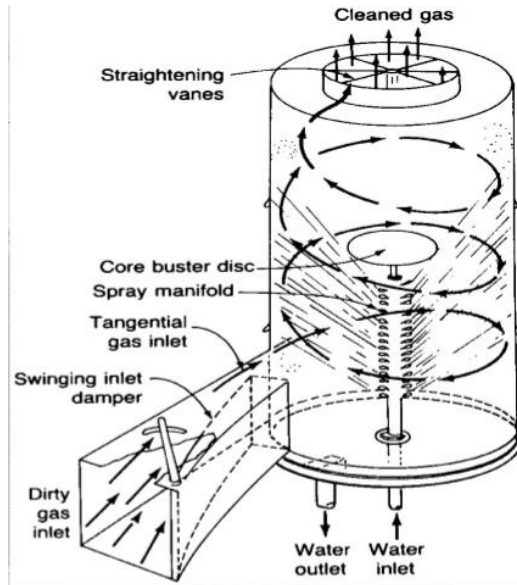




#### 4.5.2.3 Cyclone scrubbers

This is just a modification of dry cyclone by the addition of liquid phase. In cyclone scrubbers, the gas is tangentially swirled around, as same as in the dry cyclone. Water sprays are introduced in the centre of the cyclone. Scrubbing liquid is sprayed from the centre to the wall of the cyclone. These sprays help in the collection of particles preventing re-entrainment. Impingement and inertial separation are the primary collection mechanisms.

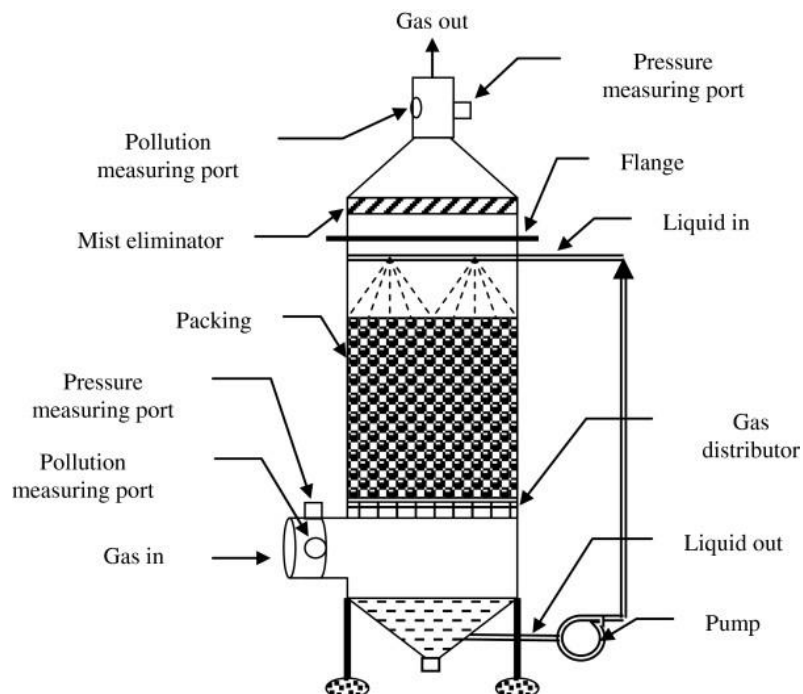
For droplets of  $100\mu\text{m}$ , efficiency may reach 100%. And 90-98% efficiency may be reached for droplets of  $5-50\mu\text{m}$ . Generally efficiencies slightly higher than those with the spray tower and dry cyclone.



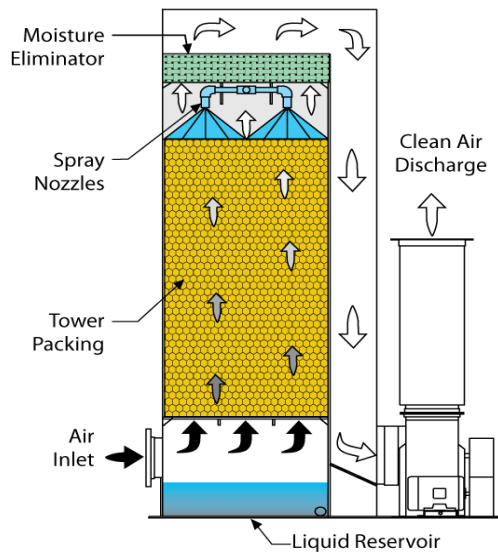
#### 4.5.2.4 Packed scrubbers

In packed scrubbers, a bed of material is packed inside. Usually fibre glass fine filaments, coke or broken stone are used as the packing bed material. The polluted gas stream moves upward in a counter current flow packed scrubber. And scrubbing liquid stream flows downward over the packed bed. The gas stream and scrubbing liquid are passed through pore spaces of packed bed, particles present in the gas are captured by the liquid. The primary collection mechanism is collision and adhesion. Smaller packing increases the efficiency. Sometimes packing towers encounter plugging problems, which can be reduced by employing sprays to wash the packed bed or by using low density spheres.

