Module 1: INTRODUCTION

Lecture	Topic	No. of Hours (10)
1	Introduction to Environmental Engineering	1
2	Environmental Acts and Rules	1
3	Standards for Ambient Air, Noise Emission and Effluents	1
4	Water Quality Monitoring: Collection of Water Samples & Estimation of Physical Parameters	1
5	Water Quality Monitoring: Estimation of Chemical Parameters	1
6	Water Quality Monitoring: Estimation of Alkalinity, BOD & COD	1
7	Water Quality Monitoring: Estimation of Fecal Indicator Bacteria	1
8	Characterization of Air Emissions	1
9	Fugitive Emission Control and Water Use Minimization	1
10	Water Recycling and Reuse	1

Lecture 1

Introduction to Environmental Engineering

MAIN OBJECTIVES OF THE COURSE

- To develop interest among Chemical Engineers regarding environment and its protection.
- To provide basic understanding of environmental engineering so that the Chemical Engineers may meet the expectation of the Industries for pollution control in their premises so as to comply with newer and tougher laws and acts that are being enforced in India and globally.
- To introduce the principles and methods to control air, water and soil pollution to the undergraduate students of chemical engineering.
- To develop basic understanding of following topics:
    - sources of water, air and land pollution
    - recycle and reuse of waste, energy recovery and waste utilization
    - air pollution and its measurement
    - design of pollution abatement systems for particulate matter and gaseous constituents
    - design of waste-water and industrial effluent treatment
    - hazardous waste treatment and disposal
    - solid-waste disposal and recovery of useful products.

ENVIRONMENTAL ENGINEERING

- According to Peavy et al. [1], it is that branch of engineering that is concerned with protecting the environment from the potentially deleterious effects of human activity, protecting human populations from the effects of adverse environmental actors and improving environmental quality for human health and well being [2].
- Environmental engineering is still an evolving branch of engineering that is closely related to Chemical and Civil engineering.
- It is closely associated with chemistry, physics and biology; and has elements of hydrology, meteorology, atmospheric sciences, environmental chemistry, microbiology and ecology.

ENVIRONMENTAL ETHICS AND EIA

- Traditionally, industries and its basic components were designed based upon technical and economic considerations only. Now-a-days, it is essential to consider environment, health and safety as factors during design [3].
- Environmental ethics is related to attitude of people towards other living beings and environment [4].
- During any project, though it is essential that ‘economic sustainability’ is attained; however, it is also essential that ‘ecological sustainability’ and ‘social sustainability’ are also attained.
- Impact assessment is a handy tool to assess the environmental compatibility of the projects in terms of their location, suitability of technology, efficiency in resources utilization and recycling, etc.
- Environmental Impact Assessment (EIA) has now been made a prerequisite for the settling up of new projects and renewal of licenses of old and existing plants.
- EIA is a major instrument in decision making and for measurement of sustainability in the context of the regional carrying capacity. It provides the conceptual framework for extending the cumulative assessment of development policies, plans and projects on a regional basis.
- Sustainable development of chemical process industries is a process in which the exploitation of resources and the direction of the investments are all made consistent with future as well as present heads.

POLLUTION DUE TO CHEMICAL PROCESS INDUSTRIES

The primary causes of industrial pollution are [5]:

- Use of outdated and inefficient technologies for product manufacturing, pollution abatement and various other operation in industries which generate a large amount of wastes
- Development of unplanned industrial conglomerations without foreseeing the effect on environment
- The existence of large number of small scale industries without defining land use patterns and environmental regulations for them
- Poor enforcement of pollution control laws for big and small industries

Major polluting industrial sectors

1) Cement
2) Thermal power plants
3) Iron & Steel
4) Fertilizer
5) Zinc Smelters
6) Copper Smelters
7) Aluminum Smelters
8) Oil Refineries
9) Distilleries
10) Pulp & Paper
11) Dyes and Dye Intermediates
12) Pesticides
13) Petro Chemicals
14) Petroleum refining
15) Sugar
16) Tanneries
17) Basic Drugs

Major Concerns of Industrial Pollution [6]

- Water and air pollution from chemical process industries need immediate attention.
- Industrial wastewaters vary widely in their composition and treatment methods, which have to take in to consideration the specific characteristic of the wastes.
- Many treatment practices have followed the approach of mixing the liquid sewage waste with industrial waste and treating the mixture by conventional methods.
- Treatment methods such as lagoon (aerobic & anaerobic), oxidation ditches and aerated lagoons have also been tried with varying degree of success. The majority of treatment plants have, however, failed to succeed. The chief reasons for this have been the omission of some of the key parameters that govern biological oxidation when industrial wastes are treated.
- Physico-chemical methods are necessary to remove or recover the chemical ingredients present in liquid effluents discharged from electroplating, chlor-alkali, pesticides, fertilizers, dyes and pigments, metallurgical, paper and pulp, etc. and other such process industries.
- The reuse of water in processes where the water quality standards are not stringent is worth considering. A considerable quantity of water is presently being reused in process industries in India but a lot more needs to be done in this area.

MAJOR DEFINITIONS AS PER INDIAN ENVIRONMENTAL ACTS [7]

- "**Environment**" includes water, air and land and the inter-relationship which exists among and between water, air and land and human beings, other living creatures, plants, micro-organism and property.
- "**Environmental pollutant**" means any solid, liquid or gaseous substance present in such concentration and may be, or tend to be, injurious to environment.
- "**Air pollutants**" means any solid, liquid or gaseous substance (including noise) present in the atmosphere in such concentration as may be or tend to be injurious to human being or other living creatures or plants or property or environment.
- "**Air pollution**" means the presence in the atmosphere of any air pollutant
- "**Ambient air**" means that portion of the atmosphere, external to buildings, to which the general public has access.

ENVIRONMENTAL CRISIS DUE TO INDUSTRIAL DEVELOPMENT

- Large scale contamination of water and air.
- Deforestation
- Increase in urban slums
- Generation of huge solid waste consisting of hazardous material.
- Water scarcity and ground water depletion.
- Global warming
- Greenhouse effect
- Ozone layer depletion

LIST OF PROJECTS OR ACTIVITIES REQUIRING PRIOR ENVIRONMENTAL CLEARANCE [8]

Table 1.1.1. Mining, extraction of natural resources and power generation (for a specified production capacity)

Sl. No.	**Project or Activity**	**Category with threshold limit**		**Conditions if any**
		A	**B**	
1(a)	Mining of minerals	≥ 50 ha. of mining lease area Asbestos mining irrespective of mining area	<50 ha ≥ 5 ha .of mining lease area.	General Condition shall apply Note Mineral prospecting (not involving drilling) are exempted provided the concession areas have got previous

				clearance for physical survey
1(b)	Offshore and onshore oil and gas exploration, development & production	All projects		Note Exploration Surveys (not involving drilling) are exempted provided the concession areas have got previous clearance for physical survey
1(c)	River Valley projects	(i) ≥ 50 MW hydroelectric power generation; (ii) ≥ 10,000 ha. of culturable command area	(i) < 50 MW ≥ 25 MW hydroelectric power generation; (ii) < 10,000 ha. of culturable command area	General Condition shall apply
1(d)	Thermal Power Plants	≥ 500 MW (coal/lignite/naphtha & gas based); ≥ 50 MW (Pet coke diesel and all other fuels)	< 500 MW (coal/lignite/naphtha & gas based); <50 MW ≥ 5MW (Pet coke ,diesel and all other fuels)	General Condition shall apply
1(e)	Nuclear power projects and processing of nuclear fuel	All projects	-	

Table 1.1.2. Primary Processing

Sl. No.	**Project or Activity**	**Category with threshold limit**		**Conditions if any**
		A	**B**	
2(a)	Coal washeries	≥ 1 million ton/annum throughput of coal	<1million ton/annum throughput of coal	General Condition shall apply (If located within mining area the proposal shall be appraised together with the mining proposal)
2 (b)	Mineral beneficiation	≥ 0.1million ton/annum mineral throughput	< 0.1million ton/annum mineral throughput	General Condition shall apply (Mining proposal with Mineral beneficiation shall be appraised together for grant of clearance)

Table 1.1.3. Materials Production

Sl. No.	**Project or Activity**	**Category with threshold limit**		**Conditions if any**
		A	**B**	

3(a)	Metallurgical industries (ferrous & non ferrous**)**	a) Primary metallurgical industry All projects b) Sponge iron manufacturing ≥ 200TPD c)Secondary metallurgical processing industry All toxic and heavy metal producing units ≥ 20,000 tonne/annum -	Sponge iron manufacturing <200TPD Secondary metallurgical processing industry i.) All toxic and heavy metal producing units <20,000 tonne /annum ii.) All other non –toxic secondary metallurgical processing industries >5000 tonne/annum	General Condition shall apply for Sponge iron manufacturing
3(b)	Cement plants	≥ 1.0 million tonne/annum production capacity	<1.0 million tonne/annum production capacity. All Stand alone grinding units	General Condition shall apply

Table 1.1.4. Materials Processing

Sl. No.	**Project or Activity**	**Category with threshold**	**limit**	**Conditions if any**
		A	**B**	
4(a)	Petroleum refining industry	All projects	-	-
4(b)	Coke oven plants	≥2,50,000 tonne/annum -	<2,50,000 & ≥25,000 tonne/annum	-
4(c)	Asbestos milling and asbestos based products	All projects	-	-
4(d)	Chlor-alkali industry	≥300 TPD production capacity or a unit located out side the notified industrial area/ estate	<300 TPD production capacity and located within a notified industrial area/ estate	Specific Condition shall apply No new Mercury Cell based plants will be permitted and existing units converting to membrane cell technology are exempted from this Notification
4(e)	Soda ash Industry	All projects	-	-
4(f)	Leather/skin/hide processing industry	New projects outside the industrial area or expansion of existing units out side the industrial area	All new or expansion of projects located within a notified industrial area/ estate	Specific condition shall apply

Table 1.1.5. Manufacturing/Fabrication

Sl. No.	**Project or Activity**	**Category with threshold**	**limit**	**Conditions if any**
		A	**B**	
5(a)	Chemical fertilizers	All projects	-	-
5(b)	Pesticides industry	All units producing	-	-

	and pesticide specific intermediates (excluding formulations)	technical grade pesticides		
5(c)	Petro-chemical complexes (industries based on processing of petroleum fractions & natural gas and/or reforming to aromatics)	All projects -	-	-
5(d)	Manmade fibres manufacturing	Rayon	Others	General Condition shall apply
5(e)	Petrochemical based processing (processes other than cracking & reformation and not covered under the complexes)	Located outside the notified industrial area/ estate -	Located in a notified industrial area/ estate	Specific Condition shall apply
5(f)	Synthetic organic chemicals industry (dyes & dye intermediates; bulk drugs and intermediates excluding drug formulations; synthetic rubbers; basic organic chemicals, other synthetic organic chemicals and chemical intermediates)	Located outside the notified industrial area/ estate	Located in a notified industrial area/ estate	Specific Condition shall apply
5(g)	Distilleries	(i)All Molasses based distilleries (ii) All Cane juice/ non-molasses based distilleries ≥30 KLD	All Cane juice/non-molasses based distilleries – <30 KLD	General Condition shall apply
5(h)	Integrated paint industry	-	All projects	General Condition shall apply
5(i)	Pulp & paper industry excluding manufacturing of paper from waste paper and manufacture of paper from ready pulp with out bleaching	Pulp manufacturing and Pulp& Paper manufacturing industry -	Paper manufacturing industry without pulp manufacturing	General Condition shall apply
5(j)	Sugar Industry	- -	≥ 5000 tcd cane crushing capacity	General Condition shall apply
5(k)	Induction/arc	-	All projects	General Condition

	furnaces/cupola furnaces 5TPH or more	-		shall apply

Table 1.1.6. Service Sectors

Sl. No.	**Project or Activity**	**Category with threshold limit**		**Conditions if any**
		A	**B**	
6(a)	Oil & gas transportation pipe line (crude and refinery/ petrochemical products), passing through national parks/sanctuaries/coral reefs/ecologically sensitive areas including LNG Terminal	All projects -		-
6(b)	Isolated storage & handling of hazardous chemicals (As per threshold planning quantity indicated in column 3 of schedule 2 & 3 of MSIHC Rules 1989 amended 2000)	-	All projects	General Condition shall apply

Table 1.1.7. Physical Infrastructure including Environmental Services

Sl. No.	**Project or Activity**	**Category with threshold limit**		**Conditions if any**
		A	**B**	
7(a)	Air ports	All projects		-
7(b)	All ship breaking yards including ship breaking units	All projects	-	-
7(c)	Industrial estates/ parks/ complexes/ areas, export processing Zones (EPZs), Special Economic Zones (SEZs), Biotech Parks, Leather Complexes.	If at least one industry in the proposed industrial estate falls under the Category A, entire industrial area shall be treated as Category A, irrespective of the area. Industrial estates with area greater than 500 ha. and housing at least one Category B industry.	-Industrial estates housing at least one Category B industry and area <500 ha. Industrial estates of area> 500 ha. and not housing any industry belonging to Category A or B.	Special condition shall apply Note: Industrial Estate of area below 500 ha. and not housing any industry of category A or B does not require clearance.
7(d)	Common hazardous waste treatment, storage and disposal facilities (TSDFs)	All integrated facilities having incineration &landfill or incineration alone	All facilities having land fill only	General Condition shall apply
7(e)	Ports, Harbours	≥ 5 million TPA of cargo handling capacity (excluding fishing harbours)	< 5 million TPA of cargo handling capacity and/or ports/ harbours ≥10,000 TPA of fish handling capacity	General Condition shall apply
7(f)	Highways	i) New National High ways; and	i) New State High ways; and	General Condition shall apply

		ii) Expansion of National High ways greater than 30 KM, involving additional right of way greater than 20m involving land acquisition and passing through more than one State.	ii) Expansion of National/ State Highways greater than 30 km involving additional right of way greater than 20m involving land acquisition.	
7(g)	Aerial ropeway		All projects	General Condition shall apply
7(h)	Common Effluent Treatment Plants (CETPs)		All projects	General Condition shall apply
7(i)	Common Municipal Solid Waste Management Facility (CMSWMF)		All projects	General Condition shall apply

Table 1.1.8. Building/Construction projects/Area Development projects and Townships

Sl. No.	**Project or Activity**	**Category with threshold limit**		**Conditions if any**
		A	**B**	
8(a)	Building and Construction projects		≥ 20000 m^2 and < 1,50,000 m^2 of built-up area#	#(built up area for covered construction; in the case of facilities open to the sky, it will be the activity area)
8(b)	Townships and Area Development projects.		Covering an area ≥ 50 ha and or built up area ≥1,50,000 m^2 ++	$^{++}$All projects under Item 8(b) shall be appraised as Category B1

Note:-

General Condition (GC): Any project or activity specified in Category 'B' will be treated as Category A, if located in whole or in part within 10 km from the boundary of: (i) Protected Areas notified under the Wild Life (Protection) Act, 1972, (ii) Critically Polluted areas as notified by the Central Pollution Control Board from time to time, (iii) Notified Eco-sensitive areas, (iv) inter-State boundaries and international boundaries.

Specific Condition (SC): If any Industrial Estate/Complex/ Export processing Zones/Special Economic Zones/Biotech Parks/ Leather Complex with homogeneous type of industries such as Items 4(d), 4(f), 5(e), 5(f), or those Industrial estates with pre –defined set of activities (not necessarily homogeneous, obtains prior environmental clearance, individual industries including proposed industrial housing within such estates/complexes will not be required to take prior environmental clearance, so long as the Terms and Conditions for the industrial estate/complex are complied with (Such estates/complexes must have a clearly identified management with the legal responsibility of ensuring adherence to the Terms and Conditions of prior environmental clearance, who may be held responsible for violation of the same throughout the life of the complex/estate).

REFERENCES

[1] Peavy, H. S., Rowe, D. R., Tchobanoglous, G. "Environmental Engineering", McGraw-Hill, 1985.

[2] http://faculty.kfupm.edu.sa/RI/suwailem/Standards/IFC%20general%20EHS%20Guidelines.pdf.

[3] Kiely, G. “Environmental Engineering”. McGraw-Hill, 1997.

[4] Vesiland, P. A., Peirce, J. J., Weiner, R. F. “Environmental Engineering”, Butterworth-Heinneman, Oxford, 3rd Ed., 1994.

[5] http://wmc.nic.in/chapter2-environmentalscenario.asp.

[6] Mahajan, S. P. “Pollution control in process industries”, Tata McGraw-Hill, 1985.

[7] Pollution Control Law Series: Pollution Control Acts, Rules and Notification Issued There under, Central Pollution Control Board, Ministry of Environment and Forest, Government of India. 2006.

[8] MoEF-EIA, Notification on EIA under under sub-rule (3) of Rule 5 of the Environment (Protection) Rules, 1986, Published on 14th September, 2006 http://moef.nic.in/legis/eia/so1533.pdf.

Lecture 2

Environmental Acts and Rules

AGENCIES FOR MAKING ENVIRONMENT LAWS & THEIR ENFORCEMENT IN INDIA

In 1972, a National Council of Environment Planning and Co-ordination was set-up at the Department of Science and Technology. Another committee was set-up in 1980 for reviewing the existing legislations and administrative machinery for environmental protection and for recommending ideas to strengthen the existing laws and environmental agencies in India. In 1980, a separate Department of Environment was set-up which was upgraded to full-fledged Ministry of Environment and Forests in 1985.

Ministry of Environment and Forests (MoEF) of Government of India serves as the nodal agency for the planning, promotion, making of environment laws and their enforcement in India. Following are the other important agencies which help the MoEF in carrying out environment related activities:

- Central Pollution Control Board
- State Pollution Control Boards
- State Departments of Environment
- Union Territories (UT) Environmental Committees
- The Forest Survey of India
- The Wildlife Institute of India
- The National Afforestation and Eco-development Board
- The Botanical and Zoological Survey of India, etc.

ENVIRONMENTAL LAWS AND RULES

Major environmental laws dealing with protection of environment can be dived into following categories **[1]**:

A. Water pollution
B. Air pollution
C. Environment protection
D. Public liability insurance
E. National environment appellate authority
F. National environment tribunal
G. Animal welfare
H. Wildlife
I. Forest conservation

J. Biodiversity
K. Indian forest service

Major acts, rules and notifications under each of the above categories are as given below:

A. WATER POLLUTION

i. **Acts**
   1. No.36 of 1977, [7/12/1977] - The Water (Prevention and Control of Pollution) Cess Act, 1977, amended 1992.
      1. No. 19 of 2003, [17/3/2003] - The Water (Prevention and Control of Pollution) Cess (Amendment) Act, 2003.
   2. No.6 of 1974, [23/3/1974] - The Water (Prevention and Control of Pollution) Act, 1974, amended 1988.

ii. **Rules**
   1. G.S.R.378(E), [24/7/1978] - The Water (Prevention and Control of Pollution) Cess Rules, 1978.
   2. G.S.R.58(E), [27/2/1975] - The Water (Prevention and Control of Pollution) Rules, 1975.
   3. Central Board for the Prevention and Control of Water Pollution (Procedure for Transaction of Business) Rules, 1975 amended 1976.

iii. **Notifications**
   1. S.O.498(E), [6/5/2003] - Date on which the Water (Prevention and Control of Pollution) Cess (Amendment) Act, 2003 (19 of 2003) came into force.
   2. S.O.499(E), [6/5/2003] - Rate of Cess notified under the Water (Prevention and Control of Pollution) Cess (Amendment) Act, 1977(36 of 1977).

B. AIR POLLUTION

i. **Act**
   1. No.14 of 1981, [29/3/1981] - The Air (Prevention and Control of Pollution) Act 1981, amended 1987.

ii. **Rules**
   1. G.S.R.6(E), [21/12/1983] - The Air (Prevention and Control of Pollution) (Union Territories) Rules, 1983.
   2. G.S.R.712(E), [18/11/1982] - The Air (Prevention and Control of Pollution) Rules, 1982.

iii. **Notifications**
   1. G.S.R.935(E), [14/10/1998] - Ambient Air Quality Standard for Ammonia (NH_3).
   2. G.S.R.382(E), [28/3/1988] - The Date on which the Air Amendment Act of 1987 came into force.

C. ENVIRONMENT PROTECTION

i. **Act**
   1. No.29 of 1986, [23/5/1986] - The Environment (Protection) Act, 1986, amended 1991.

ii. **Rules**
  1. S.O.844(E), [19/11/1986] - The Environment (Protection) Rules, 1986.
     1. G.S.R.448(E), [12/07/2004] - The Environment (Protection) Second Amendment Rules, 2004.
  2. S.O.470(E), [21/6/1999] - Environment (Siting for Industrial Projects) Rules, 1999.

iii. **Notifications**
  1. **Coastal Regulation Zone**
     1. S.O.991(E), [26/11/1998] - Constitution of National Coastal Zone Management Authority.
  2. **Delegation of Powers**
     1. S.O.729(E), [10/7/2002] - Delegation of Powers U/S 20 of E(P) Act, 1986 to CPCB.
  3. **Eco-marks Scheme**
     1. G.S.R.85(E), [20/2/1991] - The Scheme on Labeling of Environment Friendly Products (ECOMARK).
     2. G.S.R.768(E), [24/8/1992] - The criteria for labeling Cosmetics as Environment Friendly Products.

Eco-sensitive Zone
     1. S.O.133(E), [4/2/2003] - Matheran and surrounding region as an Eco-sensitive Zone.
     2. S.O.52(E), [17/1/2001] - Mahabaleswar Panchgani Region as an Eco-sensitive region.
     3. S.O.825(E), [17/9/1998] - Pachmarhi Region as an Eco-sensitive Zone.
     4. S.O.350(E), [13/5/1998] - Order Constituting the Taj Trapezium Zone Pollution (Prevention and Control) Authority.
     5. S.O.884(E), [19/12/1996] - Dahanu Taluka Environment Protection Authority, 1996, amended 2001.
     6. S.O.481(E), [5/7/1996] - No Development Zone at Numaligarh, East of Kaziranga.
     7. S.O.319(E), [7/5/1992] - Restricting certain activities causing Environmental Degradation at Aravalli Range.
     8. S.O.416(E), [20/6/1991] - Dahanu Taluka, District Thane (Maharashtra) to declare as Ecologically fragile Area, amended 1999.
     9. S.O.102(E), [1/2/1989] - Restricting location of industries, mining & other activities in Doon Valley (UP).
     10. S.O.20(E), [6/1/1989] - Prohibiting Industries in Murud-Janjira, Raigadh District, Maharashtra. .
  6. **Environmental Labs**
     1. S.O.728(E), [21/7/1987] - Recognization of Environmental Laboratories and Analysts.
  7. **Hazardous Substances Management Rules**
     1. S.O.432(E), [16/5/2001] - The Batteries (Management and Handling) Rules, 2001.
     2. S.O.908(E), [25/9/2000] - The Municipal Solid Wastes (Management and Handling) Rules, 2000.

3. S.O.705(E), [2/9/1999] - The Recycled Plastics Manufacture and Usage Rules, 1999.
    1. S.O.698(E), [17/6/2003] - The Recycled Plastics Manufacture and Usage (Amendment) Rules, 2003.
4. S.O.243(E), [26/3/1997] - Prohibition on the handling of Azodyes.
5. G.S.R.347(E), [1/8/1996] - The Chemical Accidents (Emergency Planning, Preparedness and Response) Rules, 1996.
6. G.S.R.1037(E), [5/12/1989] - The Rules for the Manufacture, Use, Import, Export and Storage of Hazardous micro-organisms Genetically engineered organisms or cells.
7. S.O.966(E), [27/11/1989] - The Manufacture, Storage and import of Hazardous Chemical Rules, 1989.
8. S.O.594(E), [28/7/1989] - The Hazardous Wastes (Management and Handling) Rules, 1989.
9. S.O.630(E), [20/7/1998] - The Bio-Medical Waste (Management and Handling) Rules, 1998.

Noise Pollution

1. S.O.123(E), [14/2/2000] - Noise Pollution (Regulation and Control) Rules, 2000.
    1. S.O.1088(E), [11/10/2002] - The Noise Pollution (Regulation and Control) (Amendment) Rules, 2002.
    2. S.O.1046(E), [22/11/2000] - The Noise Pollution (Regulation and Control) (Amendment) Rules, 2000.
2. Rules relating to Noise Pollution notified under Environment (Protection) Rules, 1986 are as under:
    1. G.S.R.520(E), [1/07/2003] - The Environment (Protection) Amendment Rules, 2003.
    2. G.S.R.849(E), [30/12/2002] - The Environment (Protection) Fourth Amendment Rules, 2002.

Ozone Layer Depletion

1. S.O.670(E), [19/7/2000] - The Ozone Depleting Substances (Regulation and Control) Rules, 2000.

D. PUBLIC LIABILITY INSURANCE

i. **Act**

1. No.6 of 1991, [22/1/1991] - The Public Liability Insurance Act, 1991, amended 1992.

ii. **Rule**

1. S.O.330(E), [15/5/l991] - The Public Liability Insurance Rules, 1991, amended 1993.

E. NATIONAL ENVIRONMENT APPELLATE AUTHORITY

i. **Act**

1. NO.22 of 1997, [26/3/1997] - The National Environment Appellate Authority Act, 1997.

F. NATIONAL ENVIRONMENT TRIBUNAL

i. **Act**
   1. No.27 of 1995, [17/6/1995] - The National Environment Tribunal Act, 1995.

G. ANIMAL WELFARE

i. **Act**
   1. No.59 of 1960 - The Prevention of Cruelty to Animals Act, 1960.

ii. **Rules**
   1. S.O.1256(E), [24/12/2001] - The Animal Birth Control (Dogs) Rules, 2001.
   2. S.O.267(E), [26/3/2001] - The Performing Animals (Registration) Rules, 2001.

iii. **Notification**
   1. G.S.R.619(E), [14/10/1998] - The Prevention of Cruelty to Animals (Restricted to Exhibit on Trained as a Performing Animals).

H. WILDLIFE

i. **Act**
   1. No. 16 of 2003, [17/1/2003] - The Wild Life (Protection) Amendment Act, 2002.
   2. The Indian Wildlife (Protection) Act, 1972, amended 1993.

ii. **Rules**
   1. S.O.1092(E), [22/9/2003] - The National Board for Wild Life Rules, 2003.
   2. S.O.445(E), [18/4/2003] - The Declaration of Wild Life Stock Rules, 2003.
   3. G.S.R.350(E), [18/4/1995] - The Wildlife (Specified Plant Stock Declaration) Central Rules, 1995.

iii. **Notifications**
   1. S.O.1093(E), [22/9/2003] - Constitution of the National Board for Wild Life.
   2. S.O.1091(E), [22/9/2003] - Coming into force of section 6 of the Wild Life (Protection) Amendment Act, 2002 (16 of 2003).
   3. S.O.446(E), [18/4/2003] - Delegation of Powers of section 58E of the Wild Life (Protection) Act, 1972 (53 of 1972).

iv. **Guideline**
   1. Guidelines for Appointment of Honorary Wildlife Wardens.

I. FOREST CONSERVATION

i. **Acts**
   1. Forest (Conservation) Act, 1980, amended 1988.
   2. The Indian Forest Act, 1927.

ii. **Rules**
   1. G.S.R.23(E) - Forest (Conservation) Rules, 2003.
   2. G.S.R.719 - Forest (Conservation) Rules, 1981, amended 1992.

iii. **Guidelines**
   1. No.5-5/86-FC, [25/11/1994] - Guidelines for diversion of forest lands for non-forest purpose under the Forest (Conservation) Act, 1980.

J. BIODIVERSITY

i. **Act**
   1. NO. 18 of 2003, [5/2/2003] - The Biological Diversity Act, 2002.
      i. S.O.753(E), [01/07/2004]- Coming in to force of sextions of the Biodiversity Act, 2002.
      ii. S.O.497 (E), [15/04/2004]- Appointment of non-official members on NBA from 1st October, 2003.
      iii. S.O.1147 (E)- Establishment of National Biodiversity Authority from 1st October, 2003.
      iv. S.O.1146 (E)- Bringing into force Sections 1 and 2; Sections 8 to 17; Sections 48,54,59,62,63,64 and 65 w.e.f. 1st October, 2003.

ii. **Rule**
   1. G.S.R.261 (E), [15/04/2004] - Biological Diversity Rules, 2004.

K. IFS (Indian Forest Service)

i. **Rule**
   1. NO.17011/03/200-IFS-II, [10/2/2001] - Rules for a competitive examination to be held by the UPSC for the IFS.

ii. **Notification**
   1. NO.A.12011/1/94-IFS-I, [14/12/2000] - Scheme for staffing posts included in the Central Deputation Reserve of the Indian Forest Service and other Forestry Posts similar in rank and status in certain other organizations under the Government of India.

