Air Pollution Control

Industrial and Petroleum Pollution Engineering

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1.Introduction

Air Pollution (is not new problem)

Air pollution is the present of contaminated substances in air in such concentrations that can produce harmful effects on man and his environment.

Pollutants

Pollutants are undesirable materials that cause pollution if they present in such concentration in air. Thesematerials may be physical, chemical or biological such as gases, particulate, radioactive materials, and many others.

Type of air pollutants:

Air pollutants are classified based on state of matter into

1. Particulate Matter (liquid drops or solid particles)
2. Gaseous pollutants

Classification of air pollutants

Air pollutants emitted into the atmosphere by natural and anthropogenic sources. These pollutants can be classifiedaccording to their origin into primary and secondary pollutants

1) **Primary pollutants**

   They are that are directly emitted into atmosphere from natural sources or are produced as a result of human activity. Some of common pollutants of this group are:

   - **Particulate Matter**
   - **Gaseous pollutants:** such as
     1. Carbon monoxide, CO
     2. Carbon dioxide, CO_2
     3. Sulfur dioxide, SO_2
     4. Hydrogen sulfide, H_2S
     5. Nitrogen oxides, NO, NO_2, N_2O
     6. Ammonia, NH_3
     7. Volatile organic Compounds, VOC

2) **Secondary pollutants**

   They are those that are formed in the atmosphere by chemical interaction among primary pollutants and normal atmospheric constituents.Some of the common pollutants, which belong to this group, are:

1. Ozone, O_3
2. Hydrogen peroxide, H_2O_2
3. Peroxyacetyl nitrate, PAN
4. Aldehydes such as formaldehyde
5. Organic hydroperoxides

1) ParticulateMatter:

Particulate matter (PM) (also called airborne particulate) is the name for a wide range of atmospheric particles that are small enough to be carried by the air. They can be solid or liquid, or mixture of both. Particulates can be composed of inert or extremely reactive materials. The classification of various particulates may be made as:

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

Smoke: Itproduced Fine particles of size ranging from 0.01 to 1 μm diameter, which is formed by incomplete combustion of organics.

Fumes: They are finely divided solid particles of the size ranging from 0.1 to 1 μm. they are produced during sublimation, distillation and molten metal processing.

Mist: Liquid droplets generally smaller than 10 μm, which are formed by condensation in the atmosphere or released from industrial operations.

Fog: It is the mist in which the liquid is water.

Smog: It is a mixture of smoke and fog

Aerosol: They are small particles, either solid or liquid, suspended in a gas. The aerosol particle size ranges from 0.01 to 100 μm.

Sources of air pollutants

Pollutants are emitted to air as a result of natural processes as well as due to human activity:

1) Natural sourcessuch as oceans, volcanoes, swamps, biologically decaying organic matter, desert and non-desert areas, forest and forest fires.
2) Created by human activities, which gives rise to air borne pollutants, are:

(a) **Industrial sources:** There are numbers of industries which are sources of air pollution. Petroleum refinery are the major source of gaseous pollutants, Cement factories emit plenty of dust, stone crushers, food and fertilizers industries which emit gaseous pollutants, chemical manufacturing industries which emit acid vapors in air,fossil fuel combustors, metallurgical and metal processing industries, food biochemical and pharmaceutical industries

(b) **Thermal power stations:** The chief pollutants are fly ash,SO_2, and other gases and hydrocarbons.

(c) **Automobiles:** the source of emission of vehicles exhaust. This exhaust produced many air pollutants such as CO, NO_x and lead oxides

Air pollution source categories

There are four types of air pollution sources:

- **Point or stationary sources:**such as electric power plants, oil refineries, industrial facilities, and factories.
- **Mobile sources:** such as cars, buses, airplanes, trucks, and anything else that moves and pollutes the air.
- **Area sources:**small and individual sources such as agricultural areas, cities, wood burning fireplaces,
- **Natural sources such as wind-**blown dust, wildfires, and volcanoes.

Effects of air pollutants

Air pollutants affected the ecosystem in various ways. The effects are manifested by bringing about some changes in an ecosystem directly or indirectly. The overall effects may be classified as:

1. Effects on atmospheric properties.
2. Effects on vegetation.
3. Effects on animals.
4. Effects on human beings.
5. Effects on land and water bodies.
6. Effect on material.

Atmosphere of earth

The atmosphere comprises of a mixture of gases surrounding the planet earth. Itacts as a gaseous blanket protecting the earth by absorption the dangerous ultraviolet solar radiation (UV), warming the surface of the earth through the heat retention (greenhouse effect).The greenhouse effect' which keeps the earth warms enough to sustain the life on the earth.It extends up to about 500 km above the surface of the earth.

Composition of Earth's atmosphere

Normal composition of clean, dry air at or near the sea is as following:

- The major gases of the atmosphere are: N_2, O_2, andWater vapor (H_2O).
- The minor gases in the atmosphere are: Argon (Ar) and carbon dioxide (CO_2).
- The trace gases in the atmosphere are: Methane, Nitrous oxide, Hydrogen, ozone. Nitrogen dioxide, Carbon monoxide, Ammonia, Neon, Helium, etc.

Layers of Earth's atmosphere:

The atmosphere which extended up to about 500 km above the earth's surface can be broadly divided into four major regions with widely varying temperature even within each region. These regions are:

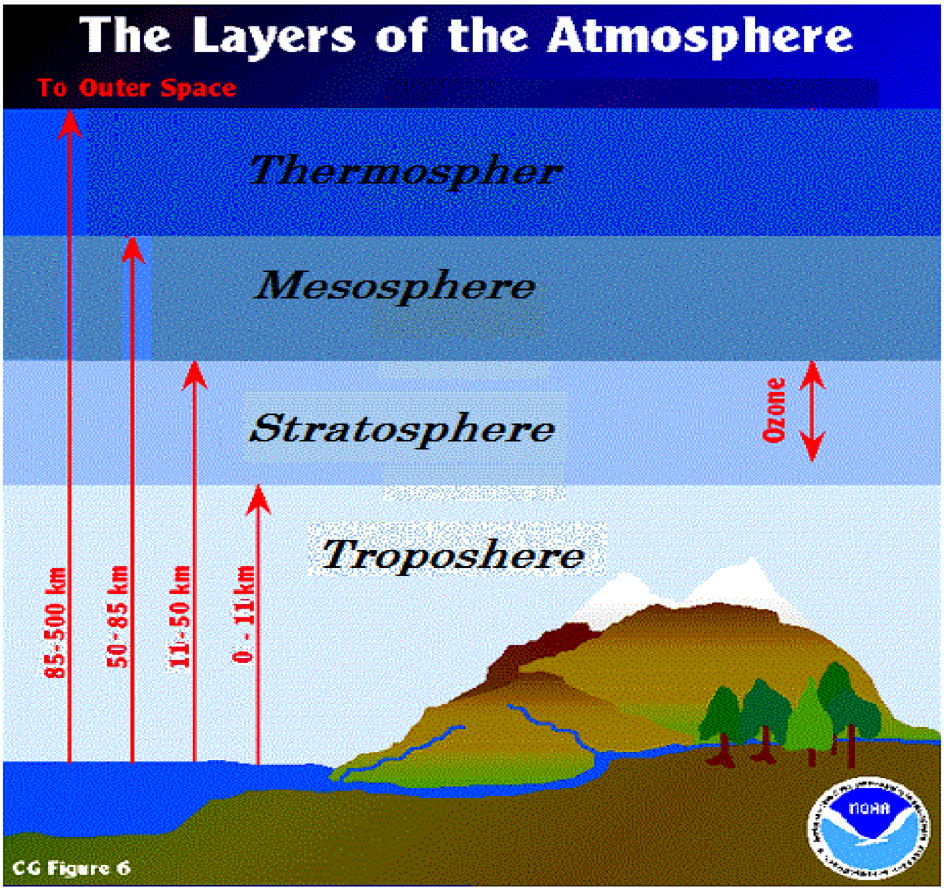


Fig.1.1 Layers of air atmosphere**Atmosphere of earth**

1. Troposphere

This layer is closest to the Earth's surface, and extends up to an altitude of 11 km. It is also the layer where majority of our weather occurs. This layer is primary composed of 78% nitrogen and 20.9% oxygen (make up air) and other gases including greenhouse gases. All atmospheric water vapor or moisture is found in this layer.

1. **Stratosphere:**

This layer lies directly above the troposphere. It extends about 11-50 km above the Earth's surface. It contains the ozone layer. About 90% of the ozone in the Earth's atmosphere is found in this region. The ozone layer absorbs the ultraviolet radiation from the Sun. very little weather occurs in the stratosphere.

2. **Mesosphere:**

This area is directly above the stratosphere, it extends about 50-85 km above the Earth's surface.

3. **Thermosphere:**

This layer extends from 85-500 km above the Earth's surface.

Major greenhouse gases are

Greenhouse Gas	Chemical symbol	Sources
Water vapor	H_2O	Naturally occurring. Rising global temperatures may act to increase water vapor in the atmosphere.
Carbon Dioxide	CO_2	Naturally occurring. Also it occurs as a result of human activities such as burning of coal, oil, and natural gases.
Methane	CH_4	It produces by both the natural and human process. It is produced when plants decay and where there is very little air. It is also called swamp gas because it is abundant around the water and swamps.
Nitrous Oxide	N_2O	Generated by burning fossil fuels, in the manufacture of nitrogen fertilizer and by use of this fertilizers in agricultural.
Ozone	O3	Naturally occurring. Ultraviolet radiation and oxygen interacted to form ozone in atmosphere. Ozone layer helps to protect the earth from ultra-violet radiation
Chlorofluorocarbons, CFCs	Various compounds	Increasing the use of CFCs tend to destroy ozone in the upper atmosphere causing depletion the ozone layer.

Among the greenhouse gases, water vapor and carbon dioxide are the most important greenhouse gases.

The greenhouse gases acting like the greenhouse allow the solar radiation in the range 300 to 2500 nm (e.g. near UV, visible and near IR region), while filtering the dangerous UV radiations (e.g. < 300 nm)

2. Regional and Global Problem

2.1. Global warming and greenhouse effects

Greenhouse Effect:

The solar energy comingfrom the sun passes through the atmosphere gases to reach the Earth's surface. Roughly one-third of this radiation is reflected directly back to the space. The remaining two-thirds are absorbed by the earth's surface and warm it. A long wave infrared (IR) radiation (heat) emitted from the Earth's surface. Some of IR radiation passes through the atmosphere into the space and some of it is absorbed by certain gases in the atmosphere, called greenhouse gases and re-emitted in all direction.The effect of this is to warm the Earth's surface and the lower atmosphere. This phenomenon is called the greenhouse effect. These gases essentially act as blanket, making the earth's surface warmer than otherwise it would be.

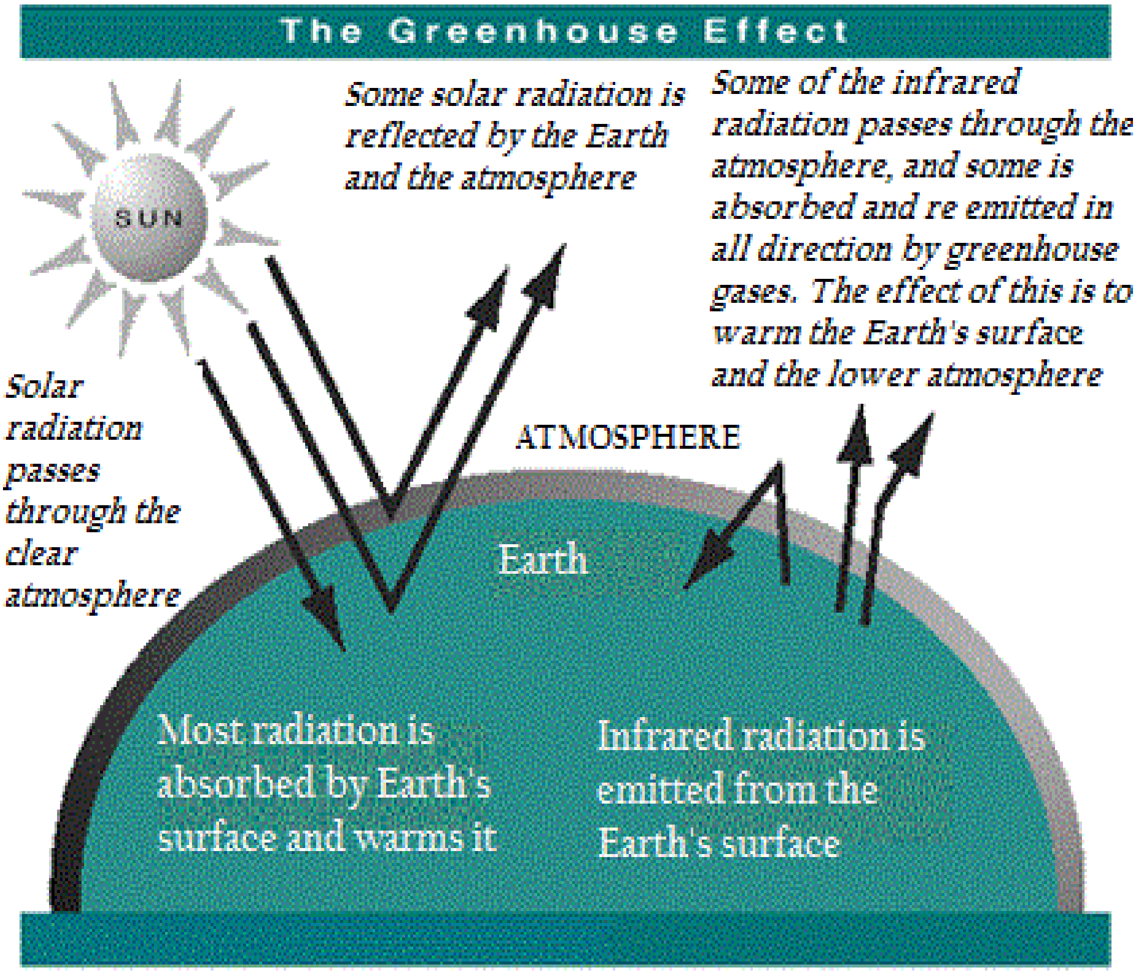


Fig.2.1 The Greenhouse effects

Important of greenhouse effect:

The important of greenhouse effect is:

1. To maintain the average temperature of world. The average temperature should remain constant and governs all life process.
2. To maintain the sea level.
3. The polar ice caps remain intact.

Global warming

Global warming is increase in global average temperature near the Earth's surface as a result ofincreasing in concentration of greenhouse gases in the atmosphere from human activities. If more greenhouse gases are added to the atmosphere from human activities, they will absorb more of infrared radiation reflected by the Earth's surface. The surface and the lower atmosphere will warm further. This extra warming is called the enhanced greenhouse effect. Enhanced greenhouse effect causes global warming.

Effects of global warming

The following effects will results from the global warming (rising temperature):

1- Thermal expansion of the water and melting of polar ice caps would cause sea level to rise.

2- Changes in regional wind systems which would influence global rainfall distribution and lead to redistribution and frequently of flood, drought, and forest fires.

3- Growth in insect population: Climate change would create favorable conditions for growth in insect population, which this have bad effect on agriculture and human health.

4- Disrupts the Water supplyand droughts would be more common.

International action to reduce global warming

Kyoto protocol : Held in December 1997, at the city of Kyoto. The Kyoto is a legally binding agreement under which 37 developing countries committed themselves to reduce their annual greenhouse gases emission to an average of5% less than 1990 levels by 2012 because they are responsible for 36% of the world CO_2 emission. Now more than 500 cities around the world have taken up programs to reduce their greenhouse gases emission.

Controlling global warming

1- Reduce deforestation and develop way to sustainable agriculture.

2- Use of technologies to absorb CO_2 from emission.

3- Increased absorption of CO_2 by planting more trees.

4- Sequester CO_2 in deep ocean.

5- Increased dependence on renewable energy source.

2.2. The Ozone Layer and Ozone Layer Depletion

The Ozone Layer

The ozone layer in the stratosphere serves as a shield, protecting the earth’s surface from the suns’ ultraviolet radiation (UV). Ozone layer absorbs 97-99% of the UV radiation. As the ozone absorbs UV-radiation, it is broken into oxygen molecule and oxygen radical. The oxygen and the oxygen radical then recombine to form new ozone molecule, available to absorb more UV-radiation.

$$O_3 \xrightarrow{UV} O_2 + O^*$$

$$O_2 + O^* \longrightarrow O_3$$

Ozone layer depletion

The ozone layer depletion occurs as results of releasing of chemicals such as chlorofluorocarbons (CFCs). CFCs when first used in air conditioning and refrigeration systems valued for their non-toxic and stable properties. CFCs introduced in the lower troposphere pass through the ozone without any change and reach the stratosphere. Here, they impact by the UV-radiation and release destructive chlorine atoms:

$$CFCl_3 \xrightarrow{UV} CFCl_2 + Cl$$

(CFC-11)

$$CF_2Cl_2 \xrightarrow{UV} CF_2Cl + Cl$$

(CFC-12)

The chlorine atom quickly reacts with the ozone molecule breaking it into oxygen:

$$Cl + O_3 \rightarrow ClO + O_2$$

The ClO produced reacts with oxygen radical forming more chlorine atom that can react with more ozone

$$ClO + O^* \rightarrow Cl + O_2$$

The above reaction also removes the oxygen radial thus preventing it from recombined with the oxygen to form an ozone molecule. The overall effect is a decrease in the amount of ozone that leads to ozone removal from stratosphere.