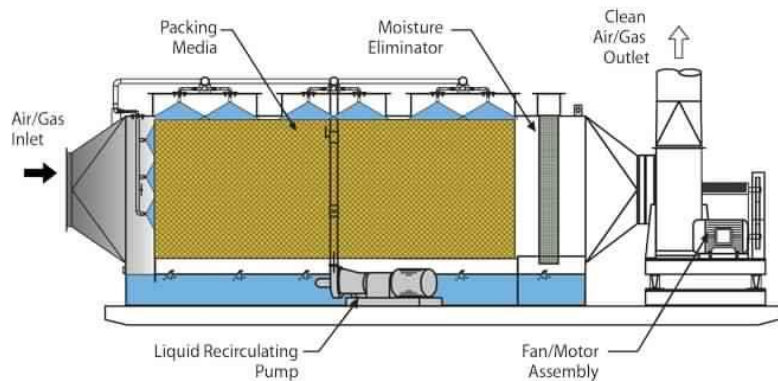
Packed towers can also be co-current or cross-flow type design (as shown in the figure) depending on the direction of liquid flow with respect to the direction of gas flow.







**Counter current packed scrubber**



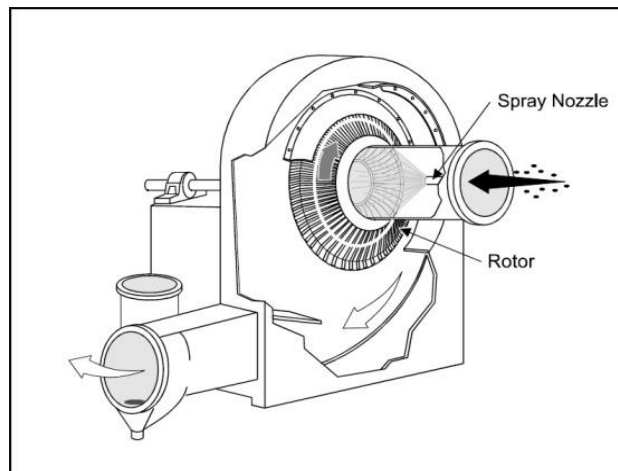
**Cross flow packed scrubber**

#### 4.5.2.5 Mechanical scrubbers

This is a mechanically aided scrubber, has a rotating mechanical part for breaking up the liquid layers into smaller droplets and simultaneously creating turbulence. These are high energy scrubbers.

Here, the liquid-particles contact is achieved by the simultaneous introduction of scrubbing liquid and gas stream on the rotating discs, blades or perforated plates. The scrubbing liquid falls down on the rotating part and violently disintegrated into fine droplets that are thrown out radially by centrifugal force and are removed quite easily.

These scrubbers have high initial cost, high operating cost and require considerable maintenance. The water use rate is also high.



#### 4.5.3 Advantages and disadvantages of Wet collectors or Scrubbers:

##### Advantages:

1. Low initial cost
2. Moderately high collection efficiency for even submicron particles

3. Applicable for high temperature installations
4. They can simultaneously remove particulates and gases
5. Valuable byproducts can be obtained.

For example, if Sulfur dioxide is present in the gas,  $SO_2 + H_2O \rightarrow H_2SO_3/H_2SO_4$  here,  $H_2O$  is scrubbing liquid and sulfuric acid is valuable byproduct.

If the ammonia is present in the gas,  $2NH_3 + H_2SO_4 \rightarrow (NH_4)_2SO_4$  here sulfuric acid is scrubbing liquid and ammonium sulfate is a valuable byproduct.

#### Disadvantages:

1. High power consumption for higher efficiency
2. High maintenance costs because of corrosion and abrasion
3. Wet disposal of the collected material

## 4.6 Electrostatic Precipitators

Electrostatic precipitation is a method of dust collection that uses electrostatic forces. They have been successfully used for removal of fine dusts from all kinds of waste gases with very high efficiencies (98-99%). Particles as small as  $0.1\mu$  can be removed.

Basically, an ESP consists of six major components,

1. A source of high voltage
2. Discharge electrodes and collecting electrodes
3. Inlet and outlet for the gases
4. A hopper for disposal of collected material
5. An electronic cleaning system
6. An outer casing form an enclosure around the electrodes (precipitator shell)

### 4.6.1 Principle:

Electrostatic precipitators (ESP) are particulate collection devices that utilise electrical energy directly to assist in the removal of the particulate matter. In an ESP, the gas containing aerosols is passed between two electrodes. Out of the two electrodes, one is a discharging electrode (anodic) and the other a collecting electrode (cathodic). Electric potentials as high as 40-60 KV are used. Because of such high voltage, a powerful ionising field is formed. This ionisation creates an active glow zone (blue electric discharge) called 'corona'. As the particulates in the carrier gas pass through this field, they get charged and migrate to the oppositely charged collecting electrode. The particles once deposited on the collecting electrode, they are removed mechanically by rapping, vibration or washing and collected in the hopper at the bottom.

