Petroleum and Minerals Engineering College Petroleum Processing Engineering Department



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Petroleum Pollution Control

Definition: Pollution is the presence of substances in air in sufficient concentration and for sufficient time, so as to be, or threaten to be injurious to human, plant or animal life, or to property, or which reasonably interferes with the comfortable enjoyment of life and property. The presence of any thing

- It is an increasing problem in all countries
- It is increased with population and industrial activities
- It has huge economical effects **Pollutant Sources:**
- 1- Stationary sources, factories, industries, forest fires
- 2- Movable, cars , automobiles Types Pollutants
- 1- Air pollutants
- 2- Water pollutants
- 3- Soil pollutants
- 4- Radioactive pollutants
- 5- Thermal pollutants
- 6- Visual pollutants
- 7- White pollutants
- 8- Emf pollutants
- 9- Ocean pollutants
- 10- Ground water pollutants

Types air Pollutants

On the basis of particle size, there are three major categories of air pollutants: gaseous pollutants, particulate pollutants and aerosols.

- 1. Gaseous pollutants consist of atoms, molecules and include harmful gases, which can freely mix with air without settling down. Some examples of gaseous pollutants of air are carbon monoxide, carbon dioxide, sulphur dioxide, hydrogen sulphide, nitrogen oxides and hydrocarbons.
- 2. Particulate pollutants include finely divided solids as well as liquids having particle size from 10⁻⁴ to 10⁻³ cm. Particulates are harmful to the living as well as non-living things. The examples of particulate pollutants in the air are: dust, smoke, clouds, fumes, mist, spray and smog.
- 3. Aerosols are suspensions of fine particulate matter in the air. Aerosols have particle size smaller than particulates. Their particle size ranges from 10⁻⁷ cm to 10⁻⁴ cm. Aerosols can be either liquid or solid particles. They are small enough

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that affects certain cycle

such as oxygen cycle, fish

cycle, amebia cycle....etc

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to remain suspended in the atmosphere for long periods of time. Smoke, fine dust, fog, clouds are examples of aerosols.

Particulates and aerosols serve as collectors of chemically active sulphur oxides, nitrogen oxides, ozone, hydrocarbons and other pollutants and are serious health hazards.

Factors Affecting Reaction Rate

- 1- Concentration of the reactants
- 2- Amounts of moisture
- 3- Degree of photoactivation
- 4- Presence of some metals like Fe, Mg, work as a catalyst or provide a surface for the reaction
- 5- Meterological conditions
- 6- Local topography and geography

Units

Air pollution is expressed either as ppm or microgram $\mu g/m^3$

1 ppm = 1 volume of pollutant/(10^6 volume of air plus pollutant)

1 ppm = 0.0001% by volume

For solid pollutants it is usual to use $\mu g/m^3$, i.e mass/volume.

At 25 C, 298K and 1 atmosphere, 101326 kpa:

 $\frac{\text{pollutant mass}}{\text{volume of air}} = \frac{\rho_p}{V_{air}} V_p \qquad (1)$ $PV = nRT = \frac{wt}{MW}RT$ $\frac{PVMW}{wt RT} = \frac{PMW}{RT\rho_p} = 1$ Multiply equation 1 by 1: $\frac{pollutant mass}{volume of air} = \frac{\rho_p V_p P * MW}{V_{air}}$ $\frac{pollutant mass}{volume of air} = \frac{V_p P * MW}{V_{air}}$ For 1 atm., T = 298K, $R = 0.08208(atm.m^3)/(kg. Mole.K)$ $\frac{pollutant \,mass}{volume \,of \,air} = \frac{V_p}{V_{air}} \frac{MW}{24.5}, multiply \,by \,10^9 \,to \,convert \,kg \,to$ μg and divide by 10^6 to convert to ppm

$\frac{\mu g}{m^3} = ppm * MW * 1000/24.5$

For same conditions but 0 C the constant 24.5 becomes 22.41

Ex: Certain gas contains 1.5% by volume of CO, find the concentration in mg/L, and μ g/L

1% = 10000 ppm

1.5% = 15000 ppm

 $\mu g/m^3 = 15000*(16+12)*1000/24.5 = 17.1*10^6$

 $= 17.1 * 10^{6*} (1/1000) (mg/\mu g)/(1000) (L/m^3) = 17.1 mg/L$

Example

Calculate SO₂ concentration in flue gas when one mole of C_7H_{13} containing 1 % sulphur is burnt in presence of stochiometric amount of oxygen .

Solution

First we write stochiometric equation for combustion :

 $C_7H_{13} + 1\ 0.25O_2 = 7\ CO_2 + 6.5\ H_2O$

Since O_2 is supplied through air which also contains nitrogen and in air each mole of oxygen is accompanied by 3.76 mole N_2 , for 10.25 mole O_2 , 38.54 mole N_2 will be supplied. Therefore we may write .

 $C_7H_{13} + 10.25O_2 + 38.54 N_2 = 7 CO_2 + 6.5 H_2O + 38.54N_2$

Therefore quantity of flue gas at STP is = 45.54 mole

22.4 L = 1 mole

 $45.54 \text{ mole} = 45.45 \times 22.4 / 1 = 1020 \text{ L}$

Since one mole $C_7H_{13} = 7 \times 12 + 13 \times 1 = 97$ g, sulfur contents of fuel = 97 x 0.01 = 0.97 g.

1 mole of sulfur plus one mole of oxygen produce 1 mole of sulfur dioxide and the molecular weight of sulfur = 64 which is the same of oxygen, therefore 1 gram of sulfur react with I gram of oxygen.

Therefore SO_2 produced = 1.94 g or 1940 mg/mole of fuel.

As an approximation, neglecting the volume of oxygen consumed in production of SO₂ ,concentration of SO₂ = 1940 mg/1020 L = 1902 mg/m³, at STP . Or $1920*273/298 = 1742 \text{ mg/m}^3$

Particulate Matters:

It is a term employed to describe airborne solid and liquid particles larger than single molecule (0.0002 micron = 0.2 nanometer) but smaller than 50 micron. 1 Micron = (1/10000)cm

- It have a life time in suspension ranging from few seconds to several months.

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- Below 0.1 micron undergo random Browinian motion and greater than 20 micron is removed by gravity or inertial processes.
- Particulate is used interchangeably with aerosol which is a dispersion of solid or liquid matter of microscopic size in gaseous media less than 1 micron.
 Measurement of Suspended Particles
- 1- Drawing known volume of air through filter, then weighing before and after and the difference in weight represent the weight of particles and expressed as microgram per litter. Chemical analysis is often made.

The amount soluble in benzene is an indication of organic materials. Typically less than 10% is benzene soluble

2- Coefficient of Haze (COH)

Transmittance of light through a deposit of particulate on a filter paper can be used as a measure of the atmosphere air quality. The light transmittance through clean and dirty filter is compared and converted to COH per 1000 linear feet of air passing through the filter.

COH is defined as the quality of light scattering solids on a filter paper to produce an optical density equivalent to 0.01 when measured by light transmission.

optical density (OD) = Log(opacity)

$$Opacity(OP) = \frac{1}{fraction transmittance(T)}$$

COH = OD/0.01

Ex: If T of particulate sample on filter paper is 60% of that of the clean filter paper. If this sample is obtained by running the filter for 60 minutes at a velocity of 2 ft/sec, find COH and COH/1000 linear feet?

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Solution

OP = 1/0.6 = 1.67,

OD = Log 1.67 = 0.22

COH = 0.22/0.01 = 22

V = 2 ft/sec *60 sec/min = 120 ft/min

Linear feet (L) = 60*120 = 7200 ft

COH/1000ft = COH/n

=(OD/0.01)/n = 100 OD/n

Where

N number of thousands = L/1000, thus:
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COH/1000ft = 100*OD*1000/L

= 100000*Log(1/T)/L



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= 100000* 0.22/7200 = 3.6 Slight level of pollution

- 1-2 moderate
- 2-3 heavy

3-4 high

Particle Size Distribution

Solid particles can vary in shape from spherical, if formed by condensation and solidification, to high irregular shape. Spherical particles may increase in size by coagulation and become non spherical.

Definition and properties of the log-normal distribution

A random variable X is log-normally distributed if log(X) has a normal distribution. Usually, natural logarithms are used, but other bases would lead to the same family of distributions, with rescaled parameters. The probability density function of such a random variable has the form

$$f(x) = \frac{1}{x \cdot \sigma \sqrt{2\pi}} \exp\left(-\frac{1}{2\sigma^2} \left(\log(x) - \mu\right)^2\right)$$

Where:

 δ = standard deviation

 μ = any real number (where the function has its maximum)

Fig C show that the distribution is log-normal and it is a characteristic of many particle size distribution. It is also a characteristics of many gaseous pollutants i.e. a concentration versus time exhibit this behavior. A plot of log ppm versus % time that certain concentration is exceeded shows straight line distribution on a probability scale.



(a) (C) A log-normal distribution with original scale (a) and with logarithmic scale (b). Areas under the curve, from the median to both sides, correspond to one, and two standard deviation ranges of the normal distribution

Particle Collection

The choice of particle collection device depends on:

- 1- Material properties , physical and chemical properties such as density, size, explosion ability
- 2- Concentration and volumes to be treated
- 3- Temperature and humidity
- 4- Required efficiency
- 5- Operating, maintenance, and installation costs
- 6- Land availability
- 7- Location of the site
- 8- Type of industry Collector Types
- 1- Gravity settling Chambers (GSC)
- 2- Centrifugal separators (cyclones)
- 3- Electrostatic precipitators (ESP)
- 4- Filters
- 5- Wet Scrubbers
- 6- Ultrasonic agglomerators

The lator is used to agglomerate particles so that it may be collected in another devices.

Intensity of sound generators is more than 150 db Sound frequency is 1000-10000 hertz Petroleum pollution control Professor dr. Muzher Mahdi Ibraheem Petroleum & Gas Refinning Engineering Department, under Graduate Study

Higher frequency is required for smaller sizes

Efficiency depend on the frequency and removal device used for the removal of particulate matter.

This method is used successfully in removing of sulferic acid mists and soda ash fumes from the craft paper mill.

Removal Mechanisms

- Gravitational mechanism
- Centrifugal forces
- Inertial impaction
- Direct interception (Collision)
- Diffusion
- Electrostatic effects

Difference between inertial impaction, direct interception and diffusion

Particles carried out at same velocity as the gas stream. Gas stream moves along stream lines around any object in its path. Solid particles resist change in motion and the larger the particle is the less tendency to change direction (Inertial impaction a). In direct interception (b), smaller particles even though they tend to



follow stream lines, may contact the interceptor at the point of closest approach. Very fine particles (less than 1 micron) imping the collector as a result of random Browinian motion or diffusion (c).

Terminal settling velocity

Particulate removed from gas by fallout frequently is referred to as sedimentation

Settling in quiescent air

$$F_{D} + F_{B} = F_{g}$$

$$\frac{C_{D}}{2}\rho_{f}A_{p}v^{2} + \rho_{f}\forall g = mg$$

$$\frac{C_{D}}{2}\rho_{f}A_{p}v^{2} = \forall g(\rho_{p} - \rho_{f})$$

$$v = \sqrt[2]{\frac{2\forall g(\rho_{p} - \rho_{f})}{C_{D}\rho_{f}A_{p}}}$$

For spherical particle, $\forall = \prod d^3/6$ and $A = \prod d^2/4$



$$v = \sqrt[2]{\frac{4 \operatorname{dg}(\rho_{p} - \rho_{f})}{3C_{D}\rho_{f}}}....(1) \text{ Newton law}$$

$$C_{D} = \frac{24}{Re} \qquad for \ Re < 1$$

$$C_{D} = \frac{24}{Re} + \frac{24}{Re^{1/3}} \qquad for \ 3 < Re < 400$$

$$C_{D} = 0.44 \qquad for \ 1000 < Re < 200000$$
For lowing flow $C = 24/\operatorname{Pe} = \frac{24}{24\mu} \frac{24\mu}{24\mu}$

For laminar flow $C_D = 24/\text{Re} = \frac{21}{vd\rho_{f/\mu}} = \frac{21\mu}{vd\rho_f}$

Thus:

 $v = \frac{(\rho_p - \rho_f)gd^2}{18\mu}$(2) Stock law

If the flow region is not known:

- 1- Assume v then find Re and C_D
- 2- Use equation 1 to find v
- 3- Repeat until acceptable error % is obtained

The symbol V refers to the terminal settling velocity and it is usually referred to as V_t

Ex: find v for a particle settle in air if d= 5 micron , air density = 0.001 gr/cm³, particle density = 1.5 gr/cm^3 , $\mu = 1.8 * 10^{-4} \text{ gr/(cm.sec)}$ Solution:

1- Assume
$$v = 100$$
 cm/sec,

 $\text{Re} = 0.001*0.5*10^{-4} \text{v} / (1.8*10^{-4}) = 0.0002777 \text{v}$

= 0.0277 which is less than 1

$$C_D = 24/0.0277 = 864.24$$

 $v = \sqrt[2]{\frac{4 * 0.5 * 0.0001 * 980 * 0.999}{3 * C_{\rm P} * 0.001}} = \sqrt[2]{\frac{65.268}{C_{\rm P}}} = 0.274 \text{ use this to find new Re and } C_{\rm D}$

V	Re	CD	V
0.274	7.6218*10 ⁻⁵	3.14884*10⁵	0.0144
0.0144	4*10-6	6*10 ⁶	0.0033
0.0033	9.15*10 -7	2.62*107	0.00157
0.00157	4.38*10-7	5.47*10 ⁷	0.0011
0.0011	3.03*10-7	7.9*10 ⁷	0.000908
0.000908	2.51*10-7	9.5 *10 ⁷	0.000828
0.000828	2.29*10-7	10.43*10 ⁷	0.00079

Error% =(0.000828-0.00079)/0.000828 *100% = 4.59%

For air at standard conditions and stock flow:

 $v = 0.003 \rho_{v} d^{2}$

V in cm/sec, ρ in gr/cm³, d in micron

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Gravity Settling Chamber (GSC)

It is used when the settling velocity is greater than 25 ft/min. (diameter is greater than 50 micron) for low particle density or down to 10 micron if density is high. Inlet gas velocity should be less than 10 ft/sec and preferably about 1 ft/sec to prevent re entrainment.

In order to design the GSC, the following presentation is made.

1- Ideal model (no vertical mixing)





 $V_s = \frac{uH}{L}$ since $u = \frac{Q}{HW}$, therefore $V_s = \frac{QH}{HWL} = \frac{Q}{LW}$ which is termed as surface over flow rate....(1)



$$d_p = \sqrt[2]{\frac{18\mu Hu}{gL\rho_p}}.....(5)$$

To increase the efficiency of GSC, i.e reduce d_p , H must be reduced by horizontal baffle.

 $V_s = \frac{uH}{nL} = \frac{Q}{nLW}$

n=number of flow channel = number of baffel +1

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$$\eta_{d} = \frac{h}{H} \qquad h = V_{t} * t \qquad H = V_{s} * t$$

$$thus \eta_{d} = V_{t} * \frac{t}{t * V_{s}} = \frac{V_{t}}{V_{s}} = \frac{V_{t}}{\frac{Q}{LW}} = \frac{LWV_{t}}{Q}$$

$$\eta_d = \frac{nV_t L}{uH} = \frac{nLWV_t}{Q}.....(5)$$

Or:

Ex: Find the minimum particle diameter that can be removed by a GSC of 7 meter long and 1.2 meter height if gas inlet velocity is 30cm/sec and particle density is 2.5 gr/cm³. Temperature is 80F

Solution

Viscosity under 80F = 0.067 kg/(m.hr) = 0.067/3600 = 0.0000186 kg/(m.s)u=30/100=0.3 m/sec

$$d_p = \sqrt[2]{\frac{18 * 0.0000186 * 1.2 * 0.3}{9.80 * 2500 * 7}} = 2.65 * 10^{-5}m = 26.5 \text{ micron}$$

2- Mixed flow model



In this model, any particle enter laminar layer (dy) is removed The fraction of particle in the layer of thickness dy is dy/H Fraction of particles collected in the control volume dy dx is:

$$dy = v_t t \quad and \ t \frac{dx}{u} \quad thus$$

$$\frac{dy}{H} = \frac{V_t dx}{uH}$$

Number of particles at any cross section x in the flow is N_x Captured particles will be:

$$(N_{x} - N_{x+dx}) = f(N_{x})$$

$$(N_{x} - N_{x+dx}) = dN_{x}$$
Fraction of particles collected in the control volume is
$$\frac{dN_{x}}{N_{x}} = \frac{-V_{t}dx}{uH}$$

$$\ln N_{x} \left[\frac{N_{x}}{N_{o}} = -\frac{V_{t}x}{uH} \right] \rightarrow \ln \left[\frac{N_{x}}{N_{o}} \right] = -\frac{V_{t}x}{uH}$$
Integrate using the particle concentration as N0 at x = 0 to obtain
$$N_{x} = N_{o}EXP(-\frac{xV_{t}}{uH})$$

Collection efficiency for x = L will be: $\eta = \frac{N_o - N_L}{N_o}$

$$\eta = 1 - \frac{N_L}{N_o} = 1 - EXP\left(-\frac{LV_t}{uH}\right) = 1 - EXP\left(-\frac{LWV_t}{Q}\right)$$

Simpler approach:

Maximum distance vertically (y) can the particle traverse is:

Y = t V_t: $\frac{y}{V_t} = \frac{dx}{u} \rightarrow y = V_t \frac{dx}{u}$ The ratio y/H is the fraction of particles reaches to the laminar layer $\frac{dN}{N} = \frac{y}{H} = -\frac{V_t}{uH} dx$ At x=0, N = N₀, at x=L, N = N_L $N_L = N_0 EXP(-\frac{xV_t}{uH})$ The fraction collection efficiency is:

$$\eta = 1 - \frac{N_L}{N_o} = 1 - EXP\left(-\frac{LV_t}{uH}\right) = 1 - EXP\left(-\frac{LWV_t}{Q}\right)$$

Ex: find the length of GSC required to obtain 90% removal for particle of 50 micron diameter and density of 2 gr/cm³ if air velocity is 0.5 m/sec and H=3m. air viscosity is 0.07 kg/(m.sec), assuming stock flow.

Solution

$$0.07*1000/(3600*100) = 0.000194(\text{ gr/cm.sec})$$
$$V_{t} = \frac{2*980*0.005^{2}}{18*0.000194} = 14 \text{ cm/sec}$$
$$\eta_{d} = \frac{nV_{t}L}{uH}$$

For n=1,

$$L = \frac{{}^{n}Hu}{V_{t}} = 0.9 * 3 * \frac{0.5}{0.14} = 9.64 \text{ m}$$

It is expected that V_t = is smaller than theoretical due to many factors such as turbulence, re entrainment. It is usual practice to divide V_t by 2. In such a case V_t = 0.07 thus L= 19.38 meter.

Another procedure

$$0.9 = 1 - EXP\left(-\frac{LV_t}{uH}\right) = 1 - EXP\left(-\frac{0.14L}{0.5 * 3}\right)$$

L=24.67 m
This is very tall, so use 2 baffle. In this case H=1
L = 0.9*1*0.5/0.14 = 3.21 m
Or:
L = 0.9*1*0.5/0.07 = 6.42 m
Or:
0.9 = 1 - EXP\left(-\frac{0.14L}{0.5 * 1}\right)

L = 8.22 m

A convenient measure of the relative rates of the particle in each direction is gravitational separation number (N_{sg})

$$N_{sg} = \frac{V_t}{u} = \frac{\Delta \rho g d^2}{18 \mu u}$$

Residence time $(\tau) = \frac{\forall}{Q} = \frac{LWH}{WHu} = \frac{L}{u}$
Maximum distance (vertically) a part

Maximum distance(vertically) a particle travel in the chamber, h, is:

$$\tau V_t = h = \frac{LV_t}{u} = \frac{\Delta \rho g d^2 L}{18\mu u}$$
$$\eta = \frac{h}{H} = \frac{\tau V_y}{H} = \frac{\tau V_t}{H} = N_{sgH} = \frac{\Delta \rho g d^2 L}{18\mu uH}$$

Ex: A dust in the range of 30-130 micron. It is required to remove particles of 100 micron and greater completely. Given the following data, size the chamber and draw efficiency versus diameter. $Q = 100 \text{ ft}^3/\text{min.}$, air and particles diameters are $1.2046*10^{-3}$ and $12.928*10^{-3} \text{ gr/cm}^3$ respectively, air viscosity is $1.76*10^{-4}$ gr/(cm.sec)

Solution

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 V_t

$$= \frac{10000 * (12.928 - 1.2046) * 980 * 0.01^{2}}{1000 * 18 * 1.76} = \frac{0.363cm}{sec} = 0.7145ft/$$

min
V₁=Q/LW, LW= Q/V₁
LW=100/0.7145 = 140ft² use 150 ft²
Use H:W:L = 5:10:15 ft
 $\forall = 5*10*15 = 750ft^{3}$
 $\tau = 750/100 = 7.5$ min.
u = Q/WH = 100/50 = 2 ft/min. which is less than 10 ft/sec. OK
 $\eta = \frac{h}{H} = \frac{\tau V_{y}}{H} = \frac{\tau V_{t}}{H}$
divide settling velocity for any diameter by that for 100 micron,
 $\frac{V_{td}}{V_{t100}} = \frac{\frac{(\rho_{p} - \rho_{f})gd^{2}}{18\mu}}{\frac{(\rho_{p} - \rho_{f})g100^{2}}{18\mu}} = \frac{d^{2}}{100^{2}}$
 $V_{td} = \frac{d^{2}}{100^{2}}V_{t100}$
 $\eta_{50} = \frac{\tau V_{t}}{H} = \frac{7.5}{5} * \frac{50^{2}}{100^{2}} * 0.7145 = 0.267$
Complete for other diameters
 $\frac{100}{Eff.} = \frac{100}{90} \frac{90}{70} \frac{70}{50} \frac{40}{0.268} \frac{30}{0.1714} \frac{30}{0.096}$
Another Approach

$$tan\theta \ge H/L$$

$$vp = \frac{H}{t}$$

$$u = \frac{Q}{A}$$

$$tan\theta \ge \frac{tv_p}{ut} \ge \frac{vp}{u} \ge \frac{Av_p}{Q}$$

$$tan\theta = \frac{vp}{u} = \frac{Av_p}{Q}$$

$$eff = 100\%$$

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$$tan \emptyset = \frac{h}{L} < tan \theta = eff$$

$$tan \emptyset = \frac{tv_p}{ut} = \frac{vp}{u} = \frac{Av_p}{Q} = \frac{LWv_p}{Q} = \frac{LWv_p}{HWu} = \frac{Lv_p}{uH} = eff$$

The advantages of gravitational settling chambers are:

- i) low initial cost,
- ii) simple construction,
- iii) low maintenance cost.
- iv) low pressure drop,
- v) dry and continuous disposal of solid particles,
- vi) use of any material for construction, and
- vii)temperature and pressure limitations will only depend on the nature of the construction material.

The disadvantages of GSC are

- i) large space requirements and
- ii) only comparatively large particles (greater than 10 micron) can be collected.

Because of the above advantages and disadvantages, settling chambers are mostly used as pre-cleaners. They are sometimes used in the process industries, particularly in the food and metallurgical industries as the first step in dust control. Use of settling chambers as pre-cleaners can also reduce the maintenance cost of high efficiency control equipment, which is more subject to abrasive deterioration.

Centrifugal Separators (Cyclones)

It employs centrifugal force generated by spinning gas stream to separate particulate matters.

- May be single large chamber or a number of tubular chambers in parallel or in series
- Efficiency is seldom exceeds 90% for particles less than 10 micron
- Efficiency drop fast beyond certain diameter
- It is of low cost, reliable and ease of operation.

$$N_e = \frac{1}{H} \left[L_1 + \frac{L_2}{2} \right]$$

Where:

H = height of inlet duct

L₁=height of main upper cylinder

L₂=height of the cone

Settling chambers discussed above are not effective in removing small particles. Therefore, one needs a device that can exert more force than gravity force on the particles so that they can be removed from the gas stream. Cyclones use centrifugal forces for removing the fine particles. They are also known as centrifugal or inertial separators.

The cyclone consists of a vertically placed cylinder which has an inverted cone attached to its base. The particulate laden gas stream enters tangentially at the inlet point to the cylinder. The velocity of this inlet gas stream is then transformed into a confined vortex, from which centrifugal forces tend to drive the suspended

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particles to the walls of the cyclone. The vortex turns upward after reaching at the bottom of the cylinder in a narrower inner spiral. The clean gas is removed from a central cylindrical opening at the top, while the dust particles are collected at the bottom in a storage hopper by gravity.

The efficiency of a cyclone chiefly depends upon the cyclone diameter. For a given pressure drop, smaller the diameter, greater is the efficiency, because centrifugal action increases with decreasing radius of rotation. Centrifugal forces employed in modern designs vary from 5 to 2500 times gravity depending on the diameter of the cyclone. Cyclone efficiencies are greater than 90% for the particles with the diameter of the order of 10 μ . For particles with diameter higher than 20 μ , efficiency is about 95%.

The efficiency of a cyclone can be increased by the use of cyclones either in parallel or in series. A brief explanation of both arrangements is given below:



The advantages of cyclones are:

- i) low initial cost,
- ii) simple in construction and operation,
- iii) low pressure drop,

iv) low maintenance requirements,

v) continuous disposal of solid particulate matter, and

vi) use of any material in their construction that can withstand the temperature and pressure requirements.

The disadvantages of cyclones include:

- i) low collection efficiency for particles below $5 10 \mu$ in diameter,
- ii) severe abrasion problems can occur during the striking of particles on the walls of the cyclone, and
- iii) a decrease in efficiency at low particulate concentration.

Typical applications of cyclones are

- i) For the control of gas borne particulate matter in industrial operations such as cement manufacture, food and beverage, mineral processing and textile industries.
- ii) To separate dust in the disintegration operations, such as rock crushing, ore handling and sand conditioning in industries.
- iii) To recover catalyst dusts in the petroleum industry.
- iv) To reduce the fly ash emissions.

The operating problems are:

- i) **Erosion:** Heavy, hard, sharp edged particles, in a high concentration, moving at a high velocity in the cyclone, continuously scrape against the wall and can erode the metallic surface.
- ii) **Corrosion**: If the cyclone is operating below the condensation point, and if reactive gases are present in the gas stream, then corrosion problems can occur. Thus the product should be kept above the dew point or a stainless steel alloy should be used.
- iii) Build up: A dust cake builds up on the cyclone walls, especially around the vortex finder, at the ends of any internal vanes, and especially if the dust is hygroscopic. It can be a severe problem.

Mathematical Formulation of Removal Efficiency

To get 100% efficiency for a particle of diameter d_P , particles enter at inner radius R_i must be thrown at R_o (outer radius) before N_e are completed. All particles of this diameter or greater enter between R_i and R_o will be 100% removed.

Other diameters smaller than d_P enters between R^* and R_o will be removed completely.

 R^* = minimum radius for which particles of diameter smaller than d_P will reach the outer wall during N_e .