Source of ozone layer depletion

The facts the ozone layer depletion was discovered in the mid of 1980. The main source of ozone layer depletion is

1- Chlorofluorocarbon, CFCs: CFCs are cause damage to ozone layer. When CFCs reach the upper atmosphere they are degraded by UV radiation to produce chlorine atom. This atom breaks up ozone molecules to form oxygen and ozone then disappear and depleted.

2- Nitrogen oxides: such as N_2O, NO and NO_2. These oxidesintroduced in the atmosphere byburning of fossil fuel, organic matter as well as microbial action on the nitrogenous fertilizers, which cause depletion of the ozone layer.

3- Nuclear test: Nuclear explosions release high quantity of various gases and other materials which damage the ozone layer.

International action to protect the ozone layer

<u>Montreal protocol:</u> isan international agreement signed in Montreal city of Canada in 1987. Its goal was to cut emission of CFCs into atmospheres by about 35% between 1989 and 2000.

2.3. Acid rain

Acid rain is mainly caused by the release of sulfur dioxide (SO_2) and oxide of nitrogen(NO_x) during fossil fuel combustion and the use sulfur coal and oil. When these gases are discharged into atmosphere they react with water, oxygen, and other gases in the atmosphere to form sulfuric acid, ammonium, and nitric acid. These acids then disperse over large areas because of wind patterns and fall back to the ground with rainwater as acid rain.

Unpolluted rain is naturally acidic with a pH of about 5.6 due to CO2 in the atmosphere, which reacts with rainwater forming carbonic acid (H2CO3):

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^-$$

Carbonic acid is a weak acid and the acidity in rainwater can quickly be neutralized on contact with materials. But the present of sulfuric acid or nitric acid in the atmosphere could lower the pH of rain droplets to value below 5.6 and such rain is considered acidic and it called "acid rain".

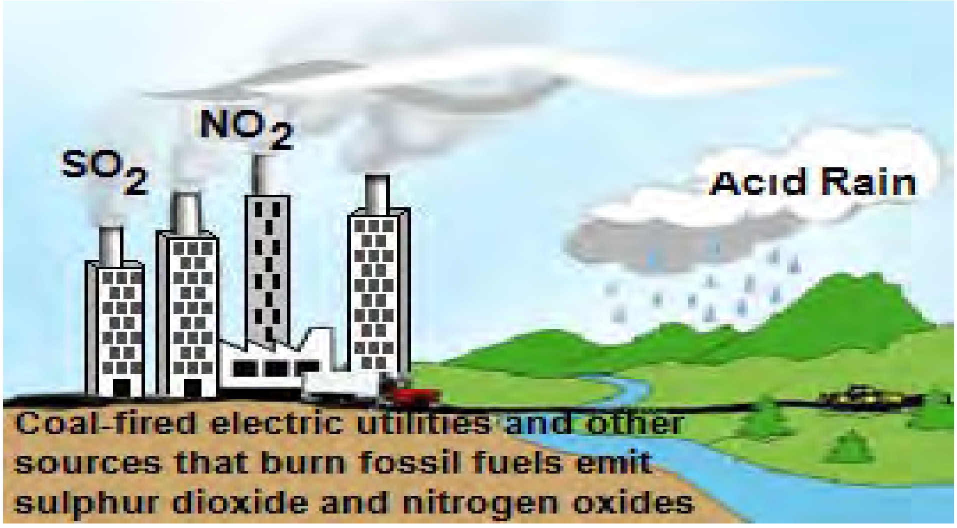


Fig.2.2 The acid rain

Effects of acid rain

The harmful effects caused by acid deposition can be categories under many effects:

1- Effects on water bodies: acid rain causes acidulation of lake and streams and contributes to damage of tree at high elevation and much sensitive forest.

2- Effect on material: acid rain accelerates the decay of building, bridge, and other structures may by corrosion.

3- Effect of human health: acid rain caused acidification of air, water and food that damage the human health. It can also release heavy metals from the pipes of the distribution systems into the potable water supply.

Chemical processes of acid formation in atmosphere

A large part of SO_2 in the atmosphere is oxidized to sulfur trioxide SO_3:

$$2SO_2 + O_2 \longrightarrow 2SO_3$$

Also SO_2 reacted with atmospheric ozone to give sulfur trioxide SO_3:

$$SO_2 + O_3 \longrightarrow SO_3 + O_2$$

Sulfur trioxide SO_3 is then quickly combined with moisture (water) in the atmosphere to form sulfuric acid mist:

$$SO_3 + H_2O \longrightarrow H_2SO_4$$

The overall reaction is:

$$2SO_2 + O_2 + 2H_2O \longrightarrow 2H_2SO_4$$

Nitrogen dioxide reacts with atomic oxygen to give nitrogen trioxide:

$$NO_2 + O \longrightarrow NO_3$$

Also NO_2 reacted with atmospheric ozone to give nitrogen trioxide NO_3:

$$NO_2 + O_3 \longrightarrow NO_3 + O_2$$

NO_3 reacted with NO_2 forming N_2O_5, which react with moisture (water) forms nitric acid:

$$NO_3 + NO_2 \longrightarrow N_2O_5$$

$$N_2O_5 + H_2O \longrightarrow 2HNO_3$$

Control strategies for acid rain

1- The use of low sulfur coal or substitution of coal by other fuels.

2- Alternative methods for power generation instead of thermal power plants, such as hydropower facilities or nuclear power.

3- Installation of flue gas desulfurization systems in large power plants can reduce emission of SO_2.

3. Meteorological Aspects of Air Pollutant Dispersion

Introduction

Air pollutants emitted from anthropogenic sourcemust first be dispersed, and diluted in the atmosphere; before these undergo various physical and photochemical and reach their receptors.Otherwise, the pollutant concentrations reach dangerous transformation levels near the source of emission.

Factors affecting the dispersion of pollutant in the air

- **Meteorological conditions** including:

Atmospheric stability

Wind speed, wind direction and turbulance

- **Emission source height**(Ground level sources such as road, traffics or high level sources such as tall chimneys).
- **The source** (fixed point such as chimney, or diffuse source such as cars)

Meteorological conditions

Dispersion of pollutant is controlled by meteorological conditions prevailing in the atmosphere. ***Hence, it is important that we understand the meteorological conditions***or factors ***that affecting the dispersion of pollutants in the atmosphere.***

The meteorological factors affecting dispersion are:

1. Atmospheric stability
2. Wind speed, wind direction and turbulence

The degree of stability of the atmosphere in turn depends on the rate of change of ambient temperature with altitude. The relation between temperature and the pressure can be explained through understanding the concept of Lapse rate.

Lapse rate

Lapserate is therate at which the Earth's atmospheric temperature decreaseswith an increase in altitude, while moving upward through the earth’s atmosphere. This represents by

$$-\frac{dT}{dz} \qquad (3.1)$$

Eq.(3.1) is the laps rate (unit of temperature/unit of altitude), T is the temperature and z is the altitude.

The relation between the temperature and the altitude Eq. (3.1), can be obtained by considering air is to be an ideal gas, as:

The pressure in the vertical direction is

$$P = \rho g z \qquad (3.2)$$

The change in the pressure in the vertical direction can be represented by the relation:

$$\frac{dP}{dz} = -\rho g \qquad (3.3)$$

where p is the atmospheric pressure, z is the altitude, ρ is the atmospheric density and g is the acceleration.

The perfect gas relationship,

$$P = \rho \frac{\overline{R}}{M} T \qquad (3.4)$$

The ratio $\frac{\overline{R}}{M}$ is the specific gas constant for air, which is represented by the symbol R, T is the absolute temperature,

$$P = \rho R T \qquad (3.5)$$

$$\rho = \frac{P}{RT} \qquad (3.6)$$

Substitution Eq. (3.6) into Eq. (3.3) gives the general expression for the variation of pressure with altitude:

$$\frac{dP}{dz} = -\frac{Pg}{RT} \qquad (3.7)$$

If we consider simple case of isothermal atmosphere, Eq. (3.7) could be integrated directly to give:

$$P = P_0 \exp\left(-\frac{g}{RT} z \right) \qquad (3.8)$$

where P_0 is the pressure at the ground level (at z=0) which is 1.013 bars.

Eq.(3) gives the exponentially decreasing pressure with altitude.

The better model for the atmospheric dependence of P and T is the polytropic atmosphere which obeys the relation,

$$T = T_0 \left(\frac{P}{P_0} \right)^{n-1/n} \qquad (3.9)$$

Substituting Eq. (3.9) for P in Eq. (3.7) and differentiating we get,

$$\frac{dT}{dz} = -\frac{n-1}{n} \frac{g}{R} \qquad (3.10)$$

Eq. (10) represents the variation of temperature with altitude for a polytropic model where the temperature decreases with altitude linearly with the slope *–(n-1)g/nR*. The decrease in temperature with altitude is known as the lapse rate.

Type of lapse rate

There are two types of lapse rate:

1. Environmental lapse rate (ELR)
2. Adiabatic lapse rate (ALR)

1. Environmental lapse rate (ELR):

This refers to the actual reduction of temperature with altitude in the stationary atmosphere (non-rising air).

Based on meteorological data, in the troposphere up to 10 km, where the temperature decreases linearly with altitude, the environmental lapse rate is found to be about 6.5 °C per kilometer as shown in Fig. 3.1. Putting this value for *dT/dz* in the Eq. 3.10 for polytropic model, we have,

$$\left(\frac{dT}{dz}\right)_{env} = -\frac{6.5°C}{1000m} - \frac{n-1}{n}\frac{g}{R} \qquad (3.11)$$

From above equations the value of *n* comes to be 1.23. The troposphere extends up to 12 km. above the troposphere is the stratosphere. In stratosphere, there are two distinct regions of temperature variation. The lower region, extending up to 25 km, has a temperature which is essentially constant, and in the upper region the temperature increase with altitude as a result of ozone layer formation. In the lower region of the stratosphere the isotherm model based on n = 1 is applicable. The temperature –altitude profiles are represented in Fig. 3.1.

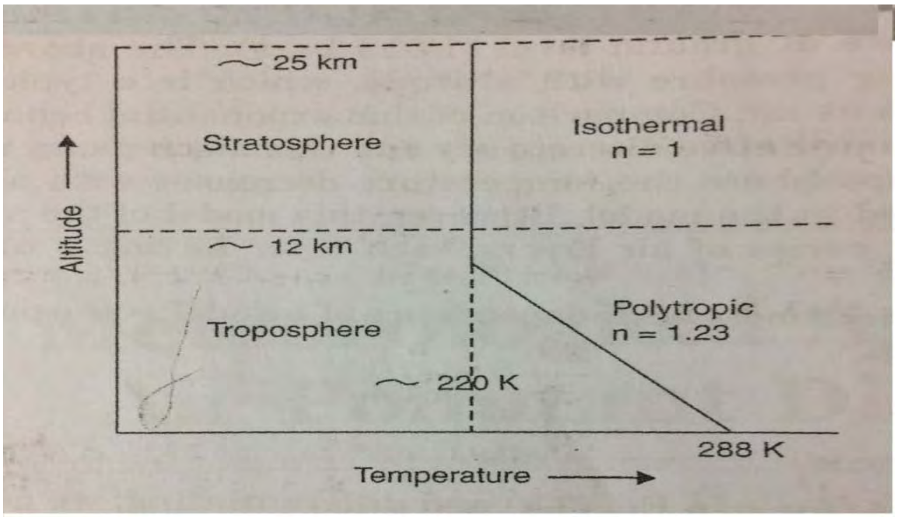


Fig.3.1 Temperature-Altitude Profiles

2. Adiabatic lapse rates (ALR):

These refer to the adiabatic decrease in temperature of an air parcel with altitude as it moves vertically without exchanging heat with its surrounding. There are two adiabatic:

1. **DALR: Dry adiabatic lapse rate**.
2. **WALR: Wet Adiabatic lapse rate**.

Adiabatic lapse rate expresion

The concept of air parcel is used to explain the movement of air pollutants, which is pictured as a little sphere of air.

As the air parcel rises in the atmosphere, it goes through a region of decreasing pressure and expands to accommodate the decreasing pressure. As it expands, it does work on the surrounding. Since the process is usually rapid, there is no heat transfer between the air parcel and the surrounding air, therefore the process is adiabatic.

For adiabatic process the first low of the thermodynamic yields

$$-dW = dU \qquad (3.12)$$

This mean that the internal energy decreases by decreasing the temperature

The term W is the work done on the surroundings and U is the internal energy $dW = pdV$ and $dU = C_V dT$, where C_V is the specific heat at constan volume. Substituting these terms in Eq.(3.12),

$$pdV + C_V dT = 0 \qquad (3.13)$$

Eq.(3.13) in term of unit mass

$$pd\nu + C_v dT = 0 \qquad (3.14)$$

where *v*, (v = V/m), the specific volume and C_v the specific heat per unit mass for perfect gas

$$P\nu = RT$$

Differentiating

$$pd\nu + \nu dp = RdT$$

$$pd\nu = RdT - \nu dp \qquad (3.15)$$

Substituting Eq.(3.15) in Eq.(3.14)

$$RdT - vdp + C_v dT = 0$$

$$(C_v + R)dT = vdp \qquad (3.16)$$

The variation of temperature with altitude can be written as

$$\frac{dT}{dz} = \frac{dT}{dp}\frac{dp}{dz} \qquad (3.17)$$

From Eq.(3.16) $\frac{dT}{dp} = \frac{v}{C_v + R}$ (3.18)

The change of pressure with altitude in vertical direction may be represent by:

$$\frac{dp}{dz} = -\rho g = -\frac{pg}{RT} \qquad (3.19)$$

Substituting Eq.(3.18) & Eq.(3.19) in Eq.(3.17), to get

$$\frac{dT}{dp} = -\frac{g}{C_v + R} \qquad (3.20)$$

Noting that $C_v + R = C_p$, where C_p is the specific heat at constant pressure per unit mass of air parcel, Eq.(3.20) can write as

$$\frac{dT}{dp} = -\frac{g}{C_p} \qquad (3.21)$$

Eq.(3.21) represent the lapse rate for dry air parcel, and it is known as the dry adiabatic lapse rate, which is denoted by Γ

$$\Gamma = \left(-\frac{dT}{dz}\right)_{adia} = 10^0 C \qquad (3.22)$$

In the present of moisture in atmosphere the lapse rate known as the wet adiabatic lapse rate.

Atmospheric stability

The ability of the atmosphere to disperse the pollutant emitted into it depends to a large extent on the degree of its stability. A comparison the adiabatic lapse rate with the environmental lapse rate gives an idea of the stability of the atmosphere. The cases of stability can be explained as:

1. **Stable:When ELR < DALR** a rising air parcel becomes cooler and more dense than its surroundings and tends to fall back to its original position, in this condition the lapse rate is said to be **subadiabatic**. Under stable condition there is very little vertical mixing (less buoyancy) and pollutantsdisperse very slowly. This associated with high pollution.
2. **Neutral stable:When the ELR = DALR**a rising parcel of air will have the same temperature, pressure and density of the surrounding and no buoyancy force. In this case the air parcel neither tends to return to its original position nor tends to continue its displacement. in the case moderate pollution.
3. **Unstable: When the ELR > DALR.**The atmospheric is said to be **superadiabatic**. Hence, a rising parcel of airwill be warmer and less dense than the surrounding environment. As a result, it becomes more buoyant and tends to continue its upward motion. There is vertical mixing and pollutant dispersed rapidly.low pollution.
4. **Condition stability CS:** occurs if the environmental lapse rate is between the two values of stability and instability.

Comparison between stable and unstable atmosphere condition

stable condition	Unstable condition
Less atmosphere mixing and therefore high pollutant concentration around level source	High atmospheric mixing and therefore low pollutant concentration around level source
Elevated emission, better dispersed rate and therefore low ground level concentration of pollutants	Elevated emission, are returned more readily to ground level leading to high ground level concentration of pollutants.

Inversions

Temperature inversion, condition in which the temperature of the atmosphere increases with altitude.

When temperature inversion occurs, cold air underlies warmer air at higher altitudes.

Under this condition the atmosphere is very stable and practically no mixing of pollutants takes place.

Wind speed:

Wind speed is caused by air moving from high pressure to low pressure. The wind velocity is influenced by: (1) the surface roughness, (2) the time of the day.

Atmospheric turbulence

Atmospheric turbulence is irregular air motions characterized by wind that vary in speed and direction. Turbulence is important because it mixes and churns the atmosphere and causes water vapor, smoke, and other substances, as well as energy, to become distributed both vertically and horizontally.

Plume behavior

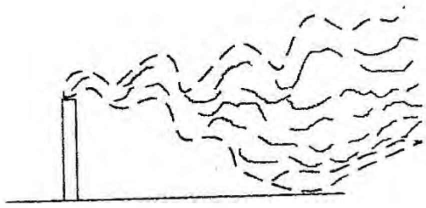
The behavior of plume emitted from an elevated source such as a tall stack depends on:

1- The degree of instability of the atmosphere,
2- The prevailing wind turbulence.