Thus four steps in the process involved are,

- 1) Gas ionisation – charging of particulates
- 2) Migration of particles to the collector
- 3) Neutralisation of the charge at collector
- 4) Removal of collected particles

### 4.6.2 Types of ESPs:

ESPs can be grouped, or classified according to a number of different features in their design.

- Based on the structural design and operation of the discharge electrodes (Ex: rigid-frame, wires or plate) and collection electrodes (Ex: pipe or plate type ESP)

- Based on the method of charging (Ex: single-stage or two-stage)
- Based on the method of particle removal from collection surfaces (Ex: wet or dry ESP)

These categories are not mutually exclusive. For example, an ESP can be a rigid-frame, single-stage, plate-type ESP as described below.

### Single stage and two stage ESPs:

ESPs are classified by the number of stages used to charge and remove particles from a gas stream.

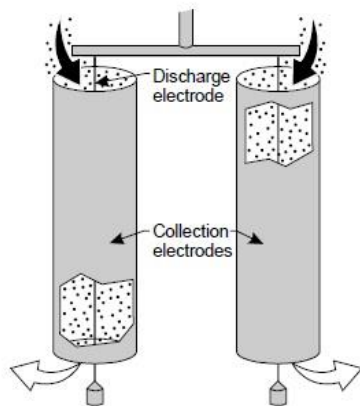
A **single-stage** precipitator uses high voltage to charge the particles, which are then collected within the same chamber on collection surfaces of opposite charge.

In a **two-stage** precipitator, particles are charged by low voltage in one chamber, and then collected by oppositely charged surfaces in a second chamber.

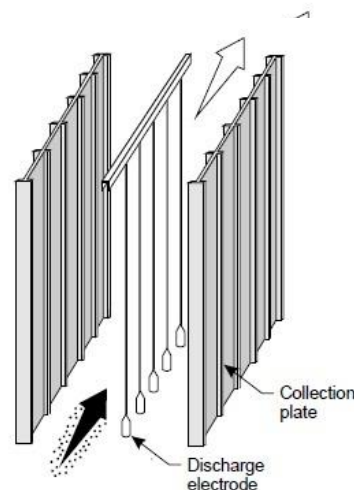
Almost all industrial precipitators are of single stage design. Usually two stage precipitator is used for lightly concentrated gases and single stage for more heavily concentrated industrial gas streams.

Single-stage ESPs use very high voltage (50 to 70 kV) to charge particles. After being charged, particles move in a direction perpendicular to the gas flow through the ESP, and migrate to an oppositely charged collection surface, usually a plate or pipe. Particle charging and collection occurs in the same stage and same chamber. Thus, the precipitators are called single-stage ESPs.