If no data are available, use $N_e = 4$

 $\eta = \frac{R_o - R^*}{R_o - R_i}$

 $R_0 - R_i$ = width of rectangular inlet

 $R_o - R^*$ = function of particle velocity normal to gas stream X time the gas is in the outer vortex

Centrifuga *l* force
$$= \frac{mV_c^2}{r} = m \omega^2 r$$

m = particle mass, V_C is tangential velocity

GD is angular velocity

Drag force $F_D = 3 \prod d_P \mu V_n$ (2)

Equating centrifugal and drag force in the radial direction assuming stock flow (not good assumption) and solve for V_n will give:



$$\omega = \frac{V_c}{r}$$

$$V_t = V_n = \frac{\rho_P d_P^2 V_c^2}{18\mu r} \dots (3)$$

$$If V_t = V_n = V_g = :r = R = \frac{R_i + R_o}{2} :and V_n is constant$$

$$V = \text{distance / time, thus}$$

$$V_n = \frac{R_o - R^*}{\Lambda t}$$

Thus

$$R_o - R^* = \frac{\Delta t \rho_P d_P^2 V_g^2}{18\mu R}$$
$$\Delta t = \frac{2\prod R N_e}{V_g}$$

Thus:

$$R_o - R^* = \frac{\prod N_e \rho_P \, d_P^2 \, V_g}{9_{\mu}}$$

Thus:

$$\eta = \frac{\prod N_e \rho_P d_P^2 V_g}{9_{\mu}W} = \frac{\prod N_e \rho_P d_P^2 Q}{9_{\mu}HW^2}$$

If the efficiency is 50% = 0.5, solve the above equation for particle diameter which is known in this case (Cut Diameter, D_C), will give:

$$D_{\mathcal{C}} = \sqrt{\frac{9_{\mu}W}{2_{\prod}N_{e}\rho_{P}V_{g}}} = \sqrt{\frac{9_{\mu}HW^{2}}{2_{\prod}N_{e}\rho_{P}Q}}$$

Ex: find D_C for the following data: W=12cm, N_e=4, V_g=15m/sec, particle density = 1.7 gr/cm^3 , air viscosity is 0.0748 kg/(m.hr)

Solution

W = 12/100=0.12 m/sec

$$\rho_P = (1.7/1000)*1000000 = 1700 \text{ kg/m}^3,$$

 $\mu = 0.0748 / 3600 = 0.00002077 \text{ kg/(m.sec)}$
 $D_C = \sqrt{\frac{9*0.00002077*0.12}{2 \Pi * 4 * 15 * 1700}} = 0.000005917m$
= 59.17 micron

Equation 3 can be written as:

$$V_t = V_n = \left[\frac{(\rho_P d_P^2)}{18\mu}\right] \frac{V_C^2}{R}$$

The term in bracket is $V_{\mbox{\tiny s}}/\mbox{\rm g}$, Thus

$$V_t = V_n = \left[\frac{V_S}{g}\right] \frac{V_C^2}{R}$$

2

Separation number is defined as $\frac{V_n}{V_s} = S$ Thus $S = \frac{V_c^2}{Rg}$ Higher sufficiency requires high inlet gas velocity and/or low R, both give higher pressure drop.



Scrubbers

Scrubbers are devices that remove particulate matter by contacting the dirty gas stream with liquid drops. Generally water is used as the scrubbing fluid. In a wet collector, the dust is agglomerated with water and then separated from the gas together with the water.

Capture Mechanisms

Particulates contact liquid droplets in wet scrubbers through several

mechanisms. Impaction is the primary capture mechanism. When waste gas approaches a water droplet, it flows along streamlines around the droplet. Particles with sufficient inertial force maintain their forward trajectory and impact the droplet. Due to their mass, particles with diameters greater than 10 μ m are generally collected using impaction [3]. Turbulent flow enhances capture by impaction.

Particles dominated by fluid drag forces follow the streamlines of the waste gas. However, particles that pass sufficiently close to a water droplet are captured by interception, capture due to the surface tension of the water droplet. Particles of of roughly 1.0 to 0.1 μ m in diameter are subject to interception [21]. Increasing the density of droplets in a spray increases interception [1].

Very small-sized particles are subject to Brownian motion, irregular motion caused by random collisions with gas molecules. These particles are captured by the water droplet as they diffuse through the waste gas. Collection due to diffusion is most significant for particles less than 0.5 μ m in diameter [1].

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Capture mechanisms that are used less frequently include condensation and electrostatics.

In condensation scrubbing, a gas stream is saturated with water vapor and the particle is captured when the water condenses on the particle [3]. In electrostatic scrubbing, contact is enhanced by placing an electrostatic charge on the particle, droplet, or both [2].

The mechanism of particulate collection and removal by a scrubber can be described as a four-step process.

- i) Transport : The particle must be transported to the vicinity of the water droplets which are usually 10 to 1000 times larger.
- ii) Collision : The particle must collide with the droplet.
- iii) Adhesion : This is promoted by the surface tension property.
- iv) Precipitation: This involves the removal of the droplets, containing the dust particles from the gas phase.

The physical principles involved in the operation of the scrubbers are:

- i) impingement,
- ii) interception,
- iii) diffusion and iv) condensation. A brief description is given below:

i)Impingement

When gas containing dust is swept through an area containing liquid droplets, dust particles will impinge upon the droplets and if they adhere, they will be collected by them. If the liquid droplet is approximately 100 to 300 times bigger than the dust particle, the collection efficiency of the particles is more, because the numbers of elastic collisions increase.

ii)Interception:

Particles that move with the gas stream may not impinge on the droplets, but can be captured because they brush against the droplet and adhere there. This is known as interception.

iii)Diffusion:

Diffusion of the particulate matter on the liquid medium helps in the removal of the particulate matter.

iv)Condensation:

Condensation of the liquid medium on the particulate matter increases the size and weight of the particles. This helps in easy removal of the particles.

The various types of scrubbers are:

Spray towers. i)

Venturi scrubbers. ii)

- iv) Cyclone scrubbers.
- v) Packed scrubbers.
- vi) Mechanical scrubbers.
- vii) Plate scrubber
- viii) Orifice scrubber
- ix) Condensation scrubbers
- x) Charged scrubber
- xi) Wet ESP_s scrubber

The simpler types of scrubbers with low energy inputs are effective in collecting particles above $5 - 10 \mu$ in diameter, while the more efficient, high energy input scrubbers will perform efficiently for collection of particles as small as $1 - 2 \mu$ in diameter.

The advantages of scrubbers are:

- i) Low initial cost.
- ii) Moderately high collection efficiency for small particles.
- iii) Applicable for high temperature installations.
- iv) They can simultaneously remove particles and gases.
- v) There is no particle re- entrainment.

The disadvantages of scrubbers are:

- i) High power consumption for higher efficiency.
- ii) Moderate to high maintenance costs owing to corrosion and abrasion.
- iii) Wet disposal of the collected material.
- The scrubbers are used in a variety of applications. Some of the situations are:
- i) They're particularly useful in the case of a hot gas that must be cooled for some reason.
- ii) If the particulate matter is combustible or if any flammable gas is present, even in trace amounts, in the bulk gas phase, a scrubber is preferred to an electrostatic precipitator.
- iii) Scrubbers can be used when there are waste water treatment systems available on the site, with adequate reserve capacity to handle the liquid effluent.
- iv) Scrubbers are also used when gas reaction and absorption are required simultaneously with particulate control.

Design Parameters

System Performance

The parameters affecting the overall performance of a wet scrubber are:

• Particle size distribution and loading;

- Waste gas flow rate, temperature and humidity;
- Gas velocity and pressure drop;
- Liquid-to-gas (L/G) ratio;
- Droplet size; and
- Residence time.

Theoretical Formulation

The major requirement for such device is the initiation of impingement or interception of a particle with a droplet.

A simplified approach: consider the following model: the particle approach the droplet as in the figure and under goes inertial impaction. At certain distance upstream from the droplet, the particle leaves the stream lines of the gas flow and proceed to the droplet. Two main forces affect the particle which are its own inertial forces and drag forces. As a result, particle eventually will come to stop relative to the droplet.

If the stopping distance X_s is greater than the original distance from the point where the particle left the stream line to the droplet, impact will result.



Impaction number N_I is the ratio between X_s and droplet diameter d_D :

$$N_{I} = \frac{X_{s}}{d_{D}}$$

Removal efficiency is directly proportional with the impaction number.

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Force balance will give: $F_{inertial} + F_{drag} = 0$ Assuming stock flow: $m \frac{dv_p}{dt} + 3 \prod v_p \mu_g d_p = 0$ Where V_p is relative velocity of particle relative to droplet $(u_p - u_D)$ For spherical particle, and: $\frac{dv_p}{dt} = \frac{dv_p}{dx} \frac{dx}{dt} = v_p \frac{dv_p}{dx}$ $\prod d^3 \qquad dv$



 $\frac{1}{dt} = \frac{1}{dx} \frac{1}{dt} = v_p \frac{1}{dx}$ $\frac{\Pi d_p^3}{6} \rho_p v_p \frac{dv_p}{dx} + 3\Pi v_p \mu_g d_p = 0$ $-\int_{v_{po}}^0 \frac{\Pi d_p^2 \rho_p dv_p}{18\mu_g} = \int_0^{x_s} dx$ $x_s = \frac{d_p^2 \rho_p v_{po}}{18\mu_g}$

in most cases V_{po} is the velocity of gas stream relative to the droplet, thus:

$$N_{I} = \frac{d_{p}^{2} \rho_{p} v_{po}}{18 \mu_{g} d_{D}} K_{C} = \frac{d_{p}^{2} \rho_{p} (u_{p} - u_{D})}{18 \mu_{g} d_{D}} K_{C}$$

According to the last equation, higher relative velocity and/or smaller droplet diameter is required to get higher efficiency.

Collection efficiency for venture is inertial impaction and for spray chamber is gravitational. For both cases the above figure is not representative. This is due to : the relative velocity is not constant over the range of droplet size. In venture meter, smaller drop is easier accelerated to gas velocity than larger droplet. In spray chamber, gas velocity does not affect droplet speed but gravitational force do. Thus higher relative velocity for higher diameter droplet. Thus, In both cases, the decrease of droplet diameter will reduce the efficiency. This is coupled with the previous figure will give an optimum droplet size that give maximum efficiency for a given particle diameter.

Estimating Pressure Drop

2.5.4.1.1 Pressure Drop Equations

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Most pressure drop equations for venturi scrubbers are of the form:

 $\Delta P = k v^2 \rho_g(\frac{L}{G})$

Where

 ΔP = pressure drop across venturi ,

v = throat velocity,

 ρ_g = gas density,

L/G = liquid to gas ratio, and

k = correlation factor for a specific scrubber design.

One of the more widely accepted equations for estimating pressure drop across a venture scrubber was published by Calvert [24]. The pressure drop is given as:

$$\Delta P = 5.4 * 10^{-4} v^2 \rho_q(\frac{L}{G})$$

Where

 ΔP = pressure drop across venturi in inches of water (in H₂O),

v = throat velocity in feet per second (ft/s),

 ρ_g = saturated gas stream density in pounds per cubic feet (lb/ft³), and

L/G = liquid to gas ratio in gallons per 1000 cubic feet (gal/1000 ft³).

The Calvert equation predicts pressure drop reasonably well at moderate liquid to gas ratios. At ratios between 3 gal/1000 ft³ and 10 gal/1000 ft³ the equation was found to perform well, but at or above 12 gal/1000 ft³ the equation over predicts the pressure drop by 80% or more [13].

1 litter/1 cubic meter = 7.48 gallons/1000 cubic feet Derivation of Calvert Model

In this model, all energy is assumed to be used to accelerate droplets Made force balance on strip dx:

$$F = m a$$

$$[P - (P + dP)]A = \rho_{L \forall L} \frac{du_D}{dt}$$

$$u_g A = Q_g$$

$$A = \frac{Q_g}{u_g}$$
Thus
$$dp \frac{Q_g}{u_g} = -\rho_L Q_L du_D$$

$$dp = -\rho_L \frac{u_g}{Q_g} Q_L du_D$$



$$\Delta p = -\rho_L u_g \frac{Q_L}{Q_g} u D_2$$

$$u_{D1} = 0 \text{ at } x = 0 \text{ , and } u_D = u_{D2} \text{ at } X = X_2$$

Assumptions:

- Gas velocity is constant
- One dimensional incompressible adiabatic flow
- No evaporation
- Droplet diameter is constant
- Pressure forces around droplet is symmetrical and ignored To find out pressure losses, it is important to find the terminal droplet velocity since all other parameters are known.

The sum of inertial and drag forces is zero, thus:

$$m\frac{du_D}{dt} = -\frac{1}{2}\rho_g(u_g - u_D)^2 A_D C_D$$

2

For spherical particle

$$\frac{du_D}{dt} = \frac{3}{4} \frac{\rho_g (u_g - u_D)^2}{\rho_L d_D} C_D$$

$$\frac{du_D}{dt} = \frac{du_D}{dx} \frac{dx}{dt} = u_D \frac{du_D}{dx}, \text{ thus}$$

$$\frac{du_D}{dx} = \frac{3}{4} \frac{\rho_g (u_g - u_D)^2}{\rho_L d_D u_D} C_D.....(1)$$

$$C_D = C_{Do}(\frac{u_g}{u_g - u_D}) Holand and Cowell....(2)$$

$$C_{Do} = 0.22 + \frac{24}{R_e} [1 + 0.15R_e^{0.6}] \text{ for } R_e = 10 - 500$$

Substitute equation 2 into equation 1 gives:

$$\frac{u_D du_D}{(u_g - u_D)^{1.5}} = \frac{3}{4} \frac{\rho_g (u_g)^{0.5} C_{Do}}{\rho_L d_D} dx$$

At X = 0 $u_D = 0$: at X=L $u_D = u_{DL}$ Make integration using integration tables:

$$u_{DL} = 2u_g [1 - m^2 + (m^4 - m^2)^{0.5}]$$

$$m = \frac{3}{16} \frac{\rho_g L C_{Do}}{\rho_L d_D} + 1$$

$$\Delta p = -\rho_L u_g \frac{Q_L}{Q_g} u D 2 \qquad 2 u_g [1 - m^2 + (m^4 - m^2)^{0.5}]$$

$$\Delta p = -\rho_L u_g \frac{Q_L}{Q_g} uD2; \qquad \Delta p = -\rho_L u_g \frac{Q_L}{Q_g} 2u_g [1 - m^2 + (m^4 - m^2)^{0.5}]$$

:if the throat is long enough,

 $u_{DL} = u_g$ thus: $\left[1 - m^2 + (m^4 - m^2)^{0.5}\right] = 1/2$

$$\Delta P = P_2 - P_1 = -\rho_L(u_g)^2 \frac{Q_L}{Q_g}$$

Where

 ΔP = pressure drop in force/unit area Other formula is

$$\Delta P = -1.03 * 10^{-3} (u_g)^2 \frac{Q_L}{Q_g}$$

Where

 ΔP is in cm water

 u_a is in cm/sec

A model for pressure drop published by **Hesketh** is also widely used [16]. The model is based upon a correlation of experimental data obtained from many different venturi scrubbers.

Hesketh's equation for pressure drop is given by:

$$\Delta P = \frac{\nu^2 \rho_g A^{0.133}}{507} \left(0.56 + 0.125 \frac{L}{G} + 0.023 \left(\frac{L}{G}\right)^2 \right) \right)$$

Where

 ΔP = pressure drop across venturi in inches of water (in H₂O),

v = throat velocity in feet per second (ft/s),

 ρ_g = saturated gas stream density in pounds per cubic feet (lb/ft³),

A = the cross-sectional area of the throat in square feet (ft^2), and

L/G = liquid to gas ratio in gallons per 1000 cubic feet (gal/1000 ft³). This equation is often simplified to:

$$\Delta P = \frac{\nu^2 \rho_g A^{0.133}}{1270} \left(\frac{L}{G}\right)^{0.78}$$

Hesketh experimentally determined a relationship between pressure drop and collection efficiency [2]. Based on the collected data, Hesketh concluded that the venturi is essentially 100% efficient for particles greater than 5 μ m. He developed a correlation between pressure drop and penetration for particles sizes below this value, given by:

$$Pt = \frac{C_i}{C_o} = 3.47 \Delta P^{-1.43}$$

Where

 C_i and C_o = concentration of particles <5 μ m at inlet and outlet of the venture on a mass basis, and

 $\Delta P = \text{pressure drop, in H}_2O.$ $Pt = 1 - eff(\eta)$

$$Pt = \exp\left[-\frac{6.1 * 10^{-11} \rho_L \rho_p f^2 K_C d_p^2}{\mu_g^2} \Delta P\right]$$

Where

 $\Delta P \text{ in } cmH_2 O: \quad \mu_g \text{ in } \frac{kg}{m.sec}: \quad \rho_L \rho_p \text{ is in } gr/cm^3: \quad d_P \text{ in micron} f \text{ constant} = 0.1-0.4 \quad \text{, average} = 0.25$

Ex: Water is introduced into a throat of a venture scrubber at a rate of 1 liter per 1 cubic meter of gas flow. Air velocity is 400 ft/sec, gas and particle density is 0.072 lb/ft³ and 1.5 gr/cm³ respectively, throat area is 125 in², temperature is 170 F under which gas viscosity is 0.0000208 kg/(m.sec), f is 0.25 and particle diameter is 1 micron. find pressure drop and penetration.

Solution

400ft/sec=400*30.48=12200cm/sec Gas flow rate $1 \text{ m}^3 = 1000 \text{liter}$ $\Delta P = -1.03 * 10^{-3} (u_g)^2 \frac{Q_L}{Q_g}$ $\Delta P = -1.03 * 10^{-3} (12200)^2 \frac{1}{1000} = 153.3 \text{ cm water} = \frac{153.3}{2.54} = 60.4 \text{ in}$ Or use: $\Delta P = \frac{v^2 \rho_g A^{0.133}}{507} (0.56 + 0.125 \frac{L}{G} + 0.023 (\frac{L}{G})^2))$ $Pt = exp[-\frac{6.1 * 10^{-11} \rho_L \rho_p f^2 K_C d_p^2}{{\mu_g}^2} \Delta P]$ $125 \text{ in}^2 = 125/144 = 0.868 \text{ ft}^2$ $1m^3 = 1/0.3048^3 = 35.31 \text{ft}^3$ 1 ft³= 7.48 gallons $1 \text{ gallons} = 3785.7 \text{ cm}^3$ 1 litter = 1000/3785.7=0.26145 gallons 1litter/1m³= 0.26415/35.31=0.00748 galoons/ft³ Thus 1liter/1m³=7.48 gallons/1000ft³ $\Delta P = \frac{400^2 * 0.072 * 0.868^{0.133}}{507} (0.56 + 0.125)$ $(*7.48 + 0.023(7.48)^2)$ = 36.2 in water

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$$K_{c}=1+0.182/d_{p} = 1+0.182/1 = 1.182$$

$$Pt = \exp\left[-\frac{6.1 * 10^{-11} * 1 * 1.5 * 1.182 * 1^{2} * 0.25^{2} * 153.3}{0.0000208^{2}}\right]$$

$$=0.0911$$
Or
$$Pt = \frac{C_{i}}{C_{o}} = 3.47\Delta P^{-1.43} = 3.47 * 36.2^{-1.43} = 0.0205$$



Fabric Filters

Fabric filtration is one of the most common techniques to collect particulate matter from industrial waste gases. The use of fabric filters is based on the principle of filtration, which is a reliable, efficient and economic methods to remove particulate matter from the gases. Air pollution control equipment using fabric filters are known as bag houses.

It is any porous structure composed of granular or fibrous Mterials which tends to retain particulate matter as the carrier gas passes through the voids of the filter. It may be arranged in deep beds, mat or fabric.

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Removal mechanism is inertial impaction and direct interception for larger than 1 micron while diffusion and electrostatic attraction play the main rule for lower diameters.

Bag Houses

A bag house or a bag filter consists of numerous vertically hanging, tubular bags, 4 to 18 inches in diameter and 10 to 40 feet long. They are suspended with their open ends attached to a manifold. The number of bags can vary from a few hundreds to a thousand or more depending upon the size of the bag house. Bag houses are constructed as single or compartmental units. In both cases, the bags are housed in



a shell made of rigid metal material. Occasionally, it is necessary to include insulation with the shell when treating high temperature flue gas. This is done to prevent moisture or acid mist from condensing in the unit, causing corrosion and rapid deterioration of the bag house.

Hoppers are used to store the collected dust temporarily before it is disposed in a landfill or reused in the process. Dust should be removed as soon as possible to avoid packing which would make removal very difficult. They are usually designed with a 60 degrees slope to allow dust to flow freely from the top of the hopper to the bottom discharge opening. Sometimes devices such as strike plates, poke holes, vibrators and rappers are added to promote easy and quick discharge. Access doors or ports are also provided. Access ports provide for easier cleaning, inspection and maintenance of the hopper.

A discharge device is necessary for emptying the hopper. Discharge devices can be

manual (slide gates, hinged doors and drawers) or automatic trickle valves, rotary airlock valves, screw conveyors or pneumatic conveyors)

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Filter Media

Woven and felted materials are used to make bag filters. Woven filters are used with low energy cleaning methods such as shaking and reverse air. Felted fabrics are usually used with low energy cleaning systems such as pulse jet cleaning. While selecting the filter medium for bag houses, the characteristics and properties of the carrier gas and dust particles should be considered.

The properties to be noted include:

- a) Carrier gas temperature
- b) Carrier gas composition
- c) Gas flow rate
- d) Size and shape of dust particles and its concentration
- e) Physical and chemical properties of particles

f) The abrasion resistance, chemical resistance, tensile strength and permeability and the cost of the fabric should be considered.

The fibers used for fabric filters can vary depending on the industrial application. Some filters are made from natural fibers such as cotton or wool. These fibers are relatively inexpensive, but have temperature limitations (< 212 F) and only average abrasion resistance. Cotton is readily available making it very popular for low temperature simple applications. Wool withstands moisture very well and can be made into thick felts easily. Synthetic fibers such as nylon, orlon and polyester have slightly higher temperature limitations and chemical resistance. Synthetic fibers are more expensive than natural fibers. Polypropylene is the most inexpensive synthetic fiber and is used in industrial applications such as foundries, coal crushers and food industries. Nylon is the most abrasive resistant

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synthetic fiber making it useful for applications filtering abrasive dusts. Different types of fibers with varying characteristics are available in the market.



Woven fabric

Efficiency:

The efficiency of bag filters may decrease on account of the following factors:

a) **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 ratios lower particulate removal efficiency and result in increased

Excessive filter ratios lower particulate removal efficiency and result in increased bag wear. Therefore, low filter ratios are recommended. Therefore, low filter ratios are recommended for high concentration of -particulate.

b) **Improper selection of filter media** - While selecting filter media, properties such as temperature resistance, resistance to chemical attack and abrasion resistance should be taken into consideration.

Operating Problems:

Various problems during the operation of a bag house are:

- a) Cleaning : at intervals the bags get clogged up with a covering of dust particles that the gas can no longer pass through them. At that point, the bags have to be cleaned by rapping, shaking or by reverse air flow by a pulse jet.
- b) Rupture of the cloth: -The greatest problem inherent in cloth filters is the rupture of cloth, which results from shaking. It is often difficult to locate ruptures and when they're found the replacement time is often considerable.
- c) Temperature

Fabric filters will not perform properly if a gross temperature overload occurs. If the gas temperature is expected to fluctuate, a fiber material that will sustain the upper temperature fluctuation must be selected. Also, whenever the effluent contains a reactive gas like SO_2 which can form an acid whenever the temperature in the bag house falls below the dew point it can create problems. Sometimes it may even be necessary to provide an auxiliary heater to make sure that the temperature in the bag house does not fall below acid gas dew point.

- d) Bleeding :This is the penetration of the fabric by fine particles, which is common in fabric filtration. It can occur if the weave is too open or the filter ratio is very high. The solution is to use a double layer material or a thick woven fabric.
- e) Humidity :This is a common and important problem, especially if the dust is hygroscopic. It would therefore be advisable to maintain moisture free conditions within the bag house, as a precautionary measure.
- f) Chemical attack: This is another problem associated with fabric filters. The possibility of chemical attack due to corrosive chemicals present in the effluent. A proper choice of fabric filter will avoid this problem.

Filter cleaning mechanisms:

The following mechanisms are used for cleaning the filters in a bag house:

- i) Rapping
- ii) Shaking
- iii)Reverse air flow (back wash)
- iv)Pulse jet

The advantages of a fabric filter are:

- i) High collection efficiencies for all particle sizes, especially for particles smaller than 10 micron in diameter.
- ii) Simple construction and operation.
- iii)Nominal power consumption.
- iv)Dry disposal of collected material.

The disadvantages of a fabric filter are:

- i) Operating limits are imposed by high carrier gas temperatures, high humidity and other parameters.
- ii) High maintenance and fabric replacement costs. Bag houses are difficult to maintain because of the difficulty in finding and replacing even a single leaking bag. Also as general rule, about 1/4th of the bags will need replacement every year.
- iii)Large size of equipment.

iv)Problems in handling dusts which may abrade, corrode, or blind the cloth.

The applications of a fabric filter are:

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Fabric filters find extensive application in the following industries and operations:

- i) Metallurgical industry
- ii) Foundries
- iii) Cement industry
- iv) Chalk and lime plants
- v) Brick works
- vi) Ceramic industry

vii)Flour mills

As the filter cake accumulates, efficiency and pressure drop increased also. Using the same procedure for wet scrubber, the efficiency is a function of impaction or separation number.

$$N_I = \frac{d_p^2 \rho_p v_p}{18 \mu_g d_f} K_C$$

stock flow

Darcy Law

$$Q \propto A \qquad Q \propto \Delta p \qquad Q \propto \frac{1}{L} \qquad Q \propto \frac{1}{\mu}$$
$$Q = \frac{Ak\Delta p}{\mu L} \qquad \rightarrow \frac{Q}{A} = \frac{k\Delta p}{\mu L} \rightarrow \frac{V\mu}{k} = \Delta p/L$$

Unit

$$k = \frac{Q\mu L}{A\Delta p} = \frac{1\left(\frac{cm^3}{sec}\right)1cp1cm}{1 atm 1cm^2} = \frac{cm^2 cp}{atm sec} = 1 darcy$$
$$= 1000md$$



Units in homogeneous system

$$k = \frac{\left(\frac{cm^3}{sec}\right)(dyne.\frac{sec}{cm^2}cm)}{\frac{dyne}{cm^2}cm} = cm^2 \quad unit of area$$

$$k(1darcy) = \frac{Q\mu L}{A\Delta p} = \frac{1\left(\frac{cm^3}{sec}\right)1cp * 0.01\frac{\left(\frac{dyne}{cm^2}\frac{sec}{cm^2}\right)}{cp}1cm}{atm * 1013260\frac{\frac{dyne}{cm^2}}{atm}cm^2}$$
$$= 9.869 * 10^{-9}cm^2 = 9.869 * 10^{-13}m^2$$

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K;cm/sec

$$Q = rac{Ak\Delta p}{\mu L}$$
 $v = rac{k\Delta p}{\mu L} = rac{k\Delta h}{\mu L} = rac{k\Delta h}{L} = kI$

Mistakes

N, m, sec, C K or kg, m, sec, C k

- 1- $\Delta h \neq \Delta p$ $\Delta p = \rho g \Delta h = \gamma \Delta h$
- 2- Δh in cm H2O and cannot cancled with length unit cm
- 3- μ cannot cancled because it is = 1cp. it is 0.01dyne sec/cm2

$$\rho = \frac{m}{v}$$
 $v = \frac{m}{\rho}$
 $v of 1 cubic meter of water = 1000kg$

https://www.researchgate.net/publication/279180316 A Discussion About Hydr aulic_Permeability_and_Permeability





Across each layer Darcy law is applicable

$$\frac{\Delta P}{x} = \frac{V\mu_g}{k}$$
$$\Delta P_o = \Delta P_f + \Delta P_p = \frac{V\mu_g x_f}{k_f} + \frac{V\mu_g x_p}{k_p}$$

All parameters are constants, thus total pressure drop is

a function of cake permeability and cake thickness which are a function of time: Mass collected W = VAt I = Ar c

 $W = VAtL_d = Ax_p\rho_c$ Thus:
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$$x_{p} = \frac{VtL_{d}}{\rho_{c}}$$
$$\Delta P = \frac{xV\mu_{g}}{\kappa_{p}} = \frac{VtL_{d}}{\rho_{c}} * \frac{V\mu_{g}}{\kappa_{p}} = \frac{V^{2}\mu_{g}tL_{d}}{\rho_{c}\kappa_{p}} = R_{p}V^{2}tL_{d}$$
$$R_{p} = \frac{\mu_{g}}{\rho_{c}\kappa_{p}}$$

Ex: If air at 170 F flows through filter for 5.4 hours after which pressure drop is 4.74 in water, cake density is 1.28 gr/cm³, pressure losses through clean filter is 0.55 in water, air velocity is 4.2 ft/min., dust load (L_d) is 14 gr/ft³. Find cake permeability.