The Common types of plume behavior under various conditions of stability are:

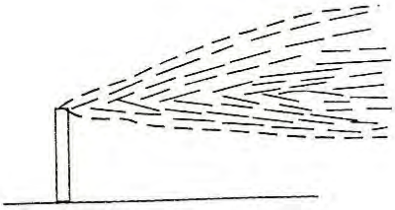
1- Looping plume
2- coning plume
3- fanning plume
4- fumigation plume
5- lofting plume
6- trapping plume

1. **Looping plume:**It occurs under superadiabatic lapse rate and solar heating. The large scale thermal eddies present in unstable air carry portions of plume to the ground level for short time periods, causing momentary high surface concentration of pollution near the stack. Looping is associated with light to moderate wind speed.



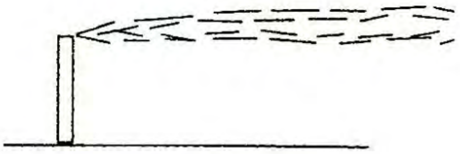
Strong instability (looping)

2. **Coning plume:** It can occur when the lapse rate essentially neutral. The plume shape is vertically symmetrical about the plume line and a major part of pollutant concentration is carried downwind fairly far before reaching the ground level. Coning is often associated with moderate to high wind speeds.



Near neutral stability (coning)

3. **Fanning plume:** It occurs when the plume is dispersed in the presence of very light winds as a result of strong atmospheric inversions. If the density of the plume is not significantly different from that of the surrounding atmosphere, the plume travels parallel to the ground in a flat, straight ribbon downwind. For high stack, fanning is considered a favorable because the plume does not contribute to ground pollution. A fanning plume is often observed at height and in early morning in all seasons.



Surface inversion (fanning)

Air dispersion model

Air dispersion model is a mathematical simulation of how pollutants dispersed in the ambient atmosphere. The dispersion models are used to estimate or to predict the downwind concentration of air pollutants from sources such as industrial plants. One of the most models is the Gaussian plume model.

Gaussian plume Model

The Gaussian plumeidea

Gaussian plume model is usually called as diffusion model and sometimes dispersion model. In this model:

- a point source such as a factory smoke stack is selected
- The downwind concentration resulting from this point source is calculated.

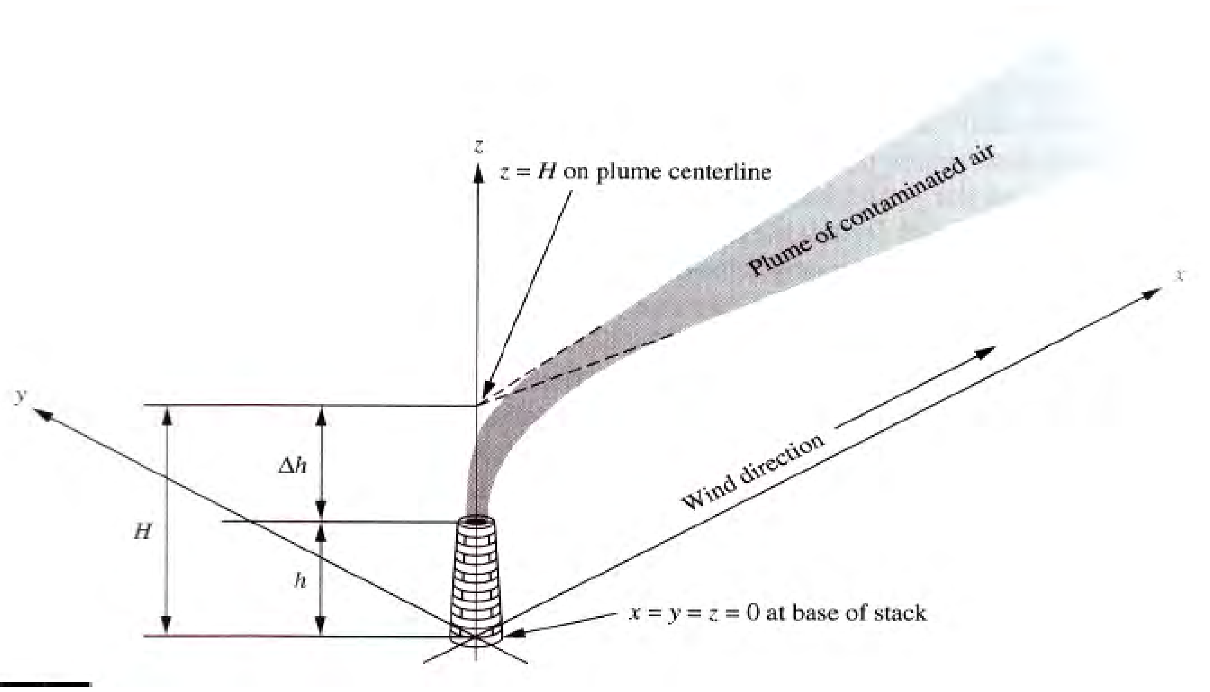


Fig. 13. Coordinate system for Gaussian plume idea

- The origin of the coordinate system is placed at the base of the smokestack with x-axis aligned in the downwind direction. The contaminated gas stream or plume rising from the smoke stack (Δh) and then travel in x direction and spread in the y and z direction as it travels.

- The plume normally rises higher above the smokestack because they are emitted at higher temperature than atmosphere and with vertical velocity.
- For calculation, the plume is assumed to be emitted at coordinate (0, 0, H), where Where H is effective stack high as illustrate in Fig. 14.

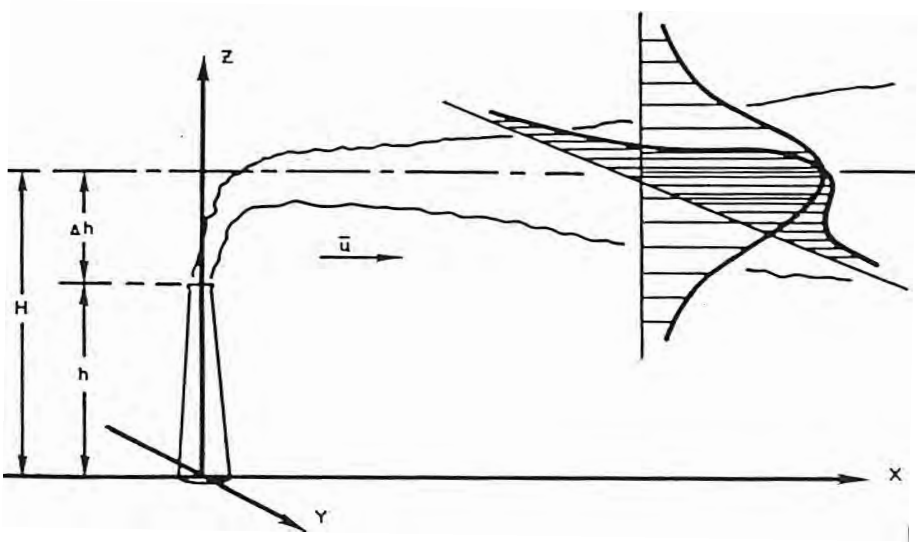


Fig.14. Gaussian Dispersion Model

- The effective stack height is the summation of physical stack height, h, and plume rise, Δh: H = h + Δh

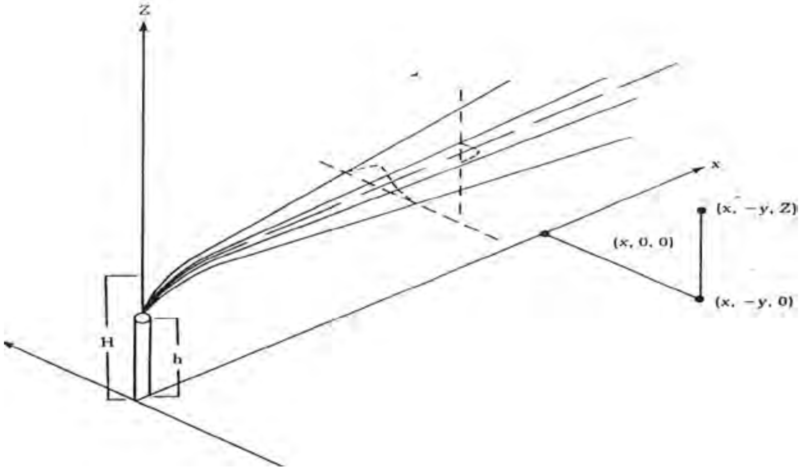


Fig.15. Plume dispersion Coordinate system

Modified of Gaussian dispersion equation

❖ Extension to elevated sources with reflection

Most pollutants are emitted into atmosphere from elevated sources such as chimney stacks so that the **equation for pollutant concentration at selected location (x, y, z) in three dimensional field downwind of the elevated point source is given by:**

$$C(x,y,z,H)=\underbrace{\frac{Q}{2\pi\sigma_y\sigma_z\bar{u}}}_{\text{Centerline}}\underbrace{\exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right)}_{\text{Horizontal}}\underbrace{\left\{\exp\left(-\frac{1}{2}\frac{(z-H)^2}{\sigma_z^2}\right)+\exp\left(-\frac{1}{2}\frac{(z+H)^2}{\sigma_z^2}\right)\right\}}_{\text{Vertical}} \quad (17)$$

where
C: pollutant concentration, µg/m^3
Q: pollutant emission rate. g/s
H: effective stack height. m
u: wind velocity, m/s
σ_y: Horizontal crosswind dispersion coefficient, m
σ_z: vertical crosswind dispersion coefficient, m

σ_y&σ_z =f (downwind distance x & atmosphere stability), m

Eq.17 consists of three terms:

- Centerline concentration as a function of downwind distance, x
- The lateral or horizontal spread relative to the centerline value, y
- The vertical spread relative to the centerline value. z

The first term in Eq.18 $(\frac{Q}{2\pi\sigma_y\sigma_z\bar{u}})$ is the concentration in the centerline of the plume.

The second and third terms (the exponential term) show how the concentration decreases as we move horizontally or vertically.

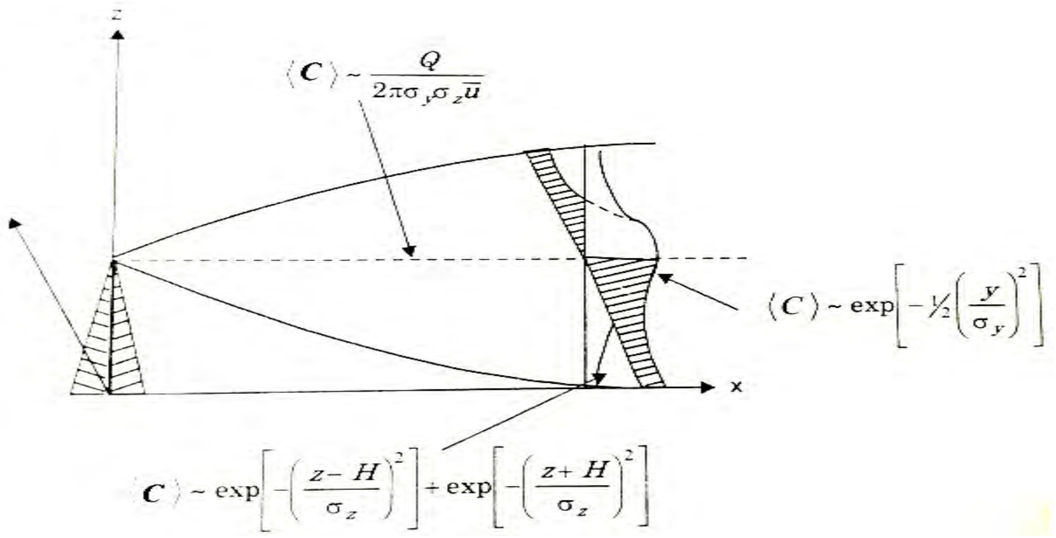


Fig.16. representation of the centerline concentration terms and lateral and vertical terms

Three common forms obtained from the basic equation are frequently used to analyze specific situations:

a) **Ground level concentration (z = 0) - plume at height** H

$$C(x, y, 0, H) = \frac{Q}{\pi\sigma_y\sigma_z\bar{u}} \exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right) \exp\left(-\frac{1}{2}\frac{H^2}{\sigma_z^2}\right) \qquad (18)$$

b) **Ground level centerline concentration: (z = 0) and (y = 0) - plume height H**

$$C(x, 0, 0, H) = \frac{Q}{\pi\sigma_y\sigma_z\bar{u}} \exp\left(-\frac{1}{2}\frac{H^2}{\sigma_z^2}\right) \qquad (19)$$

Eq.19 is used to estimate the ground level concentration expected at any distance downwind of an elevated source.

In the case of emission source is also at the ground level, i.e., $H = 0$. Eq. 19 further simplifies to

$$C(x, 0, 0, 0) = \frac{Q}{\pi\sigma_y\sigma_z\bar{u}} \qquad (20)$$

c) Maximum ground level centerline concentrations from an elevated source

The maximum ground level concentration can be obtained starting from Eq.19. If the spreading coefficient σ_y and σ_z are expressed as:

$$\sigma_y = Ax^p \tag{21}$$

and $\sigma_z = Bx^p$ (22)

where A, B and p are constants, then the value of < C > in Eq.19 can be maximized by substituting forσ_y and σ_z and setting $\frac{dC}{dx} = 0$. Then simplification of resulting expression yields:

$$\frac{-2p}{x^{2p+1}} + \frac{H^2 p}{B^2 x^{4p+1}} = 0 \tag{23}$$

From Eq.23:

$$Bx^p = \sigma_z = \frac{H}{\sqrt{2}} \tag{24}$$

This gives the downwind position at which the maximum ground level centerline concentration occurs. Substituting of $\sigma_z = \frac{H}{\sqrt{2}}$ in Eq.19 we get:

$$C_{Max}(x,0,0,H) = \frac{2Q}{\pi \bar{u} e H^2} \frac{\sigma_z}{\sigma_y} \tag{25}$$

Eq.25 shows why pollutants are emitted into the atmosphere through tall stacks.
Note: e means exponent (exp. (1)) = 2.718.

Estimation of σ_y and σ_z

- The values of σ_y and $\sigma_z$are the dispersion coefficient in the y- and z-direction. They are function of downwind distance x from the source as well as to the atmospheric stability conditions.
- Based on experimental observations of the dispersion of real plume, σ_y and σ_z of the plume can be calculated from knowledge of the atmosphere stability.
- Six categories of atmospheric stability , A through F, were suggested as shown in table 1

- When the stability category is known from appropriate weather conditions σ_y and σ_z values for any downwind distance x can be calculated from the equations:

$$\sigma_y = Ax^{0.903} \qquad (26)$$

$$\sigma_z = Bx^{p} \qquad (27)$$

Table 5 Key to Stability Categories

Wind speed (m/s) (at z =10 m	Day			Night	
	Incoming solar radiation			Thin overcast ($\geq$4/8 low cloud)	Clear ($\leq$ 3/8 cloud)
	Strong	Moderate	Slight		
< 2	A	A-B	B	E	F
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
> 6	C	D	D	D	D

A: Extremely unstable, B: Moderately unstable, C: slightly unstable, D: Neutral conditions, E: Slightly stable, F:Moderately stable

The values of A, B and p are given in table 6

Table 6. Fitted values for σ_y and σ_z

Class	A	x_1 (meters)	$x \leq x_1$		x_2 (meters)	$x_1 \leq x \leq x_2$	
			B	p		B	p
A	0.40	250	0.125	1.03	500	0.00883	1.51
B	0.295	1000	0.119	0.986	10000	0.0579	1.09
C	0.20	1000	0.111	0.911	10000	0.111	0.911
D	0.13	1000	0.105	0.827	10000	0.392	0.636
E	0.98	1000	0.100	0.778	10000	0.373	0.587