DUTIES OF INDIAN CITIZEN

Legislations alone are not the remedy for environmental management, it is the responsibility of all the citizens to strive to protect the environment for the present and future generations since it is the fundamental duty of citizens to protect and conserve the environment as enshrined in our Constitution. Virtually, environmental legislation is essentially a social legislation since environmental degradation affects all of us. The criminal nature of pollution offences have to be viewed seriously. Environmental legislation provides the framework for punitive action against the offenders.

Conservation, recycle, and reuse are the current trends observed in the control of environmental pollution. Even though there may be law regarding these aspects scattered in different Acts of Indian legislation, there is a need for comprehensive Resource Conservation and Recovery Act today. It is not always necessary that Environmental degradation or danger should occur to implement the law. One should always take steps before such happenings.

The problem of environmental degradation is a complex one which requires multi-dimensional approach. There is dearth of environmental protection laws, but we need a firm hand to implement them. Environmental education can play an important role in negating the adverse impacts of pollution.

MAJOR ENVIRONMENTAL LAWS [1, 2, 3]

I. THE WATER (PREVENTION AND CONTROL OF POLLUTION) ACT, 1974

- This act provides for the prevention and control of water pollution and the maintenance or restoration of wholesomeness of water.
- As such, all human activities having a bearing on water quality are covered under this Act.
- Subject to the provisions in the Act, no person without the pervious consent of the State Pollution Control Board (SPCB) can establish any industry, operation or any treatment and disposal system or an extension or addition there to which is likely to discharge sewage or trade effluent into a stream or well sewer or on hand and have to apply to the SPCB concerned to obtain the 'consent to establish' as well as the 'consent to operate' the industry after establishment.

II. THE WATER (PREVENTION AND CONTROL OF POLLUTION) CESS ACT, 1977

- The main purpose of this Act is to levy and collect cess on water consumed by certain categories of industry specified in the schedule appended to the Act.
- The money thus collected is used by CPCB and SPCBs to prevent and control water pollution.

III. THE AIR (PREVENTION AND CONTROL OF POLLUTION) ACT, 1981

- The objective of the Air Act 1981 is to prevent, control and reduce air pollution including noise pollution.
- Under provisions of this Act, no person shall, without previous consent of the SPCB, establish or operate any industrial plant in air pollution control area the investor has to apply to the SPCB/Pollution Control Committee (PCB) to consent.
- No person operating any industrial plant shall emit any air pollution in excess of the standards laid down by the SPCB and have to comply with the stipulated conditions.

IV. THE ENVIRONMENT (PROTECTION) ACT, 1986

- This is an umbrella Act for the protection and improvement of environment and for matters connected, which provides that no person carrying on any industry, operation or process should discharge or emit or permit to discharged or emitted any environmental pollutant in excess of such standards as may be prescribed.

- Several rules relative to various aspects of management of hazardous chemicals, wastes, etc. have been notified. Under this Act, Central Govt. has rusticated, prohibited location of industries in different areas so as to safeguard the environment.
- Many standards for air emissions, discharge of effluent and noise have been evolved and notified.
- Subject to the provision of this Act, Central Govt. has the power to take all measures as it deemed necessary for the purpose of protection and improving the environment.
- Procedures, safeguards, prohibition and restriction on the handling of hazardous substances along with the prohibition and restriction on the location of industries in different areas have notified.

V. THE HAZARDOUS WASTES (MANAGEMENT AND HANDLING) RULES, 1989 & 2000.

- Hazardous wastes have been categories in 18 categories.
- Under this rule, project proponent handling hazardous waste must report to the concerned authorities regarding handling of wastes, obtain authorization for handling wastes, maintain proper records, file annual returns, label all packages, consignments etc., report any accident immediately in for report import-export of hazardous waste.
- MOEF notified the HW (M&H) Amendment Rules in January 6, 2000 (MOEF, 2000a). Under this rule, toxic chemicals, flammable chemicals and explosive have been redefined to be termed as ‘hazardous chemical’. As per new criteria, 684 hazardous chemicals.

VI. THE MANUFACTURE, STORAGE AND IMPORT OF HAZARDOUS CHEMICAL RULES, 1989 & 2000.

- Under these rules, project proponents of any kind of hazardous industry have to identify likely hazard and their anger potential. They also have to take adequate steps to prevent and limit the consequences of any accident at site.

- Material safety Data Sheets (MSDS) for all the chemicals in handling has to be prepared. Workers on site are required to be provided with information, training and necessary equipment to ensure their safety.
- Onsite Emergency Plan is to be prepared before initiating any activity at the site. Off-site Emergency Plan is to be prepared by the District Controller in close collaboration with the project proponents for any accident envisaged on site.
- The public in the vicinity of the plant should be informed of the nature major accident that may occur on site and Do’s and Don’ts to be followed in case of such an occurrence.
- Import of hazardous chemicals is to be reported to the concerned authority within 30 days from the data of import.
- MOEF made significant amendments in the MSIHC Rules, 1989 on January 20, 2000. Under new amendments, new schedule –I is incorporated with the increase in the number of hazardous chemicals.
- Renewal of authorization will be subject to submission of ‘Annual Returns’ for disposal of hazardous waste; reduction in the waste generated or recycled or reused; fulfillment of authorization conditions and remittance processing and analysis fee.
- State government as well as occupier or its association shall be responsible for the identification site for common waste disposal facility. Public hearing is also made mandatory to be conducted by the state government before notifying any common hazardous waste disposal site.
- Central/State government will provide guidance for the design, operation and closure of common waste facility/landfill site. It is mandatory to obtain prior approval from the SPCB for design and layout the proposed hazardous waste disposal facility.

VII. PUBLIC LIABILITY INSURANCE ACT, 1991.

- This Act, unique to India, on the owner the liability to immediate relief in respect of death or to any person or damage to any property resulting from an accident while handling hazardous any of the notified hazardous chemicals.
- This relief has to be provided on ‘no fault’ basis.
- The owner handling hazardous chemical has to take an insurance policy to meet this liability of an amount equal to its “Paid up capital” or up to Rs. 500 millions, whichever less. The policy has to be renewed every year.

- New undertaking will have to take this policy before starting their activity. The owner also has to pay an amount equal to its annual premium to the Central Government's Environment Chief Fund (ERF). The reimbursement of medical expenses up to Rs. 12,500/-. The liability of the insurance is tied to Rs. 50 million per accident up to Rs. 150 million per year or up to the tenure of the policy.
- Any claims process to this liability will be paid from the ERF. In case the award still exceeds, the remaining amount shall have to be met by the owner.
- The payment under the Act is only for the immediate relief; owners shall have to provide the compensation if any, arising out of legal proceeding.

VIII. THE NATIONAL ENVIRONMENT TRIBUNAL ACT, 1995.

- The National Environment Tribunal Act, 1995 is enacted to provide for strict liability for damages arising out of indents occurring during handling of hazardous substances and for establishment of National Environment Tribunal effective and expunction disposal of cases arising from such accidents, with a view to giving relief and compensation damages to person, and the environment.

IX. THE CHEMICAL ACCIDENTS (EMERGENCY PLANNING, PREPAREDNESS AND RESPONSE RULES, 1996.

- These rule provided a statutory backup for setting up of a Crisis Group in districts and states, which have Major Accident Hazard (MAH) installations for providing information to the public.
- The rules define the MAH installations, which include industrial activity, transport and isolated store at a site handing hazardous chemicals in quantities specified.
- As per the rules, GOI has constituted a Central Crisis Group (CCG) for the management of chemical accidents a set up an alert system.
- The Chief Secretaries of all the States have also constituted Standing State Crisis Groups (SSCG) to plan and response to chemical accidents in the state.
- The District Controller has to constitute District as Local Central Crisis Groups (DCG and LCG).

- The CCG is the apex body in the country to deal with and provide expert guidance for planning and handling major chemical accidents. It continuously monitors the post-accident saturation and suggests measures for prevention occurrence of such accidents.
- MOEF, GOI has published a state-wise list of experts and concerned officials. The is the apex body of the state chaired by the Chief Secretary Consisting of GOI officials, technical experts and industry representatives and deliberates on planning, preparedness and mitigation of chemical accidents to reduce the loss of life, property and ill-health.
- The SSCG reviews all the District off-site Emergency plants for its adequacy.
- District Collector is the Chairman of DCG serving as apex body at the district level. DCG will review all the on-Emergency plants prepared by the occupier of the MAH installations and conduct one full-scale of the off-cist Emergency plan at a site each year.
- These rules enable preparation of on and off- site emergency plans, updation and conduction of mock-drills.

X. THE BIOMEDICAL WASTES (MANAGEMENT AND HANDLING) RULES, 1998.

- The Biomedical Waste (Management and Handling) Rules, 1998 regulates the disposal of biomedical wastes including anatomical waste, blood, body fluids medicines, glass wares and animals wastes by the health care institution (i.e. nursing homes, clinics, dispensaries, veterinary institutions, animal houses pathological laboratories and banks etc. in the cities having population more than 30 Lakh or all the hospitals with bed strength more than 500.
- They are required to install and commission requisite facilities like incinerators, autoclaves, microwave system etc. the treatment of biomedical waste.
- All the persons handling such sides are required to obtain permission from the Appropriate Authority.
- Segregation of biomedical waste at source been made mandatory for all the institutions and organizations dealing with them. These rules make the generator of biomedical wastes liable to segregate, pack, store, transport, treat and dispose the biomedical waste in an environmentally sound manner.

XI. MUNICIPAL WASTES (PROCESS AND DISPOSAL) DRAFT RULES, 1999.

- Under these rules, municipal authority is made responsible for implementation of the provisions of these rules and for any in structural development for collection, storage, segregation transportation, processing and disposal of MSW and to comply with these rules.
- Annual report is to be submitted by Municipal authority in From-I to the District Magistrate/ Deputy Commissioner who shall have the power to enforce these rules. We shall be managed as per Schedule-II.
- Disposal of MSW shall be through landfill as per specifications and standards laid down in schedule-III.
- The standards for compost and disposal of treated leachate shall be followed by Municipal Authorities as per Schedule-IV.

XII. THE RECYCLED PLASTIC MANUFACTURE AND USAGE RULES, 1999.

- Under these rules, use of carry bags or containers made of recycled plastics for storing, carrying dispensing or packaging of foodstuffs is prohibited.
- Carry bags or containers made of plastics can be manufactured only when (i) virgin plastic in its natural shade or white is used and (ii) recycled plastic is used for purposes other than storing and packaging foodstuff using pigments and colorants as per IS: 9833: 1981.
- Recycling of plastics is to be undertaken strictly in accordance with the Bureau of Indian standards Specification IS: 14534: 1998 entitled “The Guideline for Recycling of Plastics”.
- Manufacture has to print on each packet of carry bags as ‘Made of Recycled Material’ or ‘Virgin Plastic’. The minimum thickness of carry bags should not be less than 20 microns.
- Finally, Plastic Industry Association through their member units has to undertake self-regulatory measures.

XIII. THE FLY ASH NOTIFICATION, 1999.

- The notification to conserve topsoil and prevent the dumping and disposal of fly ash discharged from coal or lignite based thermal power plants have been issued on September 14, 1999.
- Under these directives it is mandatory for every brick manufacture within a radius of 50 km from coal or lignite based thermal power plant to mix at least 25% of ash (fly ash/bottom ash/pond ash) with soil on weight-to-weight basis to manufacture clay bricks or tiles or blocks used in construction activities.
- Every coal or lignite based thermal power plant has to make available ash, for at least ten years from the date of publication of this notification, without any payment or any other consideration, for the purpose of manufacturing ash-based products.
- Every coal or lignite based thermal power plant commissioned subject to environmental condition stipulating the submission of an action plan has to achieve the same within 9 years (15 years for plants not covered by environmental clearance).
- As per the directive, Central and state Govt. Agencies, the State Electricity Boards, NTPC and the management of thermal power plants have to facilitate utilization of ash and ash-based products in their respective schedule of specifications.
- All the local authorities have also to specify in their respective building bye-laws and regulations about the use of ash and ash-based products.

XIV. THE BATTERIES (MANAGEMENT AND HANDLING (DRAFT) RULES, 2000.

- The MOEF issued the Batteries (M&H) (Draft) Rules, 2000 to control the hazard associated with backyard smelting and unauthorized reprocessing of lead acid batteries. The lead acid batteries are widely used automobiles such as cars, trucks, buses, two-wheelers and inverters.
- As per the provision, battery manufactures, importers, assemblers and re-conditioned have to collect old batteries on a one to one basis against the sale of new batteries.
- The batteries so collect have to be sent to recyclers, registered with MOEF for recycling them in eco-friendly manner, unless battery manufactures them have such recycling facilities.

- Registration is accorded by the MOEF to only those units, which have in place appropriate manufacturing technology, pollution prevention systems and suitable arrangements for waste disposal.
- Importers of new batteries, dealers as well as organization auctioning used batteries have been brought under the purview of these rules.
- Only those re-processors registered with MOEF would be able to participate in sale by auction or contract. As a result, middlemen and backyard smelters are debarred from participation in any auction within the country.
- Manufactures have to incorporate suitable provisions for buyback, in case of bulk sale of batteries by the manufacturers to bulk consumers.
- Recycling of ferrous metals such as lead and zinc helps to save energy vis-à-vis primary metal production and is environment-friendly if reprocessing is done with suitable arrangements for pollution a control and waste disposal. They also help conserving precious metal resources.

REFERENCES

[1] Pollution Control Law Series: Pollution Control Acts, Rules and Notification Issued There under, Central Pollution Control Board, Ministry of Environment and Forest, Government of India, 2006.

[2] www.moef.nic.in.

[3] www.moefroclko.org.

Lecture 3

Standards for ambient air, noise emission and effluents

NATIONAL AMBIENT AIR QUALITY STANDARDS

The notifications on National Ambient Air Quality Standards were published by the Central Pollution Control Board in the Gazette of India. Extraordinary vide notification No(s). S.O. 384(E), dated 11th April, 1994; S.O. 935(E), dated 14th October, 1998; and S.O. 217 in Part III section 4, dated 18th November, 2009 [1].

S. No.	Pollutant	Time Weighted Average	Concentration in Ambient Air		
			Industrial, Residential, Rural and Other Area	Ecologically Sensitive Area (notified by Central Government)	Methods of Measurement
1	Sulphur Dioxide (SO_2), µg/m^3	Annual*	50	20	• Improved West and Gaeke • Ultraviolet fluorescence
		24 h**	80	80	
2	Nitrogen Dioxide (NO_2), µg/m^3	Annual*	40	30	• Modified Jacob & Hochheiser (Na-Arsenite) • Chemiluminescence
		24 h**	80	80	
3	Particulate Matter (size less than 10 µm or PM_{10}, µg/m^3	Annual*	60	60	• Gravimetric • TOEM • Beta attenuation
		24 h**	100	100	
4	Particulate Matter (size less than 2.5 µm) or $PM_{2.5}$, µg/m^3	Annual*	40	40	• Gravimetric • TOEM • Beta attenuation
		24 h**	60	60	
5	Ozone (O_3), µg/m^3	8 h**	100	100	•UV photometric • Chemiluminescence Chemical Method
		1 h**	180	180	
6	Lead (Pb), µg/m^3	Annual*	0.50	0.50	• AAS/ICP method after sampling on EPM 2000 or equivalent filter paper • ED-XRF using Teflon filter
		24 h**	1.0	1.0	
7	Carbon Monoxide	8 h**	02	02	• Non Dispersive Infra Red

	(CO), mg/m^3	1 h**	04	04	(NDIR) spectroscopy
8	Ammonia (NH_3), µg/m^3	Annual*	100	100	• Chemiluminescence
		24 h**	400	400	• Indo-phenol blue method
9	Benzene (C_6H_6), µg/m^3	Annual*	05	05	• Gas chromatography based continuous analyzer • Adsorption and desorption followed by GC analysis
10	Benzo(α)Pyrene (BaP) - particulate phase only, ng/m^3	Annual*	01	01	• Solvent extraction followed by HPLC/GC analysis
11	Arsenic (As), ng/m^3	Annual*	06	06	• AAS/ICP method after sampling on EPM 2000 or equivalent filter paper
12	Nickel (Ni), ng/m^3	Annual*	20	20	• AAS/ICP method after sampling on EPM 2000 or equivalent filter paper

*Annual arithmetic mean of minimum 104 measurements in a year at a particular site taken twice a week 24 hourly at uniform intervals.

**24 hourly or 08 hourly or 01 hourly monitored values, as applicable, shall be complied with 98% of the time in a year. 2% of the time, they may exceed the limits but not on two consecutive days of monitoring.

Note: Whenever and wherever monitoring results on two consecutive days of monitoring exceed the limits specified above for the respective category, it shall be considered adequate reason to institute regular or continuous monitoring and further investigation.

GENERAL STANDARDS FOR DISCHARGE OF ENVIRONMENTAL POLLUTANTS

These standards shall be applicable for industries, operations or processes other than those industries, operations or process for which standards have been specified in Schedule of the Environment Protection Rules, 1989 [2]:

PART - A: EFFLUENTS

S. No.	Parameter	(a) Inland surface water	(b) Public sewers	(c) Land for irrigation	(d) Marine/ coastal areas
1	Color and odor	See 6 of Annexure-II		See 6 of Annexure-II	See 6 of Annexure-II
2	Suspended solids, mg/L, maximum	100	600	200	(a) For process wastewater: 100 (b) For cooling water effluent: 10 per cent above total suspended matter of influent.
3	Particle size of suspended solids	shall pass 850 micron IS Sieve	-	-	(a) Floatable solids, maximum 3 mm (b) Settleable solids, maximum 850 microns
4	pH value	5.5 to 9.0	5.5 to 9.0	5.5 to 9.0	5.5 to 9.0
5	Temperature	shall not exceed 5°C above the receiving water temperature			shall not exceed 5°C above the receiving water temperature
6	Oil and grease, mg/L, maximum	10	20	10	20
7	Total residual chlorine, mg/L, maximum	1.0	-	-	1.0
8	Ammonical nitrogen (as N), mg/L, maximum	50	50	-	50
9	Total kjeldahl nitrogen (as N), mg/L, maximum	100	-	-	100
10	Free ammonia (as NH_3), mg/L, maximum	5.0	-	-	5.0
11	Biochemical oxygen demand (3 days at 27°C), mg/L, maximum	30	350	100	100
12	Chemical oxygen demand, mg/L,	250	-	-	250

	maximum				
13	Arsenic (as As), mg/L, maximum	0.2	0.2	0.2	0.2
14	Mercury (as Hg), mg/L, maximum	0.01	0.01	-	0.01
15	Lead (as Pb), mg/L, maximum	0.1	1.0	-	2.0
16	Cadmium (as Cd), mg/L, maximum	2.0	1.0	-	2.0
17	Hexavalent chromium (as Cr^{6+}), mg/L, maximum	0.1	2.0	-	1.0
18	Total chromium (as Cr), mg/L, maximum	2.0	2.0	-	2.0
19	Copper (as Cu), mg/L, maximum	3.0	3.0	-	3.0
20	Zinc (as Zn), mg/L, maximum	5.0	15	-	15
21	Selenium (as Se), mg/L, maximum	0.05	0.05	-	0.05
22	Nickel (as Ni), mg/L, maximum	3.0	3.0	-	5.0
23	Cyanide (as CN), mg/L, maximum	0.2	2.0	0.2	0.2
24	Fluoride (as F), mg/L, maximum	2.0	15	-	15
25	Dissolved phosphates (as P), mg/L, maximum	5.0	-	-	-
26	Sulphide (as S), mg/L, maximum	2.0	-	-	5.0
27	Phenolic compounds (as C_6H_5OH), mg/L, maximum	1.0	5.0	-	5.0
28	Radioactive materials: (a) Alpha emitters micro curie, mg/L, maximum (b) Beta emitters micro curie, mg/L, maximum	10^{-7} 10^{-6}	10^{-7} 10^{-6}	10^{-8} 10^{-7}	10^{-7} 10^{-6}
29	Bio-assay test	90% survival of	90%	90% survival	90% survival of fish

		fish after 96 hours in 100% effluent	survival of fish after 96 hours in 100% effluent	of fish after 96 hours in 100% effluent	after 96 hours in 100% effluent
30	Manganese, mg/L, maximum	2	2	-	2
31	Iron (as Fe), mg/L, maximum	3	3	-	3
32	Vanadium (as V), mg/L, maximum	0.2	0.2	-	0.2
33	Nitrate Nitrogen, mg/L, maximum	10	-	-	20

PART - B: WASTEWATER GENERATION STANDARDS

S. No.	Industry	Quantum
1	Integrated Iron & Steel	16 m^3/tonne of finished steel
2	Sugar	0.4 m^3/tonne of cane crushed
3	Pulp & Paper Industries	
	(a) Large pulp & paper	
	(i) Pulp & paper	175 m^3/tonne of paper produced
	(ii) Viscose Staple Fibre	150 m^3/tonne of paper
	(iii) Viscose Filament Yarn	500 m^3/tonne of paper
	(b) Small pulp & paper	
	(i) Agro-residue based	150 m^3/tonne of paper produced
	(ii) Waste paper based	50 m^3/tonne of paper produced
4	Fermentation Industries	
	(a) Maltry	3.5 m^3/tonne of grain processed
	(b) Brewer	0.25 m^3/kL of beer produced
	(c) Distillery	12 m^3/kL of alcohol produced
5	Caustic Soda	
	(a) Membrane cell process	1 m^3/tonne of caustic soda produced excluding cooling tower blowdown
	(b) Mercury cell process	4 m^3/tonne of caustic soad produced (mercury bearing). 10% below down permitted for cooling tower
6	Textile Industries: Man-made fibre	
	(i) Nylon & Polyster	120 m^3/tonne of fibre produced

	(ii) Voscose Ryan	150 m^3/tonne of product
7	Tanneries	28 m^3/tonne of raw hide
8	Starch Glucose and related products	8 m^3/tonne of maize crushed
9	Dairy	3 m^3/kL of Milk
10	Natural rubber processing industry Fertilizer	4 m^3/tonne of rubber
11	Biochemical oxygen demand (3 days at 27°C), mg/L, max.	
	(a) Straight nitrogenous fertilizer	5 m^3/tonne of urea orequivalent produced
	(b) Straight phosphatic fertilizer (SSP & TSP) excluding manufacture of any acid	0.5 m^3/tonne of SSP/TSP
	(c) Complex fertilizer	Standards of nitrogenous and phospathic fertilizers are applicable depending on the primary product

PART-C: LOAD BASED STANDARDS

1. Petroleum Oil Refinery

S. No.	Parameter	Quantum in kg/1000 tonne of crude processed
1.	Oil & Grease	2.0
2.	BOD (3 days, 27°C)	6.0
3.	COD	50
4.	Suspended Solids	8.0
5.	Phenols	0.14
6.	Sulphides	0.2
7.	CN	0.08
8.	Ammonia as N	6.0
9.	TKN	16
10.	P	1.2
11.	Cr (Hexavalent)	0.04
12.	Cr(Total)	0.8
13.	Pb	0.04
14.	Hg	0.004
15.	Zn	2.0
16.	Ni	0.4
17.	Cu	0.4
18.	V	0.8
19.	Benzene	0.04
20.	Benzo (a) –Pyrene	0.08

2. Large Pulp & Paper, News Print/Rayon grade plants of capacity above 24,000 tonne/annum

S. No.	Parameter	Quantum
1.	Total Organic Chloride (TOCl)	2 kg/tonne of product

PART-D: CONCENTRATION BASED STANDARDS

1. General Emission Standards

S. No.	Parameter	Concentration not to exceed (in mg/Nm^3)
1.	Particulate matter (PM)	150
2.	Total fluoride	25
3	Asbestos	4 Fibres/cc and dust should not be more than 2 mg/Nm^3
4	Mercury	0.2
5	Chlorine	15
6	Hydrochloric acid vapour and mist	35
7	Sulphuric acid mist	50
8	Carbon monoxide	1%
9	Lead	10

2. Equipment based standards

For dispersion of sulphur dioxide; a minimum stack height limit is accordingly prescribed as below:

S. No.	Power generation capacity/ Steam generation capacity	Stack height (metre)
1.	Power generation capacity:	
	-500 MW and more	275
	-200/210 MW and above to less than 500 MW	220
	-Less than 200/210 MW	$H=14Q^{0.3}$
2.	Steam generation capacity	
	-Less than 2 tonne/h	9
	-2 to 5 tonne/h	12
	-5 to 10 tonne/hr	15
	-10 to 15 tonne/h	18
	-15 to 20 tonne/h	21
	-20 to 25 tonne/h	24
	-25 to 30 tonne/h	27
	-More than 30 tonne/h	30 or as per formula $H=14Q^{0.3}$ whichever is more

Note: H=Physical height of the stack in metre; Q=Emission rate of SO_2 in kg/h.

3. Load/Mass Based Standards

S. No.	Industry	Parameter	Standard
1	Fertilizer (urea)		
	-commissioned prior to 1.1.82	Particulate Matter	2 kg/tonne of product

	-commissioned after 1.1.82	Particulate Matter	0.5 kg/tonne of product
2	Copper, lead and zinc smelter	Sulphur dioxide	4 kg/tonne of concentrated (100%) acid produced
3	Nitric acid	Oxides of nitrogen	3 kg/tonne of weak acid (before concentration) produced
4	Sulphuric acid	Sulphur dioxide	4 kg/tonne of concentrated (100%) acid produced
5	Coke oven	Carbon monoxide	3 kg/tonne of coke produced
6	Oil Refineries		
	-Distillation (atmospheric+vacuum)	Sulphur dioxide	0.25 kg/tonne of feed in this process
	-Catalytic cracker	-do	0.25 kg/tonne of feed in this process
	-Sulphur recovery unit	-do-	120 kg/tonne of sulphur in the feed
7	Aluminum plants:		
	(i) Anode bake oven	Total fluoride	0.3 kg/tonne of Aluminum
	(ii) Pot room		
	(a) VSS	-do-	4.7 kg/tonne of Aluminum
	(b) HSS	-do-	6 kg/tonne of Aluminum
	(c) PBSW	-do-	2.5 kg/tonne of Aluminum
	(d) PBCW	-do-	1.0 kg/tonne of Aluminum
8	Glass industry		
	(a) Furnace capacity		
	(i) Up to the product draw capacity of 60 tonne/day	Particulate Matter	2 kg/h
	(ii) Product draw capacity more than 60 tonne/day	-do-	0.8 kg/tonne of product drawn

Note: VSS = vertical stud soderberg; HSS = horizontal stud soderberg; PBSW = pre backed side work; and PBCW = pre backed centre work

PART-E NOISE STANDARDS

A. Noise limits for automobiles (from at 7.5 meter in dB(A) at the manufacturing stage)

1.	Motorcycle, scooters & three wheelers	80
2.	Passenger cars	82
3.	Passenger or commercial vehicles upto 4 tonne	85
4.	Passenger or commercial vehicles above 4 tonne and upto 12 tonne	89
5.	Passenger or commercial vehicles exceeding 12 tonne	91

AA. Noise limits for vehicles at manufacturing stage

The test method to be followed shall be IS:3028-1998.

(1) Noise limits for vehicles applicable at manufacturing stage from the year 2003

S. No.	Type of vehicle	Noise limits dB(A)	Date of implementation
1.	**Two wheeler**		1st January, 2003
	Displacement upto 80 cm^3	75	
	Displacement between 80 cm^3 - 175 cm^3	77	
	Displacement more than 175 cm^3	80	
2.	**Three wheeler**		1st January, 2003
	Displacement upto 175 cm^3	77	
	Displacement more than 175 cm^3	80	
3.	**Passenger Car**	75	1stJanuary, 2003
4.	**Passenger or Commercial Vehicles**		1st July, 2003
	Gross vehicle weight upto 4 tonne	80	
	Gross vehicle weight more than 4 tonne but upto 12 tonne.	83	
	Gross vehicle weight more than 12 tonne.	85	

(2) Noise limits for vehicles at manufacturing stage applicable on and from 1st April, 2005

S. No.	Type of vehicles	Noise limits dB(A)
1.0	**Two wheelers**	
1.1	Displacement upto 80 cc	75
1.2	Displacement more than 80 cc but upto 175 cc	77
1.3	Displacement more than 175 cc	80
2.0	**Three wheelers**	
2.1	Displacement upto 175 cc	77
2.2	Displacement more than 175 cc	80
3.0	**Vehicles used for the carriage of passengers and capable of having not more than nine seats, including the driver's seat**	74
4.0	**Vehicles used for the carriage of passengers having more than nine seats, including the driver's seat, and a maximum Gross Vehicle Weight (GVW) of more than 3.5 tonne**	
4.1	With an engine power less than 150 KW	78
4.2	With an engine power of 150 KW or above.	80
5.0	**Vehicles used for the carriage of passengers having more than nine seats, including the driver's seat: vehicles used for the carriage of goods.**	
5.1	With a maximum GVW not exceeding 2 tonne	76
5.2	With a maximum GVW greater than 3 tonne but not exceeding 3.5 tonne	77
6.0	**Vehicles used for the transport of goods with a maximum GVW exceeding 3.5 tonne.**	
6.1	With an engine power less than 75 kW	77
6.2	With an engine power of 75 kW or above but less than 150 kW.	78
6.3	With an engine power of 150 kW or above.	80

B. Domestic appliances and construction equipments at the manufacturing stage to be achieved by 31st December, 1993.

1.	Window air conditioners of 1 -1.5 tonne	68
2.	Air coolers	60
3.	Refrigerators	46
4.	Compactors (rollers), front loaders, concrete mixers, cranes (movable), vibrators and saws	75

ANNEXURE-I (For the purpose of Parts-A, B and C)

The state boards shall fallow the following guidelines in enforcing the standards specified under Schedule IV.