Solution

From tables, gas viscosity is 0.0503 lb_m/(ft.hr)

$$V = 4.2 \frac{ft}{min^{60}sec/min} = 0.07 \ ft/sec$$

$$L_d = 14 \frac{gr}{ft^3} \frac{1}{453.6} \frac{lb}{gr} = 0.0309 lbmass/ft^3$$
5.4 hr * 3600 sec/hr= 19940sec
1.28gr/cm³(62.4) = 79.87 Lb_m/ft³
1 atmosphere= 1033.6 cm water = 406.93 inch water
(4.74-0.55)*14.7/406.93 = 0.151 Lb_f/in²= 0.151*144=21.796 Lbf/ft²

$$\frac{0.0503 lb_m}{ft.hr * \frac{3600 sec}{hr}} = \frac{0.00001397 lb_m}{ft.sec}$$

$$k_p = \frac{V^2 \mu_g tL_d}{\rho_c \Delta P} = \frac{0.07^2 (\frac{ft}{sec})^2 * 0.0309 \frac{lb_m}{ft^3} * 19440 \ sec * 0.00001396 \frac{lb_m}{ft^3}}{21.976 \frac{lb_f}{ft^2} * 79.87 \frac{lb_m}{ft^3}}$$

$$k_p = \frac{0.07^2 * 0.0309 * 19440 * 0.00001396 \frac{ft^3}{sec * sec} \ lb_m}{21.976 * 79.87}$$

$$lb_f = lb_m * 32.2 \frac{ft}{sec^2}$$

$$k_p = \frac{0.07^2 * 0.0309 * 19440 * 0.00001396 \frac{ft^3}{sec * sec} \ lbm}{21.976 * (32.2 \frac{ft lbm}{sec^2})^{79.87}} \frac{ft^3}{sec * sec} \ lbm$$

The ratio of $\Delta P/V$ is called filter drag (S) in inch water/ft/min or N. min./m³





It is convenient to relate S with dust load

$$\frac{\Delta P}{V} = \frac{VAtL_d}{A} = VtL_d$$
$$S = R_p W$$
$$W = \text{gram/m}^2$$
$$S \propto W$$

At the beginning of operation of clean filter, the first portion, new cake

is formed of irregular layer for initial time period and the resistance to

flow is increased rapidly until the nonhomogeneous region is filled.

Once cleaning cycle begins, several possibilities are found.

1- Maximum cleaning occure, some cake present, thus there is residual drag S_R remains.



- 2- High efficient cleaning where the residual loading on the filter is 5-10% of terminal loading. W= 20-50 gr/m² where w_t =750-1000 gram/m²
- 3- Average cleaning : range for mechanical shaking The actual position of the performance curve depends on fabric type and removal method.
- $S_R = 0.2-0.8$ in water/ft/min.

Collected dust acts as a filtering media, thus cleaning affect efficiency



Electrostatic Precipitators

Electrostatic precipitators (ESP) are particulate collection devices that use electrostatic force to remove the particles less than 5 micron in diameter. It is difficult to use gravity settlers and cyclones effectively for the said range of particles. Particles as small as one-tenth of a micrometer can be removed with almost 100% efficiency using electrostatic precipitators.

The principle behind all electrostatic precipitators is to give electrostatic charge to particles in a given gas stream and then pass the particles through an electrostatic field that drives them to a collecting electrode.





Because of the high potential difference between the two electrodes, a powerful ionizing field is formed. Very high potentials – as high as 100 kV are used. The usual range is 40- 60 kV. The ionization creates an active glow zone (blue electric discharge) called the 'corona' or 'corona glow'. Gas ionization is the dissociation of gas molecules into free ions.

As the particulate in the gas pass through the field, they get charged and migrate to the oppositely charged collecting electrode, lose their charge and are removed mechanically by rapping, vibration, or washing to a hopper below. In summary, the step by step process of removing particles using ESPs is:

i) Ionizing the gas.

ii) Charging the gas particles.

iii)Transporting the particles to the collecting surface.

iv)Neutralizing, or removing the charge from the dust particles.

v) Removing the dust from the collecting surface.

The major components of electrostatic precipitators are:

- i) A source of high voltage
- ii) Discharge and collecting electrodes.

iii)Inlet and outlet for the gas.

iv) A hopper for the disposal of the collected material.

v) An outer casing to form an enclosure around the electrodes.

The ESP is made of a rectangular or cylindrical casing. All casings provide an inlet and outlet connection for the gases, hoppers to collect the precipitated particulate and the necessary discharge electrodes and collecting surfaces. There is a weatherproof, gas tight enclosure over the precipitator that houses the high voltage insulators.

There are many types of ESPs in use throughout the world. A brief description of three different types is given below:



A) Single stage or two stage:

In a single stage ESP, gas ionization and particulate collection are combined in a single step. Because it operates at ionizing voltages from 40,000 to 70,000 volts, DC, it may also be called a high voltage precipitator. It is used extensively for heavy duty applications such as utility boilers, large industrial boilers and cement kilns.

In the two-stage precipitator, particles are ionized in the first chamber and collected in the second chamber. The two stage precipitator uses DC voltages from 11,000 to 14,000 volts for ionization and is referred to as a low voltage precipitator. Its use is limited to low inlet concentration, normally not exceeding

0.025 grains per cubic feet. It is the most practical collection technique for many hydrocarbon applications, where the initial clear exhaust stack turns into a visible emission as vapor condenses.

B) Pipe type or Plate type:

In the pipe type electrostatic precipitators, a nest of parallel pipes form the collecting electrodes, which may be round, or square. Generally the pipe is about 30 cm in diameter or less. Most commonly a wire with a small radius of curvature, suspended along the axis of each pipe, is used. The wires must be weighted or supported to retain proper physical tension and location, electrically insulated from the support grid and strong enough to withstand rapping or vibration for cleaning purpose. The gas flow is axial from bottom to top.

The pipe electrodes, may be 2-5 m high. Spacing between the discharge electrode and collecting electrode ranges from 8-20 cm. Precipitation of the aerosol particles occurs on the inner pipe walls, from which the material can be periodically removed by rapping of pipes or by flushing water. The pipe type precipitator is generally used for the removal of liquid particles.

In the plate type precipitators the collection electrodes consist of parallel plates. The discharge electrodes are again wires with a small curvature. Sometimes square or twisted rods can be used. The wires are suspended midway between the parallel plates and usually hang free with a weight suspended at the bottom to keep them straight. Discharge electrodes are made from non-corrosive materials like tungsten, and alloys of steel and copper. The gas flow is parallel to the plates. The plates may be 1-2 m wide and 3-6 m high. The parallel plates should be at equally spaced intervals (between 15 and 35 cm). The collection of the aerosols takes place on the inner side of the parallel plates. The dust material can be removed by rapping either continuously or periodically. The dust particles removed fall into the hopper at the base of the precipitator.

Collection electrodes should have a minimum amount of collection surface, bulking resistance, resistance to corrosion and a consistent economic design.

Plate type precipitators are horizontal or vertical, depending on the direction of the gas flow. Gas velocities are maintained at 0.5-0.6 m/s in these precipitators. They're used for collection of solid particulate.

C) Dry and Wet Precipitators:

If particulate matter is removed from the collecting electrodes, by rapping only, it is known as a dry precipitator. If, on the other hand, water or any other fluid is used for removal of the solid particulate matter, then it is known as a wet

precipitator. In general, wet precipitators are more efficient. However, it is the dry type plate precipitators that are predominantly used.



Plate Type ESP(1,2,&3 ; Tubular ESP(4)

Efficiency:

Generally, the collection efficiency of the electrostatic precipitator is very high, approaching 100%. Many installations operate at 98 and 99% efficiency. Some materials ionize more readily than others and are thus more adapted to removal by electrostatic precipitation.

Acid mists and catalyst recovery units have efficiencies in excess of 99%. However, for materials like carbon black, which have very low efficiencies due to very low collection capacity, by proper combination of an ESP with a cyclone,

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very high efficiencies can be achieved. The gas entering the ESP may be pretreated (i.e., removing a portion of particulate) by using certain mechanical collectors or by adding certain chemicals to the gas to change the chemical properties of the gas to increase their capacity to collect on the discharge electrode and thus increase the efficiency.

Factors affecting the efficiency of electrostatic precipitators Particle Resistivity :

Dust resistivity is a measure of the resistance of the dust layer to the passage of a current. For practical operation, the resistivity should be 10^7 and 10^{11} ohm-cm. At higher resistivity, particles are too difficult to charge. Higher resistivity leads to a decrease in removal efficiency. At times, particles of high resistivity may be conditioned with moisture to bring them into an acceptable range.

If the resistivity of the particles is too low,(<10 ohm–cm), little can be done to improve efficiency. This is due to the fact that the particles accept a charge easily, but they dissipate it so quickly at the collector electrode, that the particles are re- entrained in the gas stream. This results in low efficiency.

Particle resistivity depends upon the composition of the dust and the continuity of the dust layer. Resistivity is also affected by the ESP operating temperature and by the voltage gradient that exists across the dust layer.

B) Particle re-entrainment:

This is a problem associated with particle charging. It occurs primarily in two situations – due to either inadequate precipitator area, or inadequate dust removal from the hopper. Re-entrainment reduces the precipitator performance, because of the necessity of recollecting the dust that had been previously removed from the carrier gas. The problem can be overcome by a proper design of the ESP and necessary maintenance.

The advantages of using the ESP are:

- i) High collection efficiency.
- ii) Particles as small as 0.1 micron can be removed.
- iii) Low maintenance and operating cost.
- iv) Low pressure drop (0.25-1.25 cm of water).
- v) Satisfactory handling of a large volume of high temperature gas.
- vi) Treatment time is negligible (0.1-10s).
- vii) Cleaning is easy by removing the units of precipitator from operation.
- viii) There is no limit to solid, liquid or corrosive chemical usage.

The disadvantages of using the ESP are:

i) High initial cost.

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- ii) Space requirement is more because of the large size of the equipment.
- iii) Possible explosion hazards during collection of combustible gases or particulate.
- iv) Precautions are necessary to maintain safety during operation. Proper gas flow distribution, particulate conductivity and corona spark over rate must be carefully maintained.

v) The negatively charged electrodes during gas ionization produce the ozone.

The important applications of ESPs in different industries throughout the world are given as below:

i) Cement factories:

- a) Cleaning the flue gas from the cement kiln.
- b) Recovery of cement dust from kilns.
- ii) Pulp and paper mills:
- a) Soda-fume recovery in the Kraft pulp mills.
- iii) Steel Plants:
- a) Cleaning blast furnace gas to use it as a fuel.
- b) Removing tars from coke oven gases.
- c) Cleaning open hearth and electric furnace gases.
- iv) Non-ferrous metals industry:
- a) Recovering valuable material from the flue gases.
- b) Collecting acid mist.
- v) Chemical Industry:
- a) Collection of sulfuric and phosphoric acid mist.
- b) Cleaning various types of gas, such as hydrogen, CO₂, and SO₂.
- c) Removing the dust from elemental phosphorous in the vapor state.
- vi) Petroleum Industry:
- a) Recovery of catalytic dust.
- vii) Carbon Black industry:
- a) Agglomeration and collection of carbon black.
- viii) Electric Power Industry:
- a) Collecting fly ash form coal-fired boilers.

ESP Design The charge (q) given to spherical particle of diameter greater than 1 micron is given by:

$$q = p \prod \in {}_{o}E_{C}d_{p}^{2}$$

Where
 $p = rac{3D}{D+2}$

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D = dielectric constant of the particle, = 2-8, thus p = 1.5-2.4

 E_{C} = local field strength at the time of charging

 ϵ_o = permittivity of the space, for air it is equal to 8.854*10⁻¹² Colomb/(volt. Meter)

The speed of migration (w) is called drift velocity which depends on electric and drag forces. The electric force (F_e) is proportional to the charge on the particles and collecting or precipitating field strength (E_p) .

 $F_e = qE_p = p\prod \in {}_oE_cE_pd_p^2$ $F_d = 3 \, \frac{\prod \mu_g d_p w}{k_c}$ These two forces are equal, thus $w = \frac{d_p p \in {}_o E_C E_p}{3\mu_q} \mathrm{kc}$ $w = \frac{2.95 * 10^{-12} p E_c E_p k_c}{\mu_g} \dots (A)$ W in m/sec, μ_q in kg/(m.sec) d_p in meter E in volt/m

If: μ_q in kg/(m.hr), d_p in micron, Equation A becomes

$$w = \frac{1.1 * 10^{-14} p E_c E_p dp k_c}{\mu_a} \dots (B)$$

The above equation is for bombardment or field charging which is dominant for particles larger than 1 micron

Diffusion charging is due thermal and Brownian motion which is dominant for particles less than 0.2 micron

$$w = \frac{4 * 10^{-4} E dp k_c}{\mu_a} \dots (C)$$

E average field strength, assuming that $E_C E_p = E^2 \text{ kV/in}$

Equation A and C intersect at particle diameter of 20 micron

Ex: Plate type collector of 23cm spacing and D.C voltage of 50 KV. Mean gas velocity is 1.5m/sec. Estimate the required plate length to give 100% for 0.5 micron at 420K

Solution

Assume p=2

$$w = \frac{1.1 * 10^{-14} p E_c E_p k_c}{\mu_g} = \frac{1.1 * 10^{-14} (2) \left(\frac{50000}{0.115}\right) (0.5)}{0.0863} = 0.024 \text{ m/sec}$$

T=L/V: t=S/w thus
$$L = \frac{SV}{w}$$

L=(0.23/2)(1.5)/0.024= 7.2 m

To account for time required for charging the electrodes, additional length should be added:

$$T_{c} = 0.3 \text{ sec}$$

L =7.2+ $T_{c}V = 7.2+0.3*1.5=7.65 \text{m}$

Efficiency : $\eta = 1 - e^{-\frac{1}{Q}}$ Deutsch equation A area of collecting electrodes For tubular ESP $A = 2\prod rL$ For plate ESP A = 2LB





EX: Plate type collector of 20cm spacing and D.C voltage of 30 KV. The width is 4 m, and its height is 10 m. Estimate the number of rooms required to treat $80m^{3}$ /sec of polluted air with for 2 μ if gas viscosity is 0.08 kg/(m.hr).

$$w = \frac{1.1 * 10^{-14} p E_c E_p k_c}{\mu_g} dp = \frac{1.1 * 10^{-14} (2) \left(\frac{30000}{0.1}\right) * \frac{30000}{0.1} * (2)}{0.080} = 0.0495 \text{ m/sec}$$

T=L/V: t=S/w thus
$$V = \frac{Lw}{S} = 10 * \frac{0.0495}{0.1} = 4.95 \text{ m/sec}$$

A=4*0.2=0.8m²
Q=AV=0.8*4.95=3.96m³/sec

N=Qtotal /Qfor one room=80/3.96=20.2=21

EX: Plate type collector of 20cm spacing and D.C voltage of 60 KV. Mean gas velocity is 2 m/sec. Estimate the required plate dimensions to give 100% removal with error percent not more than 1% for 2 micron if gas viscosity is 0.08kg/(m.hr) and flow rate of 0.4m³/sec.

$$w = \frac{1.1 * 10^{-14} pE_{c}E_{p}k_{c}}{\overset{\mu g}{=}} = \frac{1.1 * 10^{-14} * 2 * \frac{60000}{0.1} * \frac{60000}{0.1} * 2}{0.1} = 0.198m/sec$$

$$\eta = \mathbf{1} - e^{-\frac{Aw}{Q}}; \quad \eta = \mathbf{1} - e^{-\frac{2LBW}{2*0.2*B}}$$

$$0.99 = 1 - e^{-\frac{2L*0.198}{2*0.2}}; \quad 0.01 = e^{-\frac{2L*0.198}{2*0.2}}$$

$$-4.60517018599 = -0.198L/0.2$$

$$L=4.7m$$

$$\eta = \mathbf{1} - e^{-\frac{AW}{Q}} \quad \mathbf{0.99} = \mathbf{1} - e^{-\frac{A0.198}{0.4}}$$

$$\ln(\mathbf{0}.01) = -0.198A/0.4 \quad -4.605*0.4/0.198 = -A \quad A=9.3 \quad 2LB=A$$

$$B=9.3/(2*4.7) = 0.99m$$

EX: If 10000m3/hr of air flows through bag house filter contains 100 cylindrical filter of 20 cm diameter and 12 m height. If the maximum thickness of the cake is 2.13 mm, find the maximum running time before cleaning. Data: (Ld) is 5 gr/ft3 and cake density is 1.1 gr/cm3. If it is required to operate the filter to 5 hr so that the cake thickness not exceed 3mm, what would be the required number for filters.

$$L_{d} = 5 \frac{gr}{ft^{3}} \frac{1}{(0.3048)^{3}} \frac{1}{m^{3}/ft^{3}} = 176.554 gr/m^{3}$$

$$Q \ per \ 1 \ cylinder = \frac{10000}{100} = 100m^{3}/hr$$

$$V=Q/A$$

$$A=\pi DL=\pi * 0.2 * 12 = 7.543m2$$

$$V=100/7.543=13.257m/hr = 13.257/3600=0.00368m/sec$$

$$x_{p} = \frac{VtL_{d}}{\rho_{c}}$$

$$0.00213= 0.00368*t*0.176554/1100$$

$$T= 3606sec= 1.002hr$$

$$W \ total = Q*C*t = 10000*176.554 *5= 8827.7kg$$

$$W \ per \ 1 \ cylinder=volume*density=\pi DLXp*pc$$

$$=\pi^{*}0.2*12*0.003*1100=24.891kg$$

$$N=W \ total/W \ per \ cylinder=8827.7/24.891=354.65=355$$

Gaseous Pollutants

A lot of gaseous pollutants produced by different industries are vapors of organic matters and can be removed by one of the following methods:

Treatment Methods

Incineration

Adsorption

Absorption

Scrubbing

Incineration

The products of incineration, exothermic reaction, are carbon dioxide and water vapor

 \longrightarrow CO₂ $C + O_2$

$$H_2 + 1/2O_2 \longrightarrow H_2O_2$$

$$S + O_2 \longrightarrow SO_2$$

Air contains 79% of nitrogen and 21% of oxygen. Thus nitrogen to oxygen ratio is 0.79/0.21=3.78. Since nitrogen does not react, it will appears in the products also.

 $C + O_2 + 3.76 N_2$ — \longrightarrow CO₂ + 3.76N₂ $\begin{array}{cccc} H_2 + 1/2O_2 + 1.88N_2 & \longrightarrow & H_2O + 1.88N_2 \\ S + O_2 + 3.76N_2 & \longrightarrow & SO_2 + 3.76N_2 \end{array}$

The above equations represent stochiometric conditions and it is ideal that requires long residence time, high temperature, and high mixing. In all incinerators, such conditions are not available, therefore, excess air is provided. The above equations written with excess air or as the actual products and reactants

 $C + O_2 + 3.76N_2 \longrightarrow 0.8CO_2 + 0.2CO + 0.1O_2 + 3.76N_2$

If air is according to stochiometric equation, it is named as stochiometric air, otherwise it is called excess air

 $H_2 + O_2 + 3.76N_2 \longrightarrow H_2O + O_2 + 3.76N_2$

In this case we said, 200% of stochiometric air is used or we say 100% excess air is used

Air to fuel ratio(AF) = $\frac{28.97n_a}{(M_f n_f)}$

Ex: methane is to be burned with 50% excess air. Find AF

Solution

Write the reaction equation in its general form

CH₄ + xO₂ +3.76xN₂ \longrightarrow yCO₂ + zH₂O +3.76xN₂ Do equilibrium for this equation: C = 1, thus y must be 1: H₂ =2, thus z must be 2: For O₂, X=y + 0.5z X=1+ 0.5*2=2 Thus CH₄ + 2O₂ +7.52N₂ \longrightarrow CO₂ + 2H₂O +7.52N₂ Now add 50% EA CH₄ + 3O₂ +11.3N₂ \longrightarrow CO₂ + 2H₂O +11.3N₂ AF= $\frac{28.97(3 + 11.3)}{16(1)} = 25.9$ Ex: Calculate the stochiometric air required to burn formaldehyde

 $CH_2O + O_2 + 3.76N_2 \longrightarrow CO_2 + H_2O + 3.76N_2$

$$AF = \frac{26000}{30(1)} = 4.6$$

Adiabatic combustion temperature

Heat energy for the reactants and products can be found if temperature and pressure are known. In adiabatic reaction, all energy is stored in the system. Since the reaction is exothermic for which the energy of products is lower than that of the reactants, thus the temperature of the products is higher than that of the reactants.

In the reaction room at which burning takes place, we assume that the reactants enter at state 1 and produced at state 2. We assume that the enthalpy change for the reaction under room temperature is known. In the following figure, the process path is represented. Since the reaction is adiabatic, thus adiabatic enthalpy change is zero between states 1 and 2. Therefore they fall on same horizontal line.





Our most important concern is with T₂, adiabatic reaction temperature. We notice that:

 $H_2 = H_1$

Following the path, 1-3-4-2, we can write

$$H_2-H_1=(H_3-H_1)+(H_4-H_3)+(H_2-H_4)=0$$

Knowing that:

$$(H_4-H_3) = \Delta H_R$$
, $(H_2 - H_4) = mpr(h_2 - h_4)$, and $(H_3 - H_1) = mr(h_3 - h_1)$
where

mpr and mr are masses of the products and reactants and since the mass of them are nearly equal we can write

mpr = mr

for enthalpies h_1 , h_2 , h_3 , and h_4 take the ordinary values based on the assumption of perfect gas having variable specific heats with zero value of enthalpy assumed to be at some convenient datum temperature such as 0.

$$0 = mr(h_{3} - h_{1}) + \Delta H_{R} + mpr(h_{2} - h_{4}) \implies h_{2} = -[mr(h_{3} - h_{1}) + \Delta H_{R}] / [mpr] + h_{4}$$

$$h_{2} = (h_{4} - h_{3} + h_{1}) - \Delta H_{R} / [mr] = [h_{1} + h_{4} - h_{3}] - \Delta H_{R} / [mr]$$

$$h_{2} = h_{1} + (h_{4} - h_{3}) - \frac{\Delta H_{R}}{m_{r}}$$
Note that, $m_{r} = m_{a} + m_{f} = m_{f}(1 + AF)$

$$h_{2} = h_{1} + (h_{4} - h_{3}) + \frac{-\Delta H_{R/m_{f}}}{1 + AF}$$

In combustion reactions, products are nitrogen mainly with other compounds that have specific heat of low difference as compared to that of nitrogen. If we assume air enthalpy is equal to that of reactants and products, i.e. $h_4=h_3$ so it is acceptable assumption. Therefore, the above equation will be:

$$\mathbf{h}_2 = \mathbf{h}_1 + \frac{-\Delta H_{R/m_f}}{1 + AF}$$

The following figure represent enthalpy change with temperature. The value of $-\Delta H_{R/m_f}$ can be found from the following table

Ex: find adiabatic combustion temperature for methane at 200% excess air if the reactants temperature is 50C

Solution

From the previous example, AF=25.9 at 150% stochiometric air. Thus, in our case stochiometric air is 300%, AF=25.9*2=51.8

Substance	formula	MW	Heat of combustion, $-\Delta H_{R/m_f}$, MJ/Kg
Hydrogen	H ₂	2.016	120.9
Carbon	С	12	32.79
Sulfer	S	32	9.28
Carbon monoxide	CO	28	10.11
Methane	CH ₄	16	50.14
Ethane	C ₂ H ₆	30.1	47.6
Propane	C ₃ H ₈	44.1	46.45
Butane	C ₄ H ₁₀	58.1	45.88
Octan(l)	C ₈ H ₁₈	114.2	44.55
Methyl alcohol(l)	CH ₃ OH	32	19.97
Benzene(l)	C ₆ H ₆	78.1	40.23



From table $-\Delta H_{R/m_f} = 50.14 \text{ MJ/Kg}$

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From figure:
h₁= 0.05 MJ/Kg
h₂= 0.05 + 50.14/(1+51.8) = 0.9996 MJ/Kg
from figure, T₂ = 920 C
Ex: what is the excess air required to burn methane and get adiabatic temperature
of 700C if the reactant temperature is 150C
h₁ = 0.15 at 150 C
h₂ = 0.0.745 at 700 C

$$-\Delta H_{R/m_f} = 50.14$$
 MJ/Kg
h₂=h₁ + $\frac{-\Delta H_{R/m_f}}{1 + AF}$
AF = $\frac{-\Delta H_{R/m_f}}{h_2 - h_1} - 1 = 50.14/(0.745 - 0.15) - 1 = 83.3$
From the previous example
AF= 25.9 for stoichiometric air
Thus AF_s (AF for stoichiometric air) = 25.9/1.5 = 17.3
Our AF = 83.3 corresponds to 83.3/17.3 = 4.82 or 482% of stoichiometric Air

Design of Combustion Chamber

- in order to destruct pollutants, temperature should be 375-825C -
- residence time should be 0.5-2 seconds -
- enough mixing is required through inlet velocity of 4.5-7.5 m/sec -
- temperature losses should be minimum by insulators. If no enough data are available it is assumed to be 10%, thus increasing products temperature by $0.1(T_2-T_1)$
- volume should be enough to give the required residence time -

$$\overline{\nabla} = AVt = Qt$$

Perform calculation assuming higher temperature, thus

$$\nabla = \frac{m}{\rho_2} t = \frac{(\rho_1 Q_1 + m_f)}{\rho_2} t$$

$$A = Q_2 / V = \frac{m}{V \rho_2}$$

$$L = \nabla / A$$

$$L \text{ is the length of the reaction region only}$$

1-1.5 m must be added for the length of combustion region

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Ex: design combustion chamber to burn methane polluted air given the following data

 $Q = 10 \text{ m}^3/\text{sec}$ of standard air $C_{mv} = 0.005 \text{ Kg/m}^3$ AF = 51.8V = 5 m/s $T_1 = 50 C$ $\rho_1 = 1.185 \text{ kg/m}^3$ T = 0.5 s $\rho_2 = 0.296 \text{ kg/m}^3$ From the figure , $h_1=0.05 \text{ MJ/Kg}$ From the table, $-\Delta H_{R/m_f}$ = 50.14 MJ/Kg $h_2 = 0.05 + 50.14/(1+51.8) = 0.9996 \text{ MJ/Kg}$ from figure, $T_2 = 920 \text{ C}$ since the concentration is small, thus the mass flow rate is for air only give acceptable accuracy $m = m_a(1 + \frac{1}{AF}) = \rho_1 Q_1 (1 + 1/AF) = 1.185(10)(1 + 1/51.8))$ = 12.08 kg/s $\nabla = \frac{m}{\rho_2}t = \frac{12.08}{0.296}0.5 = 20.4 \text{ m}^3$ $A = 12.08/(0.296*5) = 8.16 \text{ m}^2$ $D = \sqrt{\frac{4A}{\pi}} = (4 * 8.16 / 3.14)^{0.5} = 3.22 \text{ m}$ L = 20.4/8.16 = 2.5 mAdd 1- 1.5 m thus L total = 3.5 - 4 m

Atmospheric layers

Dispersion of Air Pollutants

Discussion of the layers in the Earth's atmosphere is needed to understand where airborne pollutants disperse in the atmosphere. The layer closest to the Earth's surface known is as the *troposphere*. It extends from sea-level to a height of about 18 km and contains about 80 percent of the mass of the overall atmosphere. The stratosphere is the next layer and extends from 18 km to about 50 km. The third layer is the mesosphere which extends from 50 km to about 80 km. There are other lavers above 80 km, but they are insignificant with respect to atmospheric dispersion modeling.