The values in table 2 closely fit the curves shown in Figs. 17 and 18

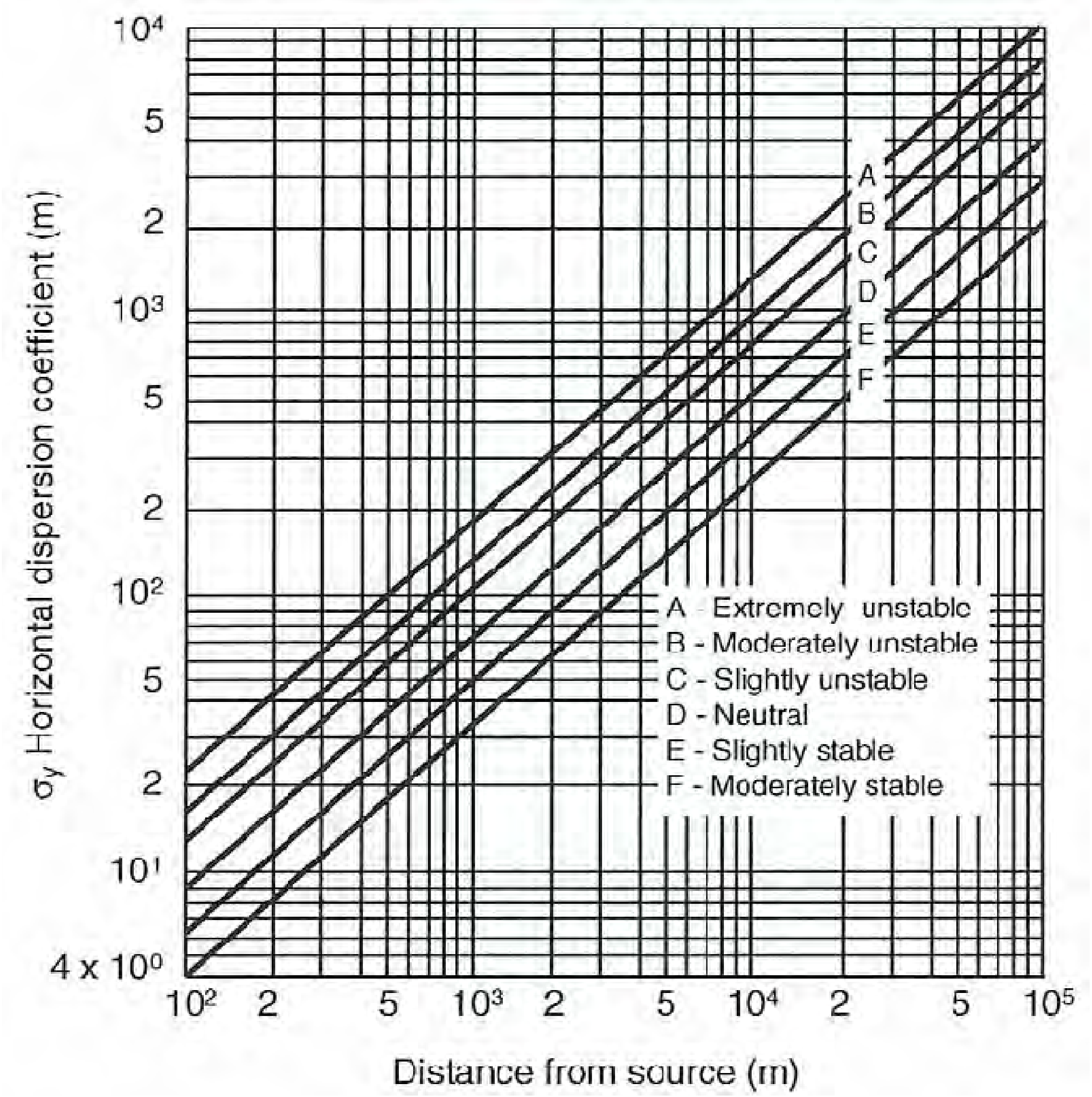


Fig.17 **Horizontal Dispersion Coefficient** σ_y

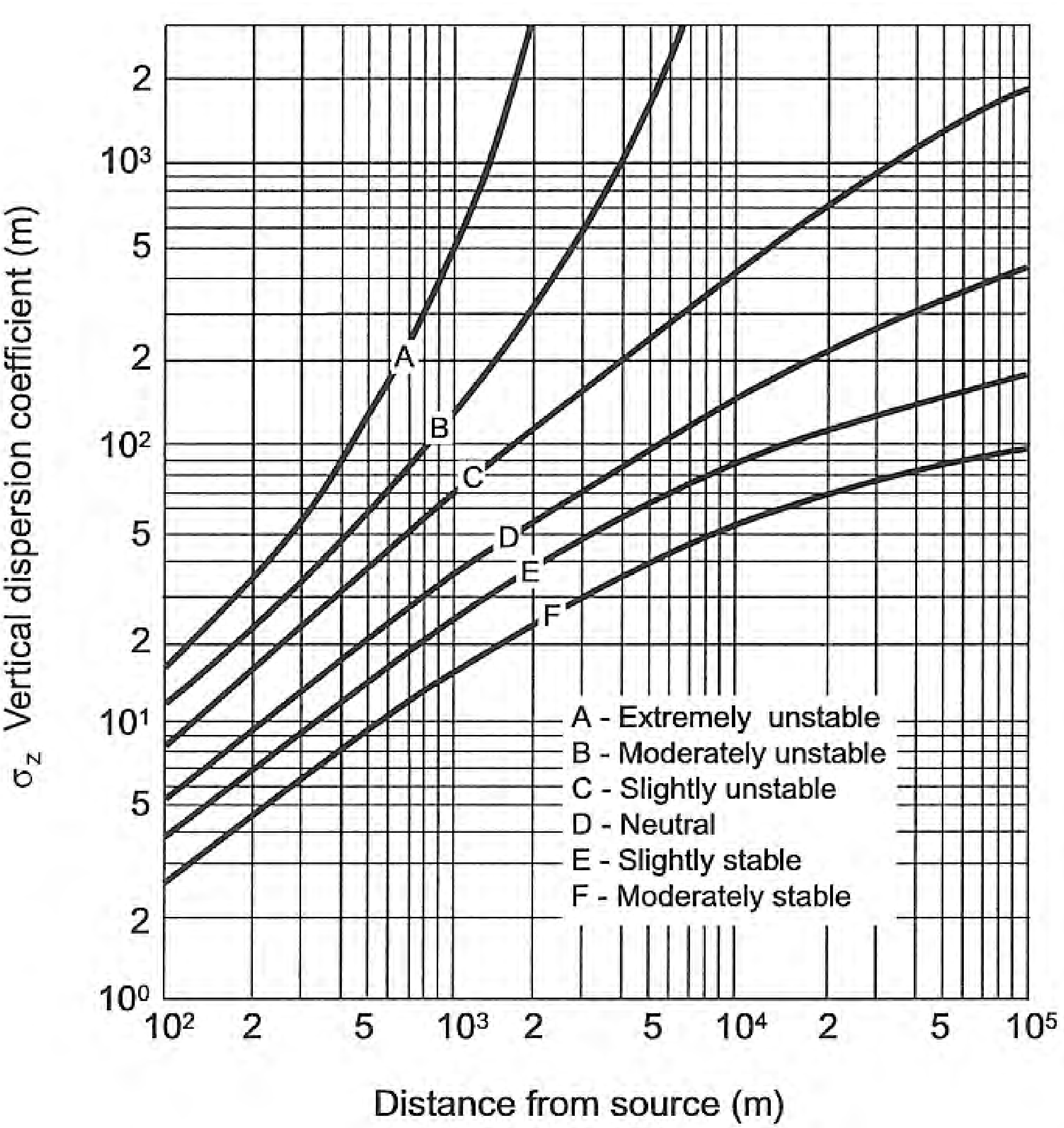


Fig.18 **Vertical Dispersion Coefficient** σ_z

Example (1):

Estimate the values of σ_y and σ_z□ at a point of 0.65km downwind from a pollutant source on abright sunny day (C category) with the wind speed 6 m/s.

Answer:
Using Figs. 17 and 18 we get:
σ_y = 70 m and σ_z= 45 m

Example (2):

A factory emits 20 g/s of CO at effective height (*H*) = 20 m. The wind speed is 5 m/s at distance 0.5 kmdownwind for *C* stability. What are the CO concentration at a point of25m to the side and 2 mabove the ground?

Solution

H = 20; Q = 20 g/s; u = 5 m/s

From Figs. 17 and 18 reading for σ_y and σ_z :

σ_y = 50 m and σ_z= 37 m

then substitute into Eq.18

$$C = \frac{Q}{2\pi\sigma_y\sigma_z\overline{u}}\exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right)\left\{\exp\left(-\frac{1}{2}\frac{(z-H)^2}{\sigma_z^2}\right)+\exp\left(-\frac{1}{2}\frac{(z+H)^2}{\sigma_z^2}\right)\right\} \quad (18)$$

$$C = \frac{20g/s}{2\pi(50m)(37m)(5m/s)}\exp\left(-\frac{1}{2}\frac{(25m)^2}{(50m)^2}\right)\left\{\exp\left(-\frac{1}{2}\frac{(2-20)^2}{(37m)^2}\right)+\exp\left(-\frac{1}{2}\frac{(2+20)^2}{(37m)^2}\right)\right\}$$

$$C = 4.96\times10^{-4}\frac{g}{m^3} = 496\frac{\mu g}{m^3}$$

So the concentration at y = 25 m and z = 2 m is 496 µg/m^3.

Average wind speed $\overline{u}$

The average wind speed at stack height Hcan be evaluated by

$$\frac{\overline{u}}{\overline{u}_1} = \left[\frac{H}{z_1}\right]^{\alpha} \qquad (28)$$

Where $\overline{u}_1$ is usually the meteorological value of the velocity at z_1 = 10 m, and$\overline{u}$ are the wind speeds at altitude H.

α = 0.25 for unstable conditions,

α = 0.50for stable conditions.

Note: the Gaussian model is most accurate for the downstream between approximately 100 and 2000 m.

Example (3):

A chimney with a design stack height of 250 m is emitting sulfur dioxide at a rate of 500 g/s on a sunny day in June with moderate wind speed at stack altitude. If the moderate wind speed at this condition is 6 m/s. Estimate the concentration of sulfur dioxide downstream for the following situations:

(a) $\left\langle C_{SO_4} \right\rangle$ (1000, 0, 0, 250)

(b) $\left\langle C_{SO_4} \right\rangle$ (1000, 50, 0, 250)

(c) $\left\langle C_{SO_4} \right\rangle$ (1000, 50, 20, 250)

(d) If $\left\langle C_{SO_4} \right\rangle$ (1000, y, 0, 250) is 100 µg/m^3, what is the value of y in meters?

solution:

on sunny day in June the incoming solar radiation will be strong, also the air will be unstable.

$\overline{u}$ = 6 m/s

From Eq.28 the velocity $\overline{u}_1$ at 10 m level can be obtained.

$$\bar{u}_1 = \bar{u}\left[\frac{z_1}{H}\right]^{\alpha}$$

For unstable condition α = 0.25, therefore,

$$\bar{u}_1 = 6\left[\frac{10}{250}\right]^{0.25} = 2.7 m/s$$

This shows that the surface wind speed is between 2 and 3 m/s.
Reference to Table 1 shows a stability class of A-B. We choose class B
From the information given in Table 2, at class B and at distance x = 1000 m:

A = 0.295 , B = 0.119, P = 0.986

Then the values of σ_y and σ_z can be calculated using Eqs. 26 and 27 respectively.

$$\sigma_y = Ax^{0.903} \qquad (26)$$

$$\sigma_y = 0.295(1000)^{0.903} = 151m$$

And

$$\sigma_z = Bx^{p} \qquad (27)$$

$$\sigma_z = 0.119(1000)^{0.986} = 108m$$

(a) $\langle C_{SO_4}\rangle$ **(1000, 0, 0, 250)**

Using the ground level centerline equations Eq.20, substituting the values of σy and σ_z and using Q = 500 g/s, $\bar{u}$ = 10 m/s, and *H* = 250 m, we get

$$C(x,0,0,H) = \frac{Q}{\pi\sigma_y\sigma_z\bar{u}}\exp\left(-\frac{1}{2}\frac{H^2}{\sigma_z^2}\right) \qquad (20)$$

$$C(1000,0,0,250) = \frac{500\times10^6}{\pi(151)(108)6}\exp\left(-\frac{1}{2}\frac{(250)^2}{(108)^2}\right) = 112\times10^{-4}\frac{g}{m^3} = 112\,\mu g/m^3$$

(b) $\langle C_{SO_4}\rangle$ **(1000, 50, 0, 250)**

Using Eq.19, we get

$$C(x,y,0,H)=\frac{Q}{\pi\sigma_y\sigma_z\bar{u}}\exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right)\exp\left(-\frac{1}{2}\frac{H^2}{\sigma_z^2}\right)\qquad(19)$$

$$C(1000,50,0,250)=\frac{500\times10^6}{\pi(151)(108)6}\exp\left(-\frac{1}{2}\frac{(50)^2}{(151)^2}\right)\exp\left(-\frac{1}{2}\frac{(250)^2}{(108)^2}\right)=106\times10^{-4}\,\frac{g}{m^3}=106\mu g/m^3$$

$\left\langle C_{SO_4}\right\rangle$ **(1000, 50, 20, 250)**

Using Eq.18, we get

$$C(x,y,z,H)=\frac{Q}{2\pi\sigma_y\sigma_z\bar{u}}\exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right)\left\{\exp\left(-\frac{1}{2}\frac{(z-H)^2}{\sigma_z^2}\right)+\exp\left(-\frac{1}{2}\frac{(z+H)^2}{\sigma_z^2}\right)\right\}\quad(18)$$

$$C(1000,50,20,250)=\frac{500\times10^6}{2\pi(151(108))}\exp\left(-\frac{1}{2}\frac{(50)^2}{(151)}\right)\times$$

$$\left\{\exp\left(-\frac{1}{2}\frac{(20-250)^2}{108}\right)+\exp\left(-\frac{1}{2}\frac{(20+250)^2}{108}\right)\right\}=113\times10^{-4}\,\frac{g}{m^3}=113\mu g/m^3$$

(c) If $\left\langle C_{SO_4}\right\rangle$ (1000, y, 0, 250) is 100 µg/m3, what is the value of y in meters?

Dividing Eq.19 by Eq.20, we get

$$\frac{\left\langle C_{SO_2}\right\rangle(1000,50,0,250}{\left\langle C_{SO_2}\right\rangle)1000,0,0,250)}=\exp\left[\frac{1}{2}\frac{y^2}{\sigma_y^2}\right]$$

$$y=\left[2\ln\frac{\left\langle C_{SO_2}\right\rangle(1000.0,0,H)}{\left\langle C_{SO_2}\right\rangle(x.y.0.H)}\right]^{1/2}\sigma_y$$

$$y=\left[2\ln\frac{\left\langle C_{SO_2}\right\rangle(1000.0,0,H)}{\left\langle C_{SO_2}\right\rangle(x.y.0.H)}\right]^{1/\ 2}(151)$$

$$y=\left[2\ln\frac{112}{100}\right]^{1/2}(151)=72m$$

Effective Stack Height

Generally, effluent plumes from chimney stacks are released into the atmosphere at elevated temperature. The rice of the plume after release to the atmosphere is caused by the buoyancy and vertical momentum of the effluent. Under windless conditions the plume rises vertically but more often it is bent as a result of the wind that is usually present. This rise of the plume adds to the stack an additional height, ΔH, such that the effective stack height, H is obtained by adding the term ΔH, the plume rise, to the actual height of the stack (physical height) , h. The plume centerline height $H = H_s + \Delta H$ is known n as the effective stack height and it is the height that is used in Gaussian plume calculations. The effective stack height is illustrated in Fig.8

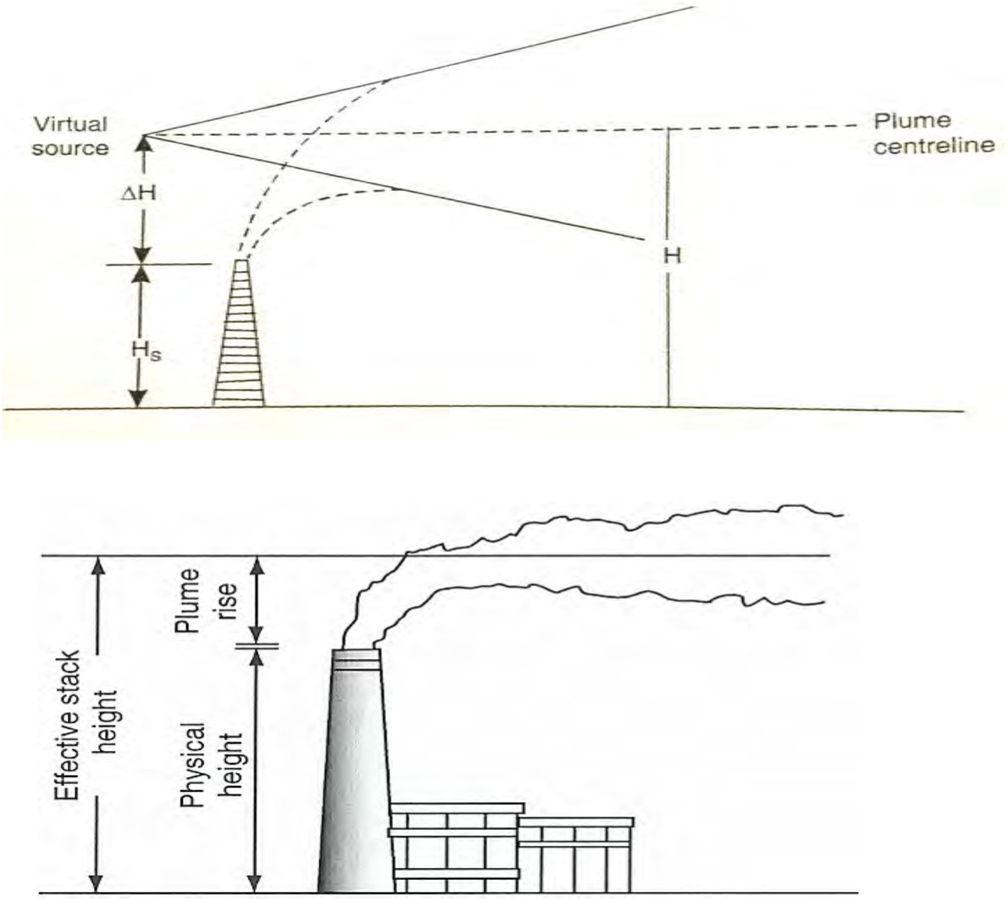


Fig.19 plume rise

The effective stack height is given by

$$H = H_s + \Delta H \qquad (29)$$

Where

H :is the effective stack h

H_s :is the actual or physical stack height

ΔH : is the plume rise

Estimation of Plume Rise

The plume rise ΔH is essentially used to estimation the effective stack height. The common formulas used to estimate the plume rise are:

1. Buoyant plumes
2. Non-buoyant plumes
3. Plume rise for larger volume source

1. Buoyant plumes

The influence of buoyancy force is greater than the influence of vertical momentum. Such plumes are usually when the release temperature are more than 50 ^{o}C greater than ambient atmospheric temperatures.