1. The wastewater and gases are to be treated with the best available technology (BAT) in order to achieve the prescribed standards.
2. The industries need to be encouraged for recycling and reuse of waste materials as far as practicable in order to minimize the discharge of wastes into the environment.
3. The industries are to be encouraged for recovery of biogas, energy and reusable materials.
4. While permitting the discharge of effluents and emissions into the environment, State Boards have to be take into account the assimilative capacities of the receiving bodies, especially water bodies so that quality of the intended use of the receiving waters is not affected. Where such quality is likely to be affected, discharges should not be allowed into water bodies.
5. The central and state boards shall put emphasis on the implementation of clean technologies by the industries in order to increase fuel efficiency and reduce the generation of environmental pollutants.
6. All efforts should be made to remove color and unpleasant odor as far as practicable.
7. The standards mentioned in this Schedule shall also apply to all other effluents discharged such as mining, and mineral processing activities and sewage.
8. The limit given for the total concentration of mercury in the final effluent of caustic soda industry, is for the combined effluent from (a) cell house; (b) brine plant; (c) chlorine handling; (d) hydrogen handling; and (e) hydrochloric acid plant.
9. All effluents discharged including from the industries such as cotton textile, composite woolen mills, synthetic rubber, small pulp & paper, natural rubber, petrochemicals, tanneries, paint, dyes, slaughter houses, food & fruit processing and dairy industries into surface waters shall conform to the BOD limit specified above, namely, 30 mg/L. For discharge of an effluent having a BOD more than 30 mg/L, the standards shall conform to those given above for other receiving bodies, namely, sewers, coastal waters and land for irrigation.
10. Bio-assay shall be made compulsory for all the industries, where toxic and non biodegradable chemicals are involved.
11. In case of fertilizer industry, the limits in respect of chromium and fluoride shall be complied with at the outlet of chromium and fluoride removal units respectively.
12. In case of pesticides.
    a. The limits should be complied with at the end of the treatment plant before dilution.
    b. Bio-assay test should be carried out with the available species of fish in the receiving water, the COD limits to be specified in the consent conditions should be correlated with the BOD limits.
    c. In case metabolites and isomers of the pesticides in the given list are found in

    significant concentrations, standards should be prescribed for these also in the same concentration as the individual pesticides.
    d. Industries are required to analyze pesticides in wastewater by advanced analytical methods such as GLC/HPLC.

13. The chemical oxygen demand (COD) concentration in a treated effluent, if observed to be persistently greater than 250 mg/L before disposal to any receiving body (public sewer, land for irrigation, inland surface water and marine coastal areas), such industrial units are required to identify chemicals causing the same. In case these are found to be toxic as defined in the Schedule - I of the Hazardous Rules, 1989, the state boards in such cases shall direct the industries to install tertiary treatment stipulating time limit.
14. Standards specified in Part A of Schedule - VI for discharge of effluents into the public sewer shall be applicable only if such sewer leads to a secondary treatment including biological treatment system otherwise the discharge into sewers shall be treated as discharge into inland surface waters.

REFERENCES

[1] http://www.cpcb.nic.in/upload/Latest/Latest_48_FINAL_AIR_STANDARD.pdf.

[2] http://cpcb.nic.in/GeneralStandards.pd

Lecture 4

Water Quality Monitoring: Collection of water samples & estimation of physical parameters

WATER QUALITY MONITORING

It is essential for devising water quality management programme to properly use water in any project. It gives information for following decisions to be taken [1]:

- Helps in identifying the present and future problems of water pollution.
- Identifying the present resources of water as per various usages.
- It helps in developing plans and setting priorities for water quality management programme so as to meet future water requirements.
- It helps in evaluating the effectiveness of present management actions being taken and devising future course of actions.

COLLECTION OF WATER SAMPLES

For physical examination, water can be collected in fully cleaned ordinary buckets or plastic cans. If the water is to be collected for chemicals tests, the container, usually glass bottles of more than 2 liter capacity should be thoroughly washed and cleaned; and then the water should be collected in it.

For the collection of water for bacteriological tests, the person who collects the water must be free from any disease. The containers and bottles must be cleaned with sulphuric acid, potassium dichromate or alkaline permanganate, and then, they should be thoroughly rinsed with distilled water and finally sterilization should be done. Immediately after collection of the samples, bottles should be closed and covered with clot to prevent accumulation of dirt, etc. The testing of water samples should be done as early as possible.

Following points should be kept in view while collecting the samples:

(i) If the water is to be collected from a tap or faucet, sufficient quantity of wastewater should be allowed to pass through the tap, before collecting sample from because it will eliminate the stagnant water.

(ii) If the water is to be collected from the surface stream or river, it should be collected about 40-50 cm below the surface to avoid the collection of surface impurities oils, tree leaves, etc. which should also removed by strainers while collecting the water through intakes.

(iii) In case the water is being collected from the ground sources i.e. through well or tube well, sufficient quantity of water should be pumped out before collecting the samples.

Table 1.4.1. Principal constituents of concern in wastewater treatment [2, 3].

Constituent	**Importance**
Suspended solids	Lead to sludge deposits and development of anaerobic conditions
Biodegradable organics	Depletion of natural oxygen and to the development of septic condition; Composed principally of proteins, carbohydrates, fats, biodegradable organics, etc.; Measured in terms of biochemical oxygen demand (BOD) and chemical oxygen demand (COD).
Pathogens	Communicable diseases
Nutrients	Nitrogen and phosphorus are principal limiting nutrients for growth; Cause eutrophication in lakes & ponds.
Heavy metals	Added wastewater from commercial and industrial activities; Many of the metals are highly toxic at small concentration also.
Priority pollutants	Organic and inorganic compounds having known or suspected carcinogenicity, mutagenicity, teratogenicity and/or high acute toxicity.
Refractory organics	Organic compounds like surfactants, phenols and agricultural pesticides, etc. resist conventional method of wastewater treatment.
Dissolved inorganics	Inorganic constituents such as calcium, sodium and sulphates are added to the original domestic water supply as a result of water use and may have to be removed if the wastewater is to be reused.

PHYSICAL PARAMETERS

The physical tests include the following tests:

Temperature: The temperature of water is measured by means of ordinary thermometers. Density, viscosity, vapor pressure and surface tension of water are all dependent upon the temperature. The saturation values of solids and gases that can be dissolved in water and the rates of chemical, biochemical and biological activity are also determined on the basis of temperature.

The temperature of surface water is generally same as the atmospheric temperature while that of ground water may be more or less than atmospheric temperature.

Color: The color of water is usually due to presence of organic matter in colloid condition, and due to the presence of mineral and dissolved organic and inorganic impurities. Transparent water with a low accumulation of dissolved materials appears blue. Dissolved organic matter such as humus, peat or decaying plant matter, etc. produce a yellow or brown color. Some algae or dinoflagellates produce reddish or deep yellow waters. Water rich in phytoplankton and other algae usually appears green. Soil runoff water has a variety of yellow, red, brown and gray colors [4, 5].

The color in water is not harmful but it is objectionable. The color of a water sample can be reported as Apparent or True color. *Apparent color* is the color of the whole water sample and consists of color from both dissolved and suspended components. *True color* is measured after filtering the water sample to remove all suspended material.

Before testing the color of the water, first of all total suspended matter should removed from the water by centrifugal force in a special apparatus. After this, the color the water is compared with standard color solution or color discs. When multicolored industrial wastes are involved, such color measurement is meaningless.

The color produced by one milligram of platinum in a litre of distilled water has been fixed as the unit of color.

Turbidity: It is caused due to presence of suspended and colloidal matter in the water. Ground waters are generally less turbid than the surface water. The character and amount of turbidity depends on the type of soil over which the water has moved.

Turbidity is a measure of the resistance of water to the passage of light through it. Turbidity is expressed in parts per million (ppm or milligrams per litre or mg/1). Earlier, the turbidity produced by one milligram of silica in one litre of distilled water was considered as the unit of turbidity.

Turbidity was previously determined by Jackson candle Turbidity units (JTU). This unit is now replaced by more appropriate unit called Nephelometric Turbidity unit (NTU) which is the turbidity produced by one milligram of formazin polymer in one litre of distilled water.

Nephelometry method has better sensitivity, precision and applicability over a wide range of particle size and concentrations as compared to older methods [6].

Tastes and odors: Tastes and odors in water are due to the presence of (i) dead or living micro-organisms; (ii) dissolved gases such as hydrogen sulphide, methane, carbon dioxide or oxygen combined with organic matter; (iii) mineral substances such as sodium chloride, iron compounds; and (iv) carbonates and sulphates.

The odor of water also changes with temperature. The odor may be classified as sweetish, vegetable, greasy, etc. The odor of both cold and hot water should be determined.

The intensities of the odors are measured in terms of threshold odor number (TON). TON indicates how many dilutions it takes to produce odor-free water. In this method, enough odor-free water is added to the flasks containing different amount of sample to create a total volume of 200 mL.

$$TON = \frac{A+B}{A} = \frac{200\text{ ml}}{\text{Sample volume (mL)}} \tag{1.4.1}$$

Where, A is the volume of sample water and B is the volume of odor-free water added to make 200 mL of total water.

Specific conductivity of water: The total amount of dissolved salts present in water can be estimated by measuring the specific conductivity of water. The specific conductivity of water is determined by means of a portable ionic water tester and is expressed as micro-mho per cm at 25°C. ‘mho’ is the unit of conductivity and it equals to 1 Ampere per volt. The specific conductivity of water in micro mho per cm at 25°C is multiplied by a coefficient generally 0.65 so as to directly obtain the dissolved salt content in mg/L or ppm. The actual value of this coefficient depends upon the type of salt present in water.

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[4] http://kolkata.wb.nic.in/environment/html/Ministry%20of%20Environment%20and%20Forests.htm.

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Lecture 5

Water Quality Monitoring: Estimation of Chemical parameters

CHEMICAL PARAMETERS

Solids: Total solids include suspended and dissolved solids. Amount of *total solids* in a water sample can be determined by evaporating the water and weighing the residue. Amount of *suspended solids* is determined by filtering the sample of water through filter paper, followed by drying the filter paper and weighing the solids. The quantity of *dissolved solids* including the colloidal solids is determined evaporating the filtered water (obtained from the suspended solid test) and weighing the residue [1].

Total solids can also be considered as the sum of organic and inorganic solids. Amount of *inorganic solids* can be determined by fusing the residue of total solids in a muffle-furnace and weighing the fused residue. Amount of *organic solids* is the difference between the amount of inorganic and total solid.

Hardness: Hardness of water is due to the presence of carbonates and sulphates of calcium and magnesium ions in the water. Sometimes hardness in the water can also be caused by the presence of chlorides and nitrates of calcium and magnesium.

Presence of hardness in water prevents the lathering of the soap during cleaning of clothes, etc.

Hardness is usually expressed in mg of calcium carbonate per litre of water. Hardness is generally determined by Versenate Method. In this method, the water is titrated against EDTA salt solution using Eriochrome Black T as indicator solution. While titrating, color changes from wine red to blue. In general, under a normal range of pH values, water with hardness up to 75 mg/L are considered as soft and those with 200 mg/L and above are considered as hard. In between, the water is considered as moderately hard. Underground water is generally harder than the surface water, as they have more opportunity to come in contact with minerals.

For boiler feed water and for efficient cloth washing, etc., the water must be soft. However, for drinking purposes, water with hardness below 75 mg/L is generally tasteless and hence, the prescribed hardness limit for drinking ranges between 75 to 150 mg/L.

Chlorides: Sodium chloride is the main substance in chloride water. The natural water near the mines and sea has dissolved sodium chloride. Similarly, the presence of chlorides may be due to the mixing of saline water and sewage in the water. Excess of chlorides is considered as dangerous and makes the water unfit for many uses.

Chloride content is determined by titrating the wastewater with silver nitrate and potassium chromate. Appearance of reddish color confirms presence of chlorides in water.

Chlorine: Dissolved free chlorine is never found in natural waters. It is present in the treated water resulting from disinfection with chlorine. The chlorine remains as residual in treated water for the sake of safety against pathogenic bacteria.

Residual chlorine is determined by the starch-iodide test. In starch-iodide test, potassium iodide and starch solutions are added to the sample of water due to which blue color is formed. This blue color is then removed by titrating with sodium thiosuplhate solution, and the quantity of chloride is calculated. On the addition of ortho-iodine solution if yellow color is formed, it indicates the presence of residual chlorine in the water. The intensity of this yellow color is compared with standard colors to determine the quantity of residual chlorine.

The residual chlorine should remain between 0.5 to 0.2 mg/L in the water so that it remains safe against pathogenic bacteria.

Iron and Manganese: These are generally found in ground water. The presence of iron and manganese in water makes it brownish red in color. Presence of these elements leads to the growth of micro-organism and corrodes the water pipes. Iron and manganese also causes taste and odor in the water. The quantity of iron and manganese is determined by colorimetric methods.

pH: pH value is the logarithm of reciprocal of hydrogen ion activity in moles per liter. Depending upon the nature of dissolved salts and minerals, water may be acidic or alkaline. When acids or alkalis are dissolved in water, they dissociate into electrically charged hydrogen and hydroxyl radicals, respectively. Dissolved gases such as carbon dioxide, hydrogen sulphide and ammonia also affect the pH of water [2]. pH of natural water is generally in the range of 6-8. Industrial wastes may be strongly acidic or basic and their effect on pH value of receiving water depends on the buffering capacity of receiving water. pH lower than 4 have sour taste and above 8.5 have bitter taste. At pH below 6.5, corrosion starts to occur in pipes [3].

Lead and Arsenic: These are not usually found in natural waters. But sometimes lead is mixed up in water from lead pipes or from tanks lined with lead paint when water moves through them. These are poisonous and dangerous to the health of public. The presence of lead and arsenic is detected by means of chemical tests.

Dissolved Gases: Oxygen and carbon dioxide gases are found in the natural waters of all types. In addition, water may contain some amount of hydrogen sulphide and ammonia depending upon the pH and anaerobic/aerobic condition of water.

Surface water absorbs oxygen from the atmosphere. Algae and other tiny plant life of water also give oxygen to the water. Dissolved oxygen is necessary for sustenance of aquatic life in water and to keep it fresh. The water absorbs carbon dioxide from the atmosphere. Calcium and magnesium salts get converted into bicarbonates in presence of carbon dioxide and cause hardness in the water. The presence of carbon dioxide can easily determined by mixing the lime solution in the water.

Nitrogen: Nitrogen may be present in the water in the form of nitrites, nitrates, free ammonia, and albuminoidal nitrogen. The presence of nitrogen in the water indicates the presence of organic maters in the water.

The presence of the nitrites in the water, due to partly oxidized organic matters, is very dangerous. Therefore, in no case nitrites should be allowed in the water.

The nitrites are rapidly and easily converted to nitrates by the full oxidation of the organic matters. The presence of nitrates is not so harmful. But nitrates > 45 mg/L can cause “mathemoglobinemia” disease to the children.

Free ammonia is obtained from the decomposition of organic matters in the beginning, therefore if free ammonia is present in the water, it will indicate that the decomposition of the organic matters has started recently. The presence of nitrites indicates partial decomposition of organic matters, whereas the presence of nitrates indicates fully oxidized matters.

Metals and other chemical substances: Water contains various types of minerals and metals such as iron, manganese, copper, lead barium, cadmium, selenium, fluoride, arsenic, etc.

Arsenic, selenium are poisonous, therefore they must be removed totally. Human lungs are affected by the presence of high quantity of copper in the water. Fewer cavities in the teeth will be formed due to excessive presence of fluoride in water.

The quantity of the metals and other substances can be done indirectly by colorimetric methods using UV-visible spectrophotometer or directly by the use of sophisticated instruments such as Atomic Absorption Spectrophotometer (AAS), Atomic Emission Spectrophotometer (AES), Inductively Coupled Mass Spectrophotometer (ICP-MS), etc.

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[2] http://www.cpcb.nic.in/GeneralStandards.pdf.

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Lecture 6

Water Quality Monitoring: Estimation of alkalinity, BOD & COD

ALKALINITY (A_T)

- Alkalinity is a measure of the ability of a solution to neutralize acids to the equivalence point of carbonate or bicarbonate. It is the water's ability to absorb hydrogen ions without significant pH change. Alkalinity is a measure of the buffering capacity of water.
- Alkalinity is equal to the stoichiometric sum of the bases in solution.
- In natural environment, carbonate alkalinity makes up most of the total alkalinity due to the common occurrence and dissolution of carbonate rocks and presence of carbon dioxide in the atmosphere.
- Other natural components that contribute to alkalinity include hydroxide, borate, phosphate, silicate, nitrate, dissolved ammonia, conjugate bases of some organic acids and sulfide.
- Alkalinity is usually expressed in meq/L (milliequivalent per liter).

$$\text{Alkalinity}(\text{mol/L}) = \left[\text{HCO}_3^-\right] + 2\left[\text{CO}_3^-\right] + \left[\text{OH}^-\right] - \left[\text{H}^+\right] \qquad (1.6.1)$$

Where the quantities in parenthesis are concentrations in meq/L or mg/L as $CaCO_3$.

$$(\text{mg/L})\ \text{of X as CaCO}_3 = \frac{\text{Concentration of X}(\text{mg/L}) \times 50\ \text{mg CaCO}_3/\text{meq}}{\text{Equivalent weight of X}(\text{mg/meq})} \qquad (1.6.2)$$

BIOCHEMICAL OXYGEN DEMAND (BOD)

- Biochemical Oxygen Demand (BOD) is a chemical procedure for determining how fast biological organisms use up oxygen in a body of water.
- It is used in water quality management and assessment, ecology and environmental science.
- BOD is not an accurate quantitative test, although it is considered as an indication of the quality of a water source.
- It is most commonly expressed in milligrams of oxygen consumed per litre of sample during 5 days of incubation at 20 °C or 3 days of incubation at 27 °C.
- The BOD test must be inhibited to prevent oxidation of ammonia. If the inhibitor is not added, the BOD will be between 10% and 40% higher than can be accounted for by carbonaceous oxidation [1].

Stages of Decomposition in the BOD test

- There are two stages of decomposition in the BOD test: a carbonaceous stage and a nitrogenous stage.

- The carbonaceous stage represents oxygen demand involved in the conversion of organic carbon to carbon dioxide.
- The second stage or the nitrogenous stage represents a combined carbonaceous plus nitrogenous demand, when organic nitrogen, ammonia and nitrite are converted to nitrate. Nitrogenous oxygen demand generally begins after about 6 days.
- Under some conditions, if ammonia, nitrite, and nitrifying bacteria are present, nitrification can occur in less than 5 days. In this case, a chemical compound that prevents nitrification is added to the sample if the intent is to measure only the carbonaceous demand. The results are reported as carbonaceous BOD (CBOD) or as $CBOD_5$ when a nitrification inhibitor is used.

BOD – Dilution Method: BOD is the amount of oxygen (Dissolved Oxygen (DO)) required for the biological decomposition of organic matter. The oxygen consumed is related to the amount of biodegradable organics.

When organic substances are broken down in water, oxygen is consumed

Organic Carbon + $O_2 \rightarrow CO_2$

Where, organic carbon in human waste includes protein, carbohydrates, fats, etc.

Measure of BOD = Initial oxygen- Final Oxygen after (5 days at 20 °C) or (3 days at 27 °C)

Two standard 300 mL BOD bottles are filled completely with wastewater. The bottles are sealed. Oxygen content (DO) of one bottle is determined immediately. The other bottle is incubated at 20 ^{o}C for 5 days or (or at 27 °C for 3 days) in total darkness to prevent algal growth. After which its oxygen content is again measured. The difference between the two DO values is the amount of oxygen consumed by micro-organisms during 5 days and is reported as BOD_5.

Since the saturated value of DO for water at 20 ^{o}C is 9.1 mg/L only and that the oxygen demand for wastewater may be of the order of several hundred mg/L, therefore, wastewater are generally diluted so that the final DO in BOD test is always ≥ 2 mg/L. Precaution is also taken so as to obtain at least 2 mg/L change in DO between initial and final values.

$$BOD_5 = \frac{(DO_i - DO_f)}{P} \qquad (1.6.3)$$

Where, DO_i and DO_f are initial and final DO concentrations of the diluted sample, respectively. P is called as dilution factor and it is the ratio of sample volume (volume of wastewater) to total volume (wastewater plus dilution water). In the above formula, it was assumed that the diluted wastewater had no oxygen demand of itself and that the dilution wastewater used was pure.

Most of the times, microorganisms are added in the dilution water (seeded water) so as to have enough microorganisms for carrying out biodegradation of organic waste. In this case, the oxygen demand of seeded water is subtracted from the demand of mixed sample of waste and dilution water. In this case,

$$\mathrm{BOD_5} = \frac{[(\mathrm{DO_i} - \mathrm{DO_f})\text{-}(\mathrm{B_i} - \mathrm{B_f})(1 - \mathrm{P})]}{\mathrm{P}} \tag{1.6.4}$$

Where, B_i and B_f are initial and final DO concentrations of the seeded diluted water (blank).

Modeling BOD as first order reaction

Assuming that the rate of decomposition of organic waste is proportional to the waste left in the flask:

$$\frac{dL_t}{dt} = -kL_t \tag{1.6.5}$$

Where, L_t is the amount of oxygen demand left after time t and k is the BOD rate constant (time^{-1}). Solving this equation yields

$$L_t = L_o e^{-kt} \tag{1.6.6}$$

Where, L_o is the ultimate carbonaceous oxygen demand and it is also the amount of O_2 demand left initially (at time 0, no DO demand has been exerted, so BOD = 0)

At any time, $L_o = BOD_t + L_t$ (that is the amount of DO demand used up and the amount of DO that could be used up eventually). Assuming that DO depletion is first order:

$$\mathrm{BOD_t} = \mathrm{L_o}\left(1 - \mathrm{e}^{-\mathrm{kt}}\right) \tag{1.6.7}$$

As temperature increases, metabolism increases, utilization of DO also increases, therefore, k is a function of temperature (T in ^{o}C). k at any temperature T (^{o}C) is obtained as:

$$\mathrm{k_T} = \mathrm{k_{20}}\left(\theta\right)^{\mathrm{T}-20} \tag{1.6.8}$$

Where, k_{20} is the value of k at 20^{o}C and θ is an empirical constant. θ = 1.135 if T is between 4 - 20 ^{o}C; θ = 1.056 if T is between 20 - 30 ^{o}C.

CHEMICAL OXYGEN DEMAND (COD)

This test is carried out on the sewage to determine the extent of readily oxidizable organic matter, which is of two types:

a. Organic matter which can be biologically oxidized is called biologically active
b. Organic matter which cannot be oxidized biologically is called biologically inactive.

COD gives the oxygen required for the complete oxidation of both biodegradable and non-biodegradable matter.

- COD is a measure of the oxygen equivalent of the organic matter content of a sample that is susceptible to oxidation by a strong chemical oxidant.
- It is an indirect method to measure the amount of organic compounds in water.
- It is expressed in milligrams per liter (mg/L), which indicates the mass of oxygen consumed per liter of solution.

Analytical Procedure

$$\text{Organic C} + Cr_2O_7^{-} \longrightarrow CO_2 + H_2O + Cr_2O_4^{2-} \qquad (1.6.9)$$

- A sample is refluxed in strongly acidic solution with a known excess of potassium dichromate ($K_2Cr_2O_7$) for 2-3 h.
- After digestion, the remaining unreduced $K_2Cr_2O_7$ is titrated with ferrous ammonium sulphate to determine the amount of $K_2Cr_2O_7$ consumed.
- Then, the oxidizable matter is calculated in terms of oxygen equivalent.
- This procedure is applicable to COD values between 40 and 400 mg/L.

Essential differences between BOD and COD [1]

- COD always oxidize things that the BOD cannot or will not measure; therefore, COD is always higher than the BOD. The common compounds which cause COD to be higher than BOD include sulfides, sulfites, thiosulfates and chlorides.
- The general relationship between BOD and COD for sewage and most human wastes is about 1 unit of BOD≈0.64–0.68 units of COD. The relationship is not consistent and it may vary considerably for industrial wastewaters.

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Lecture 7

Water Quality Monitoring: Estimation of fecal indicator bacteria

FECAL INDICATOR BACTERIA

Fecal indicator bacteria, which are directly associated with fecal contamination, are used to detect the possible presence of waterborne pathogens by assessing the microbiological quality of water.

- Fecal material from warm-blooded animals may contain a variety of intestinal microorganisms (viruses, bacteria, and protozoa) that are pathogenic to humans. For example, bacterial pathogens of the *Salmonella*, *Shigella* and *Vibrio* can result in gastroenteritis and bacillary dysentery, typhoid fever, cholera, etc.
- The presence of *E. coli* in water is direct evidence of fecal contamination from warm-blooded animals.
- A few strains of E. coli are pathogenic, such as *E. coli* O157:H7, but most strains are not.
- Densities of other indicator bacteria (total coliforms, fecal coliforms, and fecal *streptococci*) can be, but are not necessarily, associated with fecal contamination.
- Despite this limitation, total coliforms are used to indicate ground-water susceptibility to fecal contamination. Fecal coliforms also are used as a measure of water safety for body-contact recreation or for consumption [1].

Usually, five types of fecal indicator bacteria i.e. total coliform bacteria, fecal coliform bacteria, *Escherichia coli (E. coli*), *fecal streptococci*, and *enterococci* [2] are identified and quantified.

Following methods can be used to test for indicator bacteria:

- **Total count of bacteria.** In this method, total number of bacteria present in a milliliter of water is counted. The sample of water is diluted; 1 mL of sample water is diluted in 99 mL of sterilized water. Then 1 mL of diluted water is mixed with 10 mL of agar or gelatin (culture medium). This mixture is then kept in incubator at 37° C for 24 h or at 20°C for 48 h. After that, the sample is taken out from incubator and colonies of bacteria are counted by means of microscope. The product of the number of colonies and the dilution factor gives the total number of bacteria per mL of undiluted water sample.
- **Membrane-filtration method**: In this method, the sample is filtered through a sterilized membrane of special design due to which all bacteria get stained on the membrane. The member is then put in contact of culture medium in the incubator for 24 hours at 37°C.

The membrane after incubation is taken out and the colonies of bacteria are counted by means of microscope.

- **Liquid broth method, using the presence-absence format or the most-probable-number (MPN) format:** In this method, the detection is done by mixing dilutions of a sample of water with lactose broth and keeping it in the incubator at for 48 h. The presence of acid or carbon dioxide gas in the test tube indicates presence of *E-coli*. After this, the standard statistical tables (Maccardy's) are referred and the 'Most Probable Number' (MPN) of E-coli per 100 mL of water is determined. MPN is the number which represents the bacterial density which is most likely to be present.

COMPLETE ASSESSMENT OF THE QUALITY OF THE AQUATIC ENVIRONMENT

- Chemical analyses of water and aquatic organisms
- Biological tests such as toxicity tests and measurements of enzyme activities
- Descriptions of aquatic organisms including their occurrence, density, biomass, physiology and diversity
- Physical measurements of water temperature, pH, conductivity, light penetration, particle size of suspended and dissolved material, flow velocity, hydrological balance, etc. [3].

Following water quality parameters need to be determined to assess quality of water [4]:

Dissolved oxygen	Usually decreases as discharge increases. Used as a water quality indicator in most water quality models.
Biochemical oxygen demand (BOD)	A measure of oxygen-reducing potential for waterborne discharges. Used in most water quality models.
Temperature	Often increased by discharges, especially from electric power plants. Relatively easy to model.
Ammonia nitrogen	Reduces dissolved oxygen concentrations and adds nitrate to water. Can be predicted by most water quality models.
Algal concentration	Increases with pollution, especially nitrates and phosphates. Predicted by moderately complex models.
Coliform bacteria	An indicator of contamination from sewage and animal waste
Nitrates	A nutrient for algal growth and a health hazard at very high

	concentrations in drinking water. Predicted by moderately complex models.
Phosphates	Nutrient for algal growth. Predicted by moderately complex models.
Toxic organic compounds	A wide variety of organic (carbon-based) compounds can affect aquatic life and may be directly hazardous to humans. Usually very difficult to model.
Heavy metals	Substances containing lead, mercury, cadmium, and other metals can cause both ecological and human health problems. Difficult to model in detail.