The lowest part of the troposphere is called the *atmospheric boundary layer* (ABL) or the planetary boundary layer (PBL) and extends from the Earth's surface to about 1.5 to 2.0 km in height. The air temperature of the atmospheric boundary layer with decreases increasing altitude until it reaches what is called the *inversion layer* (where the temperature increases with increasing altitude) that caps the atmospheric boundary layer. The upper part of the troposphere (i.e., above the inversion



layer) is called the *free troposphere* and it extends up to the 18 km height of the troposphere.

The ABL is of the most important with respect to the emission, transport and dispersion of airborne pollutants. The part of the ABL between the

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Earth's surface and the bottom of the inversion layer is known as the mixing layer. Almost all of the airborne pollutants emitted into the ambient atmosphere are transported and dispersed within the mixing layer. Some of the emissions penetrate the inversion layer and enter the free troposphere above the ABL.

In summary, the layers of the Earth's atmosphere from the surface of the ground upwards are: the ABL made up of the mixing layer capped by the inversion layer; the free troposphere; the stratosphere; the mesosphere and others. Many atmospheric dispersion models are referred to as *boundary layer models* because they mainly model air pollutant dispersion within the ABL. To avoid confusion, models referred to as *mesoscale models* have dispersion modeling capabilities that extend horizontally up to a few

hundred kilometres. It does not mean that they model dispersion in the mesosphere.

Gaussian or Normal Distribution

Any variable x is said to be normally distributed if:

$$f(x) = \frac{1}{\delta\sqrt{2\pi}} EXP\left[-\frac{(x-\mu)^2}{2\delta^2}\right]$$
.....(1)

$$\mu$$
 = any real number

 δ = any number greater than zero (standard deviation)

Maximum f(x) is at $x=\mu$, μ shift the position of the curve, δ broaden or

sharpen the curve still having the same area which is a measure of the inflection point.

Atmospheric dispersion equation takes the form double gaussian distribution (product of two single gaussian)







$$f(y,z) = \frac{1}{2 \prod \delta_z \delta_y} EXP[-\frac{(y-\mu)^2}{2\delta_y^2} + \frac{-(z-\mu)^2}{2\delta_z^2}].....(2)$$

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Gaussian Dispersion Model

One possible model for the physical situation is shown in fig. 4-2. The following model represents the concentration profile downwards from the stack

$$C = Kx^{-1}EXP[-\{\frac{(y)^2}{D_y} + \frac{(z)^2}{D_z}\}\frac{u}{4x}].....(3)$$

K= constant

X = distance in the wind direction Y,z= distance in y and z direction

 D_y , D_z = coefficient of mass diffusivities in y and z directions

U = wind speed

C =pollutant concentration

Point Source at Ground Level

Substituting equation 4 into equation 3 gives:



$$C_{x,y,z} = \frac{Q}{2 \prod x (D_y D_z)^{0.5}} EXP[-\{\frac{(y)^2}{D_y} + \frac{(z)^2}{D_z}\} \frac{u}{4x}].....(5)$$

This equation has the same form of Eq. 2. Since for ground level source, the maximum concentration in y and z directions should occur along the center line at ground level. For this case $\mu_{y_i} \mu_z$ are zero. Thus equation 2 becomes,

$$f(y,z) = \frac{1}{2 \prod \delta_z \delta_y} EXP[-\frac{(y)^2}{2\delta_y^2} + \frac{-(z)^2}{2\delta_z^2}].....(6)$$

It is convenient to recognize eq. 5 into the form similar to eq. 6. In order to do that we make the following definitions:

$$\delta_y^2 = \frac{2xD_y}{u}$$
 and $\delta_z^2 = \frac{2xD_z}{u}$

Substitution of these two definitions into eq.5 leads to eq.7 to represent concentration down ward from a ground level point source:

$$C(x,y,z) = \frac{Q}{\prod u \delta_z \delta_y} EXP\left[-\frac{1}{2}\left[\frac{(y)^2}{\delta_y^2} + \frac{(z)^2}{\delta_z^2}\right]\dots(7)\right]$$

Arranging equation 7 so that the left hand side is (Cu/2Q), then the right hand side will have the identical form of f(y,z), described previously which is a double Gaussian type.

$$\frac{C(x,y,z)u}{2Q} = \frac{1}{2\prod \delta_z \delta_y} EXP[-[\frac{(y)^2}{2\delta_y^2} - \frac{(z)^2}{2\delta_z^2}].....(8)$$

Which is the same as eq. 6

If y and z taken to be zero, then:

$$C(x,0,0) = \frac{Q}{\prod u \delta_z \delta_y} \dots (9)$$

Point Source at Elevation H Above Ground Level With Reflection

In this case, the term containing z^2 in Eq.8 must be altered. Here the entire curve is shifted μ_z from the zero axis of Z by writing the exponential form of the term in the form of $EXP[-\frac{1}{2}[\frac{(z-\mu_z)^2}{\delta_z^2}]$. For elevated source this is an equivalent to replace z in 8 by z-H. This substitution into eq. 8 directly is not possible since K in eq. 2 is altered. K has half its value of eq. 4, likewise the coefficient in front of exponential term is half of value. former Thus its Concentration without reflection is given by:





$$C = \frac{1}{2 \prod u \delta_z \delta_y} EXP[-\frac{1}{2} [\frac{(y)^2}{\delta_y^2} - \frac{(z-H)^2}{\delta_z^2}]....(10)$$

Reflection is equivalent to have mirror image of the source at (-H). Performing linear superposition of the two curves, one centered at H and the other centered at (-H) will give:

$$C_{x,y,z} = \frac{Q}{2 \prod u \delta_z \delta_y} EXP \left[-\frac{1}{2} \frac{(y)^2}{\delta_y^2} \right] \left[exp \left\{ -\frac{(z-H)^2}{2\delta_z^2} \right\} + exp \left\{ -\frac{(z+H)^2}{2\delta_z^2} \right\} \right] \dots (11)$$

At ground level z=0

$$C_{x,y,0} = \frac{Q}{\prod u \delta_z \delta_y} EXP\left[\frac{-y^2}{2\delta_y^2}\right] \left[exp\left\{\frac{-H^2}{2\delta_z^2}\right\}\right] \qquad (12)$$

Evaluation of Standard Deviation

Different methods are available to find the standard deviation

- 1- Figs. 4-6 and 4-7 with climate stability conditions A, B, C, D, E, and F.
- 2- Due to low efficiency of the above figures, Table 4-2 is used to find standard deviation

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3- From equations

$$\delta_y = ax^b, \qquad \delta_z = Cx^d + f....(13)$$

Where

b= 0.894 and x in km. and δ in meters

a,c,d,f are obtained from table 4-3



Figure 4-5 Concentration profiles along the center line in the *x*-direction and in the *z*-direction.

Table 4-1 Key to Stability Categories

Surface wind speed at 10m, (m/sec)		Day	night		
	Incoming solar radiation			Cloud cover	
	strong	moderate	slight	Mostly overcast	Mostly clear
Class ^(a)	1	2	3	4	5
< 2	Α	A-B	B	E	F
2-3	A-B	B	С	E	F
3-5	B	B-C	С	D	E
5-6	С	C-D	D	D	D
> 6	С	С	D	D	D

(a) The natural class D should be assumed for overcast conditions during day or night. Class A is the most unstable condition and class F is the most stable , class B moderately unstable, and class E slightly stable.

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Fig. (4-6) Standard deviation δy in the vertical direction as a function of distance downwind

(b)

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Distance (km)	Stability class and δ _y values Incoming solar radiation					S	Stability	y class a	and δ_z	value	S	
							Cloud cover					
	Α	B	C	D	E	F	A	B	С	D	E	F
0.1	27	19	13	8	6	4	14	11	7	5	4	2
0.2	50	36	23	15	11	8	29	20	14	8	6	4
0.4	94	67	44	29	21	14	72	40	26	15	11	7
0.7	155	112	74	48	36	24	215	73	43	24	17	11
1.0	215	155	105	68	51	34	455	110	61	32	21	14
2.0	390	295	200	130	96	64	1950	230	115	50	34	22
4.0		550	370	245	180	120		500	220	77	49	31
7.0		880	610	400	300	200		780	360	109	66	39
10.0		1190	840	550	420	275		1350	510	135	79	46
20.0		2150	1540	1000	760	500		2900	950	205	110	60

Table 4-2 Approximate values of δ_v and δ_z as a function of downwind distance for various stability classes in meter

Table 4-3 Values of constants to be used in equation 13 as a function of downwind distance and stability condition

Stability	X < 1 km				X > 1 km		
	a	c	d	f	c	d	f
Α	213	440.8	1.941	9.27	459.7	2.094	-9.6
B	156	106.6	1.149	3.3	108.2	1.098	2.0
С	104	61	0.911	0	61	0.911	0
D	68	33.2	0.725	-1.7	44.5	0.516	-13
E	50.5	22.8	0.678	-1.3	55.4	0.305	-34
F	34	14.35	0.740	-0.35	62.6	0.180	-48.6

Ex 1:

SO₂ is emitted from a stack of 60 meter height at a rate of 160 gr/sec. Wind speed at stack height is 6 m/sec. and the atmospheric stability is class D. Determine ground level concentration along the center line at 500 meter from the stack in microgram per cubic meter.

Solution:

From figs. 4-6 and 4-7,
$$\delta_y = 36 m$$
, $\delta_z = 18.5m$
 $C_{500,0,0} = \frac{Q}{\prod u \delta_z \delta_y} EXP \left[-\frac{y^2}{2\delta_y^2} \right] \left[exp \left\{ -\frac{H^2}{2\delta_z^2} \right\} \right]$
 $= \frac{160 * 10^6}{\prod * 6 * 36 * 18.5} EXP \left[-\frac{0^2}{2\delta_y^2} \right] \left[exp \left\{ -\frac{60^2}{2 * 18.5^2} \right\} \right] = 66 \mu g/m^3$

Without reflection

$$C_{500,0,0} = \frac{Q}{2 \prod u \delta_z \delta_y} EXP \left[-\frac{y^2}{2 \delta_y^2} \right] \left[exp \left\{ -\frac{H^2}{2 \delta_z^2} \right\} \right]$$
$$= \frac{160 * 10^6}{2 \prod * 6 * 36 * 18.5} EXP \left[-\frac{0^2}{2 \delta_y^2} \right] \left[exp \left\{ -\frac{60^2}{2 * 18.5^2} \right\} \right] = 33 \ \mu g/m^3$$

EX2:

For the data given in example 1, determine the concentration cross wind at 50 meter from the center line for the down ward distance of 500 meter **Solution**

$$C_{500,50,0} = \frac{Q}{\prod u \delta_z \delta_y} EXP \left[-\frac{y^2}{2\delta_y^2} \right] \left[exp \left\{ -\frac{H^2}{2\delta_z^2} \right\} \right]$$

= $\frac{160 * 10^6}{\prod * 6 * 36 * 18.5} EXP \left[-\frac{50^2}{2 * 36^2} \right] \left[exp \left\{ -\frac{60^2}{2 * 18.5^2} \right\} \right] = 23 \ \mu g/m^3$

Ex3:

For the data given in example 1, determine the sufficient values of C as a function of x on the ground level center line so that the variation on either side of the maximum value is established

Solution

The general solution of this problem, in term of equation 12 is:

$$C_{x,0,60} = \frac{Q}{\prod u \delta_z \delta_y} EXP\left[\frac{-y^2}{2\delta_y^2}\right] \left[exp\left\{\frac{-H^2}{2\delta_z^2}\right\}\right] = \frac{160 \times 10^6}{\prod \times 6\delta_z \delta_y} \left[exp\left\{-\frac{60^2}{2\delta_z^2}\right\}\right]$$

Assume different values of x then find δ_z and δ_y from tables or figures then construct the following table. Note that the exp in the table refers to the exponential term in the equation

X	δ_y	δ_z	Q	$-H^2$	exp	C
(km)			$\overline{\prod u \delta_z \delta_y}$	$2\delta_z^2$		$(\mu g/m^3)$
0.5	36	18	13090	5.55	0.0039	50
0.8	60	27	5240	2.47	0.085	445
1.0	76	32	3490	1.76	0.172	600
1.5	110	45	1710	0.89	0.411	700
1.7	140	50	1210	0.72	0.487	590
2.0	160	55	960	0.595	0.552	530
3.0	220	71	540	0.357	0.700	380
5.0	350	100	240	0.180	0.835	200
10.0	620	150	90	0.080	0.923	83

The maximum concentration occurs at 1.5 km. The above data show that the build up of concentration with x is fast then after maximum is reached it falls slowly.

Maximum Ground Level In-Line Concentration

- (A)Turners graphical method: On the basis of Eq. 12, Figure 4-8 is developed
- 1- From the stack height and stability conditions, find point A on fig. 4-8
- 2- Then go to x-axis and y axis to find $(Cu/Q)_{max}$ and X, from which we can find C_{max} ,

The above fig. (fig. 4-8) can be represented by the following equation:

$$(Cu/Q)_{max} = \exp\left[a + b(lnH) + c(lnH)^2 + d(lnH)^3\right].....(14)$$

Where

H in meters

Cu/Q in m⁻²,

The constants a,b,c,d are obtained from Table 4-4

(c)Approximation equation :an alternate method of ascertaining the position and value of maximum concentration is based on the characteristics Figs. 4-6 and 4-7. Under moderately unstable to near neutral conditions the ratio of $\frac{\delta_y}{\delta_z}$ is nearly independent of distance x. If this ratio is taken to be constant and y is equal to zero, then Eq. 12 can be written so that C is solely function of δ_z which in turn is solely function of x for a given stability class. The result of differentiation of eq. 12 in the modified form results:

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$$\frac{2}{\delta_z} = \frac{2H^2}{2\delta_z^3} \qquad 1 = \frac{H^2}{2\delta_z^2} \qquad \delta_z = \frac{H}{\sqrt{2}} = 0.707H$$

Knowing H, δ_z can be found then from the chart of δ_z versus x, x can be determined.

If the condition $H^2 = 2\delta_z^2$ is substituted into eq. 12 and y is set equal to zero, then the maximum concentration down ward on the center line and at ground level is approximately given by:



Table 4-4 Values of constants to be used in equation 14 as a function of stability class

Stability	coefficient						
class	Α	b	c	d			
Α	-1.0563	-2.7153	0.1261	0			
B	-1.8060	-2.1912	0.0389	0			
С	-1.9748	-1.9980	0	0			
D	-2.5302	-1.5610	-0.0934	0			
Ε	-1.4496	-2.5910	0.2181	-0.0343			
F	-1.0488	-3.2252	0.4977	-0.7650			

Ex 4:

For the data of example 1, determine the position down ward on the center line at ground level where maximum concentration will occur, and determine the maximum concentration.

Solution

$$\begin{split} \delta_z &= \frac{H}{\sqrt{2}} = 0.707H = 0.707 * 60 = 42.4 m \\ \text{From fig. 4-7,x= 1.55 km, and from fig. 4-6 , } \delta_y = 105 m \\ \mathcal{C}_{max., reflection} &= \frac{0.1171 Q}{u \delta_y \delta_z} = (0.1171*160*10^6)/(6)(105)(42.4) \\ &= 700 \text{microgram/cubic meter} \\ \text{Other method, use fig. 4-8 gives,} \\ X_{\text{max}} &= 1.5 \text{km}, \quad (\text{Cu/Q})_{\text{max}} = 2.7*10^{-5} \text{ m}^{-2}, \text{ hence} \\ \text{C}_{\text{max}} &= 2.7*10^{-5}*160*10^6/6 = 720 \mu \text{g/m}^3 \\ \text{Third method} \\ (\mathcal{C}u/Q)_{max} &= \exp \left[a + b(\ln H) + c(\ln H)^2 + d(\ln H)^3\right] \\ &= \exp \left[-2.5302 - 1.561(\ln 60) - 0.0934(\ln 60)^2\right] \\ &= 2.8*10^{-5} \text{m}^{-2} \\ \text{C}_{\text{max}} &= 2.8*10^{-5}*160*10^6/6 = 740 \mu \text{g/m}^3 \end{split}$$

Calculation of the Effective Stack Height



Most analytical models for predicting the concentration of stack effluent concentration involve the location of virtual or equivalent origin $H = h + \Delta h$

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Most equations to find Δh contain momentum term and thermal buoyancy term. The first account for vertical momentum due to gas velocity V_S while the 2nd term is for difference between stack gas temperature and T_S and surrounding temperature T_a.

Carson – Moses concluded that the following is the most accurate model.

$$\Delta h = -0.029 \frac{dV_S}{u} + 2.62 \frac{Q_h^{0.5}}{u}$$

Where
$$\Delta h = \text{plume rise, m}$$

 $V_S = rising \text{ gas velocity, m/sec}$

d = stack exit diameter, m

u = air velocity at stack height, m/sec

 Q_h = heat emission rate , kJ/sec

$$Q_{\rm h} = m^* \mathcal{C}_p (T_s - T_a)$$

$$m^*=$$
 gas mass flow rate, kg/sec

$$m^* = \prod d^2 V_S P / 4RT_s$$

Where

 C_p is constant pressure specific heat of gases

 T_s and T_a in K

Ex:

If heat emission rate is 4800kJ/sec, where u = 5m/sec, $V_S = 15 m/sec$, d=2m, find plum rise:

$$\Delta h = -0.029 \frac{dV_s}{u} + 2.62 \frac{Q_h^{0.5}}{u} = -0.029 \frac{2*15}{5} + 2.62 \frac{4800^{0.5}}{5} = 36.2 \text{m}$$

Determination of the required stack height

Typical air pollution problem for new industry is:

- Pollutants have to be dispersed by stack
- Emission rate is known
- Downwind from the stack at given x, the concentration must not exceed given concentration
- wind speed is known the worst situation is when the maximum concentration present at distance x . maximum concentration occurs roughly at $H=\sqrt{2}\delta_z$

 $C_{max.,reflection} = \frac{0.1171Q}{u\delta_y\delta_z}; \ \delta_y\delta_z = \frac{0.1171Q}{uC_{max}}$

Fig. 4-9 can be used to find $\delta_{\nu}\delta_{z}$ for any stability conditions

- 1- knowing $\delta_y \delta_z$ and x, locate point A on fig. 4-9, it is usually lie between two stability lines
- 2- find the fractional distance vertically between two lines, say 75%
- 3- go to fig. 4-7, go vertically from x to the same position, same lines , and same fraction
- 4- go to right to read δ_z
- 5- find H

Ex: SO_2 is emitted at a rate of 160g/sec u=6m/sec. It is required that maximum concentration at ground level not exceed 200 microgram per cubic meter at 800m. Find H

 $\delta_y \delta_z = \frac{0.1171 * 160 * 10^6}{200 * 6} = 1.56 * 10^4$

From fig. 4-9 we see that this value with X=800 gives A is 75% between A and B

From fig. 4-7, $\delta_z = 115m$, thus : H=1.42 δ z=1.42*115= 163m





Effect of H on Maximum Concentration

$$H = \sqrt{2}\delta_z \text{ and } C_{max.} = \frac{0.1171Q}{u\delta_y\delta_z}$$

$$\frac{2\delta_z^2}{H^2} = 1, \text{ thus}$$

$$C_{max.} = \frac{0.1171Q}{u\delta_y\delta_z} * 1 = \frac{0.1171Q}{u\delta_y\delta_z} * \frac{2\delta_z^2}{H^2} = \frac{2 * 0.1171Q}{u\delta_y} \frac{\delta_z}{H^2}$$
From figs. 4-6 and 4-7, it is noted that $\frac{\delta_z}{\delta_y}$ is constant for the range of x
Thus: $C_{max.} = \frac{k}{H^2}$
Increasing H two fold will reduce C by 4 folds



It is the process of mass transfer from gas or liquid media on to solid surface. The transferred phase is called adsorbent while the receiving materials is called adsorbate

Adsorption types

- Physical adsorption: in this type, no chemical reaction takes place and it can be regenerated
- Chemical adsorption: can not be regenerated due to chemical reaction
- Combined adsorption: in which two types of adsorptions takes place at the same process

Factors affecting adsorption

- Adsorbent concentration
- Quantity of adsorbent
- Temperature
- pH
- Presence of competing materials
- Polarity of adsorbent in solution
- Surface area of adsorbate

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- Volume of adsorbent molecules
- Pore volume of adsorbate
- Type of activation

Mechanism of adsorption

- 1- As soon adsorbent in solution subjected to adsorbent materials, the molecules of adsorbent migrates to the surface of adsorbate forming single or multiple layer.
- 2- These molecules are transported to the pores of adsorbate
- 3- Those adsorbent molecules are adsorbed onto the molecular structure of adsorbate

Adsorbate Materials

Activated carbon,

GAC, PAC

Silica gel

Zeolite

Adsorption Isotherm

The amount of adsorbed material is a function of its concentration and temperature with all other parameters

Plotting adsorbed quantity versus adsorbent concentration resulting in a curve known as adsorption isotherm

Numerous models are developed to represent these isotherms into mathematical forms: the most famous are

Freundlich model

Langmuir model

Braunauer, Emmet, and Teller (BET) model

Freundlich model

 $X/M = KC^{1/n}$

Where

X/M = adsorbed quantity per unit mass of absorbent

C = equilibrium concentration in solution

n,K = constants

Log (X/M)=Log K + 1/n Log C

Ex: given the following data, find Freundlich constants

C, mg/l	10	20	30
X/M, mg/gr	0.1	0.21	0.34
Log C	1	1.3	1.477
Log(X/M)	-1	-0.67778	-0.4685
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Solution



k=0.0075

 $\frac{1/n=[0.1-0.0075]}{1=0.0925} = \frac{10.81}{n=10.81}$ $\frac{1}{n=[10^{0.1} - 10^{0.0075}]}{[1-0]} = 0.241$ n=4.14

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1/n = -1.05 - (-2.21]/[1-0]/[1] = 1.21 $1/n = \{10^{-1.05} - 10^{-2.21}\}/1 = 0.0829$

=0.826n=12.07

Langmuir model

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X/M=abC/(1+bC)

Assumption

There are limited number available for adsorption

Adsorption is reversible

Equilibrium occurs when rate of adsorption = rate of desorption

Adsorption rate depends on the driving force which is the difference between saturation concentration and equilibrium concentration, which is equal to zero at equilibrium

The previous equation can be re arranged:

C/(X/M)=1/ab+(1/a)C

Ex: show with which model the following data agree better

C mg/l	0	10	20	30
X/M, g/g	0	0.133	0.187	0.22

Solution

Draw the data according to both models

According to freundlich

Log C	1	1.301	1.477
LogX/M	-0.876	-0.728	-0.657

 $R^2 = .997$

According to Langmuir

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С	10	20	30
C/(X/M)	75	107	136

 $R^2=0.999$ and since it is greater than that of the first model, it is the better 1/ab = 45

$$1/a=[136-75]/[30-10]=3.05$$

a=0.328
 $45-1/(b*, 228)$





Since R^2 are near to each other, thus we can use either of them

Industrial Process Analysis



In industrial process, it is usual practice to use packed columns with the direction of polluted water or gas from top or from bottom. Pollutants are adsorbed at the top layer till saturation then pollutants go to the lower layer until it reaches the other end where the column is exhausted and need to be regenerated. For this reason more than one column is used.

Adsorption capacity is the maximum amount of pollutants that can be adsorbed per unit weight of adsorbent



M,g/100ml	Residual C	X(adsorbed)	X/M
0	7.7		
0.05	3.67	4.03	80.6
.1	2.2	5.5	55.0
.3	.87	6.83	22.8
1	.25	7.45	7.5

Ex: from the following data find the constants and adsorption capacity

Solution

Draw the data according to freundlich model



K=3.8

1/n = [27-3.8]/1 = 23.2 n = 0.043

Or from the graph Adsorption Capacity ADC = 160 mg/gr

Adsorption wave

As the polluted gas pass of concentration C_o through fixed bed pollutant is adsorbed but it is not uniformly adsorbed over the entire column. Instead, pollutant is adsorbed on a layer of thickness δ known as mass transfer zone. Beyond this layer the leaving gas is nearly free of pollutants. Pollutant concentration is the inlet concentration at the top of MTZ (point 1) while it is essentially zero at the bottom (point 2). In this region the bed is essentially saturated by pollutants. As time proceeds, MTZ is moved to the lower portion until it reaches the bottom of the bed resulting in breakthrough. The concentration profile of the pollutant within the MTZ is S shape. When the MTZ reaches the end of the column, measurable pollutant concentration is get known as

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breakthrough concentration. The shape of concentration profile within MTZ could be very steep or flat. The adsorption curve could be vertical. Here instant breakthrough break through would occur at some moment, which would be a disadvantage from the control stand point. However, an advantage would be that the entire bed would be saturated, so larger volumes are treated before shutdown. On the other hand, flat curve give early breakthrough with greater unused adsorbent. this will require longer bed. Thus intermediate wave shape is preferable.



Absorption

Absorbers in air pollution control applications use aqueous scrubbing liquids to remove gases and vapors.

The use of absorbers has increased since 1990 because of increased concerns about gaseous contaminants, which are classified as air toxic or volatile organic compounds (VOCs). In addition to stand-alone systems, absorbers are frequently used downstream of thermal and catalytic incinerators to remove acid gases generated from the combustion of sulfur-containing and/or halogenated compounds present in the incinerator feed.

Absorption refers to the transfer of a gaseous component from the gas phase to a liquid phase. The opposite operation, known as stripping, involves the transfer of the contaminant from the liquid to the gas phase and is important in water pollution control applications. The liquid surface area available for mass transfer and the time available for diffusion of the gaseous molecules into the liquid are important factors affecting performance.

The gaseous contaminant being absorbed (absorbate) must be at least slightly soluble in the scrubbing liquid (absorbent). Mass transfer to the liquid continues until the liquid approaches saturation. At saturation, equilibrium is established between the two phases. The mass transfer rate of the contaminant into the liquid is equal to the mass transfer rate of the dissolved species back into the gas phase. Accordingly, the solubility of the contaminant in the liquid creates a limit to the amount of pollutant removal that can occur with a given quantity of liquid. This solubility limit can be overcome by providing reactants in the liquid phase that react with the dissolved gas contaminant, forming a dissolved compound that cannot exit the liquid. This is the case in flue gas desulfurization, where a compound that reacts irreversibly with SO₂, such as CaO, is added to the liquid.

Types of Absorbers

Packed towers

Spray Towers

Plate Towers

In this process, the concentration gradient is the driving force.

It can be accelerated by high interfacial surfaces, turbulence, and large mass diffusion coefficients. The process occurs into these steps:

- 1- Pollutants is transferred from bulk liquid towards gas liquid interface by turbulent eddy diffusion.
- 2- Very close to the interface, the fluid motion is laminar and the pollutant pass this region by molecular diffusion

3- The pollutant diffuse toward the bulk liquid

4- Turbulent eddy diffusion takes the pollutants over to the bulk liquid

Spray-Tower Absorbers

Spray towers are the simplest devices used for gas absorption. They consist of an open vessel and one or more sets of liquid spray nozzles to distribute the scrubbing liquid (absorbent). Typically, the flow is countercurrent, with the contaminant gas stream entering near the bottom of the tower and flowing upward, while the liquid enters near the top and flows downward. The most dilute gas is exposed to the most dilute liquid at the top of the column while the most concentrated gas and liquid are in contact near the bottom. Figure 1 illustrates a typical countercurrent-flow spray-tower absorber. Spray towers range in size from 5 to



Figure 1. Counter-current spray-tower scrubber

100,000 ACFM (0.14 to 2800 m3/min). Spray chambers can also operate in cross-current or co-current flow arrangements when there is limited space in an industrial facility. In cross-current absorbers, the gas flow is perpendicular to the liquid flow. In co-current absorbers, the gas and liquid flow in the same direction. Because the gas stream does not "push" against the liquid stream as in countercurrent flow, higher gas stream velocities can be used. With higher gas stream velocities, the size of the unit can be reduced. However, cross-current or co-current spray towers are not usually as efficient as countercurrent units. The liquid is distributed through a series of spray nozzles.