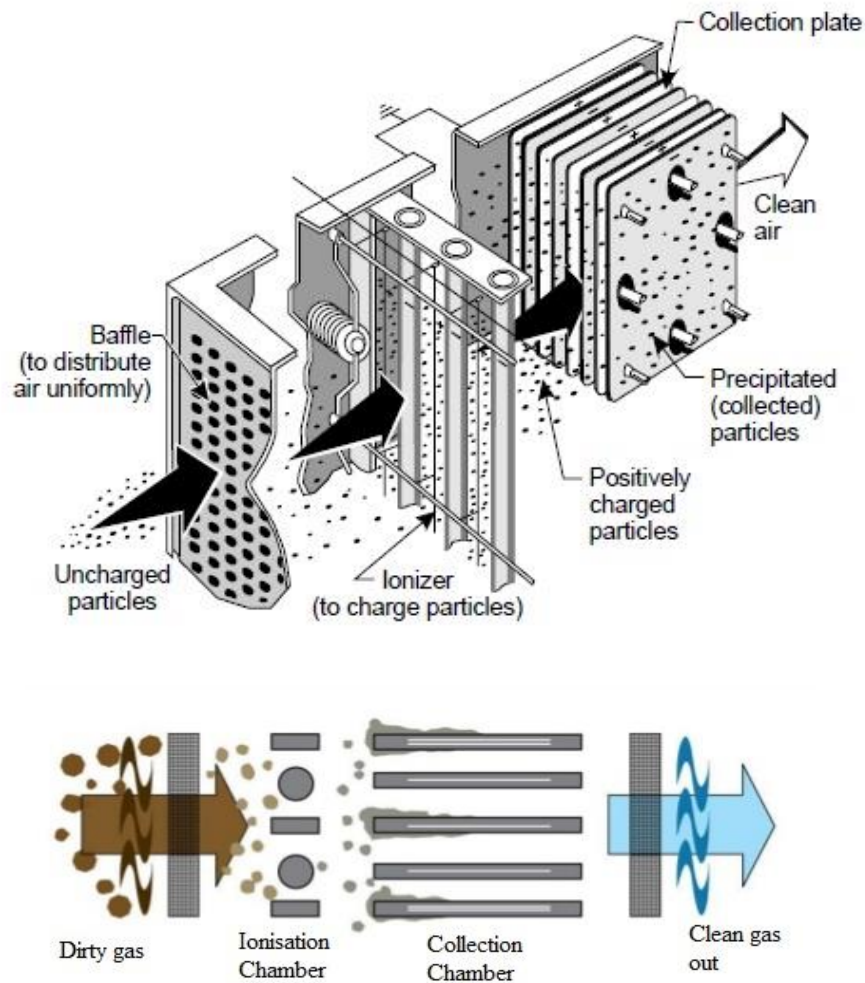
The two-stage precipitator differs from the single-stage precipitator in both design and amount of voltage applied. The two-stage ESP has separate particle charging and collection stages as shown in the figure. The ionizing stage consists of a series of small, **positively** charged wires equally spaced 2.5 to 5.1 cm from parallel grounded tubes/pipes. A corona discharge between each wire and a corresponding tube charges the particles suspended in the air flow as they pass through the ionizer. The direct-current potential applied to the wires is approximately 12 to 13 kV. The second stage consists of parallel metal plates less than 2.5 cm apart. The particles receive a positive charge in the ionizer stage (first chamber) and are collected at the collector plates in the second stage (second chamber).



**Figure: Single - stage Pipe type ESP**



**Figure : Single - stage Plate type ESP**

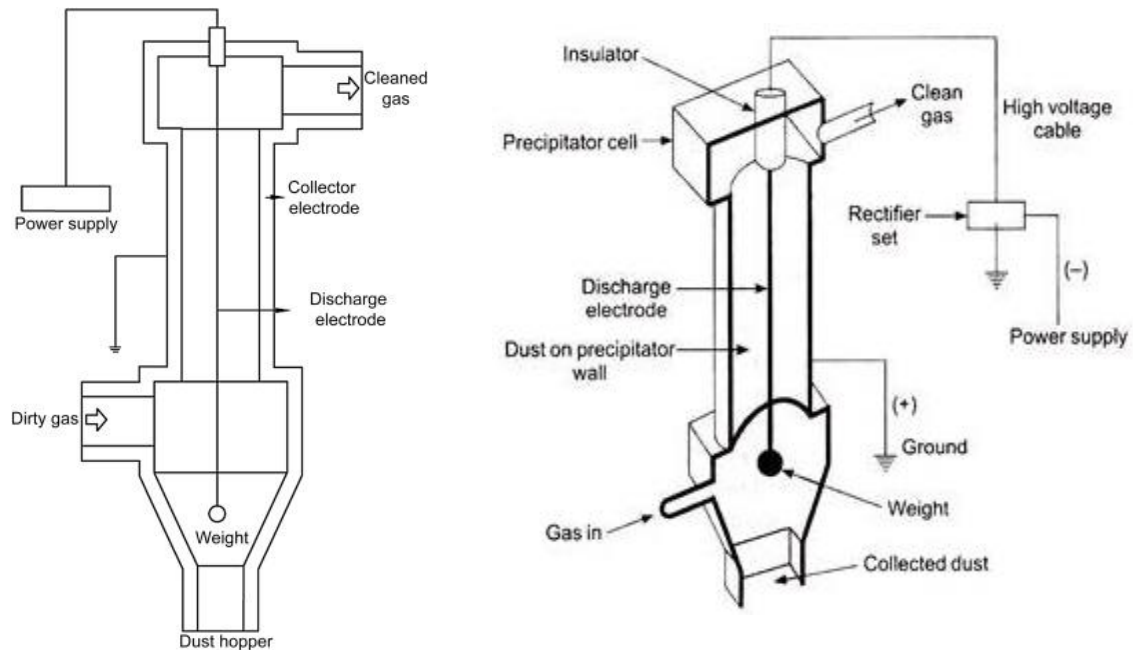


**Figure: Two – stage ESP**

### **Tubular and Plate ESPs:**

**Tubular or pipe type** precipitators consist of cylindrical collection electrodes (tubes) with discharge electrodes (wires with small radius of curvature) located in the center of the cylinder (figure). The wires/discharge electrodes must be weighted to keep them straight and in the center of cylinders. Dirty gas flows into the tubes, where the particles are charged. The charged particles are then collected on the inside walls of the tubes. Collected particles are removed by rapping of pipes or washing the pipes with water sprays located directly above the tubes. The tubes may be formed as a circular, square, or hexagonal honeycomb with gas flowing upward or downward. A tubular ESP is tightly sealed to minimize leaks of collected material. Tube diameters typically vary from 0.15 to 0.31m, with lengths usually varying from 2 to 5m. Spacing between discharge electrode and collection electrode ranges from 8 to 20cm.