Holland equation

This is one of the earliest equations proposed to calculate the plume rise. It has been widely used because of its simplicity and has been included in many plume rise studies.

$$\Delta H = \frac{\left(1.5 V_s D_s + 4 \times 10^{-5} Q_H\right)}{\bar{u}} \qquad (30)$$

where

V_s : Stack gas exit velocity, m/s

D_s : Diameter of stack outlet, m

$\bar{u}$: Wind velocity, m/s

Q_H : Heat emission rate, cal/s

ΔH : Plume rise above the stack, m

2. Non-Buoyant plumes

For sources at temperature close to the ambient and having exit speeds of at least 10 m/s.

$$\Delta H = D_s \left(\frac{V_s}{\bar{u}}\right)^{1.4} \qquad (31)$$

3. Plume rise for larger volume source

For volumes flow rates greater than 50 m^3/s, for unstable or neutral conditions, the recommended equation is

$$\Delta H = 150 \frac{F}{(\bar{u})^3} \qquad (32)$$

where, F is the buoyancy flux parameter (m^4/s^3), given by

$$F = gV_s \left(\frac{D_s}{2}\right)^2 \frac{T_s - T_a}{T_s} \qquad (33)$$

Example (4):

A chimney with a design stack height of 250 m is emitting sulfur dioxide at a rate of 500 g/s on a sunny day in June with moderate wind speed at stack altitude. The stack diameter is 5 m, the sulfur dioxide exit velocity is 13.5 m/s, and the gas temperature of the exit is 145 ^oC. If the wind speed at this condition is 6 m/s, what is the plume rise for an ambient air temperature of 30 ^oC. Calculate the ground level concentration of sulfur dioxide on the plume centerline at the downstream distance of 1 km. the density of sulfur dioxide at 145 ^oC is 1.886 kg/m^3

solution:

Calculate the volumetric flow rate of the flue gas:

$$Vol.Flow.Rate = V_s \times A_s = V_s \times \left(\frac{\pi}{4} D_s^2\right)$$

$$Vol.Flow.Rate = (13.5 m/s) \times \left[\frac{\pi}{4}(5)^2\right] = 265 m^3/s$$

Where A_s is the cross section area of the exit stack

Since the volumetric flow rate is far greater than 50 m^3/s, Eq.33 can be applied

$$\Delta H = 150 \frac{F}{(\bar{u})^3}$$

The buoyancy flux F parameter is given by Eq.34

$$F = gV_s\left(\frac{D_s}{2}\right)^2\frac{T_s - T_a}{T_s}$$

$$F = 9.8(13.5)\left(\frac{5}{2}\right)^2\frac{418+303}{418} = 227 m^4/s^3$$

Then $\Delta H = 150\frac{227}{(6)^3} = 158m$

The effective stack height H is

$$H = H_s + \Delta H = 250 + 158 = 408m$$

Using the value of H in Eq.20, we get

$$C(x,0,0,H) = \frac{Q}{\pi\sigma_y\sigma_z\bar{u}}\exp\left(-\frac{1}{2}\frac{H^2}{\sigma_z^2}\right) \qquad (20)$$

$$C(1000,0,0,408) = \frac{500(10^6)}{\pi(151)(108)6}\exp\left(-\frac{1}{2}\frac{(408)^2}{(108)^2}\right) = 1.30\mu g/m^3$$

Note: the values of σ_y and σ_z are taken from Example 3

There is a significant reduction in ground level concentration as compared to the case for zero plume rise, means H = 250+0 = 250, where

$$C(1000,0,0,250) = \frac{500(10^6)}{\pi(151)(108)6}\exp\left(-\frac{1}{2}\frac{(250)^2}{(108)^2}\right) = 112\mu g/m^3$$

Example (5):

The heat emission rate associated with a stack gas is 4800 kJ/s, the wind and stack gas speed are 5 m/s and 15 m/s respectively. The inside stack diameter at the top is 2 m. Estimate the plume rise.

Answer:

Using Holland equation, Eq.30

$$\Delta H = \frac{\left(1.5 V_s D_s + 4\times10^{-5} Q_H\right)}{\bar{u}} \qquad (30)$$

$Q_H = 4800\ kJ$,$cal = 4.184\ J$

Then $Q_H = \left(4800\, kJ/s\right)\times\frac{1kcal}{4.184kJ} = 1147 kcal/s \times \frac{1000cal}{1kcal} = 1.147\times10^{6} cal/s$

$$\Delta H = \left[\frac{1.5(15)(2) + 4\times10^{-5}\left(1.147\times10^{6}\right)}{5}\right] = 18.2m$$

Example (6):

A factory is emitting SO_2 at a rate 160 g/s through a stack with an effective height of 60 m. The wind speed is 6 m/s and atmospheric stability is of class D.
Determine the maximum ground level concentration along the centerline.

Ans.: 879 $\mu g/$ m^3

Answer:

y=0 & z=0

$$C_{Max}(x,0,0,H) = \frac{2Q}{\pi \bar{u} e H^2}\frac{\sigma_z}{\sigma_y} \text{ for max. conc. } \sigma_z = \frac{H}{\sqrt{2}} = \frac{60}{\sqrt{2}} = 42.42m$$

From Fig.7 find x (corresponding to σ_z = 42.42 m)

∴ x = 1300m

$$\sigma_y = AX^{0.903} = 0.13(1300)^{0.903} = 84.3m$$

$$C_{Max}(x,0,0,H) = \frac{2Q}{\pi \bar{u} e H^2}\frac{\sigma_z}{\sigma_y}$$

$$C_{Max}(500,0,0,60) = \frac{2(160)10^6}{\pi(6)(2.7)(60)^2}\frac{42.42}{84.3} = 2.06\times10^{-3} = 879\mu g/m^3$$

Air pollution control equipment

The various air pollution control equipment are used to control the air pollution from stationary sources. These equipment are conveniently divided into two types, one type are those which applicable for controlling particulate, and the other that used for controlling gaseous pollutants as shown in Fig.20.

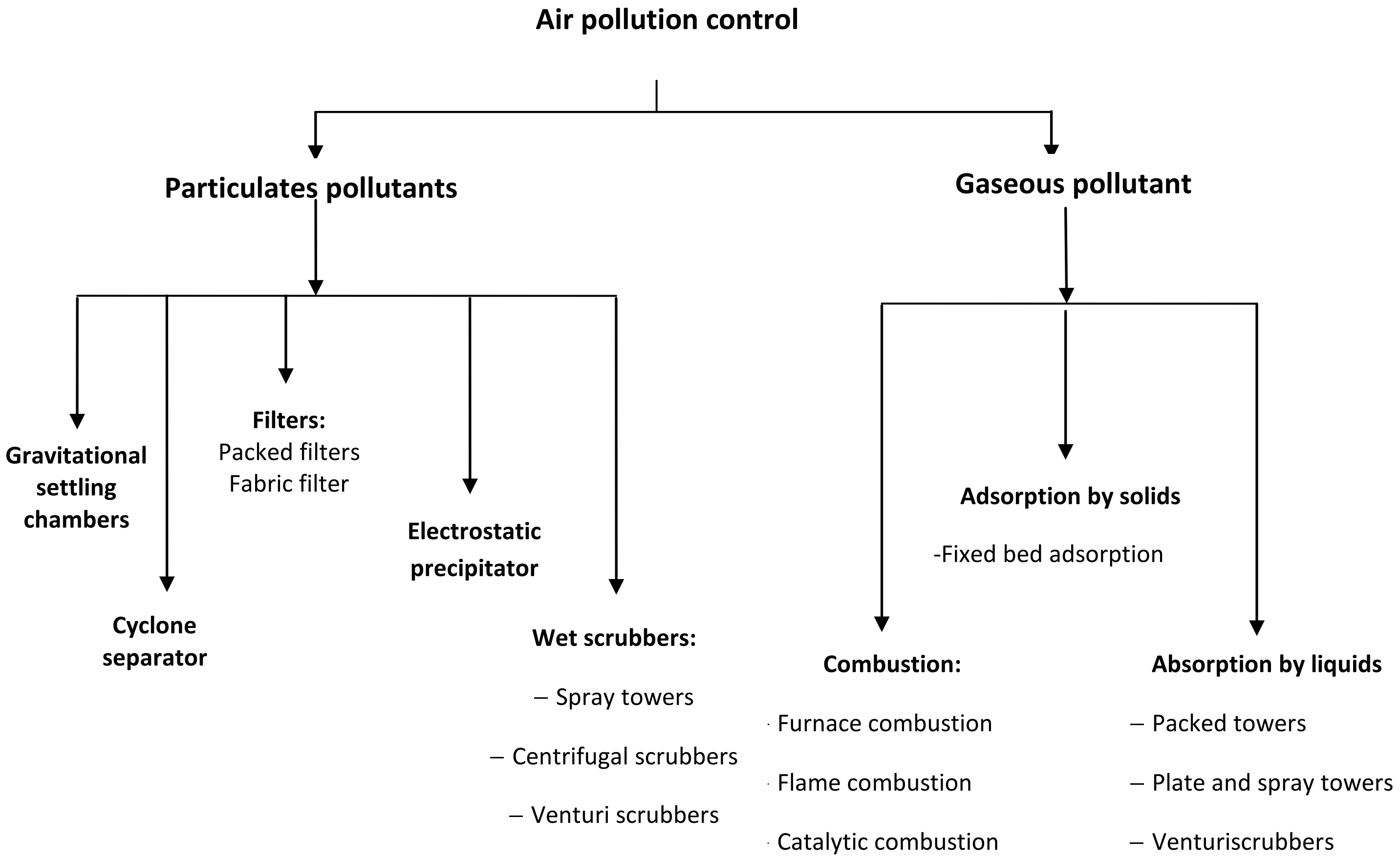


Fig.20. The most commonly equipments deal with air pollution control from stationary sources

Control of Particulate Pollutants

Particulate control equipment

Particulate matter emitted in gaseous streams consists of discrete and minute suspended particles. Particle sizes range from 100 μm to 0.1 μm and even less. The choice of collection devices depends upon a number of factors:

1- The physical and chemical properties of the particulates.
2- The range of volumetric flow rate of the gas stream.
3- Theparticulate size and its concentration in gas stream.
4- The temperature and humidity of the flow stream.
5- The toxicity and inflammability
6- The collection efficiency that required for outlet stream.

1- Gravitational settling cambers

Gravitational force may be employed to remove particulate

1) Used to remove of coarse particles larger than 50 μm from gas streams,
2) Since most of particles in the gas stream are much smaller sizes than 50 μm, these devices are used as a primarily prior to passing the gas stream through high efficiency devices.
3) They offer low pressure drop and required simple maintenance.

The efficiency of equipment depends on the residence time of the gas in the settling chamber which is related to the velocity of the gas flow and the chamber volume. The simplest form of gravity settling camber is shown in Fig.21.

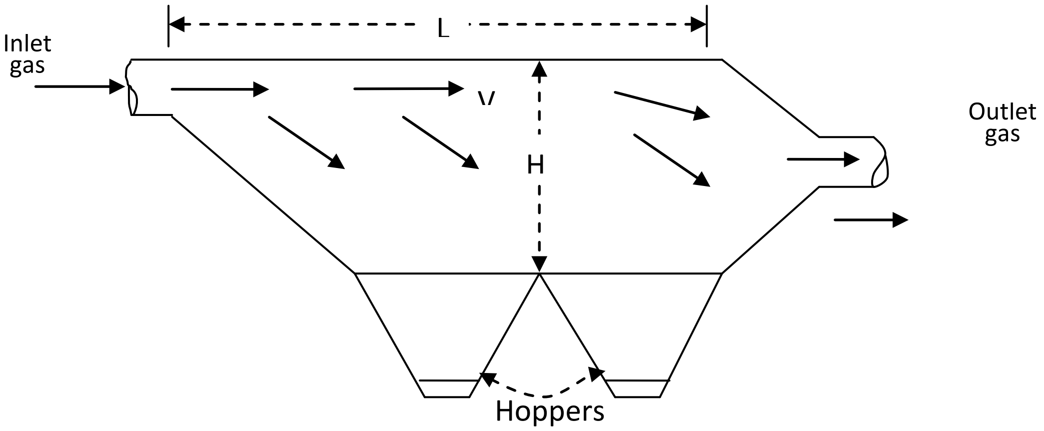


Fig.21. A gravitational settling chamber

2- Cyclone separators

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

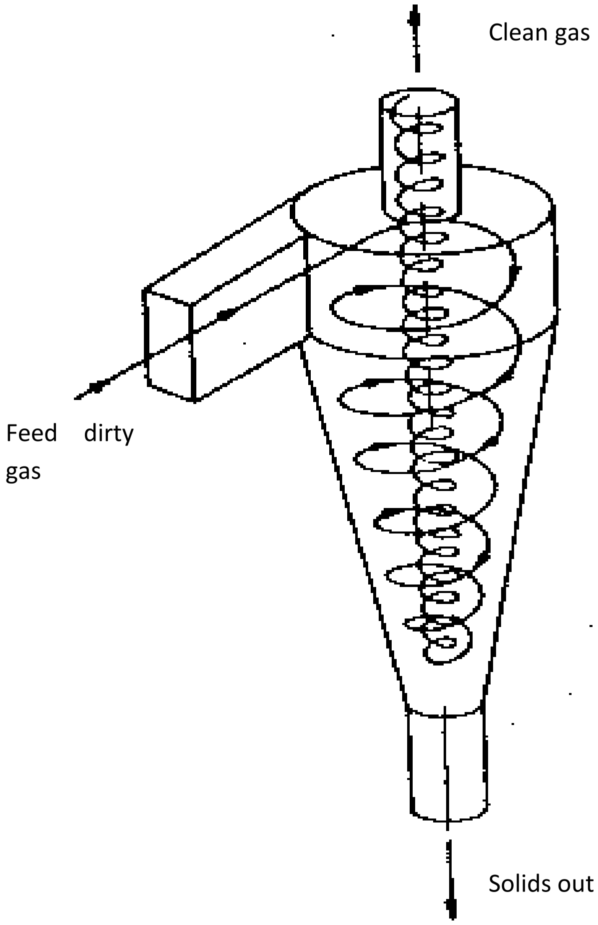


Fig.22. A cyclone separator

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

Type of cyclones

Three types of cyclones:

1- Conventional cyclones
2- High efficiency cyclones
3- High volume cyclones

Fig.23 shows typical curves for several types of equipment with their fraction collection efficiency as a function of particle size

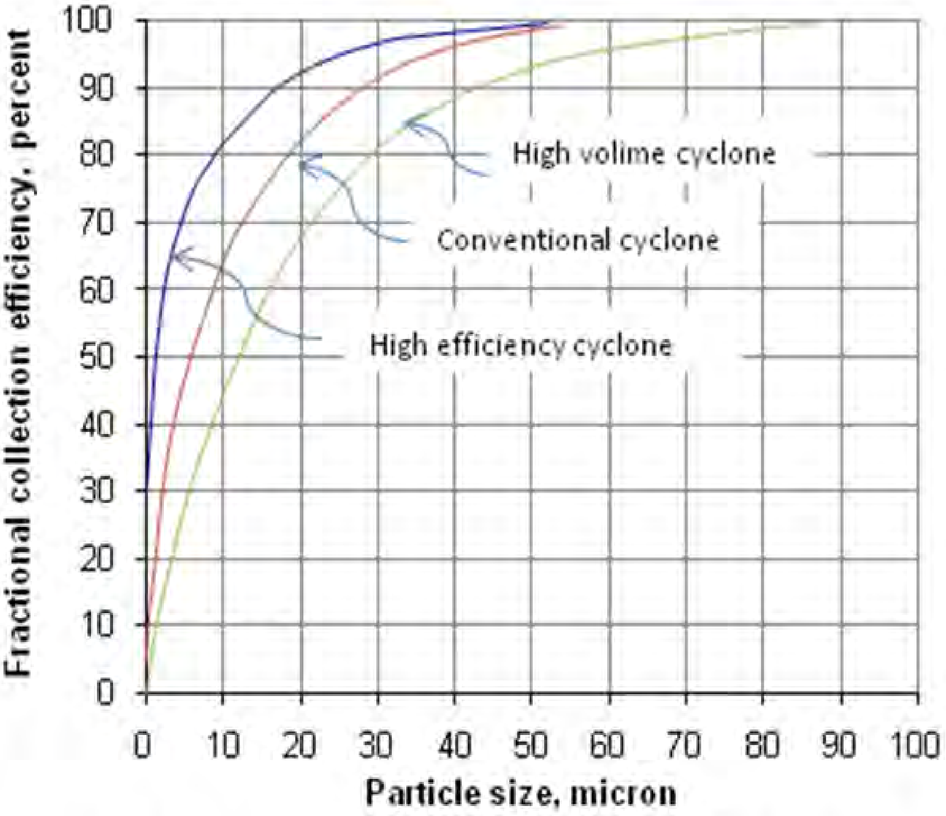


Fig.23. the fractional collection efficiency as a function of particle size for several types of cyclones.

3- Fabric filter (or bag filter)

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

The fabric filterconsists of several tubular bags or an envelope,called a baghouse, hanged in such a manner that the collected particle fall into a hopper. The dirty gas enters the bag at the bottom and passes through the fabric filter, while the particulate is deposited on the inside of the bag and the gas passes out from their side to be finely released out of the filter system as a clean gas. Fig.24 shows a typical baghouse.