Table 1.7.1. Monitoring systems used to determine the quality of water in water bodies and liquid effluents [4]

Parameter	**Sampling or monitoring system**
General	
pH	pH meter ISO (1980–91), Water Quality Standards APHA, ASTM, BS, DIN, SCA
BOD	Determine dissolved oxygen concentration in the test solution before and after incubation (APHA, ASTM, BS, DIN, ISO, SCA); 40 CFR, Part 136; USEPA Method 405.1
COD	Digest with potassium dichromate in strong acid solution with silver sulfate as catalyst after sample homogenization (APHA, ASTM, BS, DIN, ISO, SCA); 40 CFR, Part 136; USEPA Method 410.1
AOX	USEPA Method 1650 (titrimetric)
TSS	Filtration 40 CFR, Part 136; USEPA Method 160.2; APHA, BS, DIN, ISO, SCA
Total dissolved solids (TDS)	Pretreatment with membrane filtration, followed by evaporation APHA, BS, DIN, ISO, SCA
Phenol	Extract with MIBK, followed by GC analysis USEPA Methods 420.1, 420.2
Sulfide	React with dimethlphenylenediamine and ferric chloride in acid solution to form methylene blue; USEPA Methods 376.1, 376.2
Oil and grease	Extract with light petroleum, evaporate solvent, and measure weight USEPA Method 413.1
Organic compounds	
Total organic carbon	UV oxidation followed by infrared analysis USEPA Method 415.1; APHA, ASTM, DIN, ISO, SCA
Organics	40 CFR, Part 136.3 (GC, GC/MS, HPLC, ASTM D4657-87)
PAHs	Gas chromatography with flame ionization detection
Pesticides	Gas chromatography; 40 CFR, Part 136.3, Table 1-D.

Inorganic substances	
General reference	40 CFR, Part 136.3, Table 1-B.
Metals	
Arsenic	Atomic absorption spectroscopy; APHA, ASTM, SCA
Cadmium	Atomic absorption spectrometry; APHA, ASTM, BS, DIN, ISO, SCA Inductively coupled plasma emission spectrometry; ASTM, DIN, SCA
Chromium	Atomic absorption spectrometry; APHA, ASTM, BS, DIN, ISO, SCA Inductively coupled plasma emission spectrometry; ASTM, DIN, SCA
Lead	Atomic absorption spectrometry; APHA, ASTM, BS, DIN, ISO, SCA Inductively coupled plasma emission spectrometry; ASTM, DIN, SCA
Mercury	Flameless atomic absorption spectrometry; APHA, ASTM, BS, DIN, ISO, SCA
Nickel	Atomic absorption spectrometry; APHA, ASTM, DIN, SCA Inductively coupled plasma emission spectrometry; ASTM, DIN, SCA
Zinc	Atomic absorption spectrometry; APHA, ASTM, BSI, DIN, ISO, SCA
Note: See UNEP, Technical Report 27, for details. APHA, American Public Health Administration, Standard Methods for the Examination of Water and Wastewater; ASTM, American Society for Testing and Materials Standards, Annual, vols. 11.01, 11.02; BS, British Standards Institute, Water Quality, BS-6068; CFR, United States, Code of Federal Regulations; DIN, German Industrial Standard Methods for the Examination of Water, Wastewater and Sludge, DIN 38404–09; ISO, International Organization for Standardization, Water Quality Standard Method; SCA, Standing Committee of Analysts, U.K. Department of the Environment, Methods for the Examination of Waters and Associated Materials.	

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Lecture 8

Characterization of Air Emissions

AIR POLLUTION

- Air quality is affected by various economic and industrial activities which alter the composition of air and affect the environment locally, regionally and globally.
- It is estimated that anthropogenic sources have changed the composition of global air by less than 0.01%. However, this change has adversely affected the climate of the earth.
- Both natural and/or anthropogenic activities introduce air pollutants which can be solid (large or sub-molecular), liquid or gas into the atmosphere that pose problem to human health and other life forms on earth.
- These air pollutants include CO, SOx, NOx, SPM, CO_2, ozone, photochemical smog, etc. [1].

Classification of Air Pollutants

- Natural contaminants: Natural fog, pollen grain, bacteria, volcanic eruption, wind blown dust, lightning generated fires.
- Particulate (aerosols): Dust, smoke, fog, mists, fume.
- Gases and odor: SOx, NOx, CO, CO_2, halogen compounds, hydrocarbons, radioactive compounds.

PARTICULATE MATTER (PM)

- PM is a complex mixture variable in size (0.01- 100 μm), composition (metals, nitrates, sulfate, polynuclear aromatic hydrocarbons (PAH), volatile organic compound (VOC), etc.) and concentration.
- Toxicity and penetration depends on the composition and size of the particles.
- Solid or liquid particles with sizes from 0.005 – 100 μm
- General term is aerosols
- Dust originates from grinding or crushing
- Fumes are solid particles formed when vapors condense
- Smoke describes particles released in combustion processes
- Smog used to describe air pollution particles

Health Effects of Particulate Matter

- Impact depends on particle size, shape and composition
- Large particles trapped in nose
- Particles >10 μm removed in tracheobronchial system
- Particles <0.5 μm reach lungs but are exhaled with air
- Particles 2 – 4 μm most effectively deposited in lungs
- Inhalable PM includes both fine and coarse particles.
- Coarse particles
    - aggravation of respiratory conditions, such as asthma.
- Fine particles
    - increased hospital admissions and emergency room visits for heart and lung disease
    - increased respiratory symptoms and disease
    - decreased lung function
    - premature death

Other Effects of Particulate matter

- Decreased visibility
- Damage to paints and building materials

Table 1.8.1. Gaseous air pollutants, their properties and significance.

Name	Formula	Properties of Importance	Significance as Air Pollutant
Sulfur dioxide	SO_2	Colorless gas, intense acrid odor, forms H_2SO_3 in water	Damage to vegetation, building materials, respiratory system
Sulfur trioxide	SO_3	Soluble in water to form H_2SO_4	Highly corrosive
Hydrogen sulfide	H_2S	Rotten egg odor at low concentrations, odorless at high concentrations	Extremely toxic
Nitrous oxide	N_2O	Colorless; used as aerosol carrier gas	Relatively inert; not a combustion product
Nitric oxide	NO	Colorless; sometimes used	Produced during combustion and

		as anaesthetic	high-temperature oxidation; oxidizes in air to NO_2
Nitrogen dioxide	NO_2	Brown or orange gas	Component of photochemical smog formation; toxic at high concentration
Carbon monoxide	CO	Colorless and odorless	Product of incomplete combustion; toxic at high concentration
Carbon dioxide	CO_2	Colorless and odorless	Product of complete combustion of organic compounds; implicated in global climate change
Ozone	O_3	Very reactive	Damage to vegetation and materials; produced in photochemical smog
Hydrocarbons	C_xH_y	Many different compounds	Emitted from automobile crankcase and exhaust
Hydrogen fluoride	HF	Colorless, acrid, very reactive	Product of aluminum smelting; causes reactive fluorosis in cattle; toxic

Table 1.8.2. Monitoring systems used to determine the quality of ambient air [2].

Parameter	**Sampling or monitoring system**
SPM/PM_{10}	ISO/TR7708/DP 4222 (measurement of atmospheric deposit; horizontal deposit gauge method) ISO/DP 10473 (measurement of the mass of particulate matter on a filter medium; beta ray absorption); ISO/DIS 9835 (determination of a black smoke index) 40 CFR, Part 50, Appendix J (for PM10); Appendix B (for SPM)
Sulfur dioxide	ISO 4219/4221; 40 CFR, Part 50, Appendix A (pararosaniline method)
Nitrogen dioxide	ISO 6768, 7996; 40 CFR, Part 50, Appendix F (gas phase chemiluminescence method); Salzman automatic colorimeter (method used in Japan)
Ozone	40 CFR, Part 50, Appendix D; measurement of photochemical oxidants using the neutral buf-fered automatic potassium iodide colorimetric method; used in Japan

Lead	ISO/DIS 9855; 40 CFR, Part 50, Appendix G (extraction with nitric and hydrochloric acids and analysis by atomic absorption spectrometry)
Asbestos	ISO/DIS 10312/VDI 3492 (fibers counted using scanning electron microscope)
Note: SPM, suspended particulate matter; CFR, United States, Code of Federal Regulations; ISO, International Organization for Standardization.	

Table 1.8.3. Monitoring systems can be used to monitor air emissions [2].

Parameter	**Sampling and analytical methods**
Stack gases	Extractive methods using pitot tubes; 40 CFR, Part 60, Appendix A, Methods 1–4; BS1756:1977, Part 2
PM10/ TSP	In situ nondispersive infrared spectrophotometry and extractive gravimetric; ISO 9096; ISO/TC 146/SCI/WG1N16(1994); 40 CFR, Part 60, Appendix A, Methods 5, 5A, 17; BS 3405:1983 VDI 2066, Parts 1, 2
Sulfur oxides	Extractive nondispersive infrared spectrophotometry; ISO 8178; 40 CFR, Part 60, Appendix A, Method 6; BS 1756:1977, Part 4; VDI 2462, Parts 1–7
Nitrogen oxides	Extractive fluorescence; ISO 8178; 40 CFR, Part 60, Appendix A, Method 7, 7A–7E; VDI 2456 Parts 1–7
VOCs	Extractive flame ionization; 40 CFR, Part 60, Appendix A, Method 18; VDI 3493, Part 1
Total hydrocarbons	Extractive nondispersive infrared spectrophotometry; 40 CFR, Part 60, Appendix A, Methods 25, 25A, 25 B; VDI 2460 (Parts 1–3), 2466 (Part 1), 3481 (Parts 1, 2), 2457 (Parts 1–7)
Carbon monoxide	Extractive nondispersive infrared spectrophotometry; 40 CFR, Part 60, Appendix A, Methods 10, 10A, 10B; VDI 2459, Part 6
Chlorine/hydrogen chloride	Extractive nondispersive infrared spectrophotometry; VDI 3488, Parts 1 and 2; VDI 3480, Part 1
Hydrogen sulfide	Extractive electrochemical analysis; VDI 3486, Parts 1–3
Note: Metals are usually analyzed by the methods outlined in Table 2. BS, British Standards	

Institute; CFR, United States, Code of Federal Regulations; ISO, International Organization for Standardization, Method for the Gravimetric Determination of Concentration and Mass Flow Rate of Particulate Material in Gas-Carrying Ducts (Geneva 1994); VDI, Germany, Federal Minister for the Environment, Nature Conservation and Nuclear Safety, Air Pollution Control Manual for Continuous Emission Monitoring (Bonn, 1992).

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Lecture 9

Fugitive Emission Control and Water Use Minimization

FUGITIVE EMISSIONS

- Unintentional releases, such as those due to leaking equipment, are known as *fugitive emissions*
- Can originate at any place where equipment leaks may occur
- Can also arise from evaporation of hazardous compounds from open topped tanks
- Volatile organic compounds (VOCs) can be emitted from leaking valves, flanges, sampling connections, pumps, pipes and compressors.

SOURCES OF FUGITIVE EMISSIONS

Agitator seals
Compressor seals
Connectors
Diaphrams
Drains
Dump lever arms
Flanges
Hatches
Instruments

Loading arms
Meters
Open-ended lines
Polished rods
Pressure relief devices
Pump seals
Stuffing boxes
Valves
Vents

MEASURING FUGITIVE EMISSIONS

- Portable gas detector
- Catalytic bead
- Non-dispersive infrared
- Photo-ionization detectors
- Combustion analyzers
- Standard GC with flame ionization detector is most commonly used
- Average emission factor approach
- Screening ranges approach
- EPA correlation approach
- Unit-specific correlation approach

CONTROLLING FUGITIVE EMISSIONS

- Modifying or replacing existing equipment
- Implementing a leak detection and repair (LDAR) program

Table 1 .9.1. Equipment Modification

Equipment type	**Modification**	**Approximate control efficiency (%)**
Pumps	Seal less design	100
	Closed-vent system	90
	Dual mechanical seal with barrier fluid maintained at a higher pressure than the pumped fluid	100
Compressors	Closed-vent system	90
	Dual mechanical seal with barrier fluid maintained at a higher pressure than the pumped fluid	100
Pressure-relief devices	Closed-vent system	varies
	Rupture disk assembly	100
Valves	Seal less design	100
Connectors	Weld together	100
Open-ended lines	Blind, cap, plug or second valve	100
Sampling connections	Closed-loop sampling	100

2. LDAR Programs

- Designed to identify pieces of equipment that are emitting sufficient amounts of material to warrant reduction of emissions through repair
- Best applied to equipment types that can be repaired on-line or to equipment for which equipment modification is not suitable

WATER USE MINIMIZATION

- Water is a critical resource for many economic activities. Even some of the activities can proceed without water.
- It is necessary that use of water should be minimized not only in bigger economic activity but also in daily life so that these activities may be prolonged and water remains available for future generations also.
- Effective water management requires a coupling of production objectives, environmental impacts, and economic influences.
- Water Use Minimization involves a thorough evaluation of existing process operations, water utilization improvements, operational changes, plant-level design improvements, etc. [1].

IN-PLANT CONTROL TO MINIMIZE WATER POLLUTION

The following in plant control measures are suggested to minimize the wastewater generation:

- Modification in the process
- Optimum use of raw materials
- By-product recovery
- Maximum reuse of water
- Attitude of the management in reducing the pollution
- Proper operation and maintenance
- Local regulation regarding the water use and effluent quality
- Good house keeping

PROCESS AND PRODUCT CHANGE

Process and product change is in fact a continuous process which is going on for last so many decades. The process of improvement in the product is basically user oriented. Cost effectiveness is also another factor that governs production criteria. Sustainable development of industry can be achieved by:

(a) Product changes:
    a. By designing so as to have less environmental impact
    b. Increased product life

(b) Process Changes: It is of following three types:

  a. Material changes: Material purification and substitution for lesser cost, toxicity and environmental effects
  b. Technology changes:
     i. Layout changes
     ii. Increased automation
     iii. Improved operating conditions
     iv. Improved equipment
     v. New and cleaner technologies
  c. Operational changes
     i. Operating and maintenance procedures
     ii. Management practices
     iii. Stream segregation
     iv. Material handling improvements
     v. Production scheduling
     vi. Inventory control
     vii. Waste segregation

WATER SUPPLY SYSTEMS

- **Water System Audits and Universal Metering**: A water system audit quantifies how much water a system produces and purchases and where that water is going. The first step should include metering of all water-service connections.
- **Leak Detection and Repair**: Leak detection is a process to identify and repair water system leaks that are causing water loss. Leak detection methods range from visual inspection to using specialized leak detection equipment to find hidden leaks [2].
- **Water Reuse**: Highly treated wastewater can be used for many purposes, such as irrigation, dust control, and some industrial processes.

BUSINESS AND INDUSTRIAL WATER USE [2]

- **Motivation of less water usage**: Businesses and industries are motivated to use less water to reduce operating costs by lowering water bills. Cost savings comes from reduced water purchases, pumping expenses and wastewater treatment costs.
- **Cooling Water**: Cooling towers can consume 20% to 30% of the water used by commercial and industrial facilities.
- **Fixture Replacement**: Replacing faucets, toilets, showerheads, hose nozzles, and other water delivery devices with more efficient systems reduces the water use.

BOILER WATER MINIMIZATION

Boilers supply steam for process heating, space heating, power generation, etc. Boilers require makeup water to function; and generate wastewater as blow down. Boiler water minimization can be done by:

- **High Purity Water Makeup**: Pretreatment equipment such as reverse osmosis and demineralization allow the boiler to run at higher cycles of concentration. This results in lower makeup water and lower blow down rates and less energy consumption [3].
- **Increase Condensate Return:** The more condensate that can be returned to the boiler, the higher will be the number of cycles and less blow down, makeup, and heat energy will be required. [3].
- **Eliminate Condensate Contamination:** Perhaps the reason condensate isn’t being returned is condensate contamination. Condensate contamination is avoided, the conductivity would be higher. Higher the conductivity of water in a boiler, the lower the makeup and blow down rates and energy consumption.
- **Water Chemistry:** It is always a good practice to re-examine the boiler water chemistry. If the feed water quality has changed, this may directly impact the number of cycles the boiler can run. The impact may be positive or negative, but must be checked.
- **Blow down Controller:** Many boilers are manually blown down to control conductivity. With manual blow down, there are times when the conductivity is below the control range and times when it is above the control range. Automatically controlling the blow down on a boiler ensures the boiler runs within the set conductivity limits. This results in either water savings if the boiler was typically under cycled or improved steam quality if it was typically over cycled [2].

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Lecture 10

Water Recycling and Reuse

WATER RECYCLING

- Water recycling is reusing treated wastewater for beneficial purposes such as agricultural and landscape irrigation, industrial processes, toilet flushing, and replenishing a ground water basin (referred to as ground water recharge).
- For example, when an industrial facility recycles water used for cooling processes. A common type of recycled water is water that has been reclaimed from municipal wastewater, or sewage. The term water recycling is generally used synonymously with water reclamation and water reuse.
- Water recycling offers resource and financial savings.
- Recycled water for landscape irrigation requires less treatment than recycled water for drinking water.
- Gray water, or grey water, is reusable wastewater from residential, commercial and industrial bathroom sinks, bath tub shower drains, and clothes washing equipment drains. Gray water is reused onsite, typically for landscape irrigation. Use of non-toxic and low-sodium (no added sodium or substances that are naturally high in sodium) soap and personal care products is required to protect vegetation when reusing gray water for irrigation [1].

MOTIVATIONAL FACTORS FOR RECYCLING/REUSE [2]

- Opportunities to augment limited primary water sources
- Prevention of excessive diversion of water from alternative uses, including the natural environment; possibilities to manage in-situ water sources
- Minimization of infrastructure costs, including total treatment and discharge costs
- Reduction and elimination of discharges of wastewater (treated or untreated) into receiving environment [3]
- Scope to overcome political, community and institutional constraints

- **Environmental Benefits of Water Recycling**: In addition to providing a dependable, locally-controlled water supply, water recycling provides tremendous environmental benefits. By providing an additional source of water, water recycling can help us find ways to decrease the diversion of water from sensitive ecosystems. Other benefits include decreasing wastewater discharges and reducing and preventing pollution. Recycled water can also be used to create or enhance wetlands and riparian habitats [1].
- Recycling water on site or nearby reduces the energy needed to move water longer distances or pump water from deep within an aquifer. Tailoring water quality to a specific water use also reduces the energy needed to treat water [1].

USES OF RECYCLED WATER

- agriculture
- landscape
- public parks
- golf course irrigation
- cooling water for power plants and oil refineries
- processing water for mills, plants
- toilet flushing
- dust control
- construction activities
- concrete mixing
- artificial lakes

Uses of water recycled from water treatment plant:

[A] Secondary Treatment; Biological Oxidation, and Disinfection

- Surface irrigation of orchards and vineyards
- Non-food crop irrigation
- Restricted landscape impoundments
- Groundwater recharge of non-potable aquifer
- Wetlands, wildlife habitat, stream augmentation
- Industrial cooling processes

[B] Tertiary and advance treatment

- Landscape and golf course irrigation

- Toilet flushing
- Vehicle washing
- Food crop irrigation
- Unrestricted recreational impoundment
- Indirect potable reuse- Groundwater recharge of potable aquifer and surface water reservoir augmentation

QUALITY ISSUES OF WASTEWATER REUSE/RECYCLING [4]

Despite a long history of wastewater reuse in many parts of the world, the question of safety of wastewater reuse still remains an enigma mainly because of the quality of reuse water.

- There is no evidence of increased enteric diseases in urban regions housing areas irrigated with treated reclaimed wastewater, and
- There is no evidence of significant risks of viral or microbial diseases as a result of exposure to effluent aerosols from spray irrigation with reclaimed water [3].

Table 1.10.1. Pathogen survival time [3].

Type of pathogen	**Survival time in days**			
	In feces and sludge	**In sewage and freshwater**	**In soil**	**On crops**
1. Viruses				
Enteroviruses	<100(<20)	<120(<50)	<100(<30)	<60(<15)
2. Bacteria				
Fecalcoliforms	<90(<50)	<60(<30)	<70(<20)	<30(<15)
Salmonella spp.	<60(<30)	<60(<30)	<70(<20)	<30(<15)
Shigella spp.	<30(<10)	<30(<10)	-	<10(<5)
Vibrio cholerae	<30(<5)	<30(<10)	<20(<10)	<5(<2)
3. Protozoa				
Entamoeba-hystolytica cysts	<30(<15)	<30(<15)	<20(<10)	<10(<2)
4. Helminths				
Ascaris-lumbricoides eggs	many months	Many months	many months	<60(<30)

PRIMARY WATER QUALITY CRITERIA [5]

In India, the Central Pollution Control Board (CPCB) has developed a concept of "designated best use". According to which, out of several uses a particular water body is put to, the use which demands highest quality of water is called its "designated best use", and accordingly the water body is designated. The CPCB has identified 5 such "designated best uses".

Table 1.10.2. Water quality criteria [5, 6].

Designated-Best-Use	**Class of water**	**Criteria**
Drinking Water Source without conventional treatment but after disinfection	A	• Total Coliforms Organism MPN/100 mL ≤ 50 • pH between 6.5 and 8.5 • Dissolved Oxygen ≥ 6 mg/L • BOD (5 days at 20°C) ≤ 2 mg/L
Outdoor bathing (Organised)	B	• Total Coliforms Organism MPN/100 mL ≤ 500 • pH between 6.5 and 8.5 • Dissolved Oxygen ≥ 5 mg/L • BOD (5 days at 20°C) ≤ 3 mg/L
Drinking water source after conventional treatment and disinfection	C	• Total Coliforms Organism MPN/100 mL ≤ 5000 • pH between 6 to 9 • Dissolved Oxygen ≥ 4 mg/L • BOD (5 days at 20°C) ≤ 3 mg/L
Propagation of Wild life and Fisheries	D	• pH between 6.5 to 8.5 • Dissolved Oxygen ≥ 4 mg/L • Free Ammonia (as N) 1.2 mg/L or less
Irrigation, Industrial Cooling, Controlled Waste disposal	E	• pH between 6.0 to 8.5 • Electrical Conductivity at 25°C (μmhos/cm): Max. 2250 • Sodium absorption ratio: Max. 26 • Boron: Max. 2 mg/L

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Module 2: AIR POLLUTION CONTROL

Lecture	Topic	No. of Hours (8)
1	Introduction to Air Pollution and Control	1
2	Particulate Emission Control by Mechanical Separation & Wet Gas Scrubbing	1
3	Design of Cyclones	1
4	Design of Fabric Filter	1
5	Particulate Emission Control by Electrostatic Precipitation	1
6	Design of ESP	1
7	Gaseous Emission Control by Adsorption	1
8	Gaseous Emission Control by Absorption	1

Lecture 1

Introduction to Air Pollution and Control

AIR POLLUTION

Air pollution may be defined as the presence of one or more contaminants in the air in such quantities and for such durations which may be or tend to be injurious to human, animal or plant life, or property, or which unreasonably interferes with the comfortable usage of air.

Main cause of air pollution is Combustion

During combustion, elements in the fuel get burned in air to form various air pollutants.

$$\begin{array}{lcl} [\text{Fuel (C, H, S, N, Pb, Hg, ash)} & \longrightarrow & [CO_2, \text{CO, NOx, SOx, Pb, Hg,} \\ + \text{ Air } (N_2 + O_2)] & & \text{SPM, RSPM, (PM10), VOCs]} \end{array} \quad (2.1.1)$$

Types of Air Pollutants

- Primary pollutants: Pollutants which are being emitted into the air directly by point/area/line sources.
  Examples: CO, NOx, SO_2, Pb, SPM, RSPM, VOCs
- Secondary pollutants: Pollutants which are getting formed from primary pollutants in the atmosphere. Some of the reactions are catalyzed by sun light.
  Examples: acid rains, smog, O_3, H_2O_2, formaldehyde, peroxy acetyl nitrate (PAN)

Classification of Air Pollutants

Air pollutants can be classified into three broad categories:

- **Natural Contaminants:** Natural fog, pollen grain, bacteria and products of volcanic eruption.
- **Aerosols (Particulates)**: Dust, smoke, moist, fog.
- **Gases and vapors**:
  - Sulfur compounds: SO_2, SO_3, H_2S
  - Nitrogen compounds: NO, NO_2, NO_3
  - Oxygen compounds: O_2, CO, CO_2
  - Halogen compounds: HF, HCl
  - Organic compounds: Aldehydes. Hydrocarbons
  - Radio active compounds: radioactive gases

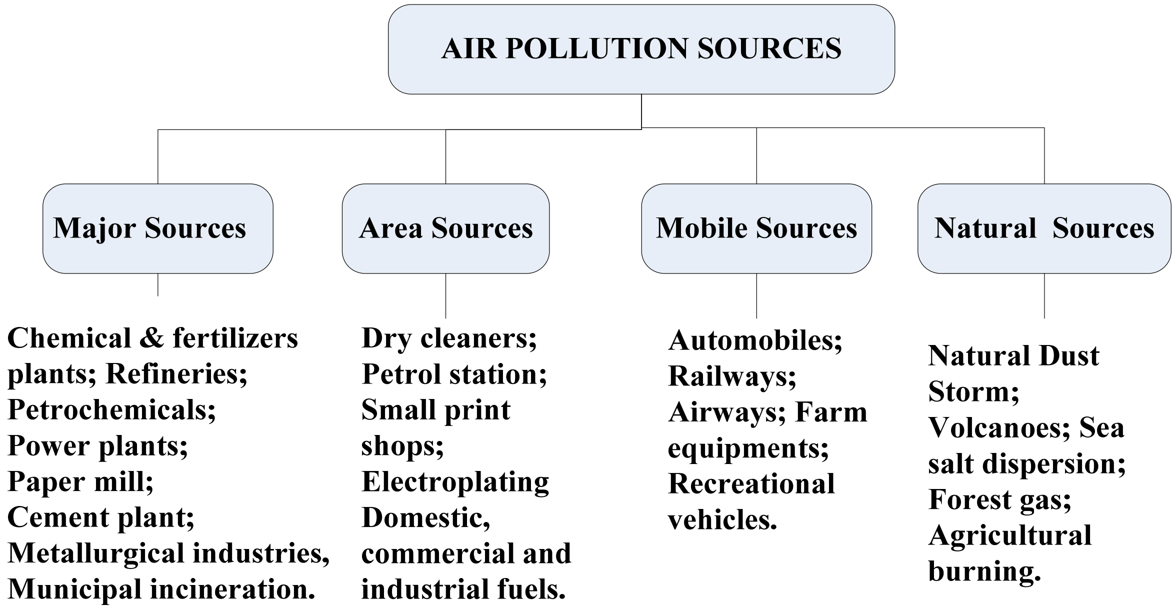

Figure 2.1.1: Air pollution sources

AIR POLLUTION CONTROL

[A] Mobile Sources

Cleaner/Alternative Fuel

- Vaporization of Gasoline should be reduced.
- Oxygen containing additives reduce air requirement e.g., ethanol, MTBE (Hazardous).
  - Methanol: (Less photochemically reactive VOC, but emits HCHO (eye irritant), difficult to start in winters: Can be overcome by M85 (85% methanol, 15% gasoline)
  - Ethanol: GASOHOL (10% ethanol & 90% Gasoline),
  - CNG: Low HC, NOx high, inconvenient refueling, leakage hazard.
  - LPG: Propane, NOx high

Three-Way Catalytic Converter

A three-way catalytic converter has three simultaneous tasks:

- Reduction of nitrogen oxides to nitrogen and oxygen
- Oxidation of carbon monoxide to carbon dioxide
- Oxidation of unburnt hydrocarbons (HC) to carbon dioxide and water

[B] Stationary Sources

Pre-combustion Control

- Switching to less sulphur and nitrogen fuel

Combustion Control

- Improving the combustion process
- New burners to reduce NOx
- New Fluidized bed boilers
- Integrated gasification combined cycle

Post-Combustion Control

- Particulate collection devices
- Flue gas desulphurization

MAJOR INITIATIVES TAKEN FOR AIR POLLUTION CONTROL IN INDIA (DURING LAST TWO DECADES) [1]

- National ambient air quality standards based on health impact evolved (1982, 1994, 2009).
- Emission standards for air polluting industries developed for major industries
- Implementation of standards in 17 categories of highly polluting industries and other small/medium scale industries (stone crushers, brick kiln, re-rolling mills, etc.).
- Action plan implementation and pollution control in identified 24 problem areas [2].
- Coal beneficiation/clean coal technology –notification regarding use of beneficiated coal in thermal power plant.
- Improvement in vehicular technology (Euro-1, Euro-2, Euro-3, Euro-4, CNG vehicles, 4 stroke engines, etc.)
- Improvement in fuel quality -diesel with low sulfur content (0.25% in whole country and 0.05% in metro cities)
- Gasoline-lead phased-out throughout the country since 2000 [2].