The quantity of liquid, normally characterized by the liquid-to-gas ratio (L/G), is a key parameter in gas absorption. The (L/G) is frequently expressed in units of gallons per minute of liquid divided by the gas flow rate in units of 1000 ACFM. Typical (L/G) ratios for spray-tower absorbers can vary from 5 to more than 50 gallons per 1000 ACF. The (L/G) is determined by the solubility of the contaminant in the liquid and by the mass transfer characteristics in the spray tower. Contaminant capture efficiency increases with increasing (L/G) and one important aspect of the design problem amounts to determining the optimum (L/G) required to satisfy emission specifications at the minimum cost.

Because of limited contact between the liquid droplets and the gas stream, spraytower absorbers are used primarily in applications where the gases are extremely

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soluble in the absorbent, where high pollutant removal efficiency is not required, or where the chemical reactions in the absorbing liquid could result in salts that could cause plugging in other types of absorber vessels. They have been used to control SiF4 and HF generated in fertilizer plants during the production of superphosphate. Spray towers are also used in a number of flue gas desulfurization systems.

The main advantage of spray-tower absorbers is that they are completely open. They have no internal components except for the spray nozzles and connecting piping. Therefore, they have a very low gas-stream static pressure drop, which ranges from 1 to 3 in. W.C. (0.25 to 0.75 kPa) for the absorber vessel.

Mist eliminators, which are used to prevent liquid droplets from exiting the absorber with the gas stream, are used in all types of gas absorber equipment. Mist eliminators used in spray towers can add a 0.3 to 4 in. W.C. (0.075 to 1.0 kPa) to the total gas-phase static pressure drop.

Mechanisms of Absorption Two-Film Theory

The two-film theory of absorption is illustrated in Figure 6-10. All resistance to mass transfer is assumed to be associated with a thin gas film and a thin liquid film immediately adjacent to the gas-liquid interface. The gaseous contaminant, component A, with mole fraction y_A , is transported by turbulent mixing action to the boundary of the gas film. The contaminant then diffuses through the gas film to the interface where the mole fraction is y_{Ai} . The interface is assumed to be at equilibrium and



the mole fraction at the liquid interface is x_{Ai} . From the interface, component A then diffuses across the liquid film to the bulk liquid where the mole fraction is x_A . The discontinuity between y_{Ai} and x_{Ai} is due to the composition difference between the gas and liquid.

When the mole fraction of A in the liquid reaches its saturation limit, the rates of mass transfer are equal in both directions. The two phases are in equilibrium and no additional contaminant removal is possible. Accordingly, it is important to design and operate absorbers so that saturation conditions are not reached. There are two ways to achieve this goal.

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- Provide sufficient liquid so that the dissolved contaminants do not reach their solubility limit
- Chemically react the dissolved contaminants so that they cannot return to the gas phase.

Control of Oxides of Nitrogen General Methods of Control

NOx control can be achieved by:

Fuel denitrogenation

Combustion modification

Modification of operating conditions

Tail-end control equipment

Selective Catalytic Reduction

Selective Non-Catalytic Reduction

Electron Beam Radiation

Staged Combustion

The most promising methods of reducing NOx emissions currently are classified into three groups. The methods for each group are:

Before burning:

Fuel denitrogenation

During burning:

Staged combustion

Catalytic combustion

In exhaust Gas:

Flue gas treatment

Catalytic emission control

Fuel Denitrogenation

One approach in reducing nitrogen oxide emission is to remove a large part of the nitrogen contained in the fuels. Nitrogen is removed from liquid fuels by mixing the fuels with hydrogen gas, heating the mixture and using a catalyst to cause nitrogen in the fuel and gaseous hydrogen to unite. This produces ammonia and cleaner fuel. This technology can reduce the nitrogen contained in both naturally occurring and synthetic fuels.

Combustion Modification

Combustion control uses one of the following strategies:

- Reduce peak temperatures of the flame zone. the methods are:
- Increase the rate of flame cooling
- Decrease the adiabatic flame temperature by dilution

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- Reduce residence time in the flame zone. For this we, change the shape of the flame zone
- Reduce Oxygen concentration in the flame one. This can be accomplished by:
 - decreasing the excess air
 - controlled mixing of fuel and air
 - using a fuel rich primary flame zone.

Modification of Operating Conditions

The operating conditions can be modified to achieve significant reductions in the rate of thermal NOx production. The various methods are:

- Low-excess firing
- Off-stoichiometric combustion (staged combustion) _
- Flue gas recirculation
- Reduced air preheat
- Reduced firing rates -
- Water Injection -

Tail End Control Equipment

Combustion modification and modification of operating conditions provide significant reductions in NOx, but not enough to meet regulations. For further reduction in emissions, tail-end control equipment is required.

Some of the control processes are:

- Selective Catalytic Reduction
- Selective non catalytic Reduction
- Electron Beam Radiation
- Staged Combustion

Methods for SO₂ removal

Sulfur dioxide can be considered as one of the most important air pollutants in micro and macro scale because of its effect on human and nature. Sulfur dioxide is a quite irritant, non flammable, colorless and non explosive suffocating smelling toxic gas. SO2 is affected by other atmospheric components catalyticaly or photochemically to produce SO₃, H₂SO₄ mists and H₂SO₄ salts (1). These acids deposit with rain drops on plants, soil, living organisms, buildings, lakes, rivers and seas. Acid rain affects the health of humans and animals living where it falls down, directly and indirectly. At some atmospheric conditions, sulfur dioxide content emitted from emission sources becomes so excessively dense locally that may cause collective death for human and animals.

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Every day, one million ton SOx is emitted to atmosphere from anthropogenic sources. A lot of districts in the world are being exposed to high SOx concentrations and taking urgent precautions is required to reduce these emissions. Especially in the developed countries, precautions to protect the air quality are to be applied immediately. A lot of methods have being developed for the removal of air pollutants present at flue gases of large combustion plants. Sulfur dioxide emitted from power plants, chemical and mineral industries, is generally found at low concentrations at huge volume of gases. Methods using removal of sulfur dioxide are summarized below:

- (i) By wet gas washing method, conversion to calcium sulfate by lime and air
- (ii) By aqueous absorption and desorption (Wellman-Lord Process), concentration and then oxidation of concentrated SO₂ to sulfuric acid cataliticaly
- (iii) At high temperature, reduction with natural gas and production of elemental sulfur
- (iv) Oxidation of SO₂ to sulfuric acid by methods using ammonia, hydrogen peroxide or manganese

All these processes have disadvantages of requiring a lot of chemicals, regeneration of reagents or oxidants, reheating of stack gases before emitting to atmosphere. Although catalytic oxidation is attractive for SO_2 removal, it has low removal rate. Electrochemical SO_2 removal is applicable as an alternative method.

Removal of Sulfur Dioxide From Flue Gases by an Electrochemical Method Gaseous pollutants can be converted to harmless components by electrochemical reactions. Electrochemical gas purification methods can be applied basically in two steps: At the first step, gases to be removed are absorbed in the aqueous electrolyte. Then, in the second step, they can be converted to harmless components by electrochemical oxidation or electrochemical reduction.

In the electrochemical SO_2 removal, while sulfur dioxide dissolved in acidic solution is anodically oxidized, hydrogen is produced at the cathode (3,4). Anode:

$$SO_2 + 2H_2O \longrightarrow SO_4^{=} + 2e^- + 2H^+$$

Cathode:

 $2H^+ + 2e^- \longrightarrow H_2$ Overall reaction: $SO_2 + 2H_2 O \longrightarrow SO_4^{=} + H_2$ *Lime Scrubbing* Process Chemistry Lime scrubbing uses an alkaline slurry made by adding lime (CaO), usually 90% pure, to water. The alkaline slurry is sprayed in the absorber and reacts with the SO_2 in the flue gas. Insoluble calcium sulfite (CaSO₃) and calcium sulfate (CaSO₄) salts are formed in the chemical reaction that occurs in the scrubber and are removed as sludge. A number of reactions take place in the absorber. Before the calcium can react with the SO2, both must be broken down into their respective ions. This is accomplished by slaking (dissolving) the lime in water and then spraying the slurry into the flue gas to dissolve the SO_2 . Simplified reactions occur simultaneously and are illustrated below.

SO₂ dissociation:

SO₂ (gaseous) \rightarrow SO₂ (aqueous) SO₂ + H₂O \rightarrow H₂SO₃ CaO(solid) + H₂O \rightarrow Ca(OH)₂ (aqueous) Ca(OH)₂ + H₂SO₃ = CaSO₃ + 2H₂O

$$CaSO_3^{=} + 0.5 O_2 \rightarrow CaSO_4^{=}$$

From the above relationships and assuming that the lime is 90% pure, it will take 1.1 moles of lime to remove 1 mole of SO_2 gas.

EX: Polluted air with 200mg/L SO_2 with a flow of $4000 \text{m}^3/\text{hr}$. If the purity of lime is 80%. Find in kg only -the followings :

- i) daily water required
- ii) the daily lime required
- iii) daily produced inerts
- iv) daily produced sludge

Solution

```
CaO + H_2O = Ca(OH)_2
  56
            18
                      74
  SO_2 + H_2O = H_2SO_3
  64
                      82
          18
  Ca(OH)_2 + H_2SO_3 = Ca SO_3 + 2H_2O
  74
                82
                            120
                                      36
  Ca SO<sub>3</sub> +0.5O2
                        = Ca SO<sub>4</sub>
  120
                            136
               16
  SO2 = 200*1000*4000*24=960000000 mg/day=9600kg/day
      Water consumed
i)
  SO_2 + H_2O
                  = H<sub>2</sub>SO<sub>3</sub>
  64
          18
                      82
  9600
           Х
                       Х
  H2O = 9600 \times 18/64 = 2700 \text{ kg/day}
  H_2SO_3 = 9600 \times 82/64 = 12300 \text{ kg/day}
```

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 $Ca(OH)_2 + H_2SO_3 = Ca SO_3 + 2H_2O$ 74 120 36 82 Х 12300 Χ Х $Ca(OH)_2 = 12300*74/82 = 11100 \text{ kg/day}$ $CaO + H_2O = Ca(OH)_2$ 18 74 56 Х 11100 Х H2O=11100*18/74=2700 kg/day Consumed water = 2700+2700= 5400kg/day ii) $Ca(OH)_2 + H_2SO_3 = Ca SO_3 + 2H_2O$ 82 120 36 74 Х Х Х 12300 $Ca(OH)_2 = 12300*74/82 = 11100 \text{ kg/day}$ $CaO + H_2O = Ca(OH)_2$ 56 18 74 X Х 11100 CaO = 11100*56/74 = 8400 kg/day pure CaO total=8400/0.8=10500 kg/day iii) Inert=10500-8400=2100 kg/day Produced water $Ca(OH)_2 + H_2SO_3 = Ca SO_3 + 2H_2O$ 74 82 120 36 Х 12300 Χ Χ X = 12300 * 36/82 = 5400 kg/day $Ca(OH)_2 + H_2SO_3 = Ca SO_3 + 2H_2O$ 74 82 120 36 Χ 12300 Х Х **Ca SO₃**= 12300*120/82=18000 kg/day Ca SO₃ +0.5O2 = Ca SO₄ 120 16 136 18000 Х **Ca SO**₄=18000*136/120=20400kg/day Produced sludge= Ca SO₄ + produced water+ inerts =20400+5400 +2100=27900 kg/day

Limestone Scrubbing

Process Chemistry

Limestone scrubbers are very similar to lime scrubbers. The use of limestone $(CaCO_3)$ instead of lime requires different feed preparation equipment and higher liquid-to-gas ratios (since limestone is less reactive than lime). Even with these

differences, the processes are so similar that an FGD system can be set up to use either lime or limestone in the scrubbing liquid. The basic chemical reactions occurring in the limestone process are very similar to those in the lime-scrubbing process. The only difference is in the dissolution reaction that generates the calcium ion. When limestone is mixed with water, the following reaction occurs:

$CaCO_3 \text{ (solid) } + H_2O \rightarrow Ca^{++} + HCO^- + OH^-$

The other reactions are the same as those for lime scrubbing.

Thermal Reduction of SO₂ to Sulphur

During 1909-11, S. W. Young investigated reduction of SO_2 with methane and other hydrocarbons on a laboratory scale. It is assumed that inability to accommodate byproduct H_2S , CS_2 and COS was considered a key drawback.

In a 1934 article, Yushkevich, and others, discuss in detail the various possible reaction products from the combination of SO_2 and a hydrocarbon reducing agent, including H_2S , COS, CS_2 and sulphur.

Experiments suggested 900-1000°C as the optimum temperature. In 1938, American Smelting and Refining Company (ASARCO) initiated investigations, which soon indicated that relatively low-grade SO₂ might be directly converted to reasonably pure sulphur by reduction with natural gas. Laboratory and smallscale pilot operations were gradually expanded until a semi-commercial 5-tpd unit was operated during 1940-45. Gas from copper roasters or converters containing 5-8% SO₂ and 9-12% oxygen was combusted with sufficient natural gas to consume all the oxygen to CO₂, plus additional fuel to react with an appropriate portion of the SO₂ according to the following overall reaction with CH₄ as shown in Eq.1.

Considerable quantities of byproduct H_2S , COS and CS_2 were formed as well.

Oxidation of SO₂ to sulfuric acid

Sulfuric acid is the product of the U.S. chemical industry produced in largest quantity in terms of mass. About 40 million tons are produced annually. There are two major processes used in the production of H_2SO_4 , the lead chamber process and the contact process. The lead-chamber process is the older of the two processes, and its product is aqueous sulfuric acid containing 62% to 78% H_2SO_4 . The contact process yields pure sulfuric acid. In both processes, sulfur dioxide, SO_2 , is oxidized to sulfur trioxide, SO_3 , and the SO_3 is dissolved in water. Sulfur dioxide is obtained by burning sulfur,

$S(s) + O_2(g) \longrightarrow SO_2(g)$

by roasting pyrite (iron sulfide) or other metal sulfides prior to melting,

4 FeS(s) + 7 O₂(g) \longrightarrow 2 Fe₂O₃(s) + 4 SO₂(g) or by burning hydrogen sulfide, H₂S(g) + O₂(g) \longrightarrow SO₂(g) + H₂O(g) The sulfur dioxide is oxidized to sulfur trioxide catalytically. 2 SO₂(g) + O₂(g) <u>catalyst</u> 2 SO₃(g)

Without the catalyst, the oxidation of SO_2 is quite slow. In the old lead-chamber process, the catalyst is nitrogen dioxide gas. In the contact process, the catalyst is vanadium(V) oxide, V_2O_5 , mixed with an alkali metal sulfate. The mixture is supported on small silica beads, and at the high temperature inside the reactor, the mixture is a liquid. The product SO_3 is dissolved in 98% sulfuric acid. The dissolved SO3 reacts with the 2% water, forming H_2SO_4 .

 $SO_3(g) + H_2O(l) \longrightarrow H_2SO_4(l)$

Pure sulfuric acid is a colorless, odorless, oily liquid. It freezes at 10.5EC. It fumes when heated, because some of the H_2SO_4 decomposes to H_2O and SO_3 . The H₂O is retained in the liquid, while SO₃ gas is released. Therefore, the concentration of H₂SO₄ decreases, reaching a concentration of 98.33%. This solution boils at 338EC and is the material sold as "concentrated sulfuric acid." Concentrated sulfuric acid, which is 18M, has a strong affinity for water and is sometimes used as a drying agent. It can be used to chemically remove water from many compounds. It dehydrates sucrose (table sugar), $C_{12}H_{22}O_{11}$, leaving a spongy black mass of carbon and diluted sulfuric acid. Concentrated sulfuric acid reacts similarly with skin, paper, and other animal and plant matter. When it is mixed with water, a highly exothermic reaction occurs, and the energy released can be enough to heat the mixture to boiling. Therefore, concentrated sulfuric acid must be diluted by adding the acid slowly to cold water while the mixture is stirred to dissipate the heat. Sulfuric acid has a wide range of uses and plays a part in the production of nearly all manufactured goods. About 65% of the H₂SO₄ produced annually is used in the production of agricultural fertilizers.

H2S Removal Method

N Methyl Diethanol Amine (MDEA)

Claus Reaction

Aqueous di-ethanol amine (DEA) is a common chemical absorbent used in refineries to remove H_2S from refinery off gases. Aqueous MDEA is used to accomplish selective removal of H2S [5]. Besides MDEA, di-isopropanol amine (DIPA) has also been reported to have a greater selectivity for H_2S over CO_2 than either MEA or DEA [3]. The removal of H_2S from the gas is termed the sweetening process.

 $2 \ H_2S + SO_2 \rightarrow 3 \ S + 2 \ H_2O$

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 $H_{2} S + Amine \longrightarrow [Amin e]H^{+} + HS^{-}.$ $CO_{2} + H_{2} O + Amine \Leftrightarrow [Amin e]COOH^{+} + OH^{-}$ $CO_{2} + H_{2} O + Amine + R_{2}CNH_{3} \Leftrightarrow R_{2}CNH_{4}^{-} + HCO_{3}^{-}$ The following chemical reactions occur in an aqueous MDEA solution when CO₂ and H₂S are present: $CO_{2} + H_{2} O \iff HCO_{3}^{-} + H^{+}$ $HCO_{3} \iff CO_{2} + H^{+}$ $H_{2} O \iff OH^{-} + H^{+}$ $RR'R'NH^{+} \iff RR'R'N + H^{+}$ $H_{2} S \iff HS^{-} + H^{+}$

Where: R corresponds to a methyl group and R' to an ethanol group

Chemial Treatment of Water Pollutants

Water Pollutants

1- Suspended solids

2- Oil and grease

- 3- Dissolved solids
- 4- Emulsions
- 5- Acid and Base
- 6- Color
- 7- Thermal pollution
- 8- Chemicals

Chemical treatment includes:

- 1- Coagulation
- 2- Chemical precipitation
- 3- Chemical oxidation
- 4- Ion exchange
- 5- Chemical neutralization
- 6- Scale control and stabilization

Coagulation

It includes all reactions and mechanisms involved in chemical destabilization of particles and in the formation of larger particles through perikinetic flocculation **Coagulant** is the chemical used to destabilize the colloidal particle so that the floc formation can result Flocculant is a chemical, typically organic, added to enhance the flocculation process Typical flocculants and coagulants include natural and organic polymers, metal salts such as alum or ferric sulfate

The term flocculation is used to describe the process wherby the size of particles increases as a result of particle collisions

Soilds in water present into two forms, colloidal and suspended solids (greater than 1 micron) and can be removed by sedimentation

Electrical double layer

Colloidal particles are usually charged with negative charge resulting into two layers

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Particle destabilization with polyelectrolytes

They are natural and synthetic. Natural electrolyte is derived from polymers of biological orign while synthetic consist of simple monomers that are polymerized into high molecular weight, they are classified as anionic, cationic and nonionic. They work by:

Charge neutralization

Polymer bridge formation

Charge neutralization and bridge formation



Particle destabilization and removal with hydrolyzed metal ions

In the past, it is thought that iron and aluminum ions are responsible for the removal of colloidal particles. Now it is shown that hydrolyzed products of them are responsible for its action

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Chemical precipitation

Alum, lime, ferrous sulfate, ferric chloride and their combinations are used Alum:

Quantity of alkalinity required to react with 10 mg/l of alum is

10*3*100/666.5=4.5 mg/L, if avalable alkalinity is less than this in water , it must be added and lime is used for this purpose

Lime

 $\begin{array}{rcl} H_2CO_3 + & Ca(OH)_2 &= & CaCO_3 + 2H_2O\\ 44 \mbox{ as } CO_2 & 56 \mbox{ as } CaO & 100 & 2*18\\ Ca(HCO_3)_2 &+ & Ca(OH)_2 &= 2CaCO_3 + 2H_2O\\ 100 \mbox{ as } CaCO_3 & 56 \mbox{ as } CaO & 2*100 & 2*18\\ \end{array}$

 $\begin{array}{rcl} Al^{+3} & + H_n PO_4^{3-n} & = & AlPO_4 & + & nH^+ \\ Fe^{+3} & + H_n PO_4^{3-n} & = & FePO_4 & + & nH^+ \\ Ex: \end{array}$

Determine the amount of liquid alum required to precipitate phosphorous in wastewater that contains 8mg/l. determine the required alum storage capacity if 30-d supply is to be stored at the treatment facility. Based on laboratory testing 1.5 mole of Al will be required per 1 mole of P. the flow rate is 12000m³/d and the following data are for liquid alum:

- 1- Formula Al₂(SO₄)₃.18H₂O
- 2- Strength 48%
- 3- Density of liquid alum is 1.2 kg/l

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Solution

```
1- Determine the weight alum Al available per liter of liquid alum
 a- Weight of alum per liter is 0.48*1.2=0.576 kg/l
 b- Weight of aluminum per liter is
Aluminum
                    alum
2*26.98
                     666.5
                    0.576
Х
X=0.0466kg/l
2- Weight of Al required per unit weight of P
 a- Theoretical dosage = 1 mole Al per 1 Mole P i.e 2*26.98Al
                                                                  30.97P
 b- Aluminum required = 1 \text{ kg} (\text{mw Al/mw P})
                      = 1*(2*26.98/30.97)=0.87 kg Al/kg P
Al
               Ρ
2*26.98A1
              30.97P
                         X=1*26.98*2/30.97=0.87kgAl/kgP
Х
                 1
Actual Al weight = 1.5*0.87 = 1.305 \text{ kgAl/kgP}
3- Required alum solution volume per kg P
    Alum weight
                         solution volume
        0.04666
                            1
         1.305
                             Х
   X=1.305*1/0.046666= 28 litter/kg P
    Alum dose = 1.5 \times (0.87 \text{ kg Al}/1 \text{ kg P})(\text{L alum solution}/0.04666 \text{ kg})
    = 28 L alum solution / kg P
 4- Amount of alum solution per day
    Weight of P per day
          =12000*(m^{3}/d)*8(g/m^{3})=96000g/day=96kg/day
    Vol Al sol
                           weight P
     28
                            1
       X
                            96 x=96*8/1=768l/day
5- Required alum storage capacity based on average flow:
  Vol /month =768*30=23040 litter
Removal of heavy metals and dissolved inorganic substances
It includes
- Chemical precipitation
- Carbon adsorption
- Ion exchange
```

- Reverse osmosis

Chemical precipitation

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Metals are precipitated most commonly as metal hydroxides through the addition of lime or caustic to a pH of minimum solubility

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Chemical Oxidation

This is performed by using ozone, hydrogen peroxide, permanganate MnO_4 , chloride dioxide ClO_2 , chlorine, or HOCL, and oxygen

Sedimentation

It is the process of removing suspended solids by the action of gravity Sedimentation mechanisms

- 1- Discrete settling
- 2- Flocculant settling
- 3- Hindered settling

4- Compression or zone settling

Discrete settling

$$F_g = (\rho_s - \rho_f) \nabla g$$
$$F_D = \frac{AC_D}{2} v_c^2$$

For spherical particles, $A=\Pi d^2/4$, $\nabla = \frac{\Pi d^3}{6}$

$$v_c^2 = \left[\frac{4g\Delta\rho d}{3\rho CD_1}\right]$$

 $C_D = 24/\text{Re}$ Re less than 1
 $C_D = 24/\text{Re} + 3/(\text{Re})^{0.5} + 0.34$ 3C_D = 0.44 1000\rho v d/\mu = v d/v

$$v_c = \frac{v_c}{18\mu}$$

 $\Theta = \nabla/Q$

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Any particle enter at the top having V_p less than V_c will not be removed. It will be removed if it enters

 $V_{\rm C} = H/\Theta$

at a point lower than the top so its vector will be parallel to that of particles having V_c .

Particles of $V_{\rm c}$ or more will be removed completely wherever it enter

 $Xr = Vp/V_C$

 $1-X_r$ = fraction of particle with $V_p > V_C$



$$\int_{0}^{X_{c}} \frac{V_{p}}{V_{C}} dx = fraction \ of \ particle \ removed \ with \ V_{p} < V_{C}$$

Fraction removed= $(1-Xr) + \int_0^{X_c} \frac{V_p}{V_c} dx$

Surface over flow rate (SOR) V=distance/t t=distance/V t=L/u t=H/V_c $L/u = H/V_c$ $V_c = Hu/L = HQ/LHW = Q / LW = SOR$



EX: determine the overall removal efficiency of primary sedimentation tank given the following data if SOR is $3000m^3/m^2/d$

V, m/min.	3	1.5	0.6	0.3	0.22	0.15
Wt fraction	0.48	0.11	0.13	0.10	0.1	0.08
on each sieve						

 $V_{\rm C} = 3000/(24*60) = 2.083$ m/min.

Draw a settling velocity curve by finding cumulative weight fraction with less than stated velocity

EX. For $V_p = 3$, CF=1-0.48=0.52

For \dot{V}_p = 1.5, CF=1-0.59= 0.41 and so on



V, m/min.	3	1.5	0.6	0.3	0.22	0.15
V, ft/min	10	5	2.0	1.0	0.75	0.5
Cumulative wt%	0.48	0.59	0.72	0.82	0.92	1.0
cumulative weight fraction with less	0.52	0.41	0.38	0.18	0.08	0.0
than stated velocity						

From the graph Xr = 0.47 which is fraction of particles having settling velocity less than 2.083 m/sec. from the graph made the following table:

Δx	0.04	0.16	0.2	0.06	0.01	Sum
Vp	0.2	0.3	0.8	1.7	2.083	
V _p dx	0.008	0.048	0.16	0.104	0.02083	0.77283

Fraction removed = $(1-X_C) + (1/V_C) \Sigma V_p dx$

= 1-0.47 + 0.77283/2.083 = 0.901 = 90.1%

Flocculant settling

Laboratory experiments must be performed using a cylinder of each diameter and depth equal to sedimentation tank. Take samples from different depth and calculate the efficiency and list the results as follows:

Time, min.		Removal percent at depth:			
	0.5m	1 m	1.5 m	2 m	2.5 m
20	61				
30	71	63	55		
40	81	72	63	61	57
50	90	81	73	67	63
60		90	80	74	68
70			86	80	75
80				86	81

Draw best contour line and draw vertical

line from detention time $Eff = \frac{\Delta h1}{h_T} \frac{(R1+R2)}{2} + \frac{\Delta h2}{h_T} \frac{(R2+R3)}{2} + \frac{\Delta h3}{h_T}$ $\frac{(R3+R4)}{2} + \frac{\Delta h4}{h_T} \frac{(R4+R5)}{2} + \dots$

Q2 find the efficiency of flocculant settling if tank depth is 3 m and surface loading of 3.6 m/hour. Giving the following lab test data



Figure 6-15 Settling column and settling curves for flocculant particles. Note: m × 3.2808 = ft

Time, min.		Removal percent at depth:			
	0.5m	1 m	1.5 m	2 m	2.5 m
20	60				
30	70	60	57		
40	80	72	64	60	59
50	90	82	75	70	66
60		88	78	78	78
70			83	84	83
80				88	86

Solution

Construct the following graph and from it find :

Detention time = depth(m)/(SOR, m/hr) = hr = 3/3.6 = 0.833hr = 50 min.

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<u>Floatation</u>

Separation in this process is usually brought about by introducing gas bubbles (air) into the liquid phase.

Dissolved air flotation

Dispersed air flotation

Design consideration for dissolved air flotation

The performance of dissolved air flotation systems depends on the ratio of volume of air to mass of solids (A/S)

$$A/S = 1.3 s_a (fP-1)/S_a$$

S_a air solubility, ml/l

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ffraction of air dissolved at pressure P usually 0.5

P = pressure atm. = (p+101.35)/101.35

= (p+14.7)/14.7 US units

p= gage pressure

 $S_a = influent$ suspended solids, g/m³, mg/l

The corresponding equation for a system with pressurized recycle is:

$A/S = 1.3 s_a (fP-1)R/S_aQ$

 $R = pressurized recycle, m^3/d$

Q = mixed liquor flow rate

In both equation, the numerator represent the weight of air and the denominator represents the weight of solids.