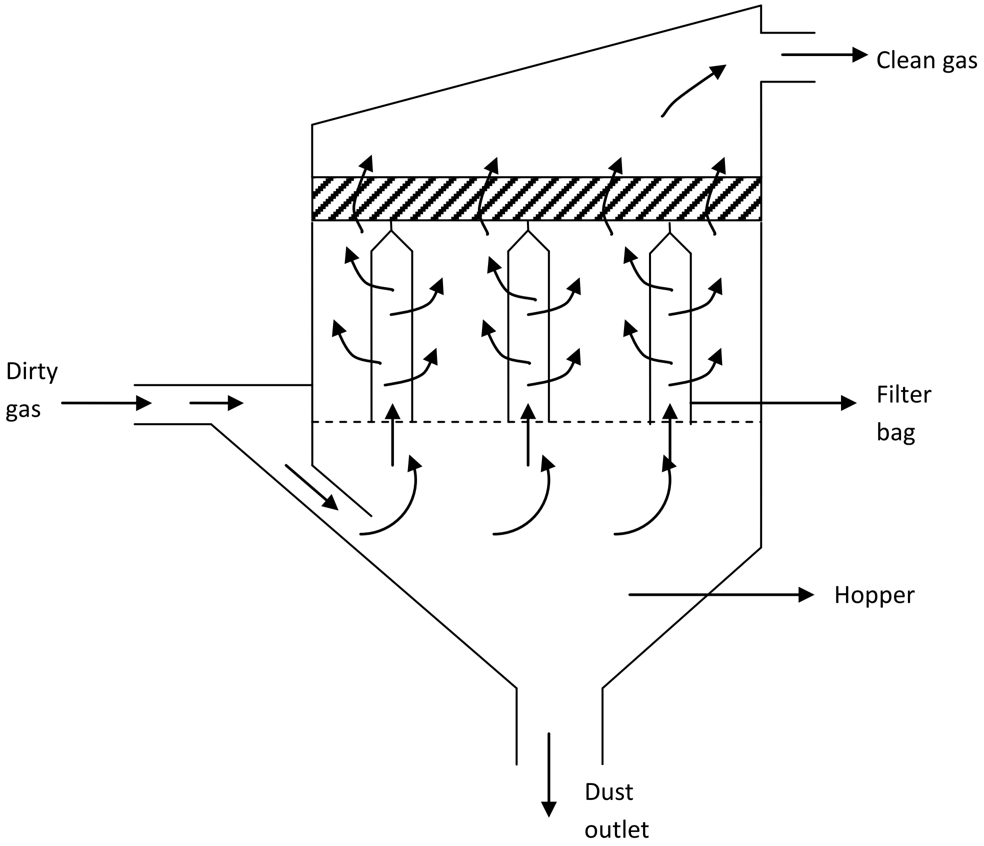


Fig.24. Typical bag house

The advantages of fabric filter

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

2- Retention of finest particles.

3- Relatively low pressure drops.

4- Collection of particulates in dry form.

The main disadvantages of fabric filter

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

4- Electrostatic precipitators, ESP

Electrostatic precipitator is a physical process by which particles suspended in gas stream are discharged electrically and, under the influence of the electrical field, separated from the gas stream. A typical wire and pipe precipitator is shown in Fig.25.

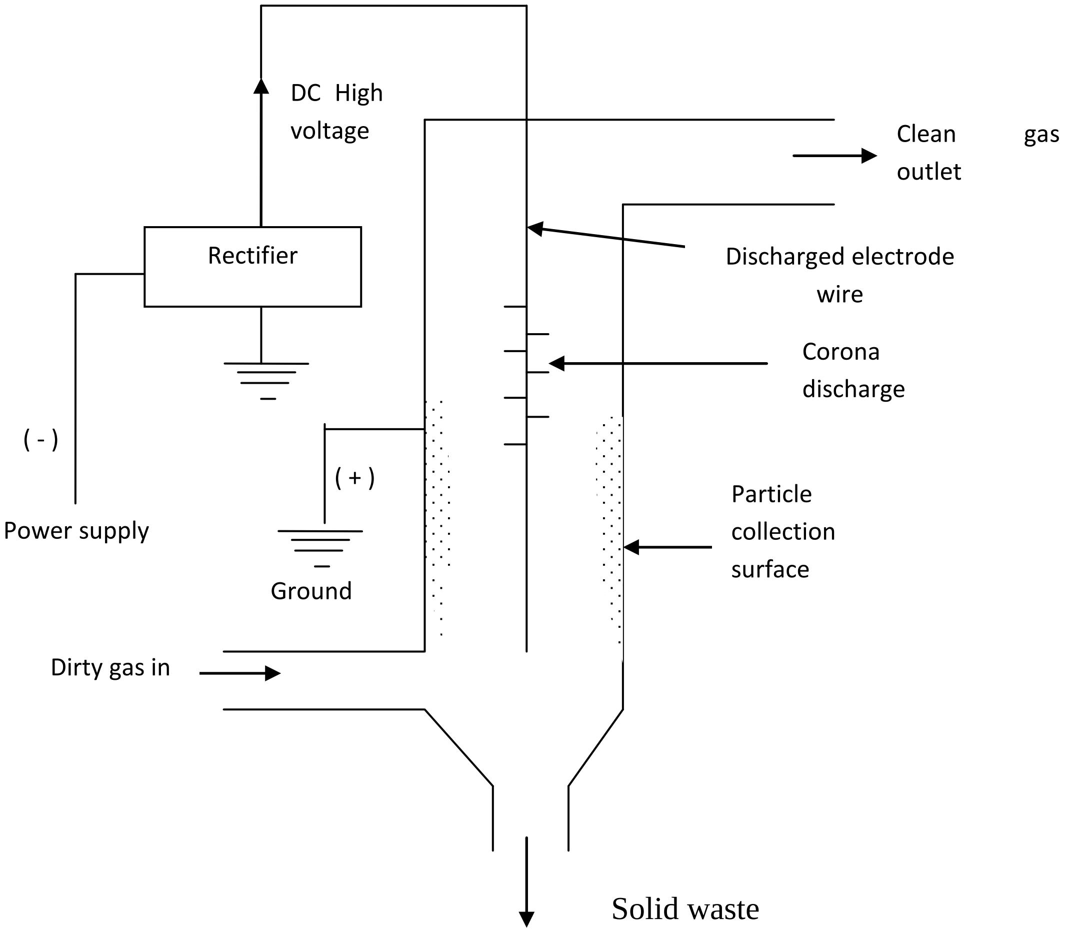


Fig.25. Electrostatic precipitators

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

Advantages of electrostatic precipitators

1- Low Pressure drop

2- High collection efficiencies very small particles can be collected wet and dry.

3- Can handle both gas and mists for high volume flows.

4- Low energy consumption.

5- Ability to operate with relatively high temperature gases.

Disadvantages of electrostatic precipitators

1- Relatively high initial cost and large space requirement.

2- It is necessary to safeguard operating person from high voltage.

3- Collection efficiency can deteriorate (تتدهور) gradually.

5- Wet scrubbers

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

The advantages of wet scrubbers

1- Simultaneously removal of gases and particulate.

2- Can effectively remove fine particulate, both liquid and solid, ranging from 0.1-20 μm from gas stream.

3- Equipment occupies only a moderate amount of space compared to dry collectors such as bag house.

The disadvantages of wet scrubbers

1- Relatively high energy costs.

2- Problem of wet sludge disposal.

3- Corrosion problems

4- The wet sludge causes water pollution and there is need to treatment method to remove particles from the water.

5- Very small particles (sub-micron sizes) may not captured.

The major types of wet scrubbers are:

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

1-Spray scrubbers

The simplest type of wet scrubbers is a spray tower (Fig.26) in which the polluted gas flows upward andwater droplet is sprayed downward by means of spray nozzles located across the flow passage. The particle from the polluted gas is colliding with water droplet and the water droplet contaminated with this particle. If the gas flow rate is relatively slow, the contaminated water droplets will settle by gravity to the bottom of the tower as slurry. A mist eliminator is usually placed at the top of the tower to remove both exes clean water droplet and dirty droplets which are very small that cannot be settled and thus carried upward by the gas flow.

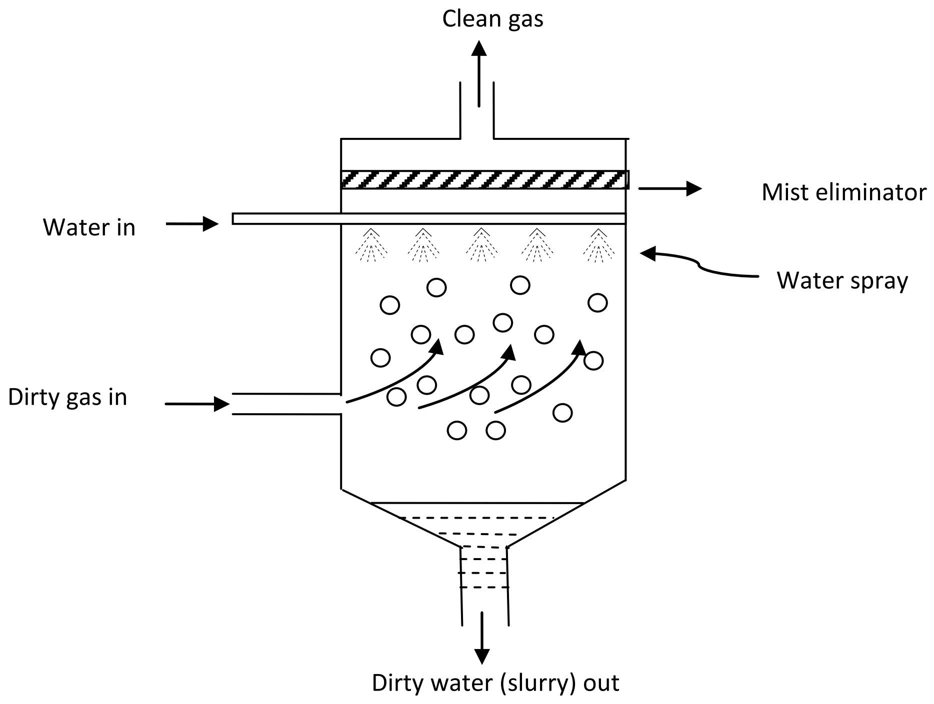


Fig.26. Sketch of a spray tower scrubber

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

Spray tower is acounter current flow and may be circular or rectangular spray tower as shown in Fig.26.

2-Centrifugal scrubbers

Fig.16. shows centrifugal scrubber. The polluted gas introduced tangentially into the lower portion of the vertical cylinder. Water drops are injectedfrom multiple nozzles, which throw the water radially outward across the flow gas stream. These droplets are caught in the spinning gas stream and are thrown upward towards the wall by centrifugal force. During their motion the, the droplets collide with particles and capture them. The scrubbing liquid along with the particles flows down the wall to the bottom of the scrubber and exits as slurry. The cleaned gas exists through a demister and is processed for the removal of any entrained water droplets.

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

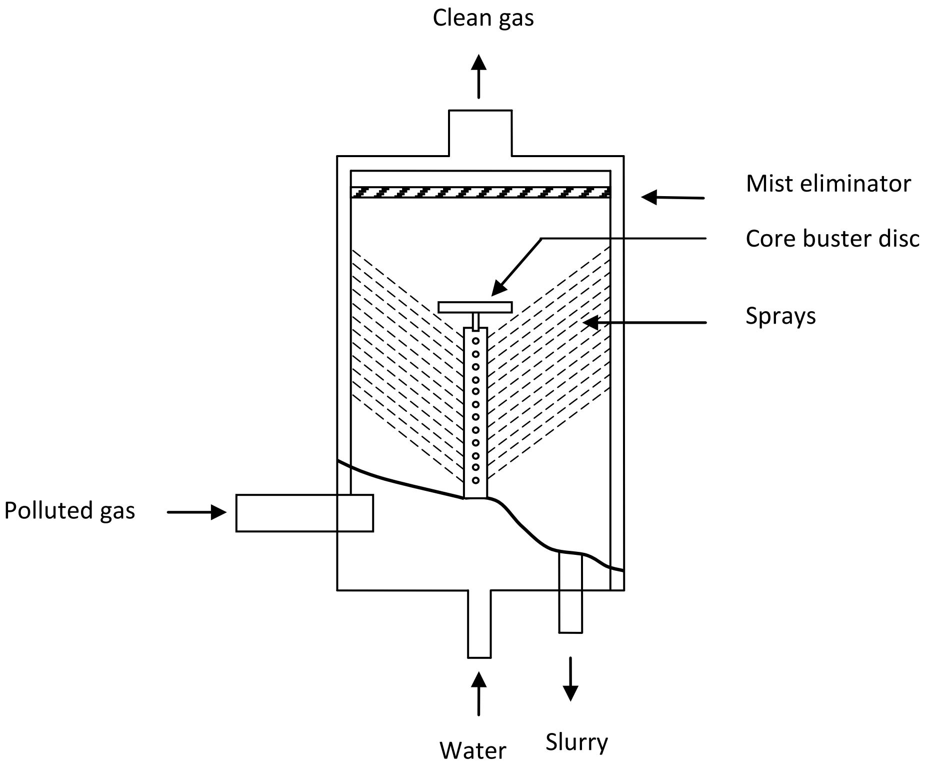


Fig.27. Centrifugal Scrubber, tangential entry

3-Venturi scrubbers

A venturi is a rectangular or circular flow channel which converges to a narrow throat section and diverges back to its original cross section area. The narrow throat causes acceleration of the velocity of the gas to a high level in the venturi section.

Fig.28. shows a vertical downward venturi with throat injection. A bank of nozzles on either side of throat injects water into high velocity gas stream. The high velocity gas

assist in atomizing the liquid injected into the gas. The drops collide with dust particles in the gas to form dust-water agglomerates. The gas-liquid mixture is then directed to a separation device such as cyclone separator where the droplets carrying the particulates are separated from the gas stream. Venturi scrubbers offer high performance collection of fine particles usually smaller than 2 to 3 µm. They are suitable when the particulate matter is sticky, flammable or highly corrosive.

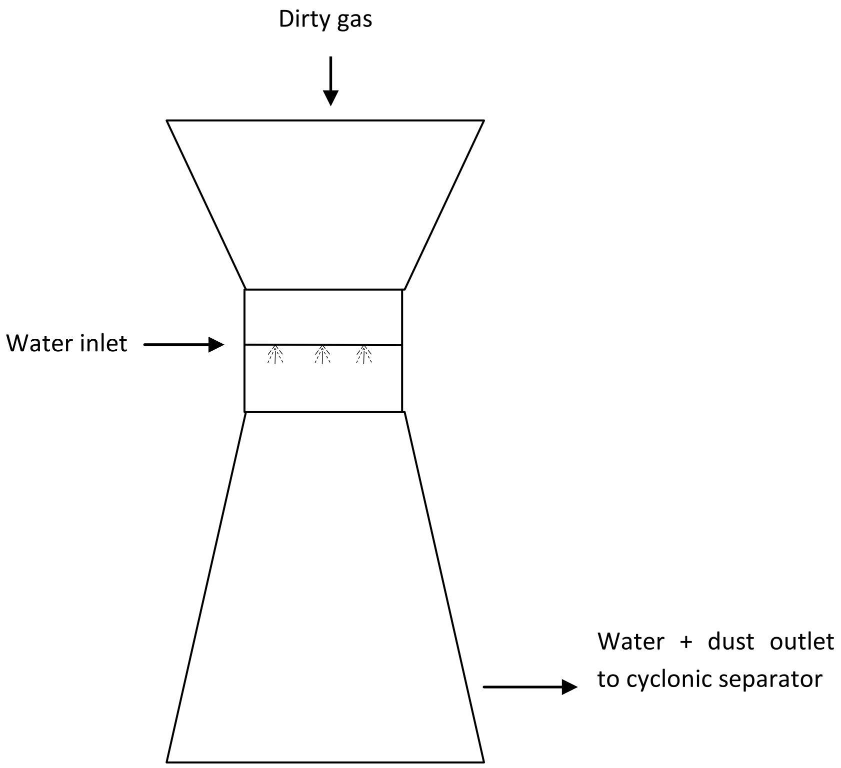


Fig.28. Vertical downward venturi scrubber with throat injection

Air pollution equipment design

Collection efficiency

The collection efficiency measures the system performance. This expressed as a percentage

$$\eta_T = 100 \times \frac{weight.of.material.collected}{Total.amount.enterin.collector}$$

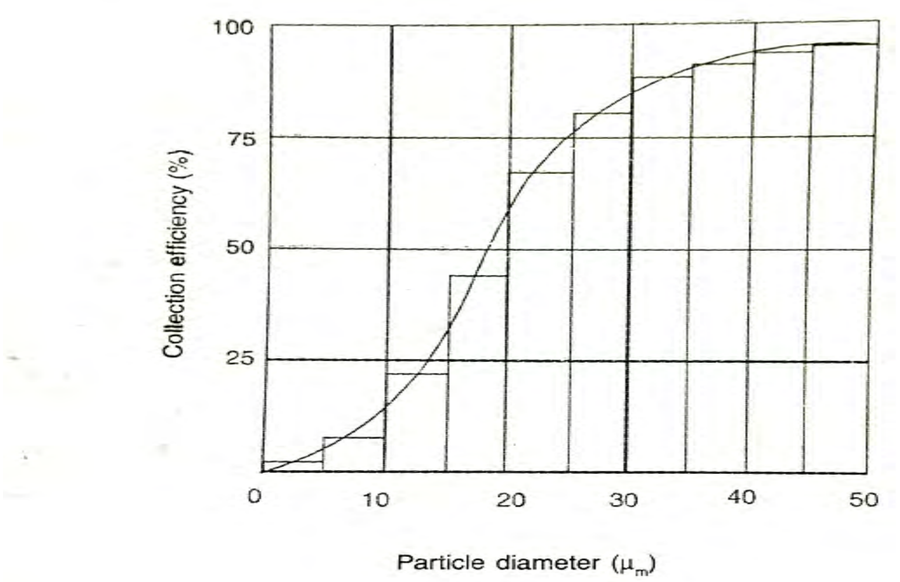


Fig.29. Fractional efficiency curve

The overall collection efficiency η_T can be calculated over n number of size Fractionsas:

$$\eta_T = \frac{\sum_{i=1}^{n} m_i \eta_i}{M} \qquad (1)$$

where M = total amount entering the collector.