EMERGING NEW AREAS FOR AIR POLLUTION CONTROL IN INDIA

- Development of low cost ash removal technology from coal and promotion of clean coal technologies

- Technology for reduction of fluoride emission (primary & Secondary) from pot room of aluminum industries using Soderberg technology
- Development of NOx control standard for thermal power plants and refineries
- Prevention and control of fugitive emission in cement industry
- Use of high calorific value hazardous waste including petroleum coke in cement kiln
- Low cost flue gas desulphurization technology for thermal power plants
- Technology development of fugitive emission control from coke oven plants of iron & steel industry [2].
- Development of technology and standard to control emission of VOC, methyl chloride, P_2O_5, HCl, etc. from pesticide industry
- Development of odor control technology for paper & pulp industry and standardization the method of odor measurement
- Fluidized bed combustion technology for solid fuel containing higher ash
- Development of improved design of Incinerators for Hazardous Waste.
- Control on emission of fine particulate matter ($PM_{2.5}$) from engine using LPG, compressed natural gas (CNG), low sulphur diesel, low sulphur petrol, etc.
- Apportionment study for fine particulate matter (PM_{10}, $PM_{2.5}$) in major cities
- Technology for mercury emission control from thermal power plants.
- Noise and emission control system for small DG sets (<200 kW)
- Development of stack height guidelines for thermal power plants and industries using ventilation co-efficient of different regions in the country [3].

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[1]

Lecture 2

Particulate emission control by mechanical separation & wet gas scrubbing

PARTICULATE EMISSION CONTROL BY MECHANICAL SEPARATION

The basic mechanism of removing particulate matter from gas stream is classified as: 1) gravitational settling 2) centrifugal impaction 3) inertial impaction 4) direct interception 5) diffusion and 6) electrostatic precipitation.

Equipment presently available, which make use of one or more of the above mechanisms, fall into the following five broad categories: 1) gravitational settling chambers 2) cyclone separators 3) fabric filters 4) electrostatic precipitator

[A] Gravitational Settling Chambers

Gravitational settling chambers are generally used to remove large, abrasive particles (usually >50 μm) from gas stream. It provides enlarged areas to minimize horizontal velocities and allow time for the vertical velocity to carry the particle to the floor. The usual velocity through settling chambers is between 0.5 to 2.5 m/s.

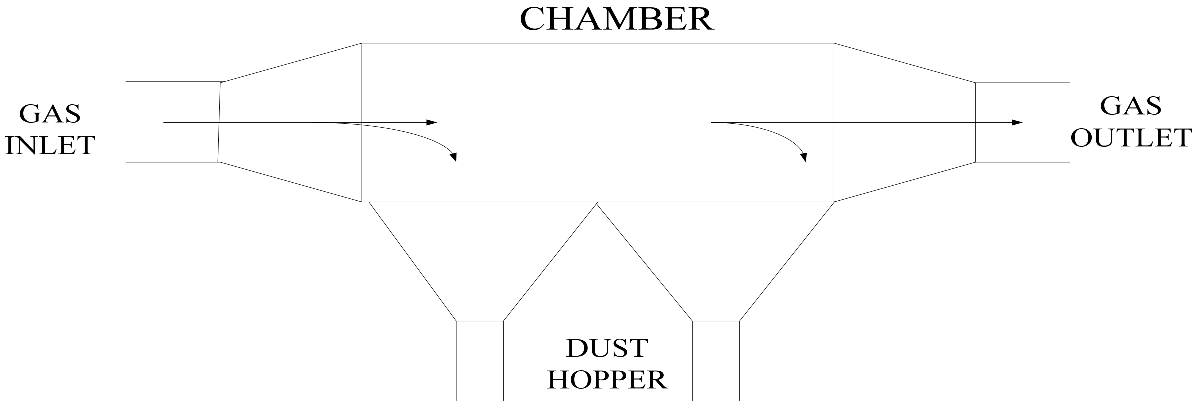

Figure 2.2.1: Gravitation settling chamber [1]

Advantage: Low pressure loss, simplicity of design and maintenance**.**

Disadvantage: Requires larger space and efficiency is low. Only larger sized particles are separated out.

Design of a gravitational settling chamber

If we assume that Stokes law applies we can derive a formula for calculating the minimum diameter of a particle collected at 100% theoretical efficiency in a chamber of length L.

$$\frac{v_t}{H} = \frac{v_h}{L} \qquad (2.2.1)$$

Where v_t=terminal settling velocity, m/s

$$v_t = \frac{g(\rho_p - \rho_a)d_p^2}{9\mu_a} \qquad (2.2.2)$$

Where, g=gravitational constant, m/s^2; ρ_p=density of particle, kg/m^3; ρ_a=density air, kg/m^3; d_p=diameter of particle, m; μ_a=viscosity of air, kg/m s; H=height of settling chamber, m; v_h=horizontal flow-through velocity, m/s; and L=length of settling chamber, m.

Solving for d_p gives an equation that predicts the largest-size particle that can be removed with 100% efficiency from a settling chamber of given dimension.

$$d_p = \sqrt{\left(\frac{18\mu_a H v_h}{gL(\rho_p - \rho_a)}\right)} \qquad (2.2.3)$$

All particles larger than d_p will also be removed with 100% efficiency, while the efficiency for smaller particles is the ratio of their settling velocities to the settling velocity of the d_p particle.

[B] Cyclone Separators

A cyclone separator consists of a cylindrical shell, conical base, dust hopper and an inlet where the dust-laden gas enters tangentially. Under the influence of the centrifugal force generated by the spinning gas, the solid particles are thrown to the wall of the cyclone as the gas spirals upward at the inside of the cone. The particles slide down the walls of the cone and into the hopper. The operating efficiency of a cyclone depends on the magnitude of the centrifugal force exerted on the particles. The greater the centrifugal force, the greater the spreading efficiency. The magnitude of the centrifugal force generated depends on particle mass, gas velocity within the cyclone, and cyclone diameter.

$$F_c = M_p \frac{v_i^2}{R} \qquad (2.2.4)$$

Where, F_c=centrifugal force, N; M_p=particulate mass, Kg; v_i equals particle velocity and R equals radius of the cyclone, m/s. From this equation, it can be seen that the centrifugal force on the particles, and thus the collection efficiency of the cyclone collector can be increased by decreasing R. Large-diameter cyclone have good collection efficiencies for particles 40 to 50 μm in diameter.

Advantage: Relatively inexpensive, simple to design and maintain; requires less floor area; low to moderate pressure loss.

Disadvantage: Requires much head room; collection efficiency is low for smaller particles, quite sensitive to variable dust loading and flow rates.

[C] Fabric Filters

In a fabric filter system, the particulate-laden gas stream passes through a woven or felted fabric that filters out the particulate matter and allows the gas to pass through. Small particles are initially retained on the fabric by direct interception, inertial impaction, diffusion, electrostatic attraction, and gravitational settling. After a dust mat has formed on the fabric, more efficient collection of submicron particle is accomplished by sieving.

Filter bags usually tubular or envelope-shaped, are capable of removing most particles as small as 0.5µm and will remove substantial quantity of particles as small as 0.1□µm. Filter bags ranging from 1.8 to 9 m long, can be utilized in a bag house filter arrangement.

As particulates build up on the inside surface of the bags, the pressure drop increases. Before the pressure drop becomes too severe, the bag must be relieved of some of the particulate layer. Fabric filter can be cleaned intermittently, periodically, or continuously [2].

Fabric and Fibre Characteristics: Fabric filter may be classified according to filtering media: woven fabric or felt cloth. Woven fabrics have a definite long range repeating pattern and have considerable porosity in the direction of gas flow. These open spaces must be bridged by impaction of interception to form a true filtering surface. Felted cloth consists of randomly oriented fibres, compressed into a mat and needled to some loosely woven backing material to improve mechanical strength. The choice of fabric fibre is based primarily on operating temperature and the corrosiveness or abrasiveness of the particle. Cotton is the least expensive fibre, and is preferably used in low temperature dust collection service. Silicon coated glass fibre cloth is commonly employed in high temperature applications. The glass fibre must be lubricated to prevent abrasion. All fibre may be applied to the manufacture of woven and felt type fabrics.

Fabric Filter System: Fabric filter systems typically consist of a tubular bag or an envelope, suspended or mounted in such manner that the collected particles fall into hopper when dislodged from fabric. The structure in which the bags are hanged is known as a bag-house.

Generally, particle laden gas enters the bag at the bottom and passes through the fabric while the particles are deposited on the inside of the bag. The cleaning is accomplished by shaking at fixed intervals of time [3].

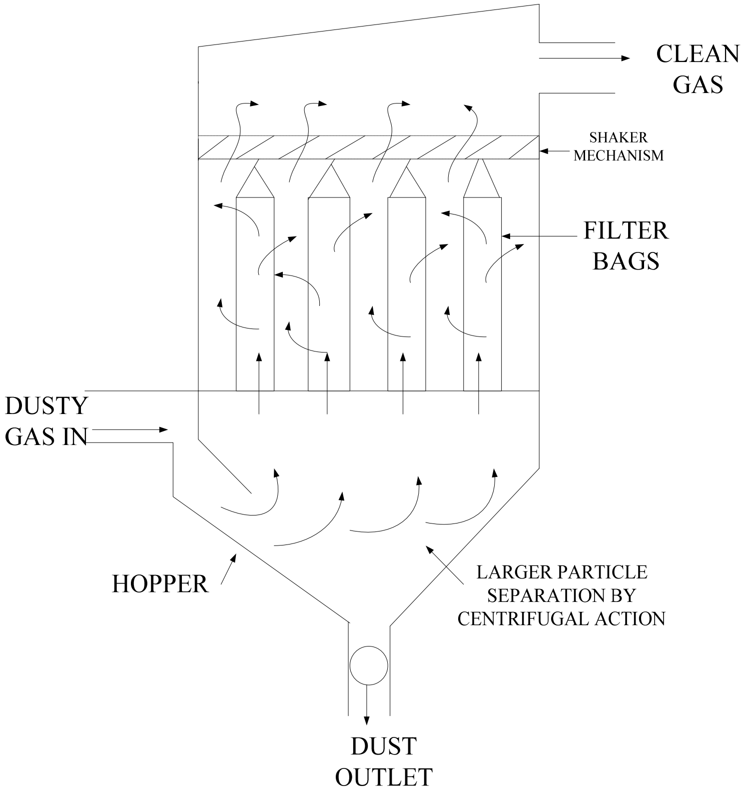

Figure 2.2.2: Typical bag-house

Advantage: Fabric filters can give high efficiency, and can even remove very small particles in dry state.

Disadvantage: High temperature gasses need to be cooled. The flue gasses must be dry to avoid condensation and clogging. The fabric is liable to chemical attacks.

[D] Electrostatic Precipitator

The electrostatic precipitator is one of the most widely used device for controlling particulate emission at industrial installations ranging from power plants, cement and paper mills to oil refineries. Electrostatic precipitator is a physical process by which particles suspended in gas stream are charged electrically and, under the influence of the electrical field, separated from the gas stream.

The precipitator system consists of a positively charged collecting surface and a high-voltage discharge electrode wire suspended from an insulator at the top and held in passion by weight t the bottom. At a very high DC voltage, of the order of 50kV, a corona discharge occurs close to the negative electrode, setting up an electric field between the emitted and the grounded surface [4].

The particle laden gas enters near the bottom and flows upward. The gas close to the negative electrode is, thus, ionized upon passing through the corona. As the negative ions and electrons migrate toward the grounded surface, they in turn charge the passing particles. The electrostatic field then draws the particles to the collector surface where they are deposited.

Periodically, the collected particles must be removed from the collecting surface. This is done by rapping or vibrating the collector to dislodge the particles. The dislodged particles drop below the electrical treatment zone and are collected for ultimate disposal [5].

Advantage:

- Maintenance is nominal, useless corrosive and adhesive materials are present in flue gases.
- They contain few moving parts.
- They can be operated at high temperature up to 300^{o}C-450^{o} C.

Disadvantage:

- Higher initial cost.
- Sensitive to variable dust loading and flow rates.
- They use high voltage, and hence may pose risk to personal safety of the staff.
- Collection efficiency reduces with time.

PARTICULATE EMISSION CONTROL BY WET GAS SCRUBBING

Wet scrubber removes particulate matter from gas streams by incorporating the particles into liquid droplets directly on contact. The basic function of wet scrubber is to provide contact between the scrubbing liquid, usually water and, the particulate to be collected. This contact can be achieved in a variety of ways as the particles are confronted with so-called impaction target, which can be wetted surface as in packed scrubbers or individual droplets as in spray scrubbers [3]. The basic collection mechanism is the same as in filters: inertial impaction, interception and diffusion. Generally, impaction and interception are the predominant mechanism for particles of diameter above 3 μm, and for particle of diameter below 0.3□μm diffusion begins to prevail. There are many scrubber designs presently available where the contact between the scrubbing liquid and the particles is achieved in a variety of ways. The major types are: plate scrubber, packed-bed scrubber, spray scrubber, venturi scrubber, cyclone scrubber, baffle scrubber, impingement-entrainment scrubber, fluidized-bed scrubber.

[A] Plate scrubber

It contains a vertical tower containing one or more horizontal plates (trays). Gas enters the bottom of the tower and must pass through perforations in each plate as it flows countercurrent to the descending water stream. Collection efficiency increases as the diameter of the perforations decreases. A cut diameter, that collected with 50% efficiency, of about □μm aerodynamic diameter can be achieved with 3.2-mm-diameter holes in a sieve plate.

[B] Packed –bed scrubber

Operates similarly to packed-bed gas absorber. Collection efficiency increases as packing size decreases. A cut diameter of 1.5 μm aerodynamic diameter can be attained in columns packed with 2.5 cm elements.

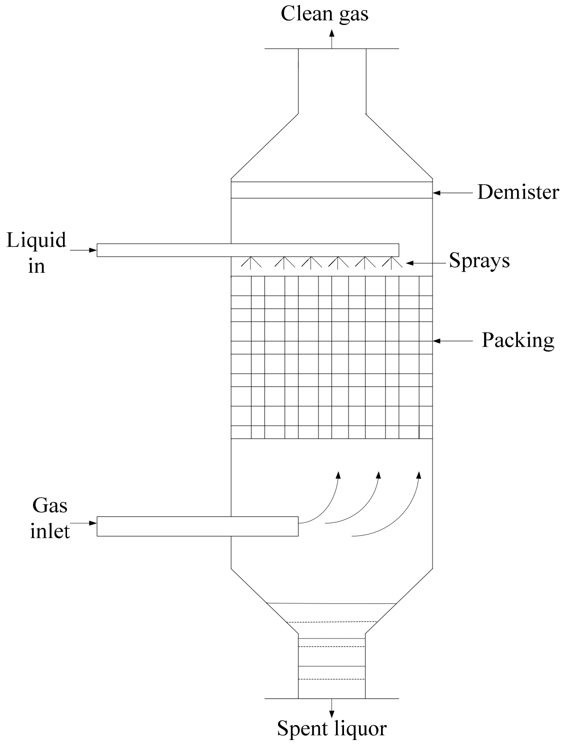

Figure 2.4.1: Packed–bed scrubber

[C] Spray scrubber

Particles are collected by liquid drops that have been atomized by spray nozzles. Horizontal and vertical gas flows are used, as well as spray introduced co-current, countercurrent, or cross-flow to the gas.

Collection efficiency depends on droplet size, gas velocity, liquid/gas ratio, and droplet trajectories. For droplets falling at their terminal velocity, the optimum droplet diameter for fine-particle collection lies in the range 100 to 500 µm.

Gravitational settling scrubbers can achieve cut diameters of about 2.0 µm. The liquid/gas ratio is in the range 0.001 to 0.01 m^3/ m^3 of gas treated.

[D] Venturi scrubber

A moving gas stream is used to atomize liquids into droplets. High gas velocities (60 to 120 m/s) lead to high relative velocities between gas and particles and promote collection.

[E] Cyclone scrubber

Drops can be introduced into the gas stream of a cyclone to collect particles. The spray can be directed outward from a central manifold or inward from the collector wall.

[F] Impingement-Entrainment Scrubber:

The gas is forced to impinge on a liquid surface to reach a gas exit. Some of the liquid atomizes into drops that are entrained by the gas. The gas exit is designed so as to minimize the loss of entrained droplets.

[G] Fluidized-bed scrubber

A zone of fluidized packing is provided where gas and liquid can mix intimately. Gas passes upward through the packing, while liquid is sprayed up from the bottom and/or flows down over the top of the fluidized layer of packing [6].

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Lecture 3

Design of cyclones

DESIGN OF CYCLONES

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

In operation, the particle-laden gas upon entering the cyclone cylinder receives a rotating motion. The vortex so formed develops a centrifugal force, which acts to particle radially towards the wall. The gas spirals downward to the bottom of the cone, and at the bottom the gas flow reveres to form an inner vortex which leaves through the outlet pipe [1].

Theory

In a cyclone, the inertial separating force is the radial component of the simple centrifugal force and is a function of the tangential velocity. The centrifugal force can be expressed by F_c

$$F_c = \frac{m v_e^2}{r} \tag{2.3.1}$$

Where, m=mass of the particle, v_e=tangential velocity of the particle at radius r, and r=radius of rotation. The separation factor S is given by

$$S = \frac{v_e^2}{gr} \tag{2.3.2}$$

The separation factor varies from 5 in large, low velocity units to 2500 in small, high pressure units. Higher the separation factor better is the performance of the cyclone.

In the cyclone, the gas, in addition to moving in a circular path, also moves radially inwards between the inlet on the periphery and the exit on the axis. Since the tangential velocities of the particle and the gas are the same, the relative velocity between the gas and particle is simply equal to the radial velocity of the gas. This result in a drag force on the particle towards the centre, and the equilibrium radius of rotation of the particle can be obtained by balancing the radial drag force and the centrifugal force:

$$3\pi\mu_g d_p v_r = \frac{\pi}{6} d_p^3 \left(\rho_p - \rho_g\right) \frac{v_\theta^2}{r} \tag{2.3.3}$$

Where, d_p=particle diameter, and v_r=radial velocity of the gas at radius r. Arranging the above equation, for v_r

$$v_r = \frac{d_p^3\left(\rho_p - \rho_g\right)v_\theta^2}{18\mu_g r} \tag{2.3.4}$$

The tangential velocity of the particle in the vortex has been found experimentally to be inversely proportional to the radius of rotation according to equation,

$$v_\theta r^n = \text{constan} \tag{2.3.5}$$

Where, n is the exponent and dimensionless. For an ideal gas n=1. The real values observed are between 0.5 to 1, depending upon the radius of the cyclone body and gas temperature. v_θ can be related to the tangential velocity at the inlet to the cyclone $\mathrm{v}_{\theta\mathrm{i}}$ as

$$v_\theta = v_{\theta i}\left(\frac{D}{2r}\right)^n \tag{2.3.6}$$

Where, D=diameter of the cyclone. $\mathrm{v}_{\theta\mathrm{i}}$ may be taken as the velocity of the gas through the inlet pipe, i.e.,

$$v_{\theta i} = \frac{Q}{A_i} \tag{2.3.7}$$

Where, Q=gas volumetric flow rate and A_i=cross-sectional area of the inlet. Therefore,

$$v_\theta = \frac{Q}{A_i}\left(\frac{D}{2r}\right)^n \tag{2.3.8}$$

$$v_r = \frac{d_p^3\left(\rho_p - \rho_g\right)}{18\mu_g r^{(2n+1)}}\left(\frac{Q}{A_i}\right)^2\left(\frac{D}{2r}\right)^{2n} \tag{2.3.9}$$

The most satisfactory expression for cyclone performance is still the empirical one. Lapple correlated collection efficiency in terms of the cut size d_{pe} which is the size of those particle that are collected with 50% efficiency. Particle larger than d_{pe} will have collection efficiency greater than 50% while the smaller particle will be collected with lesser efficiency. The cut size is given by:

$$d_{pe} = \sqrt{\frac{9\mu_g b}{2\pi N_e v_i\left(\rho_p - \rho_g\right)}} \tag{2.3.10}$$

Where, b=inlet width, v_{i}=gas inlet velocity and N_e=effective number of turns a gas makes in traversing the cyclone (5 to 10 in most cases).

Pressure drop: The pressure drop may be estimated according to the following equation,

$$\Delta P = \frac{K\rho_g v_i^2 (ab)}{2D_e^2} \tag{2.3.11}$$

Where, K=a constant, which averages 13 and ranges from 7.5 to 18.4, ΔP =pressure drop, a, b and D_e=cyclone dimensions, v_i=inlet gas velocity and ρ_g =gas density.

Problem 2.3.1: A conventional cyclone with diameter 0.5 m handles 4.0 m^3/s of standard air ($\mu_g=1.81\times10^{-5}$ kg/m-s and ρ_g being negligible w.r.t ρ_p) carrying particles with a density of 2500 kg/m^3. For N_e=6, inlet width (b)=0.25 m, inlet height (a)=0.5 m, determine the cut size of particle diameter.

Solution: Given

b=0.25, D=0.25×0.5=0.1

a=0.5, D=0.5×0.5=0.25

ρ_p=2500 kg/m^3

$\mu_g=1.81\times10^{-5}$ kg/m-s

Q=4 m^3/s

$$v_i = \frac{Q}{a\times b} = \frac{4}{0.1\times0.25} = 160 \text{ m/s}$$

$$d_{pe} = \sqrt{\frac{9\mu_g b}{2\pi N_e v_i (\rho_p - \rho_g)}}$$

$$d_{pe} = \sqrt{\frac{9\times1.81\times0.25}{2\times\pi\times6\times160\times2500}} = 5.195\times10^{-4}\text{m}$$

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Lecture 4

Design of fabric filter

DESIGN OF FABRIC FILTER

- Pressure drop and air-to-cloth ratio are the major design parameters in bag-house design.
- Higher pressure drops implies that more energy is required to pull the gas through the system.
- Air-to-cloth ratio, also referred to as the face velocity, is the the volume flow of gas received by a bag-house divided by the total area of the filtering cloth. This ratio is the result of and is usually It is expressed as acfm/ft^2. The air-to-cloth ratio determines the unit size and thus, capital cost.
- Higher air-to-cloth ratio mean less fabric, therefore less capital cost. However, higher ratio can lead to high pressure drop thus requiring higher energy. Also, more frequent bag cleanings may be required, thus increasing the downtime.
- Fabric filters are classified by their cleaning method or the direction of gas flow and hence the location of the dust deposit [1].

Pressure Drop: The pressure drop is the sum of the pressure drop across the filter housing and across the dust-laden fabric.

- The pressure drop across the housing is proportional to the square of the gas-flow rate due to turbulence.
- The pressure drop across the dust-laden fabric is the sum of the pressure drop across the clean fabric and the pressure drop across the dust cake.

$$\Delta P = \Delta P_f + \Delta P_d = K_1 v + K_2 v w \tag{2.4.1}$$

Where, *v*=the filtration velocity; K_1=the flow resistance of the clean fabric; K_2=the specific resistance of the dust deposit; *w*=the fabric dust areal density; K_1 is related to Frazier permeability, which is the flow through a fabric in cfm/ft^2 of fabric when the pressure drop across the fabric is 0.5 in w.g. as follows [1]:

$$K_1\left(\mathrm{Pa\,s\,m^{-1}}\right) = \frac{24590}{\mathrm{Frazier\,Permeability\,(cfm/ft^2\ at\ 0.5in\ w.g.)}} \tag{2.4.2}$$

Evaluation of specific resistance K_2 : The dust collected on a membrane filter and K2 should be calculated from the increase in pressure drop (ΔP_2- ΔP_1) with filter weight gain (M_2-M_1) as follows:

$$K_2 = \frac{A}{v}\left(\frac{\Delta P_2 - \Delta P_1}{M_2 - M_1}\right) \quad (2.4.3)$$

Where, A is the surface area of the membrane filter.

Problem 2.4.1. A fabric filter is to be constructed using bags that are 0.1 m in diameter and 5.0 m long. The bag house is to receive 5 m^3/s of air. Filtering velocity is 2.0 m/min. Determine the number of bags required for a continuous removal of particulate matter.

Solution:

$$N = \frac{A_t}{A_b}$$

$$A_t = \frac{Q_g}{u}$$

$$A_b = \pi d L$$

Given that: Diameter of bag (d) = 0.1 m; Length of bag (L) = 5 m; Flow rate (Q_g)= 5 m^3/s; Filtering velocity (u)=2 m/min=0.0333 m/s.

$$\text{Total area of filter} = A_t = \frac{5}{0.0333} = 150 \text{ m}^2$$

$$\text{Area of single bag} = A_b = 3.14 \times 0.1 \times 5.0 = 1.57 \text{ m}^2$$

$$\text{Number of bags} = N = \frac{150}{1.57} = 95.54 \approx 96$$

The numbers of bags required for a continuous removal of particulate matter are 96.

Problem 2.4.2. A bag house is to design to handle 1000 m^3/min of air. The filtration takes place at constant pressure so that the air velocity through each bag decreases during the time between clearing according to the relation

$$u = \frac{1}{0.267 + 0.08\,t}$$

Where, u is in m^3/m^2 min of cloth and t is time in min.

The bags are shaken in sequence row by row on a 30 min cycle. Each bag is 20 cm in diameter and 3 m height. The bag house is to be square in x-section with 30 cm spacing between bags and 30 cm clearance from the walls. Calculate the number of bags required.

Solution:

$$V_{avg} = \frac{1}{t}\int_0^t u\,dt = \frac{1}{t}\int_0^t \frac{dt}{0.267+0.08t}$$

$$A_t = \frac{Q_g}{V_{avg}}$$

$$A_b = \pi d L$$

$$N = \frac{A_t}{A_b}$$

Given: Ratio of flow rate air to cloth area (u)=$\frac{1}{0.267+0.08t}$ (m^3/m^2 min of cloth).

Time (t)=30 min; d- Diameter of bag (d)=0.2 m; Length of bag (L)=3 m; Flow rate (Q_g)=1000 m^3/min.

Average velocity (V_{avg})=? (m/min)

Total area of filter (A_t)=? (m^2).

Area of single bag (A_b)=? (m^2).

Number of bags (N)=?

Put the values in equation, we get the average velocity

$$V_{avg} = \frac{1}{30}\int_0^{30} \frac{dt}{0.267+0.08t} = \frac{28.78}{30} = 0.959 \text{ m / min}$$

$$A_t = \frac{1000}{0.959} = 1042.390 \text{ m}^2$$

$$A_b = \pi \times 0.2 \times 3 = 1.8849 \text{ m}^2$$

$$N = \frac{1042.390}{1.884} = 553.005 \approx 553$$

The numbers of bags required for a continuous removal of particulate matter are 553.

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Lecture 5

Particulate emission control by electrostatic precipitation

ELECTROSTATIC PRECIPITATORS

The electrostatic precipitator is one of the most widely used collection devices for particulates. An electrostatic precipitator (ESP) is a particulate collection device that removes particles from a flowing gaseous stream (such as air) using the force of an induced electrostatic charge.

ESP can be operated at high temperature and pressures, and its power requirement is low. For these reasons the electrostatic precipitation is often the preferred method of collection where high efficiency is required with small particles.

ESP are highly efficient filtration devices that minimally impede the flow of gases through the device, and can easily remove fine particulate matter such as dust and smoke from the air stream [1].

In the electrostatic precipitation process the basic force which acts to separate the particles from the gas is electrostatic attraction. The particles are given an electrical charge by forcing them to pass through a corona, a region in which gaseous ions flow. The electrical field that forces the charged particles to the walls comes from electrodes maintained at high voltage in the center of the flow lane [2].

Control of emissions from the industrial sources has served the threefold purpose of

1. Recovery of the for economic reason
2. Removal of abrasive dusts to reduce wear of fan component
3. Removal of objectionable natter from gases being discharged into the atmosphere

APPLICATION OF ELECTROSTATIC PRECIPITATORS:

- Pulp and paper mills, Non-ferrous metal industry, Chemical industry, Public buildings and areas
- Cement recovery furnace, steel plant for cleaning Blast furnace gas.
- Removing tars from coke oven, sulphuric acid (Pyrite raw material) , phosphoric acid plant
- Petroleum industry for recovery of catalyst, carbon black, thermal power plant.

Table 2.5.1. Advantages and Disadvantages of ESP.

Advantages	Disadvantages
High collection efficiency.	High initial cost.
Low maintenance and operating costs.	More space requirement.
Handles large volume of high temperature gas.	Possible explosion hazards.
Negligible treatment time.	Production of poisonous gas.
Easy cleaning.	

REQUIREMENT OF ELECTROSTATIC PRECIPITATION PROCESS

- Source of high voltage
- Discharge and collecting electrode
- Inlet and outlet for gas
- A means for disposal of collected material
- Cleaning system, Outer casing.