The constant 1.3 is the weight in milligrams of 1 mL of air. The number -1 accounts for the fact that the system is to be operated at atmospheric conditions. The required area for thickener is determined from the rise velocity of the solids. 8-60 L/(m^2 .min.)

T, C	0	10	20	30
S _a , ml/l	29.2	22.8	18.7	15.7

Ex: design a flotation thickener with and without recycle to thicken a sludge from 0.3 to 4%, given:

A/S = 0.008 mL/gT = 20 C $S_a = 18.7 \text{ mL/L}$ Recycle system pressure = 275 kPaFraction of saturation=0.5 Surface loading rate = $8 l/(m^2.min)$

Sludge flow rate = $400 \text{ m}^3/\text{d}$ 1- A/S = 1.3 $s_a (fP-1)/S_a$ 0.008=1.3*18.7(0.5*P-1)/3000 0.5P=0.99+1 P=3.98 = (p+101.35)/101.35p=302kPa 2- Determine the required surface area $A = (400 \text{ m}^3/\text{d})(1000 \text{ L/m}^3)/[8 \text{ L/(m}^2.\text{min.})(1440 \text{min./d})]$ $=34.7 \text{ m}^2$ Check solid loading rate $Kg/(m^2.d) = (400m^3/d)(3000g/m^3)/[34.7m^2*1000g/kg]$ = 34.6With recycle Pressure in atmosphere = (275+101.35)/101.35 = 3.37 atm. $A/S = 1.3 s_a (fP-1)R/S_aQ$ 0.008=1.3*18.7(0.5*3.73-1)R/[3000*400] $R=461.9 \text{ m}^{3}/\text{d}$ $A = (461.9 \text{m}^3/\text{d})(1000 \text{L/m}^3)/[8 \text{L/(m}^2.\text{min.})(1440 \text{min./d})]$ $= 40.1 \text{ m}^2$ API oil water separator

When it is necessary to remove oil from water, coalescing plate module type oilwater separators are often a good solution because they remove the oil using only gravity for motive force, the separator modules are permanent and require little maintenance, no absorbents or other consumable items such as filter cartridges are required, and the oil that is separated is often recyclable. No pumping or other utility costs are usually required (although pumped systems can be designed if this is required by the site conditions). They can be designed to operate under a great range of operating conditions and up to 100% oil. Separator systems can often be located underground, thus minimizing waste of valuable area on the surface.

Because oil-water separators operate using gravity as the operating principle, their design is more difficult and requires more expertise than design of filtration or other systems that operate under pressure, but the ongoing benefits of low operating and maintenance costs and the sale of recyclable oil usually outweigh the slight added expense of the initial designs. No absorbents are required, so disposal costs are limited only to the disposal of the recovered oil.

GENERAL DISCUSSION AND THEORY OF OIL-WATER SEPARATION: In 1845, an English mathematician named George Stokes first described the physical relationship that governs the settling solid particles in a liquid (Stokes's Law, 1845). This same relationship also governs the rising of light liquid droplets within a different, heavier liquid. This function, simply stated is:

$$Vp = \frac{G}{(18x\mu)} x(d_p - d_c) x D^2$$

Where:

 V_p = particle rising or settling velocity, cm/sec

G =gravitational constant, 980 cm/sec²

 μ = absolute viscosity of continuous fluid, poise

dp = density of particle (or droplet), gm/cm²

 d_c = density of continuous fluid, gm/cm²

D = diameter of particle, cm

A negative velocity is referred to as the particle (or droplet) rise velocity. Assumptions Stokes made in this calculation are:

1) Particles are spherical

2) Particles are the same size

3) Flow is laminar, both horizontally and vertically. Laminar flow in this context means flowing gently, smoothly, and without turbulence.





Concrete Vault at OEM Tire Company Steel Separator CONSIDERATIONS FOR THE SELECTION AND DESIGN OF OIL-WATER SEPARATOR SYSTEMS

General Design Considerations:

Numerous factors must be considered in the selection and design of oil-water separation systems. Among these are:

1. Flow rate and conditions.

- 2. Degree of separation required effluent quality.
- 3. Amount of oil in the inlet water.
- 4. Existing equipment such as concrete vaults or pumps
- 5. Emulsification of the oil.
- 6. Treated water facilities.
- 7. Recovered oil disposal method.

Inlet Flow (Influent) Conditions

Much of the performance of an oil-water separator depends on the influent conditions, because equipment or conditions that cause small droplet sizes in the influent to the separator will cause requirements for a larger separator to accommodate the additional time required for the smaller droplets to coalesce.

Conditions that cause small droplets are any conditions that cause shear in the incoming water. The following are (more or less in order of severity) some factors that can cause small droplet sizes:

1. Pumps, especially centrifugal pumps.

2. Valves, especially globe valves.

3. Other restrictions in flow such as elbows, tees, other fittings, or simply unduly small line sizes.

- 4. Vertical piping (horizontal is better)
- 5. Emulsifying chemical agents (soaps and detergents)

Emulsifying agents such as soaps and detergents greatly contribute to small droplet sizes in addition to disarming coalescing plates and discouraging coalescing.

Ideal inlet conditions for an oil-water separator are:

- 1. Gravity flow (not pumped) in the inlet piping.
- 2. Inlet piping sized for minimum pressure drop.

3. Inlet piping straight for at least ten pipe diameters upstream of the separator (directly into nozzle)

4. Inlet piping containing a minimum of elbows, tees, valves, and other fittings.

Filtration

Filtration is a mechanical or physical process to separate solid particulates from fluids.

Removal of suspended solids by filtration plays an important role in the natural treatment of groundwater as it percolates through the soil. It is also a major part of most water treatment. Groundwater that has been softened or treated through iron and manganese removal will require filtration to remove floc created by coagulation or oxidation processes. Since surface water sources are subject to

run-off and do not undergo natural filtration, it must be filtered to remove particles and impurities.

THE FILTRATION PROCESS

The filter used in the filtration process can be compared to a sieve or microstrainer that traps suspended material between the grains of filter media. However, since most suspended particles can easily pass through the spaces between the grains of the filter media, straining is the least important process in filtration. Filtration primarily depends on a combination of complex physical and chemical mechanisms, the most important being adsorption. Adsorption is the process of particles sticking onto the surface of the individual filter grains or onto the previously deposited materials. The forces that attract and hold the particles to the grains are the same as those that work in coagulation and flocculation. In fact, some coagulation and flocculation may occur in the filter bed, especially if coagulation and flocculation can cause serious problems in filter operation.

Filtration mechanisms

- -straining
- sedimentation
- impaction
- interception
- adhesion
- chemical adsorption
- physical adsorption
- flocculation
- biological growth

TYPES OF FILTERS



Large particles become lodged and cannot Particles stick to t continue downward through the media. continue downward The Two Removal Mechanisms

continue downward through the media. wo Removal Mechanisms

Several types of filters are used for water treatment. The earliest ones developed were the slow sand filters. They typically have filter rates of around 0.05 gpm/ft² of surface area. This type of filter requires large filter areas. The top several inches of the sand has to be removed regularly-- usually by hand--due to the mass of growing material ("schmutzdecke") that collects in the filter. The sand removed is usually washed and returned to the filter. These filters are still in use in some small plants, especially in the western United States as well as in many developing countries. They may also be used as a final step in wastewater treatment.

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Most filters are classified by filtration rate, type of filter media, or type of operation into:

A. Gravity Filters
1. Rapid Sand Filters
2. High Rate Filters
-Dual media
-Multi-media
B. Pressure Filters
-Sand or Multi-media



Pressure losses Carmen Kozeny

$$h = \frac{f(1-\infty)Lv^2}{\Phi \quad \infty^3} \frac{dg}{dg}$$

$$f = 150 \frac{1-\infty}{N_r} + 1.75$$

$$N_r = \frac{\rho v d}{\mu}$$

Fair- Hatch

$$h = kVs^2 \frac{f(1-\infty)^2}{\Phi \quad \infty^3} \frac{Lv}{d^2g}$$

Rose

$$h = \frac{1.067}{\Phi} C_d \frac{1}{\infty^4} \frac{Lv^2}{dg}$$
$$C_d = \frac{24}{R_e} + \frac{3}{R_e^{0.5}} + 0.34$$

Hazen

$$h = \frac{1}{CT + 10} \frac{Lv}{d_{10}^2}$$

C= coefficient of compactness, 600-1200

 C_d = coefficient of drag

d=grain diameter, m

 d_{10} =effective grain size diameter,mm

f=friction factor

h=head loss,m

k=filtration constant, 5 based on sieve opening, 6 based on size of separation

L=depth, m N_r = reynold number S=shape factor, 6-7.7 T=temperature, F $v = filtration \ velocity, m/s$ ∞ =porosity μ =viscosity, N.s/m² V=kinematic viscosity, m²/s ρ =density, kg/m³ $\Phi = shap \ factor, usually$ 1)

Ex: determine the clear water head loss in a filter bed composed of 30 cm of anthracite with an average size of 1.6mm and 30cm of sand with an average size of 0.5mm for a filtration rate of 160 L/(m^2 .min.) if T is 20C. Use Rose equation Solution:

1- Find R_e for anthracite and sand
V=1.003*10⁻⁶ m²/s
v=160/1000=0.16m/min=0.00267m/s
R_e=dv/V=1.6*0.00267/[(1.003*10⁻⁶)(1000)]=4.26 for anthracite
= 0.5*10^{-3*}0.00267/1.003*10⁻⁶=1.33
2- C_d=24/4.26+3/(4.26)^{0.5}+0.34=7.43 for anthracite
=24/1.33+3/(1.33)^{0.5}+0.34=20.99

$$h = \frac{1.067}{\Phi} C_d \frac{1}{\omega^4 dg} = \frac{1.067}{1} 7.43 \frac{1}{0.0256} \frac{0.3*0.00267^2}{0.0016*9.81} = 0.042m$$
 for anthracite
 $\infty = 0.4$
 $h = \frac{1.067}{\Phi} C_d \frac{1}{\omega^4 dg} = \frac{1.067}{1} 20.99 \frac{1}{0.0256} \frac{0.3*0.00267^2}{0.005*9.81} = 0.382m$ for sand
3- Total head=0.042+0.382=0.424m

Advanced Wastewater Treatment Physical, chemicals and biological properties of wastewater

Physical characteristics- Solids

• Solids are classified into three main types:

1. Total Solids (TS): All the matter that remains as residue upon evaporation at 102^{9} C to 105^{9} C

103°C to 105°C.

2. Settleable solids: Settleable solids are measured as ml/L, which is an approximate measure of the sludge that can be removed by primary sedimentation.

3. Suspended solids (SS) and Filterable solids (FS).

Physical characteristics- Odor

Odor is produced by gas production due to the decomposition of organic matter or by substances added to the wastewater.

Detection of odor: Odor is measured by special instruments such as the Portable H_2S meter which is used for measuring the concentration of hydrogen sulfide.

Odor quality	Chemical Formula	Compound
Fishy	CH ₃ NH ₂ , (CH ₃) ₃ H	Amines
Ammoniacal	NH ₃	Ammonia
Rotten eggs	$\rm NH_2 \ (CH_2)_4 \ NH_2, \ (CH_2)_5$	Diamines
	NH ₂ H ₂ S	
		Mercaptans
Decayed cabbage	СН ₃ SH, СН ₃ (СН ₂) SH	(E. g, methy1 and ethy1)
Rotten cabbage		Organic sulfides
Fecal matter		Skatole

Physical characteristics- Temperature

Temperature of wastewater is commonly higher than that of water supply. Depending on the geographic location the mean annual temperature varies in the range of 10

to 21^oC with an average of 16 ^oC.

Importance of temperature:-

Affects chemical reactions during the wastewater treatment process.

Affects aquatic life (Fish,).

Oxygen solubility is less in worm water than cold water.

Optimum temperature for bacterial activity is in the range of 25°C to 35

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Aerobic digestion and nitrification stop when the temperature rises to 50° C. When the temperature drops to about 15°c, methane producing bacteria become inactive. Nitrifying bacteria stop activity at about 5°c.

Density:-

Almost the same density of water when the wastewater doesn't include significant amount of industrial waste.

Color:-

Fresh waste wate r _____ light brownish gray. With time

→ dark gray → black (septic). More time

Some times pink due to algae or due to industrial colors.

Turbidity:-

It's a measure of the light – transmitting properties of water

Chemical characteristics of wastewater

Points of concern regarding the chemical characteristics of wastewater are:

-Organic matter

-Measurements of organic matter

-Inorganic matter

-Gases

-pH

Organic matter ($C_aH_bO_c$).

 organic. (Suspended Solids)
 organic. (Filtered Solids) 75% SS

40% FS

Organic mater is derived from animals & plants and man activities.

Proteins (40-60%).

Carbohydrates (25-50%).

Fats, Oils, and Grease (10%).

Measurements of organic matter:-

Many parameters have been used to measure the concentration of organic matter in wastewater. The following are the most common used methods:

Biochemical oxygen demand (BOD).

BOD₅ is the oxygen equivalent of organic matter. It is determined by measuring the dissolved oxygen used by microorganisms during the biochemical oxidation of organic matter in 5 days at 20°C

Chemical oxygen demand (COD)

It is the oxygen equivalent of organic matter. It is determined by measuring the dissolved oxygen used during the chemical oxidation of organic matter in 3 hours

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Total organic carbon (TOC)

This method measures the organic carbon existing in the wastewater by injecting a sample of the WW in special device in which the carbon is oxidized to carbon dioxide then carbon dioxide is measured and used to quantify the amount of organic matter in the WW. This method is only used for small concentration of organic matter.

Theoretical oxygen (ThOD)

If the chemical formula of the organic matter existing in the WW is known the ThOD may be computed as the amount of oxygen needed to oxidize the organic carbon to carbon dioxide and a other end products

Biological Oxygen Demand (BOD):

The following are the theoretical equations used to calculate the BOD.

The Figure shown is used to describe the change of BOD with time. From the figure the following correlations are derived:

 $L_0 \longrightarrow \text{ or (BOD ultimate) or UBOD.}$

Yt= BOD_t(BOD exerted).

 $L_t = L_0 e^{-kt}$ (BOD remain).

$$BOD_t = L_0 - L_t = L_0 - L_0 e^{-kt} = L_0 (1 - e^{-kt})$$

 $BOD_5 = L_0(1 - e^{-k5})$

K = 0.23d⁻¹usually, k
$$_{T}$$
 = $k_{20}\theta^{T-20}$, θ = 1.047 or as given

Example

Determine the 1-day BOD and ultimate BOD for a wastewater whose 5-day 20 °C BOD is 200 mg/L. The reaction constant $K= 0.23d^{-1}$ what would have been the 5-day BOD if it had been conducted at 25°C?



Solution:-

•BOD_t= UBOD -BOD_r = UBOD $(1-e^{-kt}) = L_0(1-e^{-kt})$ 200 = $L_0(1-e^{-0.23x5}) L_0 = 293 \text{ mg/L}$ (this is UBOD) •Determine the 1-day BOD:-BOD_t = $L_0(1-e^{-kt})$ Petroleum pollution control

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 $BOD_1 = 293 (1-e^{-0.23x1}) = 60.1 \text{ mg/L}$

•Determine the 5-day BOD at 25C:- $K_T = K_{20} (1.047)^{T-20}$ $K_{25} = 0.23 (1.047)^{25-20} = 0.29$ BOD₅= L₀(l-e ^{-kt}) = 293 (l-e^{-0.29x5}) = 224 mg/L

Theoretical Oxygen demand (ThOD):

Example Calculate the Theoretical Oxygen Demand (ThOD) for sugar C_{12} H₂₂ O_{11} dissolved in water to a concentration of 100 mg/L. Calculate "TOC".

Solution:-

 $C_{12} H_{22} O_{11} + 12O_2 \longrightarrow 12 CO_2 + 11 H_2O$ ThOD = sugar sugar 12 *32 g $O_2/342g$ sugar = 1.123 g O_2/g sugar $\text{ThOD} = \frac{100 \ mg \ sugar}{L} * \frac{1.123 \ g \ O_2}{g \ sugar} * \frac{1000 \ mg \ O_2}{g \ O_2} * \frac{1 \ g \ sugar}{1000 \ mg \ sugar}$ ThOD = $112.3 \text{ mg O}_2 / \text{L}$ TOC = 144 g carbon/ 342g sugar = 0.42 gc/ gs $TOC = 0.42 \times 100 = 42 \text{ mg carbon}$ **Chemical Oxygen demand (COD) and Total Organic carbon (TOC) Example:** Determine BOD5/COD, BOD5/TOC, TOC/BOD5ratios for the following organic compound ($C_5H_7NO_2$). Assume "K" = 0.23d⁻¹. 1. determine COD:- $C_{5}H_{7}NO_{2}+5O_{2}$ \rightarrow 5 CO₂+ NH₃+ 2H₂O Mw =113 mw =160 $COD = 160/113 = 1.42 \text{ mg } O_2/\text{ mg } C_5H_7NO_2$ 2. Determine the BOD₅of C₅H₇NO₂:- $BOD_5/UBOD5 = 1-e^{-0.23x5} = 0.68$ $BOD_5 = 0.68 \text{ UBOD}$: but COD = UBODSo BOD₅ = 0.68XCOD = 1.42X0.68=0.97 mg BOD/mg C₅H₇NO₂ 3. Determine the TOC of the compound:-TOC = 5X12/113 = 0.53 mg TOC/mg C5H7NO24. BOD₅/COD= 0.97/1.42 = 0.68BOD₅/TOC= 0.97/0.53= 1.82 TOC/COD = 0.53/1.42 = 0.37Note: COD = THOD = UBOD This is true only when the organic compound is assumed to be completely biodegradable

Inorganic Matter
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The following are the main inorganic materials of concern in wastewater treatment:

1. Chlorides:-

• High concentrations indicate that the water body has been used for waste disposal.

•It affects the biological process in high concentrations.

2. Nitrogen:-

TKN = Total Kjeldahl nitrogen. = Organic Nitrogen + ammonia Nitrogen (120 mg/l).

3. Phosphorus:-

•Municipal waste contains (4-15 mg/L)

4. Sulfur:-

```
* Sulfate exists in waste and necessary for synthesis of proteins.
Organic matter +SO_4^{-2} \rightarrow S^{-2} + H_2O+CO_2
S^{-2} + 2H^+ \rightarrow H_2S
```

Toxic inorganic Compounds:-

Copper, lead, silver, chromium, arsenic, boron.

Heavy metals:-

Nickels, Mn, Lead, chromium, cadmium, zinc, copper, iron mercury.

Gases:-The following are the main gases of concern in wastewater treatment: N_2 , O_2 , CO_2 , H_2S , NH_3 , CH_4

pH:-The hydrogen-ion concentration is an important parameter in both natural waters and wastewaters. It is a very important factor in the biological and chemical wastewater treatment. Water and wastewater can be classified as neutral, alkaline or acidic according to the following ranges:

PH = 7 neutral.

PH > 7 Alkaline.

PH < 7 Acidic

Biological Characteristics

The environmental engineer must have considerable knowledge of the biological of waste water because it is a very important characteristics factor in wastewater treatment. The Engineer should know:-

1. The principal groups of microorganisms found in wastewater.

2. The pathogenic organisms.

3.Indicator organisms (indicate the –presence of pathogens).

4. The methods used to amount the microorganisms.

5. The methods to evaluate the toxicity of treated wastewater

Main groups of Microorganisms:-

The main microorganisms of concern in wastewater treatment are Bacteria, Fungi, Algae, Protozoa, Viruses, and pathogenic microorganisms groups

Bacteria:-Types: Spheroid, rod curved rod, spiral, filamentous.

Some important bacteria:-

Pseudomonas:-reduce NO³to N_2 , So it is very important in biological nitrate removal in treatment works.

Zoogloea:-helps through its slime production in the formation of flocs in the aeration tanks.

Sphaerotilus natuns:Causes sludge bulking in the aeration tanks. Bdellovibrio:destroy pathogens in biological treatment. Acinetobacter:Store large amounts of phosphate under aerobic conditions and release it under an – anaerobic condition so, they are useful in phosphate removal.

Nitrosomonas: transform NH₄into NO₂-

Nitrobacter: transform NO₂-to NO₃-

Coliform bacteria:-The most common type is E-Coli or Echerichia Coli,

(indicator for the presence of pathogens).

E-Coli is measured in (No/100mL)

Fungi:

•Important in decomposing organic matter to simple forms.

Algae:

• Cause eutrophication phenomena. (negative effect) • Useful in oxidation ponds. (positive effect)

• Cause taste and problems when decayed. (negative effect)

Protozoa:

•Feed on bacteria so they help in the purification of treated waste water.

•Some of them are pathogenic

Viruses:

Viruses are a major hazard to public health. Some viruses can live as long as 41 days in water and wastewater at 20 oC. They cause lots of dangerous diseases.

Pathogenic organisms:

The main categories of pathogens are:-

Bacteria, Viruses, protozoa, helminthes



Screening and Grit Removal

DESCRIPTION

Wastewater contains large solids and grit that can interfere with treatment processes or cause undue mechanical wear and increased maintenance on wastewater treatment equipment. To minimize potential problems, these materials require separate handling. Preliminary treatment removes these constituents from the influent wastewater. Preliminary treatment consists of screening, grit removal, septage handling, odor control, and flow equalization. This fact sheet discusses screening and grit removal

SCREENS

The primary treatment incorporates unit operations for removal of floating and suspended solids from the wastewater. They are also referred as the physical unit operations. The unit operations used are screening for removing floating papers, rages, cloths, plastics, cans stoppers, labels, etc.; grit chambers or detritus tanks for removing grit and sand; skimming tanks for removing oils

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and grease; and primary settling tank for removal of residual settleable suspended matter

Screen is the first unit operation in wastewater treatment plant. This is used to remove larger particles of floating and suspended matter by coarse screening. This is accomplished by a set of inclined parallel bars, fixed at certain distance apart in a channel. The screen can be of circular or rectangular opening. The screen composed of parallel bars or rods is called a rack. The screens are used to protect pumps, valves, pipelines, and other appurtenances from damage or clogging by rags and large objects.

Industrial wastewater treatment plant may or may not need the screens. However, when packing of the product and cleaning of packing bottles/ containers is carried out, it is necessary to provide screens even for industrial wastewater treatment plant to separate labels, stopper, cardboard, and other packing materials. The cross section of the screen chamber is always greater (about 200 to 300 %) than the incoming sewer. The length of this channel should be sufficiently long to prevent eddies around the screen. The schematic diagram of the screen is shown in the Figure 14.1.

TROUGH



Figure 14.1 Bar Screen

Types of Screens

Screens can be broadly classified depending upon the opening size provided as coarse screen (bar screens) and fine screens. Based on the cleaning operation they are classified as manually cleaned screens or mechanically cleaned Due to need of more and more compact treatment-facilities many screens. advancement in the screen design are coming up.

Coarse Screen

It is used primarily as protective devices and hence used as first treatment unit.

Common type of these screens are bar racks (or bar screen), coarse wovenwire screens, and comminutors. Bar screens are used ahead of the pumps and grit removal facility. This screen can be manually cleaned or mechanically cleaned. Manually cleaned screens are used in small treatment plants. Clear spacing between the bars in these screens may be in the range of 15 mm to 40 mm.

Grinder or Comminutor

It is used in conjunction with coarse screens to grind or cut the screenings. They utilize cutting teeth (or shredding device) on a rotating or oscillating drum that passes through stationary combs (or disks). Object of large size are shredded when it will pass through the thin opening of size 0.6 to 1.0 cm. Provision of bye pass to this device should always be made.

Comminutors and Grinders

Processing coarse solids reduces their size so they can be removed during downstream treatment operations, such as primary clarification, where both floating and settleable solids are removed. Comminuting and grinding devices are installed in the wastewater flow channel to grind and shred material up to 6 to 19 mm (0.25 to 0.75 in) in size.

Comminutors consist of a rotating slotted cylinder through which wastewater flow passes. Solids that are too large to pass through the slots are cut by blades as the cylinder rotates, reducing their size until they pass through the slot openings. Grinders consist of two sets of counterrotating, intermeshing



cutters that trap and shear wastewater solids into a consistent particle size, typically 6 mm (0.25 in). The cutters are mounted on two drive shafts with intermediate spacers. The shafts counterrotate at different speeds to clean the cutters. Figure 2 depicts a channel wastewater grinder.

The chopping action of the grinder reduces the formation of rag "balls" and rag "ropes" (an inherent problem with comminutors). Wastewaters that contain large quantities of rags and solids, such as prison wastewaters, utilize grinders downstream from coarse screens to help prevent frequent jamming and excessive wear.

Grit Removal

Grit includes sand, gravel, cinder, or other heavy solid materials that are "heavier" (higher specific gravity) than the organic biodegradable solids in the wastewater. Grit also includes eggshells, bone chips, seeds, coffee grounds, and large organic

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particles, such as food waste. Removal of grit prevents unnecessary abrasion and wear of mechanical equipment, grit deposition in pipelines and channels, and accumulation of grit in anaerobic digesters and aeration basins. Grit removal facilities typically precede primary clarification, and follow screening and comminution. This prevents large solids from interfering with grit handling equipment. In secondary treatment plants without primary clarification, grit removal should precede hydrocyclones (cyclonic inertial separation). Various factors must be taken into consideration when selecting a grit removal process, including the quantity and characteristics of grit, potential adverse effects on downstream processes, head loss requirements, space requirements, removal efficiency, organic content, and cost. The type of grit removal system chosen for a specific facility should be the one that best balances these different Specifics on the different types of grit removal systems are considerations. provided below.

Aerated Grit Chamber

In aerated grit chambers, grit is removed by causing the wastewater to flow in a spiral pattern, As shown in Figure 3. Air is introduced in the grit chamber along one side, causing a perpendicular spiral velocity pattern to flow through the tank. Heavier particles are accelerated and diverge from the streamlines, dropping to the bottom of the tank, while lighter organic particles are suspended and eventually carried out of the tank



FIGURE 3 AERATED GRIT CHAMBER

Biological Treatment

It is used to remove the nonsettleable colloidal solids and to stabilize the organic matters.

- Aerobic
- Anoxic
- Anaerobic
- Combination

Bacterial Growth

Bacteria are reproduced by binary fission, sexual mode or budding.

1 cell for a generation time of 30 minutes yields 16777216 cell.

The general growth pattern of bacteria in a batch culture can be divided into 4 zones:

1. Lag phase: When the cells are adjusting to their new environment. During this



phase, cellular metabolism is accelerated, resulting in rapid biosynthesis of cellular macromolecules, primarily enzymes, in preparation for the next phase of the cycle. Although the cells are increasing in size, there is no cell division and therefore no increase in numbers.

2. **Exponential phase**: Under optimum nutritional and physical conditions, the physiologically robust cells reproduce at a uniform and rapid rate by binary fission. Thus there is a rapid exponential increase in population, which doubles regularly until a maximum number of cells is reached. The length of the log phase varies, depending on the organisms and the composition of the medium, although the average may be estimated to last 6 to 12 hours.

3.**Stationary phase**: During this stage, the number of cells undergoing division is equal to the number of cells that are dying. There is no further increase in cell number and the population is maintained at its maximum level for a period of time. The primary factors responsible for this phase are the depletion of some essential metabolites and the accumulation of toxic acidic or alkaline end-products in the medium.

4. **Death phase**: Because of the continuing depletion of nutrients and buildup of metabolic wastes, the microorganisms die at a rapid and uniform rate. This decrease in population closely parallels its increase during the log phase. Theoretically, the entire population should die during a time interval equal to that of the log phase. This does not occur, however, since a small number of highly resistant organisms persist for an indeterminate length of time.