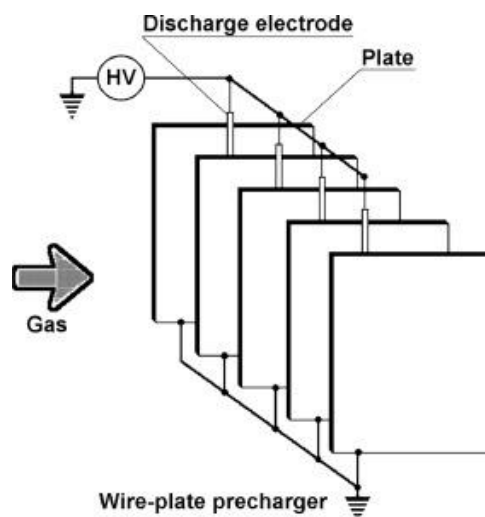
Tubular precipitators are generally used for collecting mists or fogs, and are most commonly used when collecting particles that are wet or sticky. Tubular ESPs have been used to control particulate emissions from sulfuric acid plants, coke oven byproduct gas cleaning (tar removal), and iron and steel sinter plants.



**Figure : Diagrams showing Tubular or pipe type ESP**

**Plate** electrostatic precipitators primarily collect dry particles and are used more often than tubular precipitators. Plate ESPs can have wire, rigid-frame, or occasionally, plate discharge electrodes. Figure shows a plate ESP with wire discharge electrodes. Dirty gas flows into a chamber consisting of a series of discharge electrodes that are equally spaced along the center line between adjacent collection plates. Charged particles are collected on the plates as dust, which is periodically removed by rapping or water sprays. Discharge wire electrodes are approximately 0.13 to 0.38cm in diameter. Collection plates are usually between 3 and 6m high. For ESPs with wire discharge electrodes, the plates are usually spaced from 15 to 35cm apart. For ESPs with rigid-frame or plate discharge electrodes, plates are typically spaced 30 to 38cm apart and 8 to 12m in height.

Plate ESPs are typically used for collecting fly ash from industrial and utility boilers as well as in many other industries including cement kilns, glass plants and pulp and paper mills.



#### 4.6.3 Advantages and disadvantages of ESPs:

**Advantages of ESPs:**

1. High collection efficiency
2. Particles as small as  $0.1\mu$  can be removed.
3. Low maintenance and operating costs
4. Low pressure drop
5. Satisfactory handling of large quantities of high temperature gases
6. Treatment time is negligible
7. Cleaning is easy

**Disadvantages of ESPs:**

1. High initial cost
2. Space requirement is more because of the larger size of the equipment
3. Possible explosion hazards
4. Precautions are necessary to maintain safety during operation.
5. Poisonous gas 'Ozone' is produced during gas ionization.

**4.6.4 Applications of ESPs:**

The important applications of ESP are listed in the table below.

Sl. No.	Industry	Application
1	Cement factories	Cleaning of flue gas from cement kilns, recovery of cement dust from kilns.
2	Pulp and paper	Soda-Fume recovery in Kraft pulp mills
3	Steel plants	Cleaning blast furnace gas, removing tars from coke over gases, cleaning open hearth and electric furnace gases.
4	Chemical Industries	Collection of Sox. Phosphoric Acid mist, cleaning various types of gases i.e., hydrogen, CO <sub>2</sub> , SO <sub>2</sub> , Removing dust from elemental phosphorus in the vapor state
5	Petroleum industry	Recovery of catalyst
6	Carbon black industry	Agglomeration and collection of carbon black
7	Thermal Power plants	Collecting Fly ash from coal fired boilers.

**4.6.5 Design considerations of ESP**

1. The efficiency of the ESP is given by

$$\eta = 1 - e^{\frac{(-V_p \cdot A_c)}{Q}}$$

Where,



Q= Gas flow rate

V<sub>p</sub>= Drift velocity or migration velocity

**Note:** A<sub>c</sub>= Total collection area if Q is total gas flow rate.

And also A<sub>c</sub> = Area of the one collecting electrode if Q is considered as gas flow rate in each channel.