STEPS IN ELECTROSTATIC PRECIPITATION

- Generation of Electric field high voltage Direct current 20-80kv.
- Generation of electric charges
- Transfer of electric charge to a dust particle.
- Movement of the charge dust particle in an electric field to the collection electrodes.
- Adhesion of the charge dust particle to the surface of the collection electrode.
- Dislodging of dust layer from collection electrode
- Collection of dust layer in a hopper
- Removal of the dust from the hopper.

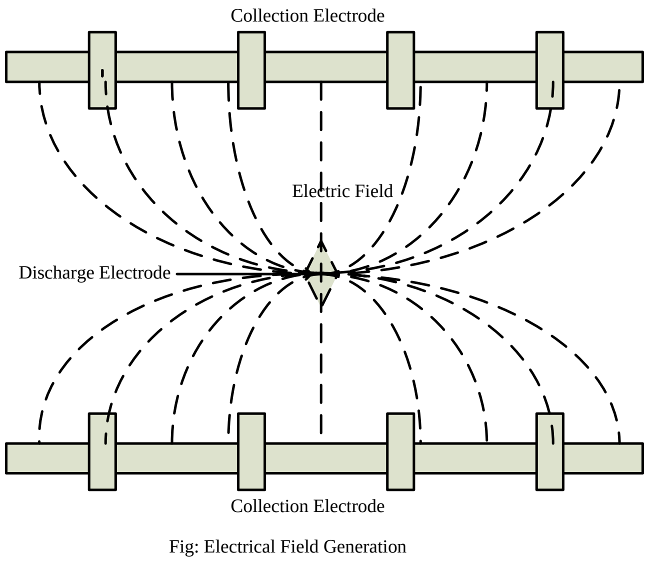

Figure 2.5.1. Electrical field generation

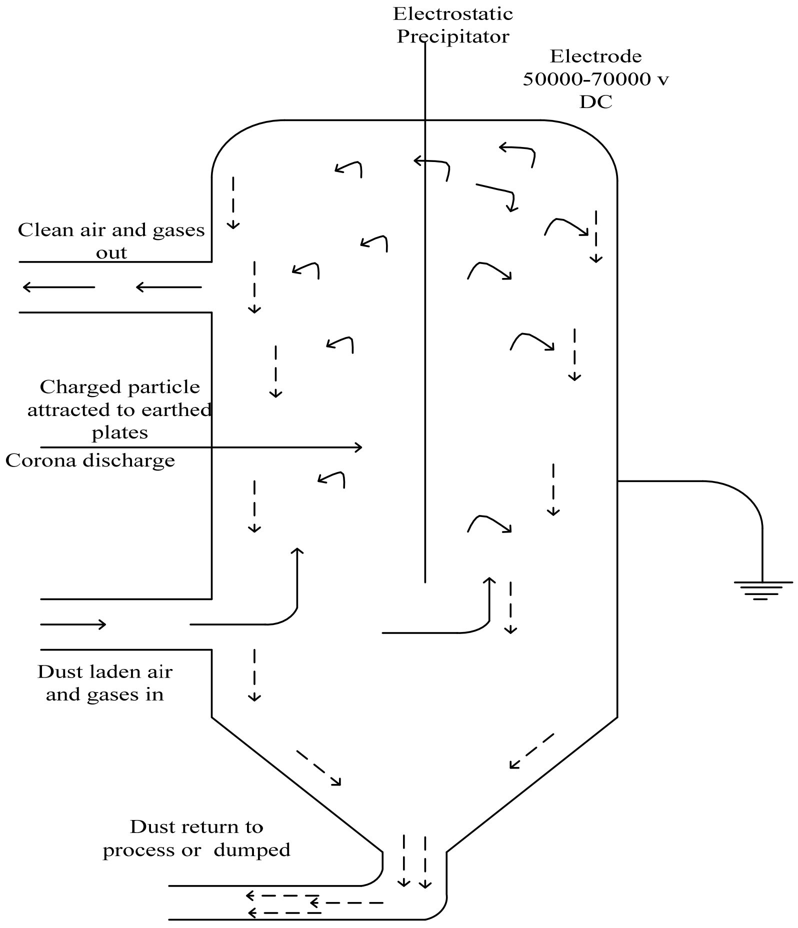

Figure 2.5.2. Movement of dust and air in ESP

PRINCIPLE OF ESP

Principle of ESP has four distinct phases as follows:

(I) Ionization or corona generation: When the potential difference between the wire and electrode increases, a voltage is reached where an electrical breakdown of the gas occurs near the wire. This electrical break down or ion discharge is known as corona formation and thereby gas is transformed from insulating to conducting state.

Two types of corona discharge can be generated which are:

(a) Negative corona: In negative corona, discharge electrode is of negative polarity and the process of electron generation occurs at narrow region

(b) Positive corona: When positive voltage is applied to discharge electrodes in the same way as negative corona, large number of free electron and positive ions are generated. Or large number of positive ions produced move towards collecting electrode and thus transfer charge to dust particles upon collision.

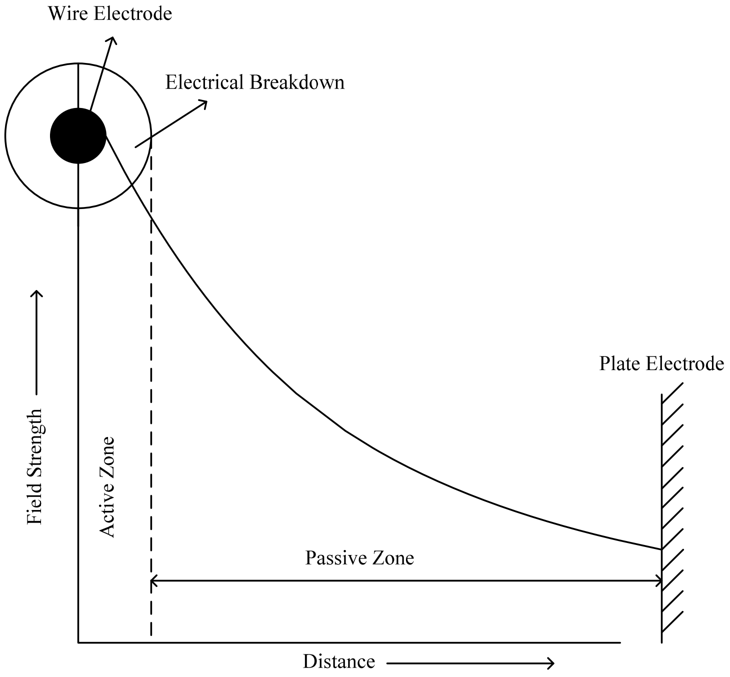

Figure 2.5.3.Variation of field strength between wire and plate electrodes

Negative coronas are more commonly used in industrial application, while for cleaning air in inhabited space positive coronas are used. Due to ozone generation in negative corona its application for air cleaning in inhabited area is avoided.

(II) Charging of Particles: Particle charging takes place in region between the boundary of corona glow and the collection electrode, where particles are subjected to the rain of negative ions from the corona process. Mainly two mechanisms are responsible for particle charging. Each mechanism becomes significant according to particle size ranges. For particles having diameter greater than 1µm, field charging is dominant force; and for particle size less than 0.2 µm diffusion charging predominates.

(III) Migration and precipitation of particle:

(IV) Removal of deposited dust: Once collected, particle can be removed by coalescing and draining, in the case of liquid aerosols and by periodic impact or rapping, in case of solid material. In case of solid material, a sufficiently thick layer of dust must be collected so that it falls into the hopper or bin in coherent masses to prevent excessive re-entrainment of the material into the gas system [2].

TYPES OF ELECTROSTATIC PRECIPITATORS

ESPs are configured in several ways. Some of these configurations have been developed for special control action, and others have evolved for economic reasons.

[A] SINGLE STAGE PRECIPITATORS

Plate-Wire Precipitators

- In a plate-wire ESP, gas flows between parallel plates of sheet metal and high-voltage electrodes.
- These electrodes are long wires weighted and hanging between the plates or are supported there by mast-like structures (rigid frames).
- Within each flow path, gas flow must pass each wire in sequence as flows through the unit.
- Plate-wire ESPs are used in a wide variety of industrial applications, including coal-fired boilers, cement kilns, solid waste incinerators, paper mill recovery boilers, petroleum refining catalytic cracking units, sinter plants, basic oxygen furnaces, open hearth furnaces, electric arc furnaces, coke oven batteries, and glass furnaces [2, 3].

Flat Plate Precipitators

- A significant number of smaller precipitators [100,000 to 200,000 actual cubic feet per minute (acfm)] use flat plates instead of wires for the high-voltage electrodes.
- A flat plate ESP operates with little or no corona current flowing through the collected dust, except directly under the corona needles or wires [3].
- Flat plate ESPs seem to have wide application for high-resistivity particles with small (1 to 2 µm) mass median diameters
- Fly ash has been successfully collected with this type of ESP, but low-flow velocity appears to be critical for avoiding high rapping losses.

Tubular Precipitators

- The original ESPs were tubular like the smokestacks they were placed on, with the high-voltage electrode running along the axis of the tube.
- Tubular precipitators have typical applications in sulfuric add plants, coke oven by-product gas cleaning (tar removal), and, recently, iron and steel sinter plants [2].

Wet Precipitators

- Any of the precipitator configurations discussed above may be operated with wet walls instead of dry.
- The water flow may be applied intermittently or continuously to wash the collected particles into a sump for disposal.
- The advantage of the wet wall precipitator is that it has no problems with rapping re-entrainment or with back coronas.
- The disadvantage is the increased complexity of the wash and the fact that the collected slurry must be handled more carefully than a dry product, adding to the expense of disposal [4].

TWO-STAGE PRECIPITATORS

- The previously described precipitators are all parallel in nature, i.e., the discharge and collecting electrodes are side by side.
- Two-stage precipitators are considered to be separate and distinct types of devices compared to large, high-gas-volume, single-stage ESPs.

- The two-stage precipitator invented by Penney is a series device with the discharge electrode, or ionizer, preceding the collector electrodes.
- Advantages of this configuration include more time for particle charging, less propensity for back corona, and economical construction for small sizes [3].

OPERATIONAL ISSUES

- Pre-Scrubbing
- Wash-down sprays and wires
- Wet/dry Interface
- Current Suspension
- Sparking
- Mist Elimination

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Lecture 6

Design of ESP

DESIGN OF ELECTROSTATIC PRECIPITATOR

Introduction

An electrostatic precipitator (ESP) is a particle control device that uses electrical forces to move the particles out of the flowing gas stream and onto collector plates. The particles are given an electrical charge by forcing them to pass through a corona, a region in which gaseous ions flow [1].

INFORMATION REQUIRED FOR DESIGNING OF ESP

The efficiency of an ESP depends upon two factors

- The size of the unit i.e. total square ft. of the collecting plate area
- Amount of independent electrical energisation

In addition following details are required for designing an ESP

1. Source of the emission : Properties of the process by which the pollutants are produced
2. Particle size distribution
3. Chemical analysis of dust in relation to particle size
4. Specific eclectic resistivity of dust
5. Dust concentration of clean gas
6. Required dust concentration of clean gas(efficiency)
7. Properties of gas: composition, temperature, pressure.
8. Corrosive properties of gas
9. Gas flow rate

Apart from these variables the design of ESP also include the determination of ancillary factors such as rappers to shake the dust loose from the plates, automatic control system, measures for ensuring high-quality gas flow, dust removal system, provisions for structural and heat insulation and performance monitoring system [2].

Firstly size distribution of dust is determined; from the information of size distribution of dust the migration velocity is calculated. After that number of charge on a particle is calculated by using appropriate equation. On the basis of precipitation rate the collecting surface area for a given efficiency at a particular flow rate is calculated by using Deutsch-Andersen relationship.

PARTICLE CHARGING

According to kinetics, the electron energy Q_d of an originally neutral dust particle is given by [3]:

$$Q_d = ne = \left(\frac{d_p KT}{2E}\right) \times \ln\left(1 + \left(\frac{d_p \pi C N e^2}{2KT}\right)\right) \tag{2.6.1}$$

Where, N=number of electronic charges; d_p=dust particle dia.; $K=1.38*10^{-23}$(J/K); T=Absolute Temp.; $E=1.602\times10^{-19}$ [C]–electrons; N=free ion density; $C=(2kT/m_i)^{1/2}$

Charging velocity is very fast at the beginning but slow down with time.

$$Q_d = ne = d_P^2\left(\frac{\pi}{4}\right)NeCt \tag{2.6.2}$$

Field Charging:

$$Q_f = ne = 0.19 * 10^{-9} r_P^2 E \tag{2.6.3}$$

Where, n=Number of electronic charge; r_p=Radius of particle; E=Average field intensity, $E=1.602*10^{-19}$

MIGRATION VELOCITY

The velocity of charged particle suspended in a gas under the influence of an electric field is known as migration velocity. The particle migration velocity is the most important parameter and is function of a large number of operation quantities such as- Electric field strength, particle size, gas viscosity, properties of the dust [3].

Principal forces acting on particle are gravitational force, electric force, viscous force and inertial force.

$$V_{pm} = \frac{qEC}{3\pi\mu d} \tag{2.6.4}$$

Where, V_{pm}=Particle migration velocity towards the collector electrode; q=ne, value of n depends upon types on charging (diffusion or field); C=Cunningham correction factor; E=Collector electric field; μ=gas viscosity; and d=particle size (μm).

Table 2.6.1 Effective migration velocity (m/s) for various type of dusts.

Dust	Migration Velocity (m/s)
Zinc Oxide	0.02-0.03
Sulfuric Acid	0.08-0.16
Metal Oxides	0.02-0.03
Calcium Carbonate	0.04-0.05
Smoke Fume pit coal furnace	0.02-0.11
Fly ash from lignite furnace	0.18-0.25
Blast furnace dust	0.05
Smelter dust	0.07-0.09
Blast furnace dust	0.05

COLLECTION EFFICIENCY OF ESP

The collection efficiency of an ESP as a function of gas flow rate and precipitator size is given by the Deutsch-Andersen Equation

Assumptions:

a. Repulsion effect is neglected.
b. Uniform gas velocity throughout the cross section
c. Particles are fully charged by field charging.
d. No hindered settling effect.

Collection efficiency mathematically expressed as follows [3]:

$$\eta = 1 - \exp\left(-\frac{V_{pm} A_c}{Q}\right) \tag{2.6.5}$$

η=Fractional Collection Efficiency; A_c=Area of the collection electrode; V_{pm}=Particle migration velocity; Q=Av=Volumetric flow rate of gas; v=gas velocity.

$$\eta = 1 - \exp\left(-\frac{V_{pm} A_c \times L}{V \times v}\right) \tag{2.6.6}$$

Where, V=Volume of precipitator.

For cylindrical type collector:

$$\frac{A_c}{V}=\frac{4}{D_c} \tag{2.6.7}$$

For parallel plate:

$$\frac{A_c}{V}=\frac{2}{S} \tag{2.6.8}$$

Where, S=distance between the two parallel plates; V=Gas Volume; W=Precipitation Rate Parameter; A=Plate Area; Q=Volumetric Flow Rate of Gas.

When the charged particle passing a charge q_p is in a region where an electric field strength of E_c is present, a force F will act on particle.

$$F=q_P E_c \tag{2.6.9}$$

The migration of particle towards the collector is resisted by a drag force and the net force on the particle is zero when it moves with a constant drift velocity (v_{pm})

$$q_P E_c=\frac{\Pi C_D d_p^2 \rho_g V_{pm}^2}{8C} \tag{2.6.10}$$

For small particle stokes law is applicable.

Hence

$$C_D=\frac{24\mu g}{\rho_g d_P V_{pm}} \tag{2.6.11}$$

Substitute C_D in above equation it gives v_{pm}

$$V_{pm}=\frac{q_P E_c C}{3\Pi d_P \mu g}$$

$$\eta=1-\exp\left(-\frac{q_P C A_c E_{cm}}{3\Pi\mu Q}\right) \tag{2.6.12}$$

Where, q_p=Particle charge; A_c=collector surface area; E_{cm}=electric field strength; d=particle size; μ=gas viscosity

$$\text{C = Cunningham correction factor} = 1+\left(\frac{2\lambda}{d_P}\right)\left(1.257+0.4e^{-\frac{0.55d_P}{\lambda}}\right) \tag{2.6.13}$$

For standard air, λ=0.066μm

For standard air, above equation becomes

$$\eta = 1 - \exp\left(-\frac{5766 q_P C A_c E_{cm}}{Qd} \right) \tag{2.6.14}$$

Collection efficiency of different types of precipitators

Ψ=(Mp1-Mp2)/Mp1. (2.6.15)

Where, Mp1 and Mp2 being the mass of dust per unit volume of the gas stream at the entrance and exit of the precipitator.

The volumetric flow rate Vg in a precipitator by the equation

$$V_g = \pi\left(\frac{d_c^2}{4}\right)v \tag{2.6.16}$$

For a plate precipitators

$$V_g = nahv \tag{2.6.17}$$

Where; h=Height of the plate which is equal to the height of the channels

The equation is related to gas velocity v and number n of the element for pipe precipitators. If particles are of a solid, the collected particles are removed from electrode by shaking it in a process known as rapping. If particles are of a liquid, after collecting on the electrode the liquid then flows down the electrode by action of gravity and collects at the bottom. The particle charging process is done by means of corona surrounding a highly charged electrode, such as wire [4].

DUST RESISTIVITY

- Dust resistivity is the most important dust property.
- With high dust resistant a large voltage in the dust layer is observed accumulated by a decreasing current.
- Specific Dust Resistivity: is the resistivity of a layer of dust will a layer thickness of 1 cm over a collection area of 1m^2
- The Specific dust resistivity is designed the symbol ρ_{rs} and measured in Ωcm

$$\rho_{rs} = \frac{A_c R_m}{\delta} \tag{2.6.18}$$

Where, A_c=collection area; R_m=mean electric resistivity; δ=dust layer thickness.

Table 2.6.1. Ranges for ESP design parameters

Parameter	Range of values
Precipitation rate V_P	1.0-10 m/min
Channel width, D	15-40 cm
$\text{Specific collection area} = \dfrac{\text{Plate area}}{\text{Gas flow rate}}$	0.25-2.1$m^2/(m^3/min)$
Gas velocity u	1.2-2.5 m/s
Aspect ratio R= $\dfrac{\text{Duct length}}{\text{Height}}$	0.5-1.5(Not less than 1 for □>99%)
Corona power ratio	1.75-17.5W/(m^3/min)
Corona current ratio	50-750 µA/m^2
Plate area per electrical set	460-7400 m^2
Number of electrical section Ns	
a. In the direction of gas flow	2-8
b. Total number of sections	1-10 bus sections/(1000 m^3/min)
Spacing between sections	0.5-2m
L_{en}, L_{ex}	2-3m
Plate height; length	8-15m; 1-3m

Problem 2.6.1: A plate type ESP use in a cement plant for removing dust particles consist of 10 equal channels. The spacing between plates is 15 cm and the plates are 3 m high and 3 m long. Unit handles 20,000 m^3/h of gas.

a) What is the efficiency of collection plates?

b) What is the collection rate of particles having density 9.2 gm/m^3?

c) What should be the length of the plate for achieving efficiency of 99% keeping other parameter same?

Solution:

$$\eta = 1 - \exp\left(\frac{-V_{pm} \times A_c}{Q_g}\right)$$

$$A_c = 2 \times n \times h \times l$$

$$q = \eta \times Q_g \times \rho$$

Given: Particle migration velocity (V_{pm})=0.1 m/sec; Number of plates (n)=10; Height of plate (h)=3 m; Length of plate (l)=3 m; Gas flow rate (Q_g)=20000 m^3/h=2.7778 m^3/sec; Density of particle (ρ)=9.2 g/m^3.

Total area of collection plates (A_c)=2×10×3 m×3 m=180 m^2.

$$\eta = 1 - \exp\left(\frac{-0.1 \times 180}{5.555}\right) = 0.9608$$

$$\eta = 96.08\%$$

The collection rate $q = 0.9608 \times 5.555 \times 9.2 = 49.1070 g/\sec$

Let us assume the length of plate is l m.

Therefore, the total collection area of plate (A_c) becomes 40 l m^2.

The length of plate can be obtained from following equation:

$$0.99 = 1 - \exp\left(\frac{-0.1 \times 40 \times l}{5.555}\right)$$

$$l = 95.9314 m$$

a) The efficiency of collection plate is 96.08%.

b) The collection rate of particles having density is 49.1070g/sec.

c) Length of the plate for achieving efficiency of 99% keeping other parameter same is 95.93 m.

Problem 2.6.2: An ESP handles 10^7 ft^3/min of gas. It uses 3.6 Amp current and has 28000 ft^2 collection plate areas. At the present operating temperature, the dust resistivity is 3×10^{11} Ω-cm. It has been suggested that the gas cooled to reduce the dust resistivity to 7×10^{10} Ω-cm assuming that average dust thickness is 0.45 inch and that voltage difference between the charging walls and outer surface of the dust layer is 30 kV must be maintained in both cases. Estimate the reduction in power requirement that cooling the gas to get neglect the effect of gas temperature on charging and drift velocity.

Solution:

$$V = \frac{\gamma \times \delta \times I}{\mathrm{A}}$$

$$P = V \times I$$

Given: Gas flow rate (Q_g)=10^7 ft^3/min; Current (I)=3.6 A; Total area of collection plates (A_c)=28000 ft^2=26.01×10^6 cm^2; Dust resistivity (γ_1)=3×10^{11} Ω-cm; Dust resistivity (γ_2)=7×10^{10} Ω-cm; Dust thickness (δ=0.45 inch=1.143 cm. Assuming that V_1 is the voltage when dust resistivity is γ_1 (kV) and voltage is V_2 when dust resistivity is γ_2 (kV) and P is the power input (kW)

For a dust resistivity of 3×10^{11} Ω-cm,

$$V_1 = \frac{\gamma_1 \times \delta \times I}{\text{A}} = \frac{3\times10^{11}\times1.143\times3.6}{26.01\times10^6} = 47.4602 \text{ kV}$$

Total applied voltage is 30 kV+47.4602 kV=77.4602 kV

Therefore, the power input when dust resistivity is γ_1

$$P_1 = V_1 I = 77.4602\times3.6 = 278.856 \text{ kW}$$

For a dust resistivity of 5×10^{10} Ω-cm,

$$V_2 = \frac{\gamma_2 \times \delta \times I}{\text{A}} = \frac{7\times10^{10}\times1.143\times1.6}{26.01\times10^6} = 11.074 \text{ kV}$$

Total applied voltage is 30 kV+11.07 kV=41.074 kV

The power input $P_2 = V_2 I = 41.074\times3.6 = 147.886$ kW

Therefore by cooling of gas, power input gets reduced to ΔP=P_1- P_2.

ΔP=278.856-147.886=130.97 kW.

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Lecture 7

Gaseous emission control by adsorption

GASEOUS EMISSION CONTROL BY ABSORPTION AND ADSORPTION

INTRODUCTION

Combustion processes generate various primary and secondary air pollutants such as carbon oxides (mainly CO), nitrogen oxides (NO_x), sulphur oxides (SO_x), ozone, along with organic acid, inorganic acid, petrochemical oxidant gas and hydrocarbons (HC). Different treatment processes are applied for controlling these and other gaseous emissions. These processes include adsorption and absorption. Selection of appropriate technique depends in part, physical and chemical characteristic of specific gas and the vapour phase compounds present in the gas stream.

For stationary air pollution sources, we can select single or combined air pollution control technique. Variety of devices are used for controlling gaseous pollutant, and choosing most cost effective, most cost efficient unit requires careful attention to the particular operation for which control devices are intended. In order to control the emissions within given standard emissions it is necessary to monitor emissions carefully after selecting best control technique.

PROPERTIES OF GAS STREAM FOR SELECTION OF A CONTROL SYSTEM

The selection and design of a gaseous contaminant control system is done based on some specific information concerning the gas stream to be treated. Following are some factors considered during selection of a process

- Gas stream particulate matter characteristics
- Gas stream average and peak flow rates
- Gas stream average and peak temperatures
- Gas stream particulate matter average and peak concentrations
- Gas stream minimum, average, and maximum oxygen concentrations
- Contaminant average and peak concentrations
- Contaminant ignition characteristics

ADSORPTION

In adsorption process the contaminant removal is done by passing a stream of effluent gas through a pours solid material (adsorbent) contained in adsorption bed. The surface of porous solid material attracts and holds the gas (the adsorbate) by either by physical or chemical adsorption. The basic difference between physical and chemical adsorption is the manner in which the gas molecule is bonded to the adsorbent.

Table 2.7.1 Difference between physical and chemical adsorption

Physical Adsorption	Chemical adsorption
Gas or vapour molecule is weakly held to the solid surface by intermolecular attractive forces.	Gas contaminant and is held strongly to the solid surface by valence forces.
It is accompanied by capillary condensation within the pores.	Chemical reaction occurs between the adsorbent and the gaseous contaminant.
Physical adsorption is easily reversed by the application of heat or by reducing the pressure.	Chemical reaction is usually irreversible.
Commonly used for the capture and concentration of organic compounds.	It is frequently used for the control of acid gases. Chemical adsorption is also used for the control of mercury vapour.
Gas temperature is usually maintained at levels less than approximately 120°F.	Chemical adsorption can be conducted at higher temperatures(100°F to 400°F)
Higher the boiling point greater will be adsorption.	Much slower than the physical adsorption. Amount of gas adsorb depends upon temperature and pressure.
It is directly proportional to surface area available and multilayer adsorption can take place.	Liberates greater amount of heat and hence requires much energy.

SALIENT FEATURE OF ADSORPTION PROCESS

(1) Adsorption processes are used extensively on large-scale applications having solvent vapour concentrations in the range of 10 to 10,000 ppm.

(2) Prior to becoming saturated with the solvents, the adsorbent is isolated from the gas stream and treated to drive the solvent compounds out of the solid adsorbent and into a small volume, high concentration gas stream.

(3) The desorbed gas stream is then treated to recover and reuse the solvents.

(4) The adsorbent is cooled (if necessary) and returned to adsorption service.

(5) Because the adsorbent is treated and placed back in service, these adsorption processes are termed regenerative.

(6) Adsorption processes usually operate at efficiencies of 90% to 98% over long time periods.

Table 2.7.2 Physical Properties of Major Type of Adsorbents

Adsorbent	Internal Porosity (%)	Surface Area (m^2/gm)	Pore Volume (cm^3/gm)	Bulk Dry density (gm/cm^3)	Mean Pore Diameter (Å)
Activated carbon	55-75	600-1600	0.8-1.2	0.35-0.50	1500-2000
Activated alumina	30-40	200-300	0.29-0.37	0.90-1.00	1800-2000
Zeolite(Molecular sieves)	40-55	600-700	0.27-0.38	0.80	300-900
Synthetic Polymers	-	1080-1100	0.94-1.16	0.34-0.40	-

STEPS IN ADSORPTION PROCESS

Adsorption occurs in three steps

Step 1: The contaminant diffuses from the bulk gas stream to the external surface of the adsorbent material [1].

Step 2: The contaminant molecule migrate external surface to the macropores, transitional pores, and micropores within each adsorbent.

Step 3: The contaminant molecule adheres to the surface in the pore. Following figure illustrates this overall diffusion and adsorption process.

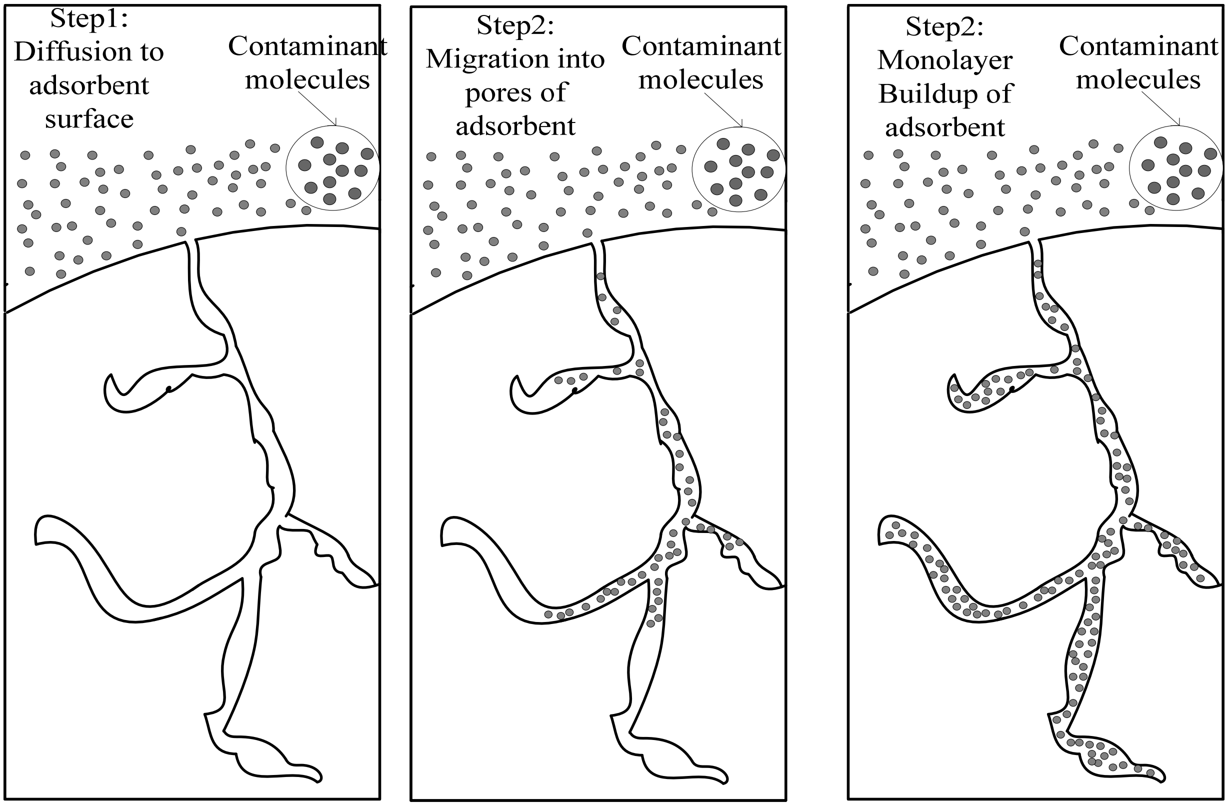

Figure 2.7.1: Adsorption steps

Steps 1 and 2 are diffusional processes that occur because of the concentration difference between the bulk gas stream passing through the adsorbent and the gas near the surface of the adsorbent. Step 3 is the actual physical bonding between the molecule and the adsorbent surface. This step occurs more rapidly than steps 1 and 2 [2].