Bacterial Respiration

In aerobic process, three process take place as follows:

Oxidation: dissimilatory

COHNS + O_2 + bacteria = CO_2 +NH₃+ end products + energy Synthesis

 $OHNS + O_2 + bacteria + energy = C_5H_7NO_2$ (new bacterial cell

Endogenous Respiration

$C_5H_7NO_2 + 5O_2 = 5CO_2 + NH_3 + 2H_2O + energy$ Logarithmic growth: Batch Culture

In batch culture, the bacterial growth (r_g) mass per unit volume . time, is proportional with the concentration of microorganism(X), mass per unit volume

 $r_g = \mu X$(1) $\mu = specific growth rate, time^{-1}$

Substrate limited growth

The Basic Model for Microbial Growth

where

 $\mu_m = maximum \ specific \ growth \ rate, \ time^{-1}$ $S = concentration \ of \ growth$ $- limiting \ substrate \ in \ solution, \ mass \ per \ unit \ volume$ $K_S = half \ velocity \ constant, \ substrate \ concentration \ at \ one \ half \ maximum$ $growth \ rate, \ mass \ per \ unit \ volume$



 $r_{su} = \mu_m \frac{XS}{Y(K_S + S)}$ (5) Let Professor dr. Muzher Mahdi Ibraheem

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Where k is the maximum rate of substrate utilization per unit mass of microorganisms

Thus eq. 6 becomes

Effect of endogenous metabolism

In bacterial system, not all organisms are in the log growth phase, there is a decay due to cell death and other factors. Thus correction of all these factors must be performed

 $r_d(endogenous \ decay) = -k_d X_{abs}$ (8) $k_d = endogenous \ decay \ coefficient, \ time^{-1}$

Combining eq.8 with eqs. 3 & 4 gives

 $r_g^- = \mu_m \frac{XS}{(K_S + S)} - k_d X.$ (9) $r_g^- = -Yr_{su} - k_d X....(10)$ r_{g}^{-} = net rate of bacterial growth, mass/(unit volume.time) The corresponding equation for the specific growth rate is

$$\mu^{-} = \mu_{m} \frac{S}{(K_{S} + S)} - k_{d}....(11)$$

 $\mu^{-} = net \ specific \ growth \ rate, \ time^{-1}$

The effect of endogenous respiration on the net bacterial yield are accounted by defining an observed yield as follows

Microorganism and substrate mass balance

In continuous flow stirred tank reactor the material balance is as follows



Rate of accumulation of	Rate	of	flow	of	Rate	of	flow	of	r	let	growth	of
microorganisms in the	micro	organ	isms	into	micro	organ	isms ou	t of	r	nicroo	rganisms	within
system boundary	the sy	stem	bounda	ary	the sy	stem	boundar	У	t	he sys	tem bound	dary

Accumulation = inflow - outflow + net growth

$$\frac{dX}{dt}V = QX_o - QX + Vr_g^{-}....(13)$$
Where

dX/dt = rate of change of microorganism concentration in the reactor, mass of volatile suspended solids, VSS, /(unit volume. Time)

V = reactor volume

Q = flow rate

 X_o =microorganism concentration in the influent, mass VSS/unit volume X = microorganism concentration in the reactor, mass VSS/unit volume

Substitute eq. 9 into eq. 12 will give

$$\frac{dX}{dt}V = QX_o - QX + V\left[\mu_m \frac{XS}{(K_S + S)} - k_d X\right].$$
(14)

If we assume that the microorganism effluent concentration is negligible and the system is at steady state (dX/dt=0), then

$$\frac{Q}{V} = \frac{1}{\theta} = \mu_m \frac{S}{(K_S + S)} - k_d.$$
(15)

Where θ = hydraulic time, = V/Q

The substrate balance is

$$\frac{dS}{dt}V = QS_o - QS + V\left[\frac{KXS}{(K_S + S)}\right] \dots (16)$$

At steady state (dS/dt=0), then

$$S_o - S - \theta \left[\frac{KXS}{(K_S + S)} = 0....(17)\right]$$

Prediction of effluent microorganism and substrate concentration

To find them, solve eq. 15 for $\frac{S}{(K_S + S)}$ then substitute the resulting expression ito eq. 17 and simplify the result using eq.6:

Similarly the effluent substrate concentration is:

$$S = \frac{K_s(1+k_d\theta)}{\theta(Yk-k_d)-1}$$
....(19)

Development of process design relationship

If the definition of net growth, $r_{\overline{g}}$, given by eq.10 is used in eq. 13, the resulting eq. is:

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 $\frac{dX}{dt}V = QX_o - QX + V[-Yr_{su} - k_dX]....(20)$ Under steady state conditions and X_o is zero , eq.20 will be: $\frac{Q}{V} = \frac{1}{A} = -Y \frac{r_{su}}{Y} - k_d....(21)$ Using eqs. 9-11, it can be shown that Multiply Q and V by X and take the reciprocal of eq.22: $\theta_c = cell residence time$ Substitute θ_c for θ into eq. 21 will give: $\frac{1}{\theta_c} = -Y \frac{r_{su}}{X} - k_d....(24)$ The term $-\frac{r_{su}}{x}$ is known as specific substrate utilization rate ,U $U = -\frac{r_{su}}{x}....(25)$ $r_{su} = -\frac{Q}{V}(S_o - S) = -\frac{S_o - S}{A}$(26) $\frac{1}{\theta_c} = YU - k_d....(28)$ The observed yield is $E = \frac{S_o - S}{S_o} * 100....(33)$

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Determination of Kinetic Coefficients

Kinetic coefficients of interest for the design of activated sludge process are:

k = Maximum rate of substrate utilization per unit mass of microorganisms, time⁻¹

 K_d = Endogenous decay coefficient, time⁻¹

 K_s = Half velocity constant, substrate concentration at one-half of the maximum growth rate, mass/unit volume

= Cell yield coefficient, mg/mg (defined as the ratio of the mass of cells formed to the mass of substrate consumed.

$$r_{su} = \frac{kXS}{(K_S + S)} = -\frac{S_o - S}{\theta}$$

divide by X and take the reciprocal then arrange will give

$$\frac{\theta X}{S_o - S} = \frac{K_S}{k} \frac{1}{S} + \frac{1}{k}$$

Plot the right term with 1/S will give a of straight line of slope = K_S/k and intercept of 1/k

$$\frac{1}{\theta_c} = -Y\frac{r_{su}}{X} - k_d = Y\frac{S_o - S}{\theta X} - k_d$$

Plot the right term with $\frac{S_o - S}{\theta X}$ will give a of straight line of slope Y and intercept of k_d

To find out the kinetic coefficient, a lab scal apparatus is used



Ex:

Determine the kinetic coefficients from the following data obtained from lab tests

Run No.	S _o , mg/L	S, mg/L	$\theta_c = \theta$, day	X, mg VSS/L
1	300	7	3.2	128

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2	300	13	2	125
3	300	18	1.6	133
4	300	30	1.1	129
5	300	41	1.1	121

Solution

1- Construct the following table

So-S, mg/L	$X \theta$, mg VSS/D/L	$\frac{\theta X}{S_o - S}, d$	1/S, 1/mg/L
293	409.6	1.398	0.143
287	250	0.865	0.077
282	212.8	0.755	0.056
270	141.9	0.526	0.033
259	133.1	0.514	0.024

2- Plot the data as follows:



And from the plot we find:

1/k=0.32d thus $k=3.125d^{-1}$

 $Slop = K_s/k=0.5d/0.065(mg/L)^{-1}=7.692 mg/(d.L)$ Thus

 $K_{s} = 7.692 \times 3.125 = 24 \text{ mg/L}$

3- Construct the following table

$1/\theta_{\rm c}, 1/d$	(So-S)/Xθ, 1/d
0.313	0.715
0.5	1.156
0.625	1.325
0.909	1.901
0.909	1.946

Plot the following figure



From the fig. we find that, - k_d = -0.05 thus k_d =0.05 d^{-1} Slope = Y = 0.35/0.7=0.5

4- Find $\mu_m = kY = 3.125 * 0.5 = 1.563 \left(\frac{1}{d}\right)$

Activated Sludge System Process Description:

• It is aerobic suspended growth biological wastewater treatment method in which dissolved organic and inorganic matter can be removed.

•This treatment is achieved in tanks called aeration tanks.

Oxygen is supplied to these tanks to allow aerobic biochemical reaction to occur.

• In the aeration tank, the microorganisms feed on dissolved solids mainly organic matter and produce large amounts of bacteria (colonies). This means that microorganisms convert dissolved solids into suspended solids (the bacterial colonies).

•After the aeration tank, a secondary sedimentation tank is installed to separate the bacteria from liquid

• The separated bacteria is called activated sludge. Part of the sludge is wasted and the remaining part is returned back (Recycle) to the aeration tank. The recycle of the sludge to aeration tank is very important to keep a specific concentration of the bacteria in the system to perform wastewater treatment.

• The mixture of wastewater with bacteria in the aeration tank is called mixed liquor suspended solids (MLSS)



 \mathbf{Q} = waste water flow rate

 \mathbf{X} = the mixed liquor suspended solids concentration (MLSS) bacteria concentration

 X_r = concentration of recycled activated sludge

 X_e = effluent suspended solids concentration

 Q_w = waste sludge flow rate

 Q_r = return sludge flow rate

 S_o = concentration of pollutants such as BOD

S = concentration of dissolved pollutants in the aerated tank and the effluent

V = volume of the aerated tank

The hydraulic time for the system is given by

$$\theta_s = \frac{V_S}{Q}$$

The hydraulic time is given by

$$\theta = \frac{V}{Q}$$

For the system shown θ_c is given by:

$$\theta_c = \frac{VX}{Q_w X + (Q - Q_w) X_e} \dots (A)$$

Where

 Q_w = waste flow rate from the reactor X_e = microorganism concentration in effluent from settling tank

Since this concentration is very low, thus:

$$\theta_c = \frac{V}{Q_w}$$



Activated Sludge Flow Diagram & Parameters

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Accumulation = inflow – outflow + net growth

$$\frac{dX}{dt}V = QX_o - [Q_wX + [Q - Q_wX_e] + Vr_g^-$$

Substitute eq. 10 and assuming the inflent solid concentration is zero and steady state conditions:

$$\frac{[Q_w X + (Q - Q_w X_e)]}{V X} = \frac{-Y r_{su}}{X} - k_d....(b)$$

Make use of eq. A, eq. B can be arranged and simplified to give:

$$1/\theta_c = \frac{-Yr_{su}}{X} - k_d \dots \dots \dots (C)$$

Or, by using eq. 24
$$1/\theta_c = YU - k_d$$

X in the reactor can be obtained by using eq. 25 with eq. C and solving for X:

$$X = \frac{\theta_c Y[S_o - S]}{\theta(1 + \theta_c k_d)}$$

Sludge is usually drained from recycle line. Thus:

$$\theta_{c} = \frac{VX}{Q_{w}X_{r} + (Q - Q_{w})X_{e}}$$

Since X_e can be neglected, thus
$$\theta_{c} = \frac{VX}{Q_{w}X_{r}}$$

V=VX/X
$$VX = \frac{Q\theta_{c}Y[S_{o} - S]}{(1 + \theta_{c}k_{d})}$$

Sludge production rate dx/dt = XV/ θ_{c}
$$P_{x} = \frac{Y_{obs}Q(So - S)}{1000gm/kg}$$

QrXr = (Q + Qr)X
Qr = QX/[Xr - X]
r = X/[Xr - X]
$$P_{x} = \frac{Y_{obs}Q(So - S)}{1000gm/kg} = \frac{Qw(So - S)}{1000gm/kg}$$

Oxygen requirements
 $C_{5}H_{7}NO_{2} + 5O_{2} = 5CO_{2} + NH_{3} + 2H_{2}O + energy$

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Kg O_2 /kg cell = 160/113 = 1.42

The theoretical oxygen demand for the removal of carbonaceous organic matter in wastewater for an activated sludge system can be computed:

Kg $O_2/d=$ total mass BOD_L utilized, kg/d – 1.42 mass of wasted organism,

Px

 $\frac{kgO_2}{d} = \frac{Q(So - S)}{f_{1000g/kg}} - 1.42 Px$

f is conversion factor of converting BOD₅ to BOD_L

Since $BOD_5 = 0.68 BOD_1$, thus f=1.47 and

$$\frac{kgO_2}{M} = \frac{1.47Q(So - S)}{1.42} - 1.42$$

1000g/kgd

EX: Given the following data for an activated sludge system : Design an activated sludge unit to treat a waste flow of 30000m³/day with BOD₅ of 300 mg/L. the effluent BOD and SS is to be 20 and 25 mg/L respectively. Assume: Xr = 20000 mg/L, X =3000 mg/L, Sludge age = 10 days, Y = 0.5, kd=0.05. Find the followings:

- i) Reactor volume and sludge production rate,
- ii) Recirculation flow rate and Hydraulic retention time,
- iii) Oxygen requirements

Solution

The BOD₅ of the effluent solids is estimated to be 0.63 * SS = 15.75 mg/LThe soluble BOD5 of the effluent must be reduced to 20-15.75 = 4.25 mg/L Thus:

$$VX = \frac{Q\theta_c Y[S_o - S] * 1000}{(1 + \theta_c k_d)} = \frac{30000 * 10 * 0.5 * 1000[300 - 4.25]}{(1 + 0.05 * 10)} = 2.95$$

* 10¹⁰mg
$$V=VX/X = 2.95 * \frac{10^{10}mg}{3000mg/L} = 9858000L = 9858m^3$$

Sludge production rate
$$dx/dt = XV/\theta_c = 2.95 * \frac{10^{10}mg}{10d} = 2.95 * \frac{10^9mg}{d} = 2950 \ kg/d$$
assuming solid is 0.8 volatile, thus total sludge is 2950/0.8=3687 kg/d
$$r = \frac{X}{[Xr - X]} \qquad r = \frac{3000}{[30000 - 3000]} = 0.111$$

Qr=0.11*30000=3300m³/d
Retention time = V/Q = 9858/30000=0.329day = 7.89 hr.

$$\theta_c = \frac{VX}{Q_w X_r}$$

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$$Q_w = \frac{VX}{\theta_c X_r} = \frac{2950 kg/d}{\frac{30000 mg}{L} * 10 * 0.000001 kg/mg}} = 9833 \frac{L}{d} = 9.83 m^3/d$$

$$\frac{kg O_2}{d} = \frac{1.47 Q(So - S)}{1000 g/kg} - 1.42 Px$$

$$\frac{O_2}{d} = \frac{1.47 * 30000[m^3/d] * 1000L/m^3(300 - 4.25)}{1000 g/kg} - 1.42 * 30000^*9830/1000$$

$$= 12623817g/d = 12623 kg/d$$
If air density is 1.2 kg/m³ and its percentage in air is 0.232, thus
$$Q air = 12623/[1.2*0.232] = 45738 m^3/d$$
Assume air transfer efficiency is 8%
Air required is 45738/0.08 = 571730m^3/d
$$air required = \frac{(300 - 4.25)mg}{L} * \frac{30000m^3}{d} * \frac{1000L}{m^3} * 10^{-6}kg/mg} = 6.44 m^3/kgBOD$$

Oil Spill



Source Natural Oil in the Environment: Seeps

The U.S. has proved oil reserves of about 21.32 to 30.46 billion barrels.5 Some of this crude oil is naturally discharged each year from "natural seeps", natural springs from which liquid and gaseous hydrocarbons (hydrogen-carbon compounds) leak out of the ground. Oil seeps are fed by natural underground accumulations of oil and natural gas (U.S. Geological Service) Oil from U.S. sub-marine (and inland subterranean) oil reservoirs comes to the surface each year, as it has for millions of years due to geological processes

Natural discharges of petroleum from submarine seeps have been recorded

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throughout history going back to the writings of Herodotus and Marco Polo.

Archaeological studies have shown that products of oil seeps were used by Native American groups living in California - including the Yokuts, Chumash, Achomawi, and Maidu tribes - well before the arrival of European settlers.

In recent times, the locations of natural seeps have been used for exploration purposes to determine feasible locations for oil extraction. The magnitude of natural seeps is such that, according to prominent geologists,

Kvenvolden and Cooper (2003), "natural oil seeps may be the single most important source of oil that enters the ocean, exceeding each of the various sources of crude oil that enters the ocean through its exploitation by humankind." Worldwide, natural seepage totals from about 4.2 million barrels to as much as 14 million barrels annually. In U.S. waters, natural seeps are also the largest source of oil inputs.

Each year an estimated 1,123,000 barrels of crude oil 10 seeps from geologic formations below the seafloor into U.S. waters, mainly in the Gulf of Mexico and off southern California.

Spillage from Offshore Oil Exploration and Production Activities

Areas in which natural seeps occur have provided opportunities for oil exploration and production. During the last decade (1998 – 2007), an estimated 1,273 barrels of crude oil spilled from offshore platforms into federal and state waters of the U.S. each year. An additional 2,614 bbl spilled annually from offshore



pipelines, for a total of 3,887 bbl per year. This represents a nearly 66 percent reduction in spillage from the previous decade, and an 87 percent reduction in spillage since the 1970s.27

-Spills from Platforms

- Spills from Offshore Pipelines
- Oil Exploration and Production Spills
- Spills from Inland Production Wells

Spillage from Oil Transport

Spills from Oil Tankers (Tank Ships)

- Spills from Tank Barges
- Oil Spillage from Tank Vessels in Relation to Oil Transported

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- Oil Spillage from Coastal and Inland Pipelines
- Spills from Railroads
- Spills from Tanker Trucks Spillage from Oil Refining
- Refinery Spills
 Spillage Related to Oil Consumption and Usage
- Spills from "Non-Tank Vessels" (Cargo Ships)
- Spills from Smaller Vessels
- Spills from Coastal Marine Facilities
- Spills from Gas Stations and Truck Stops
 Spills from Inland EPA-Regulated Facilities (Excluding Refineries)
- Spills from Residential Home Heating Oil Tanks
- Spills from Other Motor Vehicles
- Spills from Other Inland Sources

Treatment methods Deep Sea Oil Spill Cleanup Techniques: ------Applicability, Trade-offs and Advantages

As the explosion of BP's Deepwater Horizon oil rig in the Gulf of Mexico has shown, recovering large amounts of crude oil from a spill is a daunting task. The range of clean-up efforts varies widely and depends on a number of factors, including:

- oil type and density,
- water temperature,
- the volume of the spill,
- proximity to shorelines,
- waves, currents, weather and speed of response, Among others. From low-tech approaches, such as physical containment and skimming burning,

dispersants-

giant separators that basically vacuum oil from the surface seeding with oil-eating microorganisms,

the technique(s) applied to any given spill must be carefully chosen.

Countless marine and terrestrial wildlife species rely on sea and coastal habitats for food, cover and breeding space, creating a variety of ways for spilled oil to threaten fish, birds, mammals and reptiles.



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Detection and Assessment of an Oil Spill's Extent

For the foreseeable future, as today, spill response will depend on the ability to trap and remove oil. That reality places heavy importance on the speed and accuracy of detection, because these physical methods, according to Larry Nies, a professor of civil engineering at Purdue University, —are generally most effective if you get there in time and are the first line of defense." [1]

In practice, the majority of oil spill detection continues to be performed by the least costly method: visual observation from the air, along with still and video photography.

Discovery Guides Two critical deficiencies of this approach include limitations on seeing ability imposed by atmospheric and sea conditions, as well as complete inoperability in rain, fog or darkness.

Increasingly, aircraft-based remote sensors (which work by detecting color, reflectance, temperature, roughness and other sea *surface* properties) are

proving useful in a variety of oil spill detection modes, such as large area

surveillance, site specific monitoring, and tactical assistance in emergencies. [2] Yet, while airborne sensors offer greater accuracy and the advantage of operating beyond the optical spectral region, they are expensive and require highly trained personnel to control the systems and interpret results.

At the top end of spill detection technology, the ideal system:

1. would be completely automatic to reduce operational staff,

2. would be capable of delivering real-time data (including wave and current information) with no need for post-processing, and

3. would be able to see oil spills in the dark, enabling 24-hour vigilance.

Containment: Oil Booms

When oil is accidentally released into a body of water, the most urgent priority is limiting the spill's spread to minimize the natural resources at risk and to facilitate cleanup and removal. Swift and skillful deployment of a containment boom is essential for achieving both of these goals.

Boom Basics





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Because oil is less dense than water, it rises to the surface, where floating fences called booms can corral it. In its simplest form, a boom consists of a length of rugged fabric with buoyant filler stitched into the side intended to float above the water, and a heavy chain or other ballast inserted into the bottom to weigh down the subsurface skirt and make it sink. Boom material is brightly



colored for ease of recovery and to help crews spot a break in the line. The freeboard (above surface) component is commonly designed to reduce splashover, while the skirt is engineered to keep oil from escaping beneath the boom.

Under ideal conditions, a spill is quickly contained by booms strung end to end until they completely encircle the floating oil. Realistically, however, a number of factors, such as water current, wave height, wind velocity and oil viscosity steadily work to churn up the surface and hamper a boom's capacity to contain oil. [8] The result is that



in heavy seas or during rough weather, some of the oil sloshes over and under the boom, making a single line inadequate. These cases require multiple concentric circles of oil boom extending over increasing diameters until the spatial extent of the leak is contained.

When a slick becomes too dispersed for circular containment or when it begins to approach land, a mobile retention boom, with or without a built-in recovery system or skimmer, can be deployed to assist the oil roundup.

Modified Boom

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A variety of booms designed to repel water (hydrophobic) and soak up oil (oleophilic) serve as a backup or replacement for physical containment booms. Unlike barrier-only booms, absorbent booms are lightweight, easy to deploy, and have the ability to simultaneously contain a spill and begin the recovery process. They also require timely retrieval or an anchor point to prevent sinking as the booms become heavy with oil.

Commercial absorbent booms are commonly made of an outer mesh with



polypropylene filler and are engineered for easy deployment and maximum absorbency, as well as a long flotation period. While booms made of natural sorbents [9] like hair, hay and even a 3,000-year-old Egyptian hi-biscus plant called kenaf [10] reflect the largely low-tech measures still used to clean up oil spills, they are also environmentally safe and stimulate community involvement. [11]

Mechanical Recovery: Skimmers and Separators

Once booms have concentrated oil in sufficiently thick layers on top of the water, mechanical methods such as skimming, separating and vacuuming can be mobilized where conditions are favorable. But because these techniques take place at the surface, they are subject to the same disruptions that applied to booms, particularly those posed by wind, waves and currents.

Skimmers

Skimmers are slow yet very effective machines used for surface removal in calm or sheltered waters and along shorelines. They work by taking advantage of the adhesive nature of the oil, which will cling to any surface that it comes into contact with. Using rotation, suction, gravity or other forces to drive motion, these machines:



1. provide a never-ending surface for the spilled petroleum to cling to,

2. clean the surface, and

3. repeat that process continuously

Separators

Water can contain oil in three major forms:

1. free oil (droplets larger than 20 microns in diame-ter),

2. emulsified oil (droplets that have been mechanically or chemically reduced in size to smaller than 20 microns in diameter), and

3. dissolved oil (molecular-scale particles capable of dissolving in water). [16]

Because they take advantage of the differences in the specific gravities of water and oil to achieve separation, traditional gravity-type separators will not separate emulsified or dissolved oil from water. A gravity separator has a chamber



designed to provide controlled flow conditions that help globules of free oil rise to the surface of the water and form a separate oil mass that can be removed mechanically.

The "rise rate" of oil globules (their vertical velocity) is the speed at which oil particles move toward the separator surface because of the difference in densities of oil and water. The closer the density of the oil or the grease is to that of water, the longer it takes for separation to occur.

High-tech centrifuge separators also leverage the density difference between oil and water, but by using centripetal force to quickly spin and separate the two fluids, they can slurp up as much as 200 gallons of oil every minute. [17]

Mechanical collection by skimmers and separators cannot recover all the petroleum dumped in a major spill, a deepwater leak or a spill in rough waters where oil is rapidly churned and emulsified. These situations require: chemical, microbial and

Cleanup: Chemicals and Microbes Dispersants



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Dispersants are chemical formulations composed of solvents, surfactants and other additives that disrupt the solid surface of an oil slick by reducing the surface tension between oil and water. Composed of molecules with a watercompatible (hydrophilic) end and an oilcompatible (lipophilic) end, dispersants link an oil droplet to nearby water



molecules and allow the natural agitation caused by waves and wind to pull the droplets apart into increasingly smaller droplets.

Once the decision to use dispersants has been made, there are additional considerations such as choosing the most effective commercial product and determining the optimal application system.

Microbes

Bioremediation (the use of natural microorganisms, plants or fungi to correct a contaminated or altered environment) may have a role to play in restoring oilcontaminated environments and habitats. But when it comes to using microorganisms and their enzymes to return areas to their original conditions, there are two opposing schools of thought. Many scientists agree that naturally occurring bacteria capable of degrading oil are already present in marine environments, but the limited availability of nutrients like nitrogen and phosphorus prevent the oil-eaters from performing to their full potential. [30] Others, like Ben Lyons, a research scientist and engineer at the small biotech firm Evolugate, think greater potential lies in seeding oil spills with more bacteria.

Shoreline Cleanup

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FRESHWATER and marine shoreline areas are important public and ecological resources. However, their cleanliness and beauty, and the survival of the species that inhabit them, can be threatened by accidents that occur when oil is produced, stored, and transported. Oil is sometimes spilled from vessels directly into waterways; spills from land-based facilities can flow into waters and foul shorelines. These accidents affect both oceans and freshwater environments. Despite the best efforts of response teams to contain spilled oil, some of it may contaminate shorelines of oceans and lakes, banks of rivers and streams, and other ecologically sensitive habitats along the water's edge. To help protect these resources from damage and to preserve them for public enjoyment and for the survival of numerous species, cleaning up shorelines following oil spills has become an important part of oil spill response.

SHORELINES:

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PUBLIC AND ENVIRONMENTAL RESOURCES

FRESHWATER and marine shoreline areas serve as homes to a variety of wildlife during all or part of the year. Many bird species build their nests on sand or among pebbles, while others regularly wander the shoreline searching for food. Marine mammals, such as elephant seals and sea lions, come ashore to breed and bear their pups. Fish, such as salmon, swim near



shorelines on their upriver migrations during spawning season, and their offspring swim through these same areas on their trips to the sea in the following year. In addition, freshwater environments are important to human health as they are often used for drinking water and are home to many different mammals, aquatic birds, fish, insects, microorganisms, and vegetation. Freshwater and marine shorelines also provide public recreation throughout the world. Rivers, streams, and other freshwater bodies are known for their fishing activities, while many beaches are famous for their wide expanses of beautiful sand and rugged rocky cliffs, providing opportunities for sports such as swimming, boating, and windsurfing. When response teams develop strategies for cleaning up a shoreline after an oil spill, they must consider the characteristics of the shoreline and the natural and recreational resources it provides.

FACTORS AFFECTING CLEANUP DECISIONS

FREQUENTLY, oil spills will start on land and reach shore areas. Whenever possible, control and cleanup of an oil spill begins immediately. If the oil spill can be controlled, it is less likely that it will reach sensitive freshwater or marine habitats. If the oil does reach the shore, however, decisions about how best to remove it must be made.

These decisions will be based on factors such as the following:

- Type of oil spilled
- Geology of the shoreline and rate of water flow
- Type and sensitivity of biological communities likely to be affected

CLEANUP PROCESSES AND METHODS

BOTH NATURAL processes and physical methods aid in the removal and containment of oil from shorelines. Sometimes physical methods are used to enhance naturally occurring processes. Examples of a technology that uses both natural processes and physical methods to clean up an oil spill are biodegradation and bioremediation, which are described later.

Natural processes that result in the removal of oil from the natural environment include evaporation, oxidation, and biodegradation.