2. Gas flow rate is calculated by

$$Q = \frac{\pi D^2}{4} \times V_g \quad \text{For pipe or tubular ESP}$$

$$Q = HS \times V_g \quad \text{For parallel plate ESP}$$

Where ,

D= Diameter of the cylinder (0.1 to 0.5m)

H= height of the collecting electrode (2 to 6m)

S= Spacing between the plates

3. Area of collecting electrode is calculated by

$$A_c = \pi DL \quad \text{For pipe type ESP}$$

$$A_c = 2HL \quad \text{For plate type ESP}$$

Where,

L= length of the collecting electrode

If many number of channels are there, then total collection area A<sub>c</sub> = 2HL x n

Where n is the number of channels.

4. Migration / Drift velocity is the velocity of particles migrating towards attractive collection electrodes after being charged in the corona field. It depends upon different operational quantities like electric field strength, particle size, viscosity of gas and dielectric & resistivity properties of the dust. V<sub>p</sub> normally ranges from 0.05 to 0.2m/s.

The drift velocity is given by

$$V_p = a \times d_p$$

d<sub>p</sub> = diameter of the particles

a = constant and is a function of voltage applied

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#### Problem 4.13:

Design a parallel plate type ESP with 10 channels to handle 10000m<sup>3</sup>/hr of gas for efficiency of 90%, 99% and 99.9%.

Soln: Given Q= 10000 m<sup>3</sup>/hr = 2.78m<sup>3</sup>/sec

n= no. of channels = 10

Assume V<sub>p</sub> = 0.1m/sec and H= 2m

Area of each collecting plate 2HL = 4L m<sup>2</sup>

For 10 channels, total collecting area = 2HL x n = 40L m<sup>2</sup>

$$\eta = 1 - e^{\frac{(-V_p \cdot A_c)}{Q}}$$

$$\text{For } 90\%, Ac = \frac{-Q}{v_p} \ln(1 - \eta) = \frac{-2.78}{0.1} \times \ln(1 - 0.90) = 64.011 m^2$$

64.011m<sup>2</sup> is the total collection area,

Then length of each collecting plate can be calculated as,

$$40L = 64.011 m^2$$

$$L = 1.6 m$$

$$\text{For } 99\%, Ac = \frac{-Q}{v_p} \ln(1 - \eta) = \frac{-2.78}{0.1} \times \ln(1 - 0.99) = 128.023 m^2$$

$$40L = 128.023 m^2$$

$$L = 3.20 m$$

$$\text{For } 99.9\%, Ac = \frac{-Q}{v_p} \ln(1 - \eta) = \frac{-2.78}{0.1} \times \ln(1 - 0.999) = 192.03 m^2$$

$$40L = 192.03 m^2$$

$$L = 4.80 m$$

----- OR -----

Soln: Given  $Q = 10000 \text{ m}^3/\text{hr} = 2.78 \text{ m}^3/\text{sec}$

$n = \text{no. of channels} = 10$

Gas flow rate in each channel = total  $Q/n = 2.78/10 = 0.278 \text{ m}^3/\text{sec}$

Assume  $V_p = 0.1 \text{ m/sec}$  and  $H = 2 \text{ m}$

Area of each collecting plate  $2HL = 4L \text{ m}^2$

$$\eta = 1 - e^{\frac{(-V_p \cdot Ac)}{Q}}$$

$$\text{For } 90\%, Ac = \frac{-Q}{v_p} \ln(1 - \eta) = \frac{-0.278}{0.1} \times \ln(1 - 0.90) = 6.4011 m^2$$

$$4L = 6.4011 m^2$$

$$L = 1.6 m$$

$$\text{For } 99\%, Ac = \frac{-Q}{v_p} \ln(1 - \eta) = \frac{-0.278}{0.1} \times \ln(1 - 0.99) = 12.8023 m^2$$

$$4L = 12.8023 m^2$$

$$L = 3.20 m$$

$$\text{For } 99.9\%, Ac = \frac{-Q}{v_p} \ln(1 - \eta) = \frac{-0.278}{0.1} \times \ln(1 - 0.999) = 19.203 m^2$$

$$4L = 19.203 m^2$$

$$L = 4.80 m$$

**(Note:** For total collection area  $Ac$  of all the collecting plates, consider  $Q$  as the total gas flow rate. If you take  $Ac$  as area of a single collecting electrode plate, then  $Q$  is taken as gas flow rate in each channel i.e., total  $Q/n$ )

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**Problem 4.14:**

Design a parallel plate ESP with an efficiency of 90, 99 and 99.9% of removal of  $0.75\mu\text{m}$  sized fly ash from a cement industry with gas flow rate of  $10\text{m}^3/\text{sec}$ . Pilot plant studies showed that drift velocity  $V_p = 2.5 \times 10^5 \text{ dp m/sec}$ .