ADSORPTION-CAPACITY RELATIONSHIPS

Three types of equilibrium graphs are used to describe adsorption capacity, (1) isotherm at constant temperature, (2) isobar at constant pressure, and (3) isostere at constant amount of vapour adsorbed.

Isotherm: The isotherm is a plot of the adsorbent capacity versus the partial pressure of the adsorbate at a constant temperature. Adsorbent capacity is usually given as pound of adsorbate per 100 pound of adsorbent. These type of graphs are used to estimate the quantity of adsorption. Isotherms can be concave upward, concave downward, or “S” shaped [3, 4].

Isostere: The isostere is a plot of the natural log of the pressure versus the reciprocal of absolute temperature (ln(p) vs. 1/T) at a constant amount of vapour adsorbed. Adsorption isostere lines are straight for most adsorbate-adsorbent systems. The isostere is important because the slope of the isostere corresponds to the differential heat of adsorption. The total or integral heat of adsorption is determined by integration over the total quantity of material adsorbed [4, 5].

Isobar: It is a plot of the amount of vapour adsorbed versus temperature at a constant pressure. Below figure shows an isobar line for the adsorption of benzene vapours on activated carbon.

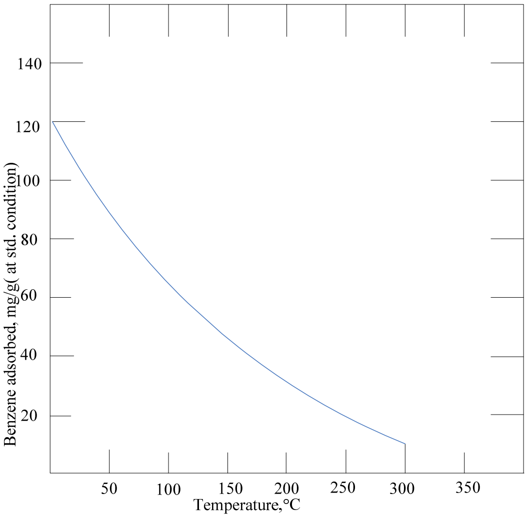

Figure 2.7.2. Adsorption isobar for benzene adsorption onto carbon.

ADSORBENT REGENERATION METHODS

After a long period of operation and when adsorption bed becomes saturated replacement or regeneration of the adsorbent bed is necessary in order to maintain continuous operation. When the adsorbate concentration is high, and/or the cycle time is short (less than 12 hours), replacement of the adsorbent is not feasible, and in-situ regeneration is required. Regeneration is accomplished by reversing the adsorption process, usually increasing the temperature or decreasing the pressure [3, 4, 6].

Following four main methods used commercially for regeneration.

Thermal Swing: The bed is heated so that the adsorption capacity is reduced to a lower level. The adsorbate leaves the surface of the carbon and is removed from the vessel by a stream of purge gas. Cooling must be provided before the subsequent adsorption cycle begins.

Pressure Swing: The pressure is lowered at a constant temperature to reduce the adsorbent capacity.

Inert Purge Gas Stripping: The stripping action is caused by an inert gas that reduces the partial pressure of the contaminant in the gas phase, reversing the concentration gradient. Molecules migrate from the surface into the gas stream [3, 4, 7].

Displacement Cycle: The adsorbates are displaced by a preferentially adsorbed material. This method is usually a last resort for situations in which the adsorbate is both valuable and heat sensitive and in which pressure swing regeneration is ineffective.

FACTORS AFFECTING THE PERFORMANCE OF ADSORPTION SYSTEM

Temperature: For physical adsorption processes, the capacity of an adsorbent decreases as the temperature of the system increases. With increase in the temperature, the vapour pressure of the adsorbate increases, raising the energy level of the adsorbed molecules. Adsorbed molecules now have sufficient energy to overcome the van der Waals’ attraction and migrate back to the gas phase. Molecules already in the gas phase tend to stay there due to their high vapour pressure.

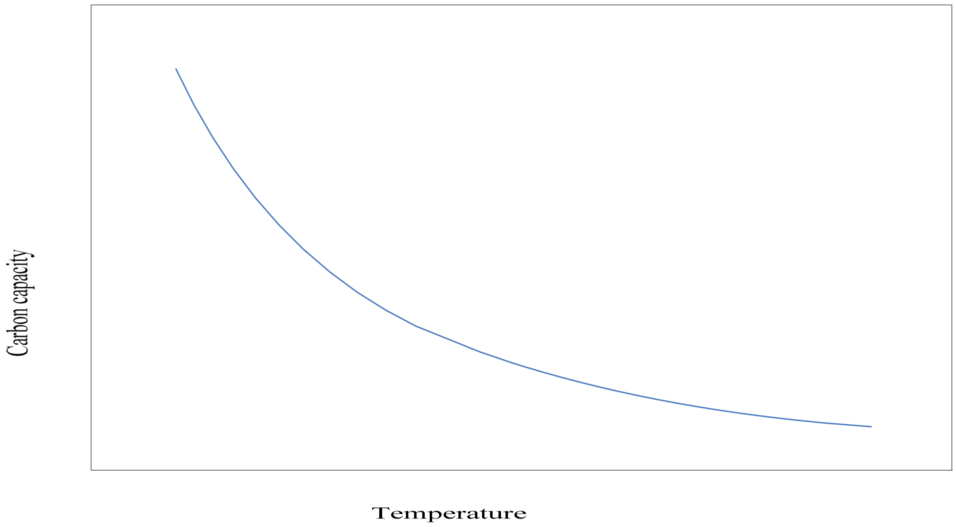

Figure 2.7.3. Carbon capacity versus gas stream temperature

Pressure: Adsorption capacity increases with an increase in the partial pressure of the vapour. The partial pressure of a vapour is proportional to the total pressure of the system. Any increase in pressure will increase the adsorption capacity of a system. The increase in capacity occurs because of a decrease in the mean free path of vapour at higher pressures [7, 8].

Gas velocity: The gas determines the contact or residence time between the contaminant stream and adsorbent. The slower the contaminant stream flows through the adsorbent bed, the greater the probability of a contaminant molecule reaching an available site.

In order to achieve 90% or more capture efficiency, most carbon adsorption systems are designed for a maximum airflow velocity of 100 ft/min (30 m/min) through the adsorber. A lower limit of at least 20 ft/min (6 m/min) is maintained to avoid flow problems such as channeling. Gas velocity through the adsorber is a function of the cross-sectional area of the adsorber for a given volume of contaminant gas.

Humidity: Activated carbon has more affinity towards nonpolar hydrocarbons over polar water vapour. The water vapour molecules in the exhaust stream exhibit strong attractions for each other rather than the adsorbent. At high relative humidity, over 50%, the number of water molecules increases to the extent that they begin to compete with the hydrocarbon molecules for active adsorption sites. This reduces the capacity and the efficiency of the adsorption system [8].

Bed Depth: Providing a sufficient depth of adsorbent is very important in achieving efficient gas removal due to the rate that VOC compounds are adsorbed in the bed. There are practical minimum and maximum limits to the bed depth.

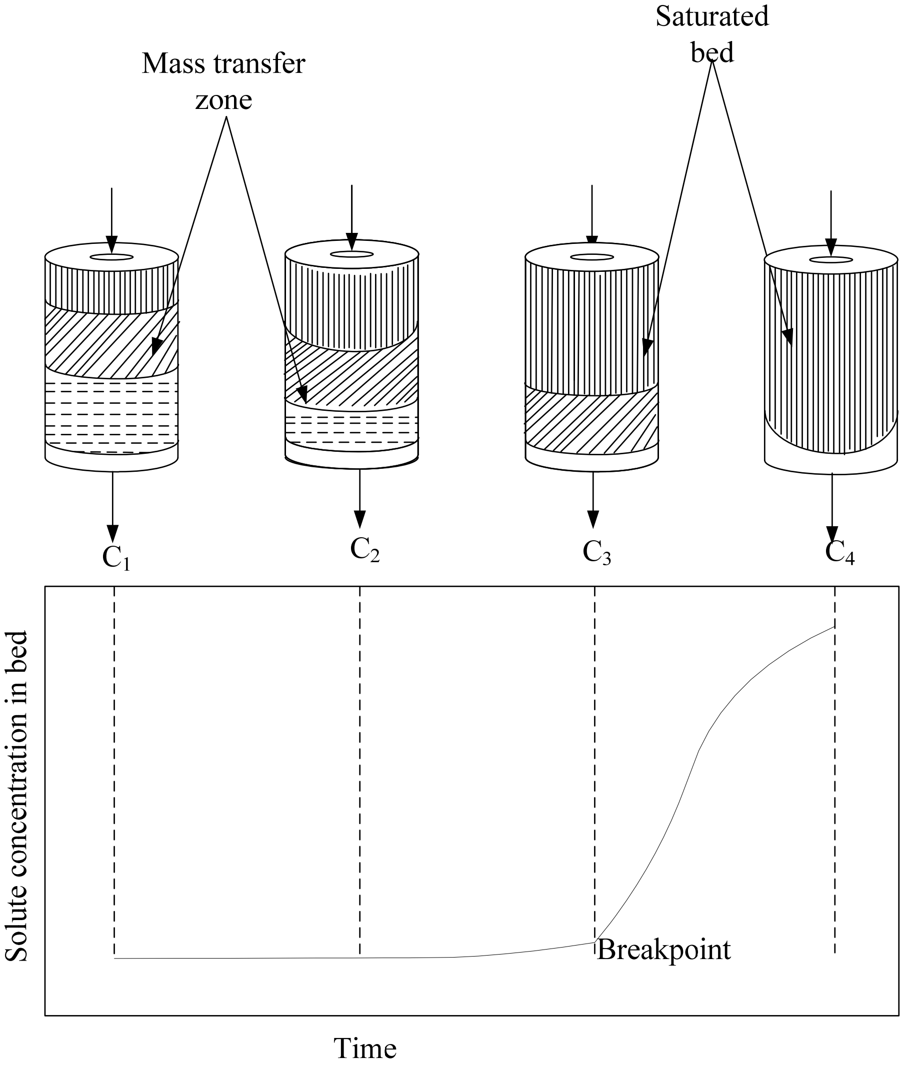

Figure 2.7.4. Mass transfer zone

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Lecture 8

Gaseous emission control by absorption

ABSORPTION

Absorption is a process where transfer of a gaseous component from gas phase to liquid phase takes place. More specifically in air pollution control, absorption involves the removal of objectionable gaseous contaminant from a process stream by dissolving them in liquid. Common terms used in absorption process are as follows:

1. Absorbent: the liquid, usually water, into which contaminant is absorbed
2. Absorbate or solute The gaseous contaminant being absorbed, such as SO_2, H_2S, etc.
3. Carrier gas: the inert portion of gas stream, usually air, from which the contaminant is to be removed [1].
4. Interface: the area where the gas phase and the absorbent contact each other.
5. Solubility: the capability of the gas to be dissolved in a liquid.

Absorption equipment used to remove gaseous contaminants are referred to as absorber or wet scrubber. Wet scrubbers usually cannot be operated to optimize simultaneous removal of both gases and particulate matter. In designing absorber from gaseous emissions, optimum mass transfer can be accomplished by:

1. Providing a large interfacial contact area.
2. Providing good mixing between gas and liquid phases.
3. Allowing sufficient residence or contact time between the phases.
4. Ensuring a high degree of solubility of the contaminant in the absorbent [1].

MECHANISM OF ABSORPTION

The gaseous contaminant are removed in absorption process by passing (contacting) a contaminated laden gas through a liquid. The following three steps occur during this process:

Step1: The pollutant diffuses from bulk area of the gas phases to the gas liquid interface.

Step2: gaseous pollutant transfer across the interface to the liquid phase. This second step is extremely rapid.

Step3: The pollutant diffuses bulk area of the liquid, making room for additional gas molecule to absorb.

The rate of mass transfer (absorption) is dependent on the diffusion rate in either the gas phase or liquid phase. The diffusion rate of gaseous pollutant molecule through a gas is always faster than its diffusion rate through the liquid because molecules in the gas are further apart than are molecules in the liquid. However the mass transfer rate depends primarily upon the solubility of the pollutant in the liquid [1].

SOLUBILITY

Solubility of contaminant affects the amount of contaminant that can be adsorbed. It is a function of both the temperature and, to a lesser extent pressure of a system. As we increase the temperature of the system the amount of gas that can be absorbed by liquid decreases, while as with increasing the pressure generally absorption increases. The solubility data are analyzed by equilibrium diagram [2].

Under certain conditions, Henry's law may also be used to express equilibrium solubility of gas liquid system, henry's is expresses as

$$p^* = Hx \tag{2.8.1}$$

Where:

p^*=partial pressure of solute at equilibrium

x=mole fraction of solute in the liquid

H=Henry's law constant, pressure/mole fraction

Henry's law can be rearranged as

$$y^* = mx$$

Where:

y^*=mole fraction in gas phase in equilibrium with liquid.

H=Henry's law constant, mole fraction in vapour phase/mole fraction in liquid phase

Restriction on Henry's law:

1. Henry's law can be used to predict solubility only when the equilibrium line is straight.
2. Henry's law does not hold good for gases that react or dissociate upon dissolution.

ABSORPTION UNIT

SPRAY TOWER

Spray towers are useful for large volume handling with relatively low pressure drop and high efficiency. In general smaller the droplet size the greater the turbulence, the more chance for absorption of the gas. Absorbing liquid usually water is sprayed through the contaminated gas and the absorbent contaminant solution falls downwards for removal while clean gas exits through an outlet valve in the top of unit. Moisture eliminator reduces the amount of moisture in the gases being released. Spray tower has less gas liquid interfacial area so they are less effective in removal of gaseous contaminant.

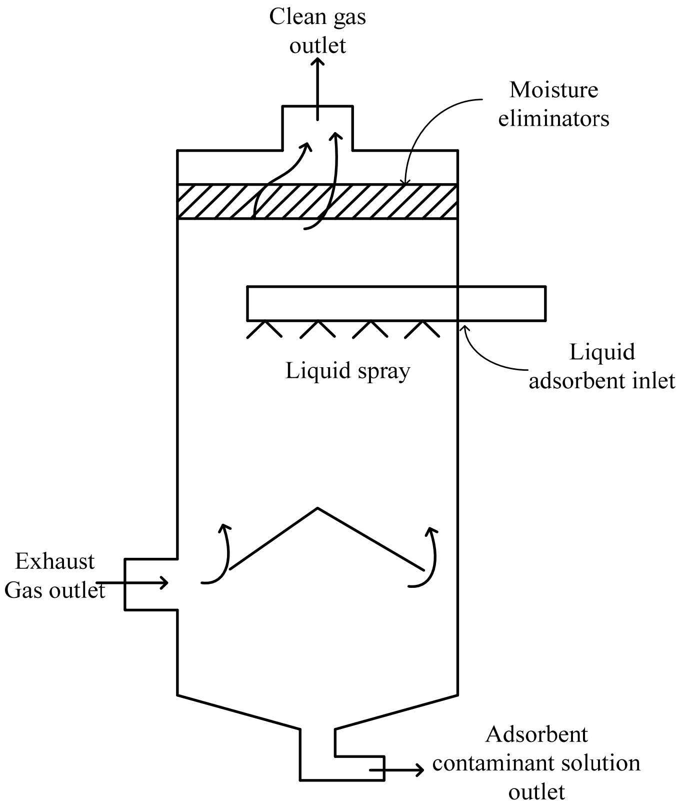

Figure Spray Tower

Figure 2.8.1. Spray Tower

PLATE OR TRAY TOWER

This type of tray contains horizontal trays or plate that provides large gas liquid interfacial areas. The polluted air is introduced from one side of the bottom of the column, rise up through the opening in each tray, and the rising gas prevents the liquid from draining through the opening. Due to repeated contact of gas and liquid the contaminant are removed and the clean air emerges from the top.

In bubble cap tray column, the contaminated gas moves upward until they strike the cap, at which point they are diverted downward and discharged as small bubbles from slots at the bottom of the caps [3]. Since gas continues flow in upward direction so repeated interaction takes place and contaminated gas is removed and clean gas emerged from the top. The contaminant-laden liquid flows to the bottom and is drawn off.

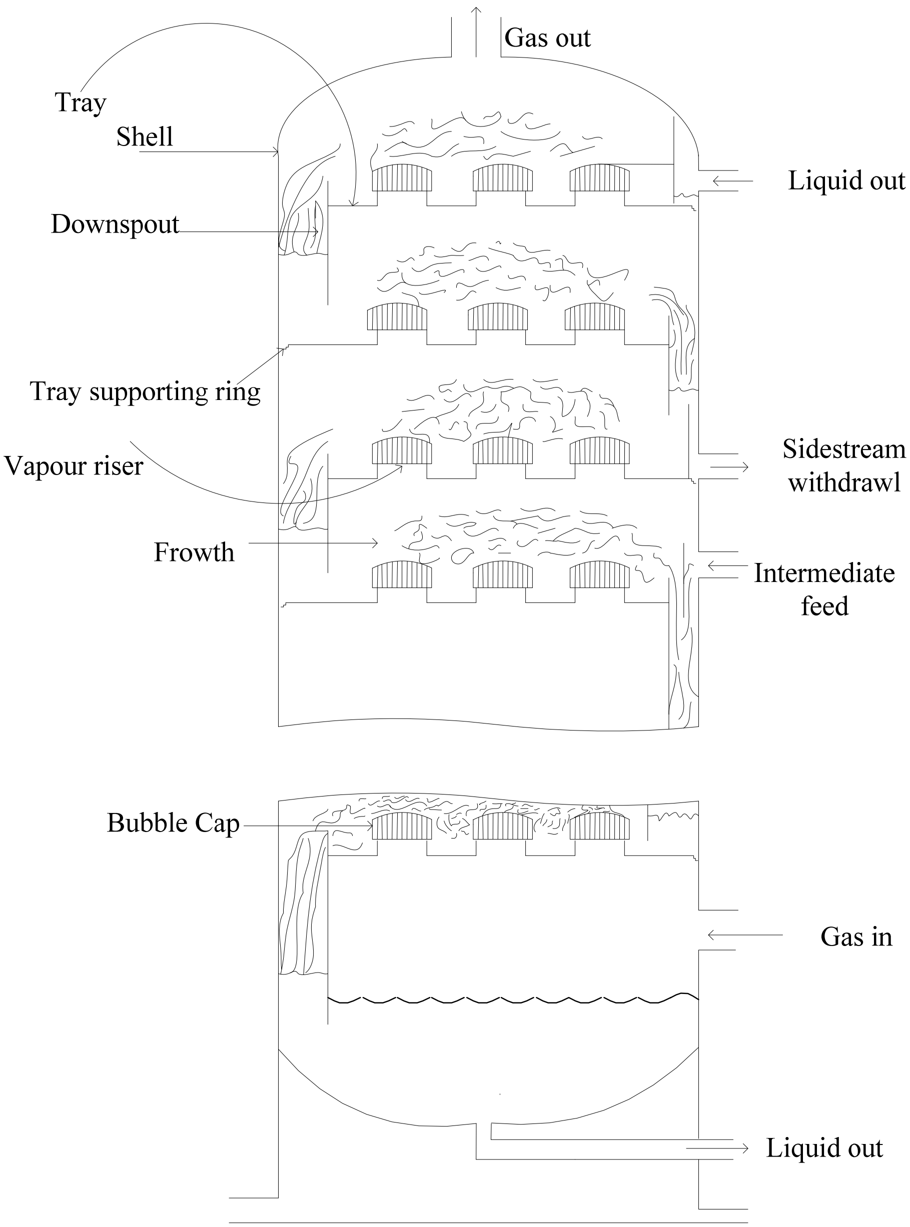

Figure Schematic diagram of bubble cap tray tower

Figure 2.8.2. Schematic diagram of bubble cap tray tower

PACKED TOWER: In packed tower the contact time between vapour and liquid is increased by introducing packing. The packing material has a large surface to volume ratio and a large void ratio that offers minimum resistance to gas flow.

Generally packed tower are operated counter currently, with gas entering at the bottom of tower and liquid entering from the top. Liquid flows over the surface of the packing in a thin film causing continuous contact with the gases [4, 5].

Packed towers are highly efficient but they become easily clogged when gas with high particulate loads are introduced.

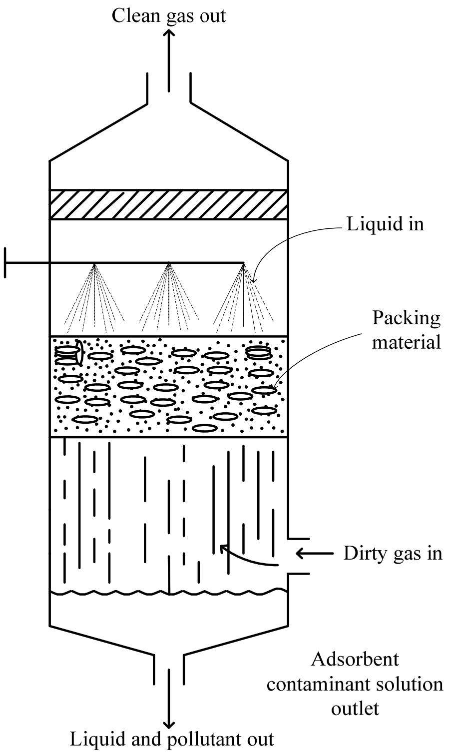

Figure Counter current flow Packed tower

Figure 2.8.3. Counter current flow packed tower

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Module 3: WATER POLLUTION CONTROL BY PHYSICO-CHEMICAL AND ELECTROCHEMICAL METHODS

Lecture	**Topic**	**No. of Hours (13)**
1	Introduction to Water Pollution and Control	1
2	Pre-treatment & Physical treatment: Flow equalization	1
3	Pre-treatment & Physical treatment: Aeration - Part 1	1
4	Pre-treatment & Physical treatment: Aeration – Part 2	1
5	Pre-treatment & Physical treatment: Coagulation and Flocculation - Part 1	1
6	Pre-treatment & Physical treatment: Coagulation and Flocculation - Part 2	1
7	Setting and Sedimentation: Part 1	1
8	Setting and Sedimentation: Part 2	1
9	Settling Chamber Design	1
10	Filtration	1
11	Water Pollution Control By Membrane Based Technologies	1
12	Water Pollution Control by Adsorption: Part 1	1
13	Water Pollution Control by Adsorption: Part 2	1
14	Electrochemical Treatment	1

Lecture 1

Introduction to Water Pollution and Control

WATER TREATMENT

Each wastewater treatment and disposal system consists of the following: collecting the wastewater, transporting it to treatment plant, treating the wastewater, and disposing of the resulting effluent.

The objective of wastewater treatment is to remove undesirable compounds and residues as possible and bring the wastewater to the quality of the designated use. Although potable water is never produced at the treatment plant, wastewater treatment is done to at least of that minimum quality that no nuisance condition or health hazard results because of the final disposal of the effluent and that the quality of the water in receiving streams is not altered.

It is also necessary that the effluent from the treatment plant meets the discharge standards as decided by Central Pollution Control Board.

WASTEWATER COLLECTION SYSTEMS

The water collection system transports wastewater from its origin to a designated destination. The purpose of a wastewater collection system is to safeguard the public and other persons involved from health hazards associated with the wastewater. Sanitary collection systems which use conveying structures and pumps are designed to remove these domestic and industrial wastes. Interceptors and traps are used as preventive maintenance measures prior to the wastewater entering the collection system [1].

WASTEWATER TREATMENT

There are basically three types of stages or processes that take place to render wastewater for disposal. These processes are called primary, secondary, and tertiary treatment. Likewise, there are three types of treatment plants -- primary, secondary, and tertiary -- that reduce the pollutant load in wastewater and chlorinate it before discharging the effluent into outfall sewer.

UNITS FOR TREATMENT OF WATER

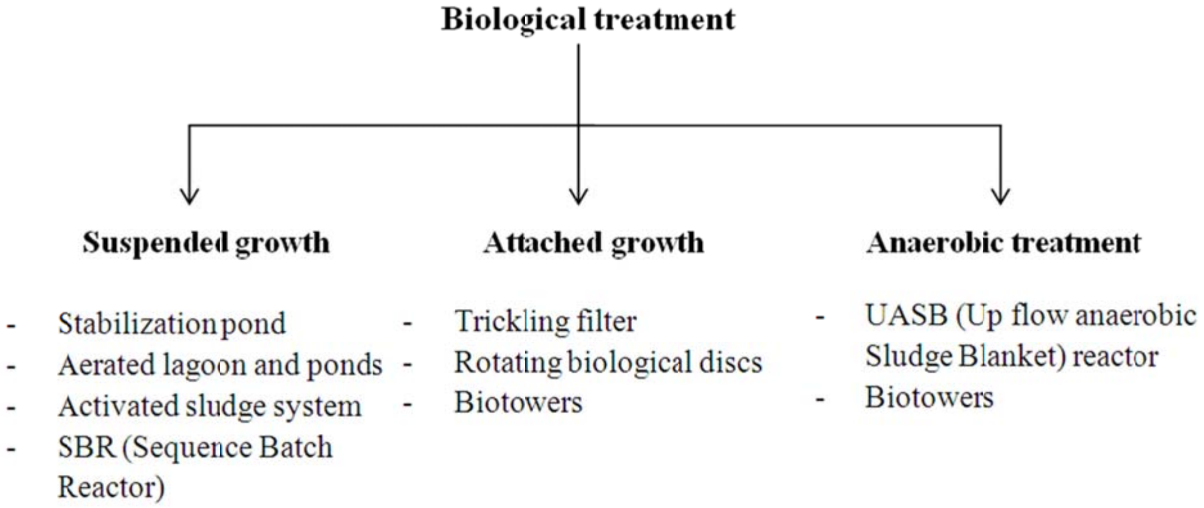
A. **Pre- and primary treatment.** This includes one or many of the following:

- Screening: Removes bigger size debris like bricks, glass, etc. that may damage later equipmets
- Grinding (includes shredding): Reduces the size of bigger size of solids to smaller size that can be handled by the later equipments
- Grit removal: Blocks gravel, sand, silt, etc. from going further

- Flow equalization: Helps in equalizing the hydraulic and organic loadings to optimum values for maximum efficiency
- Aeration/air floatation: Removes soluble odorous gases such as H_2S, improves solids separation and settling, etc.
- Primary sedimentation: Separates settleable organic and floatable solids
- Sludge removal: Removes solids settled during primary sedimentation

Overall primary treatment removes 90-95% settleable solids, 40-60% total suspended solids and 25-35% BOD_5 [2].