Evaporation occurs when liquid components in oil are converted to vapor and released into the atmosphere. It results in the removal of lighter-weight substances in oil. In the first 12 hours following a spill, up to 50 percent of the light-weight components may evaporate. Since the most toxic substances in oil tend to be those of lightest weight, this evaporation decreases the toxicity of a spill over time. Oxidation occurs when oxygen reacts with the chemical compounds in oil. Oxidation causes the complex chemical compounds in oil to break down into simpler compounds that tend to be lighter in weight and more able to dissolve in water, allowing them to degrade further.

Biodegradation occurs when naturally occurring bacteria living in the water or on land consume oil, which they can use to provide energy for their various biological needs. When oil is first spilled, it may be toxic to some bacteria, which makes the initial rate of biodegradation quite slow.

As the oil evaporates and the more toxic substances are removed, the population of bacteria grows and biodegradation activity accelerates.

In nature, biodegradation is a relatively slow process. It can take years for a population of microorganisms to degrade most of the oil spilled onto a shoreline. However, the rate at which biodegradation occurs can be accelerated by the addition of nutrients, such as phosphorus and nitrogen, that encourage growth of oil-degrading bacteria.

This process is called biostimulation. Biodegradation rates can also be increased by adding more microorganisms to the environment, especially species that are already used to consuming the type of oil spilled. Adding microorganisms is referred to as bioaugmentation. The use of nutrients or the addition of microorganisms to encourage biodegradation is called bioremediation.

When oil spill response personnel develop bioremediation strategies, they have to consider the effects of waves, tides, and currents on the nutrients and microorganisms they are applying to oil-contaminated areas. Contamination of coastal areas by oil from offshore spills usually occurs in the intertidal zone where waves and tides can quickly carry away dissolved nutrients. Adding nutrients may not be effective on beaches with a great deal of wave action and tidal flows because most of the nutrients will be lost to dilution. On calmer shorelines, adding nutrients may be an effective bioremediation strategy. Physical Methods Physical removal of oil from shorelines, and especially beaches, is timeconsuming and requires much equipment and many personnel. Methods used to physically clean oil from shorelines include the following:

- Wiping with absorbent materials
- Pressure washing
- Raking or bulldozing

Before physical cleaning methods are used, booms made of absorbent material are often set up in the water along the edge of the bank. Booms prevent oil released during bank cleanup activities from returning to the water and contain the oil so that it can be skimmed from the water for proper disposal.

Wiping with Absorbent Materials

Materials that are capable of absorbing many times their weight in oil can be used to wipe up oil from contaminated shorelines. These materials are often designed as large squares, much like paper towels, or shaped into "mops." The squares or mops are used to wipe the shoreline or oily rocks during which time the absorbents are filled with as much oil as they can hold. There are advantages to the use of absorbents. They can be used to clean up any kind of oil on any shoreline that can be reached by response personnel.

The use of absorbents is generally not harmful to the shoreline itself or to the organisms that live on it, and no material is left behind following the cleanup effort. Some sorbents are reusable, reducing the need for disposal after a spill Wiping with absorbent materials requires the use of a large quantity of material and several personnel. Personnel must wear proper protective clothing to minimize direct contact with the oil as they are removing it. Oil-filled absorbents and protective clothing that are used by response personnel must be properly disposed of following cleanup, which can be costly. In addition, the intrusion of many people onto an isolated shoreline may disrupt animal behaviors such as breeding or nesting

Pressure Washing

Pressure washing involves rinsing oiled shorelines and rocks using hoses that supply low- or high-pressure water streams. Hot or cold water can be used to create these streams. The oil is flushed from the shoreline into plastic lined trenches, then collected with sorbent materials and disposed of properly. Since many river banks, and some lakes, have vegetation extending down into or growing in the water, plants may have to be cleaned or removed.

Depending on the type of oil, low-pressure washing will usually remove most of the oil from the vegetation. In a marine ecosystem, high-pressure washing

usually does more harm than good by driving the oil deeper into the beach and by killing many of the organisms on the beach.

Additionally, high-pressure water streams can accelerate bank erosion and dislodge organisms, such as algae and mussels, from the rocks and sediments on which they live, or can force oil deeper into sediments, making cleanup more difficult Pressure washing has the advantage of being relatively inexpensive and simple to apply; however, it requires many people

Raking or Bulldozing

When oil moves downward into the sands or between pebbles and cobbles on a shoreline, it becomes more difficult to remove. If the oil has moved downward only a short distance, tilling or raking the sand can increase evaporation of the oil by increasing its exposure to air and sunlight. If the oil has penetrated several inches into the sand, bulldozers may be brought in to remove the upper layers of sand and pebbles. This allows the oil to be exposed so it can be collected and removed from the site, washed with pressure hoses, or left to degrade naturally. Raking and bulldozing are simple methods for helping to remove oil that might otherwise escape into sediments. However, these methods can disturb both the natural shape of the shoreline and the plant and animal species that live on and in the sediments. In addition, the use of bulldozers requires specially trained operators who can maneuver them without damaging the shoreline unnecessarily; raking and tilling are time-consuming and require many people.

DISPOSAL OF OIL AND DEBRIS

CLEANUP FROM an oil spill is not considered complete until all waste materials are disposed of properly. The cleanup of an oiled shoreline can create different types of waste materials, including liquid oil, oil mixed with sand, and tar balls. Oil can sometimes be recovered and reused, disposed of by incineration, or placed in a landfill. States and the federal government strictly regulate the disposal of oil. Reuse or recovery of oil requires that the oil be processed and separated from the other materials, such as water, that are mixed in with it. The recovered oil can then be blended with other fuels for use in power plants or boilers.

Incineration uses extremely high temperatures to convert compounds, such as oil, into carbon dioxide and water. When a mobile incinerator is used at a remote spill site, the need for transporting large volumes of oiled wastes to distant disposal sites is eliminated. This can be a practical and efficient method to manage large volumes of waste generated during a cleanup. Because incineration can potentially produce air pollution, it is important that it be used

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in strict compliance with air pollution laws. Landfilling is another method of disposing of oiled debris.

The oil is mixed with chemicals, such as calcium oxide ("quicklime"), that stabilize the oil and make it less able to leak into groundwater or soils. Mixtures of quicklime and oil must sometimes be taken to specially designed landfills for disposal

Oily sludge treatment Centrifuge

Processing the collected sludge is carried out by a variety of units depending on defining factors such as kinematic viscosity, oil content, how easily the given type of sludge separates, solids content and presence of any toxic chemicals.

Low solids "fresh sludges" are generally easier to separate and may require only centrifugation and no real pre-treatment

to achieve the require degree of separation. In this case we would use a specially designed decanter centrifuge.

The sludge is fed into the centrifuge. The 3000 g centrifugal force enerated in the unit splits the oil/water/sediment by density. The sediment is discharged

through the cone end directly into a container placed under the machine. It may be necessary to add a flocculant to assist with separation of more difficult sludges.

Following centrifuge processing,

the following remains:

 \rightarrow Oil on solids < 1.5%

 \rightarrow Oil in water < 0.5%

>> Water in oil < 2%

To enable final solids to be further

treated to completely remove all traces of

oils and chemicals and also to treat drill cuttings Argus offer the latest available Thermal Desorption Technology

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Thermal Desorption





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The Thermal Desorption Unit (TDU) is an indirectly heated rotary drum, which is operated in parallel flow configuration. The burner flame and exhaust gases do not come into contact with the contaminated material. The drum rotates within an insulated chamber, which can be heated by combination fuel burners capable of burning natural gas, fuel oil, syngas, or propane.



As the drum rotates, the surface of the contaminated material exposed to the metal surface is continuously renewed which facilitates the transfer of heat from the heated chamber through the drum to the material. The material is heated to a sufficient temperature to volatilize the contaminants. This is achieved under anaerobic conditions thereby preventing oxidation of the hydrocarbons

The system operates at a maximum temperature of 450°C but generally 380°C is sufficient for treatment purposes. The system essentially removes all oil from solids and water.

Biological Methods Making use of state of the art technology and know how, the Argus Group offers a unique biological process and equipment for completely removing solids from oily sludge.

Solids with from 5 to 50% oil product contamination are subject to treatement. The process is analogous to composting in agriculture in which stacks are turned to enhance microorganism growth.

The first stage for effective treatment is the diffusion of oxygen into the rows to encourage growth and activity of microbes in an anaerobic environment.

The second stage is to irrigate and control the



moisture when introducing water and nutritive elements during the aeration of the rows. These two conditions are essential for enhancing growth of microorganisms which attack hydrocarbons. For this purpose careful control of water and air input is essential. Thirty to sixty days is the ideal amount of time required for full decomposition. The process encompasses the formation of rows, introduction of nutrients, periodic water irrigation and daily oxygen diffusion with the aid of special equipment. Petroleum pollution controlProfessor dr. Muzher Mahdi IbraheemPetroleum & Gas Refinning Engineering Department, under Graduate Study

Use of Surfactants Steam stripping Incineration, Landfilling Anarobic thermal desorption Solvent extractor for oil recovery from petroleum sludge Biodiesel production from oily sludge by acidcatalyzed estrification



Precipitation of Heavy Metals from Wastewaters Typical Heavy Metals Found in Industrial Wastewaters

Heavy metals (as soluble ions) are common contaminants of industrial wastewaters. Because of their toxicity they are typically removed prior to wastewater discharge. The most common heavy metal contaminants are:

- Arsenic Mercury
- Barium Nickel
- Cadmium
 Selenium
- Chromium Silver
- Copper Zinc
- lead

Precipitation of Heavy Metals

The heavy metal contents of wastewaters can be effectively removed to acceptable levels by precipitating the metal in an insoluble form.

· Heavy metals are typically precipitated from wastewater as:

- hydroxides
- sulfides or sometime sulfates
- carbonates

Metal co-precipitation during flocculation with iron or aluminum salts is also possible for some metals (e.g., arsenic).

Precipitation of Heavy Metals as Hydroxides

Precipitation by hydroxide formation is the most common heavy metal precipitation method. The precipitation typically follows the reaction:

 $M^{+n} + n OH^{-} = Mn(OH)_n$

Many heavy metals are amphoteric. Therefore their solubility reaches a minimum at a specific pH (different for each metal)

The addition of caustic materials is used to raise the pH. The most common caustics are:

- sodium hydroxide (NaOH)

- calcium hydroxide (Ca(OH)2; lime)

Sodium hydroxide is more expensive than lime.

Lime has the advantage of also acting as a coagulant during the precipitation/settling process, whereas NaOH does not

Lime must be produced on site (via slaking) from CaO (quicklime), and the resulting slurry continuously stirred to prevent cake formation.

Lime may react with sulfates in the wastewater producing a hard precipitate and resulting in scaling formation.

Wastewater Pretreatment Prior to Metal Precipitation

If the wastewater contains complexing agents that can keep the metals in solution and prevent them from precipitating the complexing agent must be destroyed prior to metal precipitation as hydroxides.

 \cdot This is especially true for the case of cyanide salts because many heavy metals form strong complexes with cyanide.

 \cdot Cyanide is typically removed via oxidation with chlorine under alkaline conditions

Precipitation of Heavy Metals as Sulfides

 \cdot Metal sulfides are typically very insoluble. Therefore metals can be precipitated by adding sulfide ions (S⁻²).

 \cdot Metal sulfides have much lower solubilities than the corresponding metal hydroxides, thus allowing lower residual metal concentrations in the treated wastewater.

Hydrogen sulfide (H₂S) is a weak acid and dissociates in two steps according to $H_2S = H^+ + HS^-$

 $HS^{-} = H^{+} + S^{-2}$

Sulfide salts undergo hydrolysis, partially reforming the undissociated acid:

 $S^{-2} + H_2O = HS^- + OH^-$

 $HS^- + H_2O = H_2S^- + OH$

 \cdot S⁻² is not the dominating species until the pH is very high (~14). Hence, by adding a sulfide salt an equilibrium is generated resulting in only the partial formation of the S⁻² ions actually used in precipitation.

 \cdot Sulfide precipitation is always conducted under alkaline conditions to promote sulfide ion formation.

· Sulfide precipitation is rather insensitive to the presence of chelating agents

 \cdot Sulfide precipitates tend to form colloidal particles requiring the addition of coagulants to settle. However, sulfide sludges are easier to dewater than hydroxide sludges.

 \cdot Sulfide sludges are more prone to oxidation resulting in resolubilization of the metals as sulfates.

 \cdot Evolution of H₂S is a potential hazard if the pH is not carefully maintained in the alkaline region.

Precipitation of Heavy Metals as Carbonates

 \cdot Some metals (lead, cadmium, nickel) form insoluble carbonates that can be used in carbonate precipitation.

 \cdot Some wastewaters already contain enough carbonates to allow precipitation to occur. Alternatively, inorganic carbonates (e.g., Na₂CO₃) can be added

· Carbonate precipitation takes place only if carbonate ions (CO_3^{-2}) are present. Free carbonate ions are present only if the pH is high. A caustic is often added to raise the pH.

 \cdot High pH's also promote the precipitation of the metals as hydroxides. Hence, carbonate precipitation is often a co-precipitation

 \cdot pH values above 10 promote the formation of metal hydroxy complexes that can increase the metal solubility and reduce the precipitation effectiveness.

 \cdot Carbonate precipitates settle and can be dewatered more easily than the corresponding hydroxide precipitates.

Arsenic in Industrial Wastewaters

Arsenic is present in the wastewaters of a number of industries producing:

- metallurgical products
- glassware and ceramic
- tannery products
- dye stuff
- pesticides
- synthetic chemicals
- petroleum refinery products

Precipitation of Arsenic from Industrial Wastewaters

 \cdot Arsenic can be removed by precipitation as sulfide, through the addition of sodium sulfide or hydrogen sulfide to the wastewater. The effluent concentration is 0.05 ppm

• Arsenic can also be removed by coprecipitation with $FeCl_3$ when a $Fe(OH)_3$ floc is formed. The effluent concentration is 0.005ppm

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Barium in Industrial Wastewaters

Barium is present in the wastewaters of a number

of industries producing:

- · metallurgical products
- \cdot glassware and ceramic
- \cdot dye stuff
- \cdot explosives
- \cdot rubber products

Precipitation of Barium from Industrial Wastewaters

 \cdot Barium can be removed by precipitation as sulfate, by adding any sulfate ion source

 \cdot The solubility of barium sulfate is 1.4 ppm

 \cdot Even lower residual barium concentrations (0.5 ppm) can be obtained using an excess of sulfate ions

Cadmium in Industrial Wastewaters

Cadmium is present in the wastewaters of a number of industries producing:

- metallurgical products
- \cdot ceramics
- · electroplated products
- · photographic products
- · pigments
- \cdot textiles

• synthetic chemicals

Precipitation of Cadmium from Industrial Wastewaters

• Cadmium can be removed by precipitation as hydroxide at pH ranging from 8 (solubility: 1ppm) to 11 (solubility: 0.05 ppm)

 \cdot Cadmium can be removed by precipitation as sulfide. The effluent concentration

is 0.05 ppm

 \cdot Cadmium can also be removed by coprecipitation at pH 6.5 with FeCl₃ when a Fe(OH)₃ floc is formed. The effluent concentration is 0.008 ppm

Precipitation of Cadmium from Industrial Wastewaters

 \cdot Cadmium can also be removed by precipitation as carbonate. The pH required in this case is between 7.5 and 8.5. The effluent concentration is comparable to that obtained through hydroxide precipitation at high pH

 \cdot Cyanides interfere with any of these processes and must be removed prior to cadmium precipitation
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Chromium in Industrial Wastewaters

Chromium is present in the wastewaters of a number of industries producing:

- · steel manufacturing
- \cdot chrome plated products
- · tannery products
- · dye stuff
- · paints

Precipitation of Chromium from Industrial Wastewaters Chromium is typically precipitated in two steps:

• hexavalent chromium (Cr^{+6}) is reduced to trivalent chromium (Cr^{+3}). Compounds such as FeSO₄, Na₂S₂O₅ (sodium bisulfite) or SO₂ (sulfur dioxide) are used as reducing agents.

The reaction is conducted at low pH (< 3)

• trivalent chromium is precipitated as Cr(OH)₃.

Lime is typically used for the precipitation reaction. The effluent concentration is 0.2 ppm at pH 7.5

Precipitation of Chromium from Industrial Wastewaters

The reactions involved in chromium precipitation are:

Reduction reaction (at pH < 3):

 $H_2 Cr_2 O_7 + 3SO_2 = Cr_2 (SO_4)_3 + H_2 O$

(i.e., 1.85 ppm SO₂/ppm Cr) or, alternatively:

 $H_2 Cr_2 O_7 + 6Fe_4 SO_2 + H_2 SO_4 = Cr_2 (SO_4)_3 + 3Fe_2 (SO_4)_3 + 7H_2 O_4$

Precipitation reaction (at pH of 8 to 9):

 $Cr_2(SO_4)_3 + 3Ca(OH)_2 = 2Cr(OH)_3 + Ca_2SO_4$

(i.e., 2.13 ppm Ca(OH)₂/ppm Cr)

Copper in Industrial Wastewaters

Copper is present in the wastewaters of a number of industries producing:

- · Chemicals using copper salts
- · Chemicals using copper catalyst
- · Metal processing products

· Metal plated products

Precipitation of Copper from Industrial Wastewaters

• Copper can be removed by precipitation as hydroxide at pH ranging from 9 to 10.3(solubility: 0.01 ppm as cupric oxide)

 \cdot Copper can be removed by precipitation as sulfide at pH 8.5. The resulting effluent concentration is 0.01 - 0.02 ppm

 \cdot The presence of cyanide or ammonia may interfere with copper precipitation. In such a case activated carbon can be used to remove copper cyanide

Lead in Industrial Wastewaters

Lead is present in the wastewaters of a number of industries producing:

- \cdot batteries
- · pigments
- printing products

Precipitation of Lead from Industrial Wastewaters

 \cdot Lead can be removed by precipitation as hydroxide (lime) at pH 11.5. The effluent concentration is 0.02 to 0.2 ppm

 \cdot Lead can be removed by precipitation as sulfide at pH 7.5 to 8.5 \cdot Lead can also be removed by precipitation as carbonate. The pH required in this case is between 7.5 and 8.5. The effluent concentration is comparable to that obtained through hydroxide precipitation at high pH

Mercury in Industrial Wastewaters

Mercury is present in the wastewaters of a number of industries producing:

- · chlor-alkali
- · explosive
- · electronic products
- · pesticides
- · petrochemical products

Precipitation of Mercury from Industrial Wastewaters

 \cdot Mercury can be removed by precipitation as sulfide, through the addition of sodium sulfide or hydrogen sulfide to the wastewater. The effluent concentration is 0.01 ppm

- · Mercury can be removed by co-precipitation
- with alum. The effluent concentration is 0.001 to 0.01 ppm

 \cdot Mercury can be removed by co-precipitation with FeCl3 when a Fe(OH)3 floc is formed. The effluent concentration is 0.0005 to 0.005 ppm

Nickel in Industrial Wastewaters

Nickel is present in the wastewaters of a number of industries producing:

· Metal products (e.g., aircrafts) · Steel · Chemicals

Precipitation of Nickel from Industrial Wastewaters

- Nickel can be removed by precipitation as hydroxide at pH ranging from 10 to 11(solubility: 0.12 ppm)
- · Nickel can be also be removed by precipitation as sulfate or carbonate
- The presence of cyanide may interfere with nickel precipitation

Metal Complexation

- Many transition metals (e.g., Cd, Co, Cu, Fe, Hg, Ni, Zn) can form complexes with a number of different ligands such as hydroxides, sulfides, chlorides, cyanides, EDTA (ethylenediaminetetraacetic acid).
- Metal complexes (e.g., $Na_2Cd(CN)_4$, sodium cadmiocyanide) can increase the solubility of a metal far beyond what the solubility of the metal is (e.g., as hydroxide).

Precipitation of Complexed Metals

- Precipitation of complexed metals is typically impossible until the metal complex is destroyed or the equilibrium is shifted by adding massive amounts of the precipitant.
- Oxidation is typically the most common method to destroy metal complexes.
- Oxidants such as chlorine, hypochlorite, and ozone are often used for this purpose.
- After the complexing agent is destroyed the metals are precipitated as usual. Cyanide Removal Via Alkaline Chlorination
- Cyanides are compounds that need to be removed prior to wastewater discharge.
- Furthermore, cyanides often form metal complexes that must be destroyed before the metals are precipitated.
- Wastewaters containing cyanides (up to 1000 mg/L) are often treated with sodium hypochlorite (NaClO) or chlorine gas mixed with sodium hydroxide (to form sodium hypochlorite) in a two-step process.
- The first step is the conversion of cyanide (CN⁻) to cyanate ion (OCN⁻) in a tworeaction sequence at a pH above 10 (reaction time: 30 min. to 2 h): $CN^- + H_2 O + CIO^- \Leftrightarrow CNCI + 2OH^{-2}$

 $CNCI + CIO^{-} \Leftrightarrow OCN^{-} + CI^{-} + H_2 O$

• The second step is the oxidation of cyanate with hypochlorite at pH 8.5 to increase the kinetics (reaction time: 10 min. to 1 h):

 $20CN^{-} + 3CIO^{-} + H_2 O \Leftrightarrow 2CO_2 + N_2 + CF + OH^{-}$

Soil contamination or soil pollution

Soil contamination or soil pollution as part of land degradation is caused by the presence of xenobiotics (human-made) chemicals or other alteration in the natural soil environment.

It is typically caused by:

industrial activity, agricultural chemicals improper disposal of waste.

The most common chemicals involved are petroleum hydrocarbons, polynuclear aromatic hydrocarbons (such as naphthalene



and benzo(a) pyrene), solvents, pesticides, lead, and other heavy metals. Contamination is correlated with the degree of industrialization and intensity of chemical substance. The concern over soil contamination stems primarily from health risks, from direct contact with the contaminated soil, vapours from the contaminants, or from secondary contamination of water supplies within and underlying the soil. Mapping of contaminated soil sites and the resulting cleanups are time-consuming and expensive tasks, requiring extensive amounts of geology, hydrology, chemistry, computer modeling skills. and GIS in Environmental Contamination, as well as an appreciation of the history of industrial chemistry.

Causes

Soil pollution can be caused by the following (non-exhaustive list)

- **Microplastics** •
- Oil spills •
- Mining and activities by other heavy industries •
- Accidental spills may happen during activities, etc. ٠
- Corrosion of underground storage tanks (including piping used to transmit the • contents)
- Acid rain •
- Intensive farming •
- Agrochemicals, such as pesticides, herbicides and fertilizers
- Petrochemicals
- Industrial accidents
- Road debris •
- Drainage of contaminated surface water into the soil
- Ammunitions, chemical agents, and other agents of war •
- Waste disposal

- Oil and fuel dumping
- Nuclear wastes
- Direct discharge of industrial wastes to the soil
- Discharge of sewage
- Landfill and illegal dumping
- Coal ash
- Electronic waste

The most common chemicals involved are petroleum hydrocarbons, solvents, pesticides, lead, and other heavy metals.

Any activity that leads to other forms of soil degradation (erosion, compaction, etc.) may indirectly worsen the contamination effects in that soil remediation becomes more tedious.

Historical deposition of coal ash used for residential, commercial, and industrial heating, as well as for industrial processes such as ore smelting, were a common source of contamination in areas that were industrialized before about 1960. Coal naturally concentrates lead and zinc during its formation, as well as other heavy metals to a lesser degree. When the coal is burned, most of these metals become concentrated in the ash (the principal exception being mercury). Coal ash and slag may contain sufficient lead to qualify as a "characteristic hazardous waste", defined in the US as containing more than 5 mg/l of extractable lead using the TCLP procedure. In addition to lead, coal ash typically contains variable but significant concentrations of polynuclear aromatic hydrocarbons (PAHs; e.g., benzo(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, indeno(cd)pyrene, phenanthrene, anthracene, and others). These PAHs are known human carcinogens and the acceptable concentrations of them in soil are typically around 1 mg/kg. Coal ash and slag can be recognised by the presence of off-white grains in soil, gray heterogeneous soil, or (coal slag) bubbly, vesicular pebble-sized grains.

Treated sewage sludge, known in the industry as biosolids, has become controversial as a "fertilizer". As it is the byproduct of sewage treatment, it generally contains more contaminants such as organisms, pesticides, and heavy metals than other soil.^[3] In the European Union, the Urban Waste Water Treatment Directive allows sewage sludge to be sprayed onto land. The volume is expected to double to 185,000 tons of dry solids in 2005. This has good agricultural properties due to the high nitrogen and phosphate content. In 1990/1991, 13% wet weight was sprayed onto 0.13% of the land; however, this is expected to rise 15 fold by 2005. Advocates sav there is a need to control this SO that pathogenic microorganisms do not get into water courses and to ensure that there is no accumulation of heavy metals in the top soil.



Cleanup options

Cleanup or environmental remediation is analyzed by environmental scientists who utilize field measurement of soil chemicals and also apply computer models (GIS in Environmental Contamination) for analyzing transport and fate of soil chemicals. Various technologies have been developed for remediation of oil-contaminated soil and sediments. There are several principal strategies for remediation:

- Excavate soil and take it to a disposal site away from ready pathways for human or sensitive ecosystem contact. This technique also applies to dredging of bay muds containing toxins.
- Aeration of soils at the contaminated site (with attendant risk of creating air pollution)
- Thermal remediation by introduction of heat to raise subsurface temperatures sufficiently high to volatize chemical contaminants out of the soil for vapor

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extraction. Technologies include ISTD, electrical resistance heating (ERH), and ET-DSP.

- Bioremediation, involving microbial digestion of certain organic chemicals. • Techniques used in bioremediation include landfarming, biostimulation and bioaugmentating soil biota with commercially available microflora.
- Extraction of groundwater or soil vapor with an active electromechanical with with subsequent stripping of the contaminants from the extract.
- Containment of the soil contaminants (such as by capping or paving over in place).
- Phytoremediation, or using plants (such as willow) to extract heavy metals.
- Mycoremediation, or using fungus to metabolize contaminants and accumulate • heavy metals.
- Remediation of oil contaminated sediments with self-collapsing • air microbubbles.
- Surfactant leaching

Visual pollution

Visual pollution is an aesthetic issue and refers to the impacts of pollution that impair one's ability to enjoy a pleasant view. Visual pollution disturbs the visual areas of people by creating harmful changes in the natural environment. Billboards, open storage of trash. antennas, electric wires, buildings. and automobiles often considered are visual pollution.

An overcrowding of an area causes visual pollution. Visual pollution is defined as the whole of irregular formations, which are mostly found in nature.

Effects of exposure to visual pollution include distraction, eye fatigue, decreases in opinion diversity, and loss of identity.^[3] It has also been



shown to increase biological stress responses and impair balance

Local managers of urban areas sometimes lack control over what is built and assembled in public places. As businesses look for ways to increase the profits, cleanliness, architecture, logic and use of space in urban areas are suffering from visual clutter.^[6] Variations in the built environment are determined by the location of street furniture such as public transport stations, garbage cans, large panels and stalls. Insensitivity of local administration is another cause for visual pollution. For

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example, poorly planned buildings and transportation systems create visual pollution. High-rise buildings, if not planned properly or sufficiently, can bring adverse change to the visual and physical characteristics of a city, which may reduce said city's readability.

A frequent criticism of advertising is that there is too much of it. Billboards, for example, have been alleged to distract drivers, corrupt public taste, promote meaningless and wasteful consumerism and clutter the land. See highway beautification. However, with the introduction of new communication technologies, the fragmentation and incentive nature of advertising methods will improve, reducing clutter. Thus, with the increase of mobile device usage, more money goes to advertising on social media websites and mobile apps. Vandalism, in the form of graffiti is defined as street markings, offensive, inappropriate, and tasteless messages made without the owner's consent. Graffiti adds to visual clutter as it disturbs the view.



Artificial tree to hide a mobile phone base station

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Graffiti