Soln: Given  $Q = 10\text{m}^3/\text{sec}$

$$dp = 0.75\mu\text{m} = 0.75 \times 10^{-6}\text{m}$$

$$V_p = 2.5 \times 10^5 \times dp = 2.5 \times 10^5 \times 0.75 \times 10^{-6} = 0.1875\text{m/sec}$$

Total collection area,

For 90% efficiency,

$$\eta = 1 - e^{\frac{(-V_p \cdot Ac)}{Q}}$$

$$\frac{-V_p \cdot Ac}{Q} = \ln(1 - \eta)$$

$$Ac = \frac{-Q}{V_p} \ln(1 - \eta) = \frac{-10}{0.1875} \times \ln(1 - 0.90) = 122.8\text{m}^2$$

For 99% efficiency,

$$Ac = \frac{-Q}{V_p} \ln(1 - \eta) = \frac{-10}{0.1875} \times \ln(1 - 0.99) = 245.6\text{m}^2$$

For 99.9% efficiency,

$$Ac = \frac{-Q}{V_p} \ln(1 - \eta) = \frac{-10}{0.1875} \times \ln(1 - 0.999) = 368.4\text{m}^2$$

Assume  $L = 10\text{m}$ ,  $H = 2\text{m}$ ,  $S = 0.15\text{m}$

$\therefore$  Area of each channel =  $2HL = 2 \times 10\text{m} \times 2\text{m} = 40\text{m}^2$

$\therefore$  Number of channels

$$1) \text{ For 90\% efficiency, } n = \frac{122.8}{40} = 3$$

$$2) \text{ For 99\% efficiency, } n = \frac{245.6}{40} = 6$$

$$3) \text{ For 99.9\% efficiency, } n = \frac{368.4}{40} = 9$$

$\therefore$  Number of plates required for 90, 99 and 99.9% efficiency are 4, 7 and 10 respectively.

**Problem 4.15:**

A plate ESP is used in a cement plant for removing dust particles consist of 10 equal channels. The spacing between plates is 15cm and the plates are 3m high and 3m long. Unit handles  $20000\text{m}^3/\text{hr}$  of gas.

1. What is the efficiency of collection plates?
2. What should be the length of the plate for achieving efficiency of 99% keeping other parameters same?

Soln: Given  $n=10$

$L=3\text{m}$ ,  $H=3\text{m}$

$Q=20000\text{ m}^3/\text{hr} = 20000/3600 = 5.555\text{m}^3/\text{sec}$

Assume  $V_p=0.1\text{m}/\text{sec}$

Total collection area  $A_c = 2HL \times n = 2 \times 3 \times 3 \times 10 = 180\text{m}^2$

$$\eta = 1 - e^{\frac{(-V_p \cdot A_c)}{Q}}$$
$$\eta = 1 - e^{\frac{-0.1 \times 180}{5.555}}$$
$$\eta = 0.9608 = 96.08\%$$

Now to increase the efficiency of 96.08% to 99%,

Total collection area  $A_c = 2HL \times n = 2 \times 3 \times L \times 10 = 60L\text{ m}^2$

$$\eta = 1 - e^{\frac{(-V_p \cdot A_c)}{Q}}$$
$$0.99 = 1 - e^{\frac{-0.1 \times 60L}{5.555}}$$
$$e^{\frac{-0.1 \times 60L}{5.555}} = 1 - 0.99$$
$$\frac{-0.1 \times 60L}{5.555} = \ln(0.01)$$

$L=4.26\text{m}$

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#### Problem 4.16:

Dust has particles with migration velocity of  $0.25\text{m}/\text{sec}$ . For a total air flow of  $65\text{m}^3/\text{sec}$ , what must be the number of collecting plates each having area of  $100\text{m}^2$ . Assume collection efficiency to be 95%.

Soln: Given  $Q=65\text{m}^3/\text{sec}$ ,  $V_p=0.25\text{m}/\text{sec}$ ,  $A=100\text{m}^2$

$$\eta = 1 - e^{\frac{(-V_p \cdot A_c)}{Q}}$$
$$\frac{-V_p \cdot A_c}{Q} = \ln(1 - \eta)$$

$$\text{Total collection area } A_c = \frac{-Q}{V_p} \ln(1 - \eta) = \frac{-65}{0.25} \times \ln(1 - 0.95) = 778.8\text{m}^2$$

$$\text{Number of plates} = \frac{\text{Total collection area}}{\text{Area of each plate}} + 1$$

$$\text{Number of plates} = \frac{778.8}{100} + 1 = 8.78 \cong 9 \text{ Plates}$$

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**Problem 4.17:**

Design a tubular ESP for the gas flow rate of 2.78m<sup>3</sup>/sec with 30cm diameter tubes for efficiencies of 90%, 99% and 99.9%. Assume inlet gas velocity 1m/sec.