Example 1

The following table shows the size distribution of dust sample and the fraction efficiency of removal in a gas cleaning equipment. Calculate the overall collection efficiency.

Dust size	Weight per 100 g of dust (g)	Fractional efficiency η_i (%)
< 5	2	1
5-10	2	7
10-15	4	16
15-20	7	44
20-25	10	67
25-30	8	81
30-35	7	88
35-40	10	92
40-50	15	93
50-60	20	95
60-70	10	98
>70	5	100

Answer

Using Eq.1 we can calculate the overall collection efficiency $\eta_T$as

$$\eta_T = \frac{\sum_{i=1}^{n} m_i \eta_i}{M} = \sum_{i=1}^{n} w_i \eta_i \qquad (1)$$

where $w_i = \frac{m_i}{M}$, the weight fraction in each size. Then the following we get

Dust size	Weight per 100 g of dust (g)	Weight fraction w_i	Fractional efficiency η_i (%)	w_i x η_i
< 5	2	0.02	1	(0.02 x1)
5-10	2	0.02	7	(0.02x7)
10-15	4	0.04	16	(0.04x16)
15-20	7	0.07	44	(0.07x44)
20-25	10	0.1	67	(0.1x67)
25-30	8	0.08	81	(0.08x81)
30-35	7	0.07	88	(0.07x88)
35-40	10	0.1	92	(0.1x92)
40-50	15	0.15	93	(0.15x93)
50-60	20	0.2	95	(0.2x95)
60-70	10	0.1	98	(0.1x98)
>70	5	0.05	100	(0.05x100)
				η_T = 80.17

1. Settling chamber design (gravity settling)

1.1. Terminal settling velocity

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

If the particle is settling in a fluid at its terminal velocity, three forces acting on it: drag, buoyancy, gravity force,as shown in Fig.30.The terminal settling velocity of the particles is found from forces balance as:

$$F_g = F_D + F_B \qquad (2)$$

where

F_g = gravity force (secondary Newton law) = $m_p g$ (3)

F_D = drag force = $F_D = \frac{\rho_g V_t^2 A C_D}{2}$ (4)

F_B = buoyancy force = $F_B = m_p \left(\frac{\rho_g}{\rho_p} \right) g$ (5)

m_p = mass of particle = $\rho_p V_p$

g = gravitational acceleration, m/s^2

ρ_g = gas density, kg/m^3

ρ_p =particle density, kg/m^3

C_D = drag coefficient

V_t = terminal velocity, m/s

A = frontal cross sectional area, m^2

V_p = volume of particle, m^3

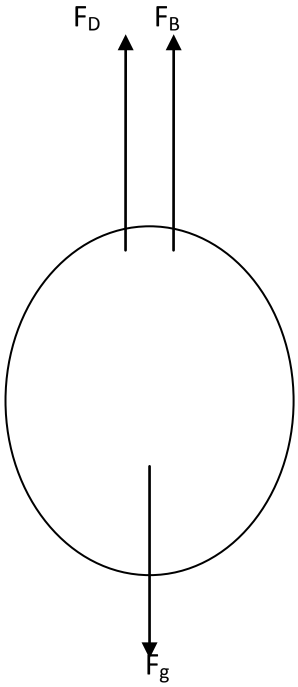


Fig.30 the forces acting on a particle in a fluid

Substituting Eqs. 3,4 and 5 in the overall balance Eq. 2 we get

$$m_p g = \frac{\rho_g V_t^2 A C_D}{2} + m_p \left(\frac{\rho_g}{\rho_p} \right) g \qquad (6)$$

The general solution to Eq.6, in term of V_t, is

$$V_t = \sqrt{\frac{2 m_p g(\rho_p - \rho_g)}{\rho_p \rho_g A C_D}} \qquad (7)$$

for spherical particle

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

where d_p = particle diameter, m. substituting the value of V_p and A in the above equation of V_t, we get

$$V_t = \sqrt{\frac{4 g d_p (\rho_p - \rho_g)}{3 C_D \rho_g}} \qquad (8)$$

Eq.8 is the general equation for the terminal settling velocity

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

Where $$\mathrm{Re}_p = \frac{\rho_g V_t d_p}{\mu_g} \qquad (9)$$

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

- **In Stocks law region**, laminar flow around the particle

$$C_D = \frac{24}{\mathrm{Re}_p} \text{ for } \mathrm{Re}_p < 0.1 \qquad (10)$$

- **In transition region, (0.1< Re < 1000)** this region between the Stokes law region and turbulent region

$$C_D = \frac{18.5}{\mathrm{Re}_p^{0.6}} \text{ for } 0.1 \leq \mathrm{Re}_p \leq 1000 \qquad (11)$$

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

$$C_D = 0.45 \text{ for } \mathrm{Re} > 1000 \qquad (12)$$

The drag coefficient can be calculating within the required range of Reynolds number and then substituted in the Eq(8) to determine the terminal velocity as:

1. Substituting Eqs.9 and 10 into Eq,8, we can calculate the terminal settling velocity in the Stokes region:

$$V_t = \frac{g d_p^2 \left(\rho_p - \rho_g\right)}{18 \mu_g} \qquad (13)$$

2. Substituting Eqs.9 and 11 into Eq.8 we can calculate the terminal settling velocityIn the transition region.

$$V_t = 0.153 \frac{g^{0.71} d_p^{1.14} (\rho_p - \rho_g)^{0.71}}{\rho_g^{0.29} \mu_g^{0.43}} \qquad (14)$$

3. Substituting Eqs.9 and 12 into Eq.8 , we can calculate the terminal settling velocity in the turbulent region:

$$V_t = 1.73 \left[\frac{g d_p (\rho_p - \rho_g)}{\rho_g} \right]^{1/2} \qquad (15)$$

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

$$K = d_p \left[\frac{g(\rho_p - \rho_g)\rho_g}{\mu_g^2} \right]^{1/3} \qquad (16)$$

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

If K < 3.3 then Stokes region applied to estimate V_t, Eq.13.

If $3.3 \le K \le 43.6$ then transition region applied to estimate V_t, Eq.14.

If K value > 43.6 then turbulent region applied to estimate V_t, Eq.15

Example 2

Three different fly ash particles settled through air, their sizes are 0.4, 40, 400 µm. calculate the terminal settling velocity for each particle assume the particle are spherical. Data required given below:

$T_{air} = 114.5\ ^oC$, $P_{air} = 1$ atm, $\mu_{air} = 0.021$ cp, sp.gr. of fly ash = 2.31

Note: Use K-value as a guide for the region.

Answer

$$K = d_p \left[\frac{g(\rho_p - \rho_g)\rho_g}{\mu_g^2} \right]^{1/3} \qquad (16)$$

the gas is air. The density of gas

$$\rho_g = \frac{P.MWt}{RT}$$

Gas constant $R = 0.082 \frac{atm.m^3}{kgmol.K}$, $T_{air} = 114.5 + 273 = 387.5K$, then the air density

$$\rho_g = \frac{(1)(29)}{(0.082)(387.5)} = 0.9126 kg/m^3$$

The viscosity of air

$$\mu_g = 0.021cp = 0.021 \times 10^{-3} kg/m.s$$

The density of fly ash = ρ_p

$$\rho_p = sp.gr \times \rho_{H_2O} = 2.31 \times 1000 = 2310 kg/m^3$$

$$K = d_p \left[\frac{9.81(2310 - 0.9126)(0.9126)}{(0.21 \times 10^{-3})^2} \right]^{1/3}$$

$$K = 36056.5 d_p \qquad \text{(a)}$$

For d_p = 0.4 µm = 0.4 x 10^{-6} m

$$K = 36056.5(0.4 \times 10^{-3}) = 0.014$$

K < 3.3 then use stocks region for calculating the settling velocity Eq.13

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

$$V_t = \frac{9.81(0.4 \times 10^{-6})^2 (2310 - 0.9126)}{18(0.21 \times 10^{-3})} = 9.58 \times 10^{-6} m/s$$

For the other particle diameter (40 and 400 µm) are illustrated in the following table

Particle Size µm	K	Region	V_t m/s
0.4	0.014	Stocks	9.58 x 10^{-6}
40	1.442	Stocks	0.0958
400	14.423	Transition	26.72

1.2. Retention time, τ

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

$$\tau = \frac{V}{Q} = \frac{L * W * H}{W * H * u} = \frac{L}{u} \qquad (17)$$

where

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

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

u = linear gas velocity, m/s

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

1.3. Chamber efficiency, η

$$\eta = \frac{V_t L}{Hu} \text{ or } \eta = \frac{V_t WL}{Q} \quad (18)$$

For most air pollution applications, Stock's law Eq.13 is appropriate substituting in Eq.10 as

$$\eta = \frac{d_p^2 g(\rho_p - \rho_g)L}{18\mu_g Hu} \qquad (19)$$

With 100% efficiency (η =1), Eq.19 becomes

$$d_{p,\min} = \sqrt{\frac{18\mu_g Hu}{g(\rho_p - \rho_g)L}} \qquad (20)$$

or

$$d_{p,\min} = \sqrt{\frac{18\mu_g Q}{g(\rho_p - \rho_g)WL}} \quad (21)$$

Eq.20 & 21 is to determine the minimum particle size $d_{p,min}$can removed with 100% efficiency (completely removed).

Example 3

A hydraulic acid mist in air at 25 ^{o}C is to be collected in a gravity settling chamber. Calculate the smallest mist droplet that will be collected by the chamber, applying stock's law. The operating data and dimension of settler are given below:

Wide (W) = 30 ft, Height (H) = 20 ft, Length (L) = 50 ft, Q_{gas} = 50 ft^3/s, ρ_g = 0.076 lb/ft^3, μ_g = 1.24 x 10^{-5} lb/ft.s, sp.gr of acid mist = 1.6

Answer

$$d_{p,\min} = \sqrt{\frac{18\mu_g H u}{g(\rho_p - \rho_g)L}} \qquad (20)$$

$$\rho_p = sp.gr \times \rho_{H_2O} = 1.6 \times 62.4 = 99.84 lb/\ ft^3$$

$$u = \frac{Q}{A} = \frac{Q}{HW} = \frac{50}{(20)(30)} = 0.083\, ft/s$$

$$d_{p,\min} = \sqrt{\frac{18(1.24 \times 10^{-5})(20)(0.083)}{32.2(99 - 0.076)(50)}}$$

$$= 4.81 \times 10^{-5}\ ft \left(\frac{0.3048m}{1\,ft}\right)\left(\frac{10^6\ \mu m}{1m}\right)$$

$$= 14.7\mu m$$

Design of settling chamber

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

$$WL = \frac{18\mu_g Q}{g\rho_p d_p^2} \quad (22)$$

$$A_c = WH = \frac{Q}{u} \qquad (23)$$

where

A_c= cross sectional area of the settling tank

Q = volumetric flow rate of the gas stream

W = width of settling chamber

H = height of settling chamber

L = Length of settling chamber

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

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

Note Eq. 22 estimated from Eq.19 assuming η = 1 for design purpose

Example 4

Design a gravity settler to remove all the iron particles from a dust laden stream. The particles diameter d_p = 35 µm. Use the following data:

Gas is air at ambient condition with characteristics:

Q_g = 130 ft^3/s, u = 10 ft/s. ρ_g = 0.0775 lb/ft^3, $\mu_g = 1.23 \times 10^{-5}$ lb/ft.s, ρ_p = 475.7 lb/ft

Answer

The gas densitycan be neglected compare to the particle density

$$d_p = 35\mu m\left(\frac{1m}{10^6\,\mu m}\right)\left(\frac{1\,ft}{0.3048m}\right) = 11.48 \times 10^{-5}\ ft$$

$$WL = \frac{18\mu_g Q}{g\rho_p d_p^2} = \frac{18(1.23\times10^{-5})(130)}{9.81(475.7)(11.48\times10^{-5})^2}$$

$$WL = CollectionArea = 142.5\,ft^2$$

$$Q = u \times Frontal.Area = u * H * W$$

$$HW = \frac{Q}{u} = \frac{130}{10} = 13\,ft^2$$

The minimum vertical height required for cleaning purpose (H = 1 m = 3.3 ft)

$$\because\ HW = 13\,ft^2 \Rightarrow W = \frac{13}{H} = \frac{13}{3.3} = 3.94\,ft$$

$$\because\ WL = 142.5\,ft^2 \Rightarrow L = \frac{142.5}{3.94} = 36.2\,ft$$

$\therefore$ Total volume of settler $= WHL$

$$= (3.94)(3.3)(36.2)$$

$$= 470.7\,ft^3$$

Design multi-tray Settling chamber

A more elaborate settling chamber is the Howard type whose simplified diagram is shown in Fig.31

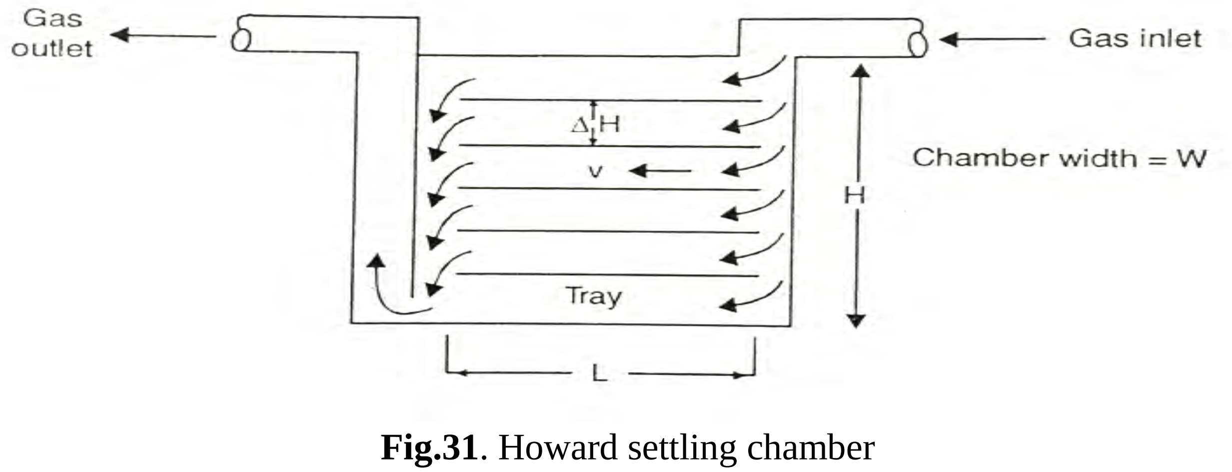


Fig.31. Howard settling chamber

For settling chamber having the dimensions L x W x H and n number of trays including the bottom surface (Fig.31), the hydraulic diameter for flow passage between the trays is given by

$$D_h = \frac{2W\Delta H}{W + \Delta H} \qquad (24)$$

and the Reynolds number,

$$\mathrm{Re} = \frac{\upsilon D_h \rho_g}{\mu_g} \qquad (25)$$

$$\upsilon = \frac{Q}{nW\Delta H}$$

where Q = volumetric flow rate of the gas stream

Substituting for υ and D_h in the Eq.25, we get

$$\mathrm{Re} = \frac{2Q\rho_g}{n\mu_g(W + \Delta H)} \qquad (26)$$

The spacing between the trays is, ΔH is given by

$$\Delta H = \frac{H}{n}$$

Provided there is no dust layer initially present on the tray surface. Substituting for ΔH in Eq.26 we have

$$\mathrm{Re} = \frac{2Q\rho_g}{\mu_g(nW + H)} \qquad (27)$$

The efficiency of collection

$$\eta = \frac{V_t nWL}{Q} \qquad (28)$$

and the minimum particle size that can removed 100% efficiency can be found from the equation,

$$d_{p,\min} = \sqrt{\frac{18\mu_g Q}{nWLg(\rho_p - \rho_g)}} \qquad (29)$$

N ote: previous equations assuming the laminar flow

Example 5

A multi-tray settling chamber having 8 trays. Including the bottom surface, handles 6 m^3/s of air at 20 ^oC. The trays are spaced 0.25 m a part and the chamber is to be 1 m wide and 4 m long.

1. What is the minimum particle size of density 2000 kg/m^3 that can be collected with 100% efficiency?

2. What will be the efficiency of the settling chamber if 50 µm particles are to be removed?

Assume Laminar flow condition within the chamber.

μ_g at 20 ^oC = 1.81×10^{-5} kg/m.s, ρ_p = 2000 kg/m^3.