Soln: Given Q=2.78 m<sup>3</sup>/sec, D=0.3m, V<sub>g</sub>= 1m/sec  
Assume V<sub>p</sub> = 0.075m/sec

$$\begin{aligned} & \text{Number of cylinders of 0.3m dia required to maintain an inlet gas velocity of 1m/sec} \\ &= \frac{\text{total gas flow rate}}{\text{gas flow rate in each tube}} \\ &= \frac{2.78}{\pi/4 \times D^2 \times V_g} = \frac{2.78}{\pi/4 \times 0.3^2 \times 1} = 39.3 \text{ say } 40 \end{aligned}$$

Corrected gas flow rate for each tube = 2.78/40 = 0.0695m<sup>3</sup>/sec

$$\eta = 1 - e^{\frac{(-V_p \cdot A_c)}{Q}}$$

$$\frac{-V_p \cdot A_c}{Q} = \ln(1 - \eta)$$

$$\frac{-V_p \cdot \pi D L}{Q} = \ln(1 - \eta)$$

$$L = \frac{Q}{-V_p \cdot \pi \cdot D} \ln(1 - \eta)$$

$$L = \frac{0.0695}{-0.075 \times \pi \times 0.3} \ln(1 - 0.90) = 2.26m$$

$$L = \frac{0.0695}{-0.075 \times \pi \times 0.3} \ln(1 - 0.99) = 4.52m$$

$$L = \frac{0.0695}{-0.075 \times \pi \times 0.3} \ln(1 - 0.999) = 6.78m$$

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**Problem 4.18:**

A cement plant was emitting flue gases at the rate of 20000m<sup>3</sup>/hr. Assuming inlet gas velocities of 2m/sec, design a tubular ESP with 0.20m diameter with 7 cylinders to achieve the efficiency of 90% and 95%.

Soln: Given Q= 20000 m<sup>3</sup>/hr = 5.555 m<sup>3</sup>/s  
V<sub>g</sub>= 2m/s, D= 0.2m  
Assume V<sub>p</sub>= 0.2m/sec

Gas flow rate in each tube = total flow / no. of tubes = 5.555 / 7 = 0.7935 m<sup>3</sup>/s

$$L = \frac{Q}{-V_p \cdot \pi \cdot D} \ln(1 - \eta)$$

$$\text{For } 90\%, \quad L = \frac{0.7935}{-0.2 \cdot \pi \cdot 0.2} \ln(1 - 0.9) = 14.53\text{m}$$

$$\text{For } 95\%, \quad L = \frac{0.7935}{-0.2 \cdot \pi \cdot 0.2} \ln(1 - 0.95) = 18.91\text{m}$$

**Problem 4.19:**

A cylindrical ESP of diameter 0.3m is used for separating pulverised coal flyash particles from a furnace gas stream. If the volumetric flow rate of the gas is 0.05m<sup>3</sup>/sec, what will be the length of the precipitator for obtaining a collection efficiency of 99.9%? What percent change in electrode collection area is required to increase the collection efficiency from 99.9 to 99.95%?

Soln: Given Q= 0.05m<sup>3</sup>/sec, D= 0.3m  
Assume V<sub>p</sub>= 0.1m/sec

Area of the collecting electrode Ac = π x D x L = 0.3 π L

For 99.9%,

$$\eta = 1 - e^{\frac{(-V_p \cdot Ac)}{Q}}$$

$$Ac = \frac{-Q}{V_p} \cdot \ln(1 - \eta)$$

$$Ac = \frac{-0.05}{0.1} \ln(1 - 0.999) = 3.45\text{m}^2$$

$$0.3 \pi L = 3.45$$

$$L = 3.661\text{m}$$

For 99.95%,

$$Ac = \frac{-Q}{V_p} \cdot \ln(1 - \eta)$$

$$Ac = \frac{-0.05}{0.1} \ln(1 - 0.9995) = 3.80\text{m}^2$$

$$\text{Percentage increase in collection area} = \frac{\text{Final value} - \text{Initial value}}{\text{Initial value}} = \frac{3.80 - 3.45}{3.45} = 10.14\%$$

**Problem 4.20:**

An industrial installation has two ESPs, each designed to handle 48m<sup>3</sup>/sec. The collecting surface per precipitator is 1440m<sup>2</sup>. For a migration velocity of 0.13m/sec, calculate the efficiency of each precipitator. If one of the precipitator is shut down and it is decided to treat the total gas volume in the other precipitator, calculate the new efficiency.

Soln: Given Q= 48m<sup>3</sup>/sec, Ac = 1440m<sup>2</sup>, V<sub>p</sub>= 0.13m/sec

$$\eta = 1 - e^{\frac{(-V_p \cdot Ac)}{Q}}$$

$$\eta = 1 - e^{\frac{-0.13 \times 1440}{48}}$$

$$\eta = 0.979 = 97.9\%$$

If one of the precipitator is shut down and it is decided to treat the total gas volume in the other precipitator,

$$\eta = 1 - e^{\frac{-0.13 \times 1440}{48 \times 2}}$$

$$\eta = 0.8577 = 85.77\%$$

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