Answer

From Eq.29

$$d_{p,\min} = \sqrt{\frac{18\mu_g Q}{nWLg(\rho_p - \rho_g)}}$$

Since the $\rho_p >> \rho_g$, ρ_g may be neglected in the above equation.

$$d_{p,\min} = \sqrt{\frac{18(1.81\times10^{-5})6}{8(1)(4)(9.81)(2000)}} = 5.6\times10^{-5} m = 56\mu m$$

From Eq.28 and using Stock's law for V_t

$$\eta = \frac{V_t nWL}{Q} = \frac{g d_p^2(\rho_p - \rho_g)nWL}{18\mu_g Q}$$

$\eta_{100} = 1$, then the efficiency to remove 50 µm is:

$$\frac{\eta}{\eta_{100}} = \left(\frac{d_p}{d_{p.\min}}\right)^2$$

$$\frac{\eta}{1} = \left(\frac{50}{56}\right)^2 = 80\%$$

Turbulent Flow model (well-mixed settling)

This model is often referred as the well-mixed settling model.

Assume that the gas flow is totally mixed in y-direction and not in x-direction

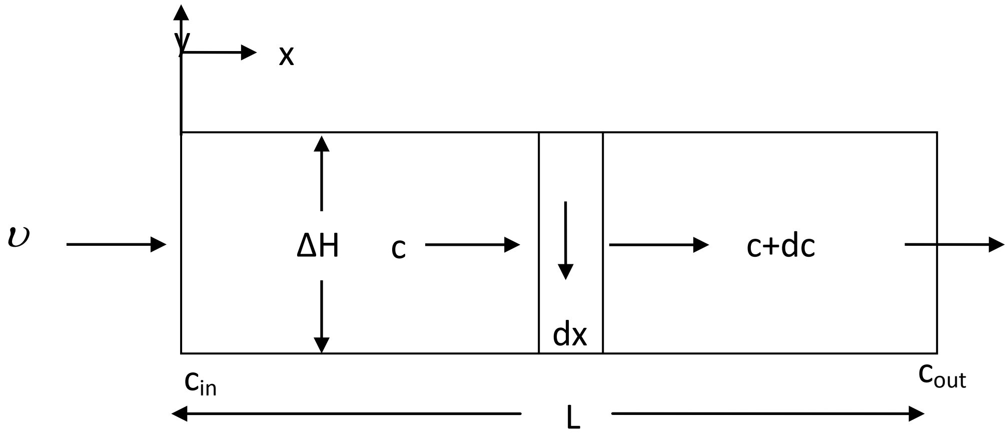


Fig.32. Gravity settling in a horizontal duct: turbulent flow

{ Mass concentration of particles entering the elemental volum (*Adx*) = Mass concentration of particles leaving the elemental volum (*Adx*) + Mass concentration of particles leaving the elemental volum (*Adx*) }

$$cAv = (c + dc)Av + cv_t Wdx$$

where c = mass concentration of the particles, and A = WΔH

$$\int_{c_{in}}^{c_{out}} \frac{dc}{c} = \frac{\upsilon_t W}{A\upsilon}\int_0^L dx$$

$$\ln\frac{c_{out}}{c_{in}} = \frac{\upsilon_t WL}{A\upsilon} \quad (31)$$

The efficiency $$\eta = 1 - \frac{c_{out}}{c_{in}} \quad (32)$$

Substituting Eq.31 into Eq.32 we get the efficiency in term of volumetric flow rate,

The efficiency $$\eta = 1 - \exp\left[-\frac{nWL\upsilon_t}{Q} \right] \quad (32)$$

Noting that the term in the bracket is the negative of the efficiency term for the laminar flow (Eq.28), we can write as:

$$\eta_{turb} = 1 - \exp\left(-\eta_{lami}\right) (32)$$

Example 6

In example 5, is the laminar flow assumption justified? If not, what is the collection efficiency for 56 and 50 µm particles?

answer

The Reynolds number calculated using Eq.27 as:

$$\mathrm{Re} = \frac{2Q\rho_g}{\mu_g\left(nW + H\right)} \qquad (27)$$

The kinematic viscosity of air at 20 ^{o}C, is 1.51x10^{-5} m^{2}/s.

where The kinematic viscosity = $\frac{\mu_g}{\rho_g} = 1.51 \times 10^{-5} m^2 / s$, and H = 2 m, then:

$$\mathrm{Re} = \frac{2Q\rho_g}{\mu_g\left(nW + H\right)}$$

$$= \frac{2Q}{\left(\frac{\mu_g}{\rho_g}\right)\left(nW + H\right)}$$

$$= \frac{2(6)}{1.51 \times 10^{-5}\left(8 \times 1 + 2\right)} = 79470$$

The flow is turbulent and the laminar flow assumption in example 5 was not justified. Hence, using Eq.32 we get:

$$\eta = 1 - \exp\left[-\frac{nWL\upsilon_t}{Q} \right] \qquad (32)$$

The terminal velocity using stock's law Eq.13:

$$V_t = \frac{gd_p^2\left(\rho_p - \rho_g\right)}{18\mu_g} \qquad (13)$$

The dynamic viscosity of air μ_g = 1.81x10^{-5} kg/m.s

$$\eta = 1 - \exp\left[-\frac{(8 \times 1 \times 4)\upsilon_t}{6} \right]$$

The terminal velocity:

$$V_t = \frac{9.8 \times 2000 \times d_p^2}{18(1.81 \times 10^{-5})}$$

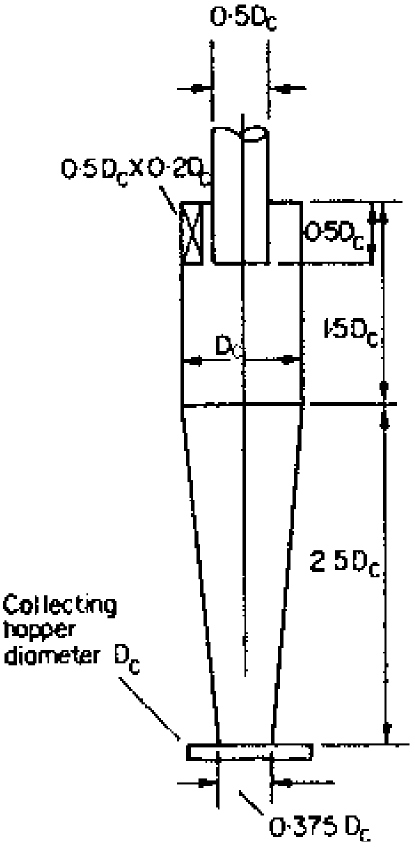
$d_{p,}$ µm	$V_{t,}$ m/s	η
50	0.15	o.55 or 55%
56	0.188	0.63 r 66%

2. Centrifugal separators (Cyclone separators)design

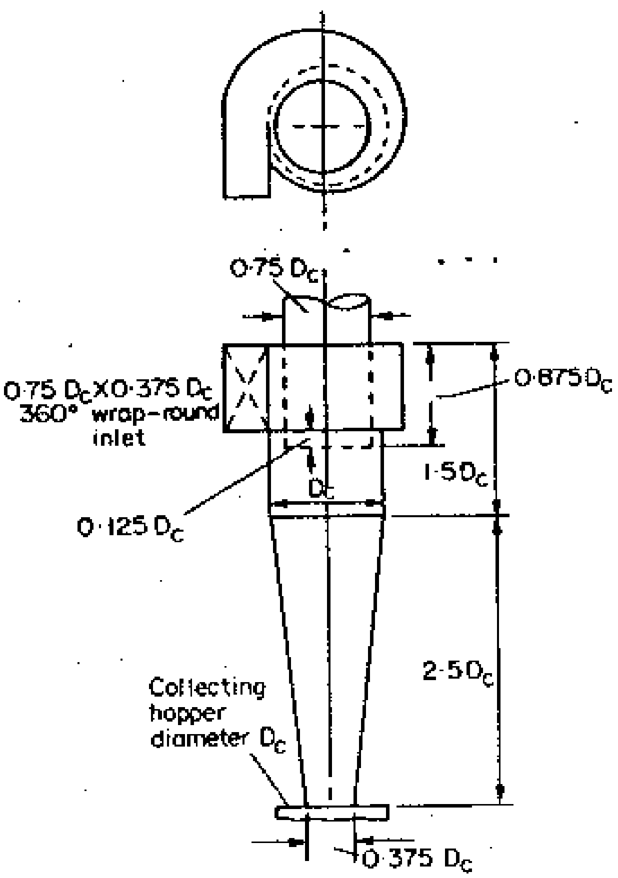
2.1. Cyclone design

Two standard designs for gas-solid cyclones; (a) high-efficiency cyclone, Fig.11a and (b) high gas flow rate cyclone, Fig.12b. The performance curves for the high efficiency cyclone and high gas rate cyclone are shown in Fig.33 a and b these curves can be transformed to other cyclone sizes and operating conditions by use the following scaling equation for a given separating efficiency:

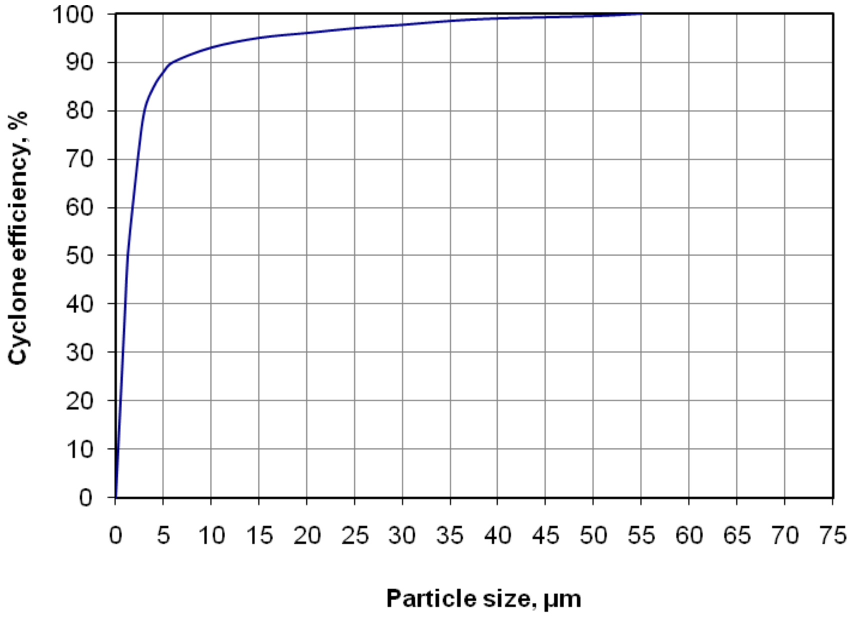
$$d_2 = d_1\left[\left(\frac{D_{C2}}{D_{C1}}\right)^3 \times \frac{Q_1}{Q_2} \times \frac{\Delta\rho_1}{\Delta\rho_2} \times \frac{\mu_2}{\mu_1}\right]^{\frac{1}{2}} \tag{14}$$



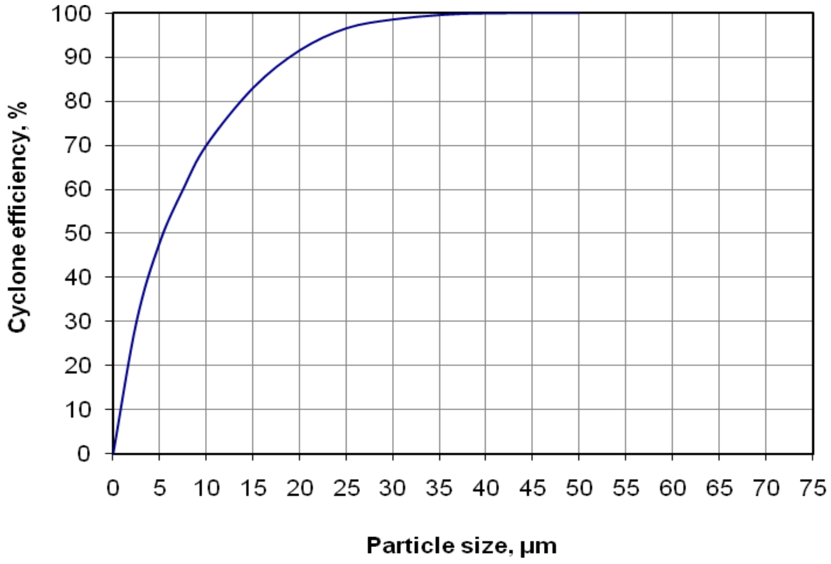
(a) High efficiency cyclone



(b) High gas rate cyclone



(a) High efficiency Cyclone



(b) High gas rate cyclone

Fig.34. Performance curves, standard conditions

where

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

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

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

D_{C2} =diameter proposed cyclone, mm

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

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

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

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

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

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

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

μ_2 = fluid viscosity, proposed design.

Hint

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

2.2. Cyclone pressure drop

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

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

where

Δp = cyclone pressure drop, millibars.

ρ_g = gas density, kg/m^3.

u_1 = inlet duct velocity, m/s.

u_2 = exit duct velocity, m/s.

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

r_e = radius of exit pipe, m

ϕ =fraction from Fig.13.

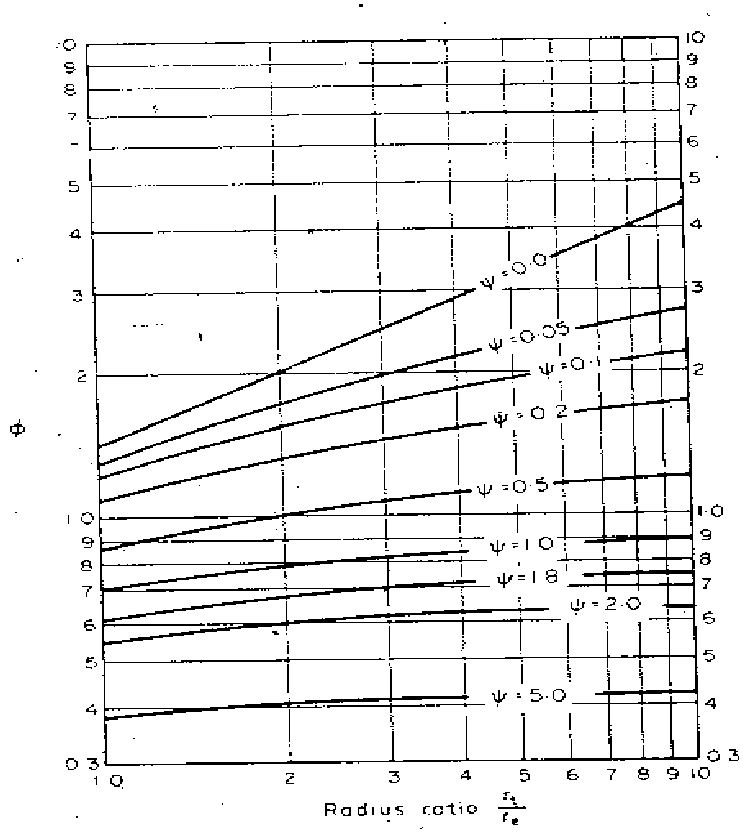


Fig.35. Cyclone pressure drop factor

Ψ = parameter in Fig.14..

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

where

f_C = fraction factor, taken as 0.005 for gas.

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

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

A_1 = area of inlet duct, m^2.

2.3. Cyclone efficiency

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

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

where

μ_g = gas viscosity, kg/m.s.

b = cyclone inlet width, m.

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

V_g = inlet gas velocity, m/s.

ρ_p = particle density, , kg/m^3.

P_p = gas density, kg/m^3.

The cut diameter can be used to establish the collection efficiency for any other diameter particle, d_p, as shown in Fig.36.

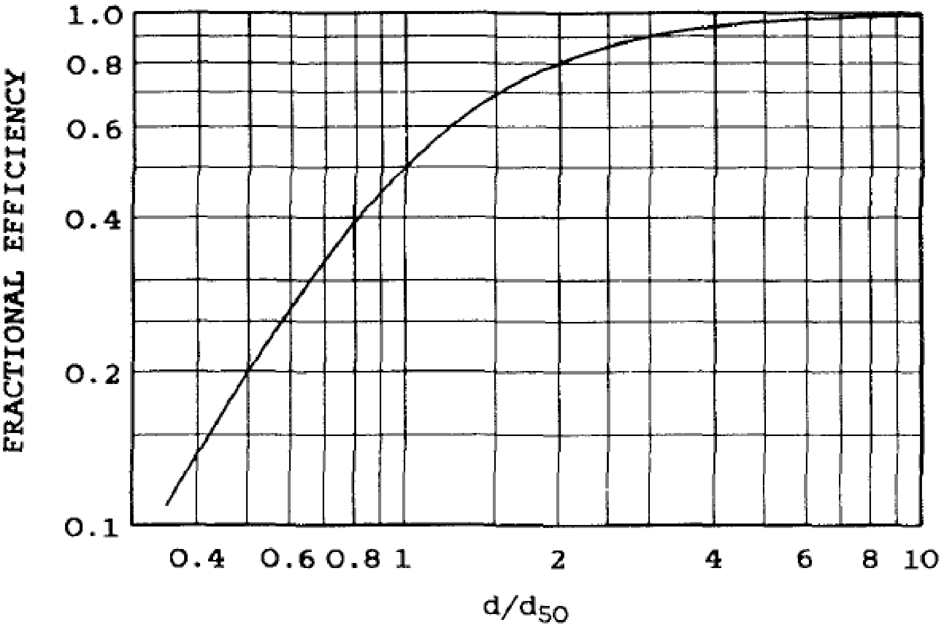


Fig.36. Cyclone efficiency versus particle-size ratio

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