B. Secondary treatment: This mainly involves biological treatment, settling, clarification and sludge removal. Biological treatment can be done by a number of methods as given below:



- Biological processes convert dissolved, suspended and colloidal organic wastes to more stable solids and thus remove majority of BOD.
- Secondary sedimentation: Removes the accumulated biomass after the secondary treatment

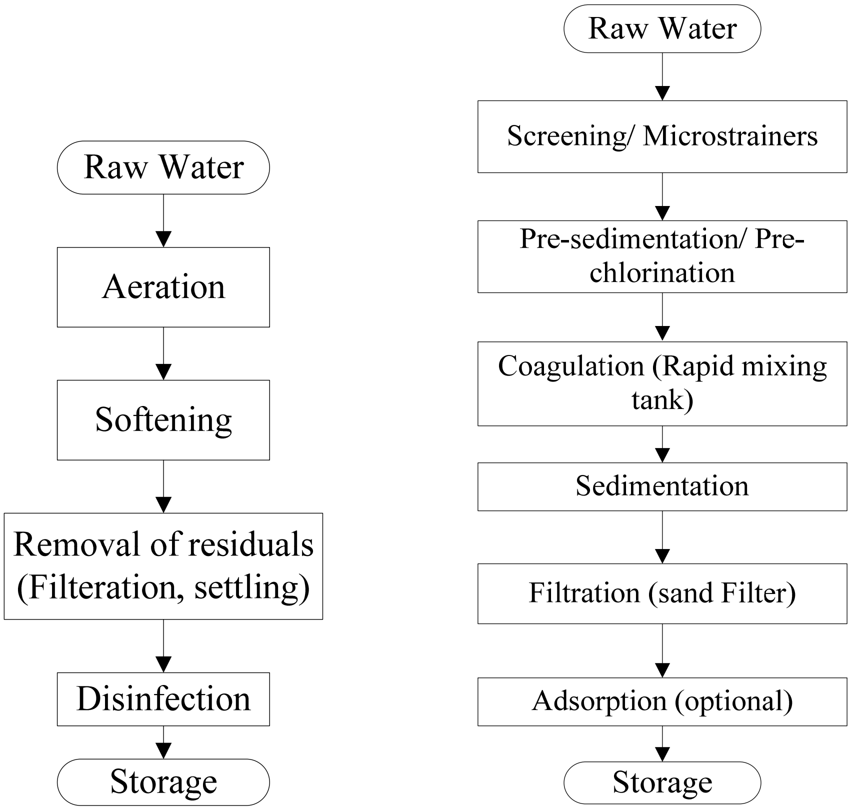
C. **Tertiary Treatment:** This may include, but is not limited to, one or more of the following:

- Carbon absorption: Removes recalcitrant pollutants
- Nutrient Removal: Removes limiting nutrients such as nitrogen and phosphorus that could affect the receiving water body and cause eutrophication [2].
- Chemical oxidation including wet-air oxidation: Oxidizes recalcitrant pollutants
- Membrane processes: Removes inorganic and other pollutants based upon its size

- Electrodialysis: Electricity is used for the separation process and removing charged particles
- Reverse osmosis: Pressure is for forcing water molecules to the cleaner side
- Ion exchange: Removes ionic pollutants by exchange process
- Chlorination including ozone treatment, UV treatment: Destroys pathogens present in the effluent
- Disposal: Treated effluent is either used for some beneficial use such as irrigation, etc. or is directly discharged to water bodies
- Land application: Reduces TSS, BOD, nutrients, etc.

D. Solid Treatment: Converts sludge generated in primary and secondary sedimentation to biosolids for use as soil conditioners, fuel, etc. [3].

Differences in the treatment methodologies for ground water and surface water like from a river can be envisaged from the figures as given below:



Hard ground water **Turbid surface water**

Figure 3.1.1: Treatment steps for ground and surface water [3].

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Lecture 2

Pre-treatment & Physical treatment: Flow equalization

FLOW EQUALIZATION

- The wastewater to be treated in the wastewater treatment plant has a lot of variations in flow rate, concentration of pollutants and characteristics.
- A wastewater treatment plant already designed for some flow rate and loading rate can’t sustain such large seasonal or other variations in flow rate.
- Flow equalization is a method to overcome problems related to fluctuations in flow rate & pollution load.
- Flow equalisation basin is located after most of the primary treatment units such as screening and grit removal but before primary sedimentation.
- Flow equalisation method controls the short term, high volumes of incoming flow, called surges, through the use of basin. It helps in equalizing the flow rate and optimizing the time required for treatment in secondary and tertiary processes. It also helps in lowering the strength wastewater by diluting it with wastewater already present in the equalization basin.
- Basin volume and dimensions, mixing and air requirements, etc. are the basic things that are considered in designing an equalisation basin.

Advantages

- Helps in improving the performance of down- stream operations and reduces the operating & capital cost of down- stream process.
- Biological treatment is enhanced because of elimination of shock load due to flow rate & pollution load.

- Thickner/ settler and filter performance gets enhanced and their required surface area gets reduced.

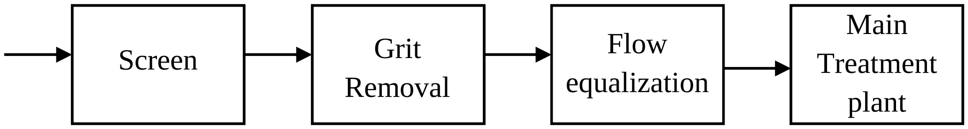
Disadvantages

- Large land area may be required.
- Additional capital and operating cost may be required.
- May cause odor problem for nearby residential colonies.

TYPES OF FLOW EQUALIZATION

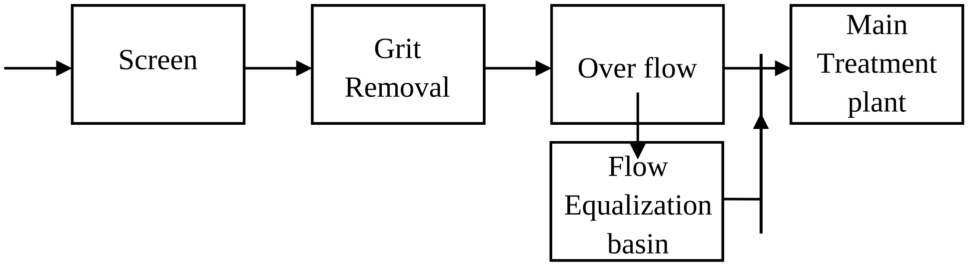
a. In- line equalization

In this case, all the flow passes through the equalization basin and helps in achieving reducing fluctuations in pollutant concentration and flow rate.



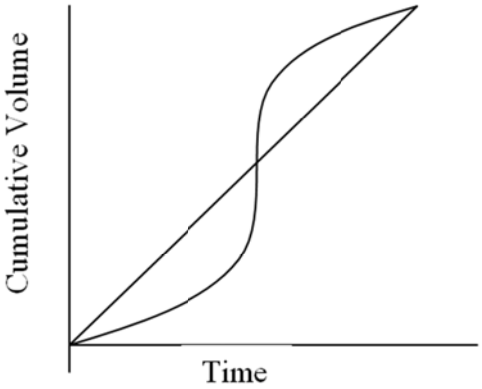
b. Off- line equalization

In this case, only over-flow above a predetermined value is diverted into the basin. It helps in reducing the pumping requirements. In this method of equalization, variations in loading rate can be reduced considerable. Off-line equalisation is commonly used for the capture of the "first flush" from combined collections systems.

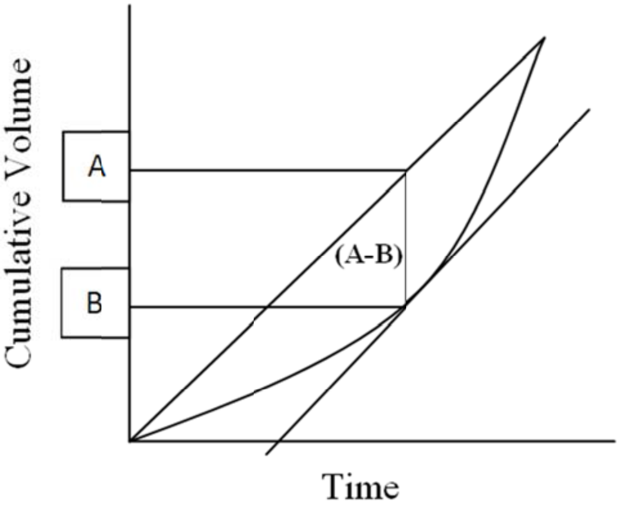


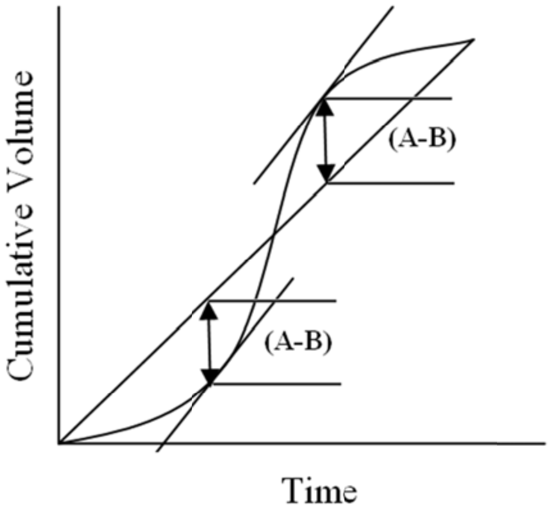
DETERMINATION OF THE VOLUME OF FLOW EQUALIZATION BASIN

Step 1: First a cumulative volume versus time diagram is drawn (as shown in figure below) for the period in which all variations in flow can be accounted.



Step II: Required storage volume is determined by drawing a line (parallel to avg. flow rate line) which is tangent at low and high point [1].





Required reaction volume = Max. of |(A-B)|

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Lecture 3

Pre-treatment & Physical treatment: Aeration 1

AERATION BASICS

Factors affecting removal of compounds by aeration

- Physico- chemical properties of compound to be removed like hydrophobicity, surface area, etc.
- Temperature of water & air.
- Process parameters for aeration like air to water ratio, available area of mass transfer, contact time, etc.

Calculation of solubility of gases

Henrys' Law is defined as:

$$p_A = Hx_A \tag{3.3.1}$$

Where p_A is the partial pressure of any compound A in air (atm), H is the Henrys' constant which depends upon temperature and x_A is the mol fraction of compound A in water. By definition

$$x_A = \frac{\text{Moles of compound A in liquid solution}}{\text{Moles of compound A in liquid solution} + \text{Moles of water in liquid solution}}$$

Since moles of oxygen in liquid solution are usually very less as compared to moles of water in liquid solution, therefore,

$$x_A = \frac{\text{Moles of compound A in liquid solution}}{\text{Moles of water in liquid solution}} = \frac{\text{moles of compound A}}{\text{moles of water}}$$

$$x_A = \frac{\text{moles of compound A}}{\text{moles of water}} = \frac{\text{(Weight of compound A (in g)/Molecular Weight)}}{\left(\left(\text{Density} \times \text{Volume of Water}\right)/\text{Molecular Weight of Water}\right)}$$

$$x_A = \frac{\text{(Weight of compound A (in g)/Molecular Weight)}}{\left(\left(1000/18\right) \times \text{ Volume of Water (in Litre)}\right)} \tag{3.3.2}$$

$x_A = \left(\left(\text{Concentration of compound A (in g/L)} \times 18\right) / \left(\text{Molecular Weight of compound A (in g/mol)} \times 10^3\right)\right)$
$x_A = \left(\left(\mathrm{C}_A \text{ (in g/L)} \times 18\right) / \left(\mathrm{MW}_A \text{(in g/mol)} \times 10^3\right)\right)$

Putting in earlier equation

$$\mathrm{C}_A \text{ (in g/L)} = \frac{p_A \times \left(\mathrm{MW}_A \text{(in g/mol)} \times 10^3\right)}{\left(H \times 18\right)}$$

$$\mathrm{C}_A \text{ (in mg/L)} = \frac{p_A \times \mathrm{MW}_A \text{(in g/mol)} \times 10^6}{\left(H \times 18\right)} \tag{3.3.3}$$

Where, C_A is the solubility of compound A in water.

Variation of solubility of gases with temperature

Solubility of gases decreases with an increase in temperature. The change in Henrys' constant with temperature can be computed using van't Hoff type of equation:

$$\log_{10} \mathrm{H} = \frac{-\Delta \mathrm{H}}{\mathrm{RT}} + \mathrm{b} \tag{3.3.4}$$

Where, $-\Delta\mathrm{H}$ is the Heat of absorption in kcal/kmol, R is the gas constant (=1.987 kcal/K-kmol), T is temperature in K and b is a dimensionless empirical constant.

Problem 3.3.1: The particle pressure of O_2 in atmosphere is 0.21 atm. Find the concentration of O_2 in water (in mg O_2/ litre of water) at 20 ^{o}C & 5 ^{o}C. Given that for oxygen, Henry's constant (H) is equal to 4.3×10^4 atm at 20 ^{o}C, ΔH=1.45 10^3 kcal/kmol, and b=7.11.

Solution: Given that: p_A= 0.21 atm, H = 4.3×10^4 atm at 20 ^{o}C.

$$\mathrm{C}_{O_2} \text{ (in mg/L)} = \frac{p_{O_2} \times \mathrm{MW}_{O_2} \text{(in g/mol)} \times 10^6}{\left(H \times 18\right)}$$

$\mathrm{C}_{O_2} \text{ (in mg/L)} = \dfrac{0.21 \times 32 \times 10^6}{\left(4.3 \times 10^4 \times 18\right)}$ =8.682 mg O_2/ litre of water at 20 ^{o}C.

Now calculating Henrys' constant at 5 ^{o}C

$$\log H_{5oC} = \frac{-1.45\times 10^{3}}{1.987\times(273)} + 7.11$$

$$H_{5oC} = 30650.64 \text{ atm}$$

C_{O_2} (in mg/L) $= \dfrac{0.21\times 32\times 10^{6}}{(30650.64\times 18)}$ =12.17 mg O_2/ litre of water at 5 ^{o}C.

AERATION TYPES

- **Diffused or Submerged Aeration:** Submerged aeration systems are used in lakes, reservoirs, and wastewater treatment facilities to increase dissolved oxygen (DO) levels and promote water circulation. Submerged diffusers release air or pure oxygen bubbles at depth, producing a free, turbulent bubble-plume that rises to the water surface through buoyant forces. The ascending bubble plume entrains water, causing vertical circulation and lateral surface spreading. Oxygen transfers to the water across the bubble interfaces as the bubbles rise from the diffuser to the water surface [1].
- **Spray aeration:** Spray aeration removes low levels of volatile contaminants. In a spray aeration system, water enters through the top of the unit and emerges through spray heads in a fine mist. Treated water collects in a vented tank below the spray heads. Volatile contaminants are released and vented to the outside [2].
- **Water fall type of aeration:** It involves flow of water over media forming droplets or thin film of water so as to contact with air.

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Lecture 4

Pre-treatment & Physical treatment: Aeration 2

REMOVAL OF VOCs BY AERATION IN COMPLETE STIRRED TANK REACTOR (CSTR) [1]

[A] VOC removal by surface aeration in CSTR

A mass balance for VOC in CSTR having surface aeration is given as:

$$\begin{pmatrix}\text{Rate of accumulation}\\ \text{of VOC within the}\\ \text{system boundary}\end{pmatrix} = \begin{pmatrix}\text{Rate of flow of}\\ \text{VOC into the}\\ \text{system boundary}\end{pmatrix} - \begin{pmatrix}\text{Rate of flow of}\\ \text{VOC out of the}\\ \text{system boundary}\end{pmatrix} + \begin{pmatrix}\text{Rate of VOC}\\ \text{removal by stripping}\\ \text{or surface aeration}\end{pmatrix}$$

$$V\frac{dC}{dt} = QC_{in} - QC + r_{VOC}V = QC_{in} - QC + \left[-(k_La)_{VOC}(C - C_S)\right]V \qquad (3.4.1)$$

Where, V is the volume of the CSTR (m^3), dC/dt is the rate of change of VOC in the CSTR, Q is the liquid flow rate in and out of the reactor (m^3/s), C_{in} is the VOC concentration in influent to the CSTR ($\mu g/m^3$) and C is the VOC concentration in effluent from the CSTR ($\mu g/m^3$). R_{VOC} is the rate of VOC mass transfer ($\mu g/m^3 s$) and is given as:

$$r_{VOC} = -(k_La)_{VOC}(C - C_S) \qquad (3.4.2)$$

Where, C_S is the saturation concentration of VOC in the liquid ($\mu g/m^3$) and $(k_La)_{VOC}$ is overall mass transfer coefficient (s^{-1}) and it is determined using the oxygen mass transfer coefficient, $(k_La)_{O2}$ using the following equation:

$$(k_La)_{VOC} = (k_La)_{O_2}\left(\frac{D_{VOC}}{D_{O_2}}\right)^n \qquad (3.4.3)$$

Where, D_{VOC} and D_{O2} are the diffusion coefficients of VOC and O_2 in water, respectively (cm^2/s) and n is an empirical constant.

Assuming steady state condition, V/Q=τ and C_S=0, equation 1 becomes:

$$\frac{C_{in} - C}{\tau} = (k_La)_{VOC}C \qquad (3.4.4)$$

$$\text{Fraction of VOC removed}=1-\frac{C}{C_{in}}=1-\left[1+(k_La)_{VOC}\tau\right]^{-1} \tag{3.4.5}$$

[B] VOC removal by diffused aeration in CSTR

At steady state, mass balance on VOC in diffused aeration system in CSTR is given as:

$$\begin{pmatrix}\text{Rate of in-flow of}\\ \text{VOC in the}\\ \text{liquid stream}\end{pmatrix}=\begin{pmatrix}\text{Rate of out-flow}\\ \text{of VOC with the}\\ \text{liquid stream}\end{pmatrix}+\begin{pmatrix}\text{Rate of out-flow}\\ \text{of VOC with}\\ \text{the exit gas}\end{pmatrix}$$

$$QC_{in}=QC+Q_gC_{g,e} \tag{3.4.6}$$

Where, Q_g is the diffused gas flow rate inside the CSTR (m^3/s), $C_{g,e}$ is the VOC concentration in exit gas ($\mu g/m^3$). Bielefeldt and Stensel [2] gave the following relationship for $C_{g,e}$ with C:

$$C_{g,e}=H_uC\left[1-\exp\{-\phi\}\right]=H_uC\left[1-\exp\left\{\frac{-(k_La)_{VOC}V}{H_uQ_g}\right\}\right] \tag{3.4.7}$$

Where, H_u=(H/RT) is the dimensionless value of Henry's constant and ϕ is VOC saturation parameter. After putting the value of $C_{g,e}$ and rearranging, we get

$$\text{Fraction of VOC removed}=1-\frac{C}{C_{in}}=1-\left[1+\frac{Q_gH_u}{Q}\exp\left\{\frac{-(k_La)_{VOC}V}{H_uQ_g}\right\}\right]^{-1} \tag{3.4.8}$$

Problem 3.4.1: Wastewater flow rate in a complete-mix activated sludge reactor having volume=2000 m^3 and depth=8 m is 6000 m^3/d. If the influent concentration of benzene is 200 $\mu g/m^3$ and that the air flow rate (at standard condition) is 100 m^3/min, determine the fraction of benzene that can be stripped off if the complete mix activated sludge reactor is equipped with

(a) surface aeration system

(b) diffused-air aeration system

Also given that: Oxygen diffusivity=2.11×10^{-5} cm^2/s, benzene diffusivity=0.96×10^{-5} cm^2/s, temperature=20 °C, n=1, Henry's constant=5.49×10^{-3} m^3atm/mol.

Solution: First the value of $(k_La)_{VOC}$ is determined.

$$(k_La)_{VOC} = (k_La)_{O_2}\left(\frac{D_{VOC}}{D_{O_2}}\right)^n$$

$$(k_La)_{Benzene} = 6.2\ h^{-1} \times \left[\frac{0.96\times10^{-5}\ cm^2/s}{2.11\times10^{-5} cm^2/s}\right]^1 = 2.8208\ \ h^{-1} = 0.047\ \ min^{-1}$$

Case a: Surface aeration system

$$\tau = (V/Q) = (2000/6000) = 0.333\ d = 7.992\ h$$

$$\text{Fraction of VOC removed} = 1 - \frac{C}{C_{in}} = 1 - [1 + (k_La)_{VOC}\tau]^{-1}$$

$$\text{Fraction of VOC removed} = 1 - [1 + 2.8208 \times 7.992]^{-1} = 0.9575$$

Case b: Diffused aeration system

$$H_u = \frac{H}{RT} = \frac{5.49\times10^{-3}}{0.0821\times(273.15+20)} = 0.2282$$

We need gas flow rate at the actual condition i.e. at half of the tank depth (=4 m) and at 20 °C. We know:

$$\frac{P_{st}Q_{st}}{T_{st}} = \frac{P_{ac}Q_{g,ac}}{T_{ac}}$$

$$Q_g = Q_{g,ac} = \left(\frac{P_{st}}{P_{ac}}\right)\frac{T_{ac}}{T_{st}}Q_{st} = \left(\frac{P_{st}}{\rho_{water}gh}\right)\frac{T_{ac}}{T_{st}}Q_{st} = \left(\frac{1.013\times10^5}{1000\times9.81\times(8/2)}\right)\frac{293}{273}\times100 = 277.06\ \ m^3/min$$

$$\phi = \frac{(K_La)_{VOC}\times V}{H_uQ_g} = \frac{0.047\times2000}{0.2282\times277.06} = 1.48675$$

$Q = 6000\ m^3/d = 4.1667\ m^3/min$

$$\text{Fraction of VOC removed} = 1 - \frac{C}{C_{in}} = 1 - \left[1 + \frac{Q_gH_u}{Q}\exp\{-\phi\}\right]^{-1}$$

$$\text{Fraction of VOC removed} = 1 - \left[1 + \frac{277.06\times0.2282}{4.1667}\exp(-1.48675)\right]^{-1} = 0.7738$$

PACKED TOWER AERATION

In packed tower aeration (PTA), wastewater to be treated in sprayed on the top of a tower. The tower is about 3-10 m in height and is packed with various types of packing which provide high surface area to volume ratio. Air is pumped simultaneously counter-currently through the packing from the bottom and removes the VOC from wastewater which itself in trickling over the packing. Air along with the VOC gets removed from the top while treated water is collected at the bottom.

Design of Packed-tower aeration unit

The height of the tower can be calculated using the following equation:

$$Z = HTU \times NTU \tag{3.4.8}$$

Where, HTU is the height of transfer unit and NTU is the number of transfer units. HTU represents the rate of mass transfer for a particular type of packing. It determines the efficiency of mass transfer from liquid to gas phase. It is related to liquid loading rate and is given by:

$$HTU = \frac{L}{k_L a C_o} \tag{3.4.9}$$

Where, L is the ratio of superficial molar to mass liquid flow, $K_L a$ is the overall mass transfer coefficient; C_o is the molar density of VOC in water (kmol/m^3)

$$\frac{R}{(R-1)} \ln\left[\frac{\left\{\frac{C_{in}}{C_{out}}(R-1)\right\}+1}{R}\right] \tag{3.4.10}$$

Where, $R=H_uG/L$ is called the stripping factor, H_u is Henrys' constant dimensionless, $G=(Q_G/A)$ is the superfacial gas flow rate (kmol/h m^2), A is the cross–sectional area of packed bed (m^2) and Q_G is the gas flow rate (kmol/h).

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Lecture 5

Pre-treatment & Physical treatment: Coagulation and flocculation – Part 1

GENERAL

Coagulation has been defined as the addition of a positively charged ion such as Al^{3+}, Fe^{3+} or catalytic polyelectrolyte that results in particle destabilization and charge neutralization [1].

- The purpose of coagulation is removal of finely divided suspended solids and colloidal material from the waste liquid.
- These contaminants cannot be separated by sedimentation alone except by the use of reasonably long detention periods; truly colloidal particles cannot be removed by settling.
- If these suspended pollutants are organic, they can often be oxidized by biological means, as on trickling filter; biochemical oxidation, however, is slower for suspended matter than for dissolved organic contaminants. If the quantity of insoluble organic matter is large, bio-oxidation equipment must be increased in size to care for this added duty; it is usually more economical to remove the greater part of such matter by chemical coagulation instead of in a trickling filter or activated sludge tank.

Flocculation and Settling

Flocculation is the formation of clumps or flocs of suspended solids by agglomeration of smaller suspended particles.

- Most chemical precipitates do not possess the property of flocculation to any appreciable degree, but rather tend to form dense, compact, crystalline particles that settle rapidly.
- Precipitates of ferric hydroxide, aluminum hydroxide, silica, and certain other substances formed by chemical reaction of coagulant chemicals, however, have the property of forming large flocs of high surface area. As these flocs move through the liquid in a settling tank, they remove other suspended solids by adsorption or mechanical sweeping, and hence perform a better clarification than could be achieved by plain sedimentation alone.
- Flocculation is aided by mild agitation for a period of 20 to 60 minutes, to allow time for maximum floc formation and growth.
- The agitation should be gentle, in order not to break flocs already formed. Gentle air agitation has also been employed to promote floc growth.

- After the floc has formed and grown to its most effective size, the waste passes to a sedimentation chamber for solids removal. Floc formation and growth may be retarded or stopped by surface-active chemicals such as soaps and synthetic detergents.

COAGULATION FUNDAMENTALS

Colloidal solutions that do not agglomerate naturally are called *stable*. This is due their large surface-to-volume ratio resulting from their very small size. In these small particles, molecular arrangements within crystals, loss of atoms due to abrasion of the surfaces, or other factors causes their surfaces to be charged [2].

The colloids contained in the water are negatively charged at $pH>pH_{iso}$ and positively at $pH<pH_{iso}$. These colloids are stable due to the repulsive forces between the negative charges. These colloids are destabilized by positively charged ions formed from the hydrolysis of coagulants. Destabilization of colloidal particles can be influenced by the [3] double layer compression, adsorption and charge neutralization, entrapment in precipitates (sweep flocculation) and interparticle bridging.

1. Double layer compression: The negative colloid and its positively charged atmosphere produce an electrical potential across the diffuse layer. This is highest at the surface and drops off progressively with distance, approaching zero at the outside of the diffuse layer and is known as Zeta potential [4].

- When a coagulant is added, it destabilizes the negatively charged particles. A cationic coagulant such as a metal salt reduces the zeta potential of the particles by adding positive charge.
- Double layer compression involves adding salts to the system. As the ionic concentration increases, the double layer and the repulsion energy curves are compressed until there is no longer an energy barrier. Particle agglomeration occurs rapidly under these conditions [4].
- The thickness of the double layer depends upon the concentration of ions in solution. A higher level of ions means more positive ions are available to neutralize the colloid. The result is a thinner double layer.

2. Adsorption and charge neutralization: Inorganic coagulants (such as alum, Ferrous sulphate) often work through charge neutralization. When these metal based coagulants are added to water, it dissociates and metal ions formed. Fe^{2+}/Al^{3+} are liberated, if ferrous salt/alum is used. Liberated Fe^{2+}/Al^{3+} and OH^- ions react to form various monomeric and polymeric hydrolyzed species [5].

The concentration of the hydrolyzed metal species depends on the metal concentration, and the solution *pH*. The percentage of Fe^{2+} and Al^{3+} hydrolytic products can be calculated from the following stability constants [6, 7]:

$$Fe^{2+} + H_2O = Fe(OH)^{+} + H^{+} \quad pK_1=9.5 \tag{3.5.1}$$

$$Fe(OH)^{+} + H_2O = Fe(OH)_2 + H^{+} \quad pK_2=11.07 \tag{3.5.2}$$

$$Fe(OH)_2 + H_2O = Fe(OH)_3^{-} + H^{+} \quad pK_3=10.43 \tag{3.5.3}$$

$$Al^{3+} + H_2O = Al(OH)^{2+} + H^{+} \quad pK_1=4.95 \tag{3.5.4}$$

$$Al(OH)^{2+} + H_2O = Al(OH)_2^{+} + H^{+} \quad pK_2=5.6 \tag{3.5.5}$$

$$Al(OH)_2^{+} + H_2O = Al(OH)_3 + H^{+} \quad pK_3=6.7 \tag{3.5.6}$$

$$Al(OH)_3 + H_2O = Al(OH)_4^{-} + H^{+} \quad pK_4=5.6 \tag{3.5.7}$$

The speciation diagram of Fe^{2+} and Al^{3+} as drawn using above stability constants is presented in Figure 3.5.1 and Figure 3.5.2, respectively.

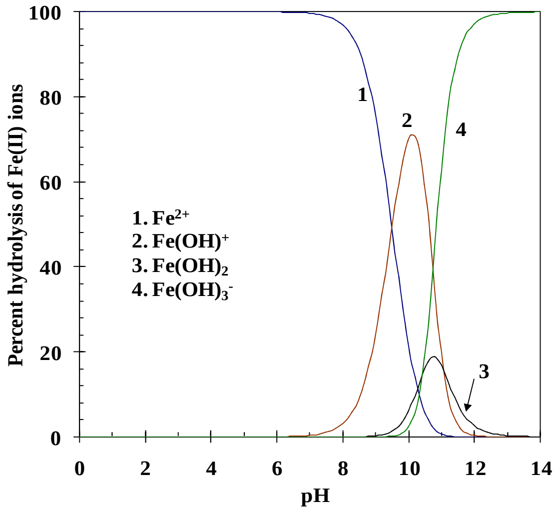

Figure 3.5.1. Speciation diagram of Fe^{2+}

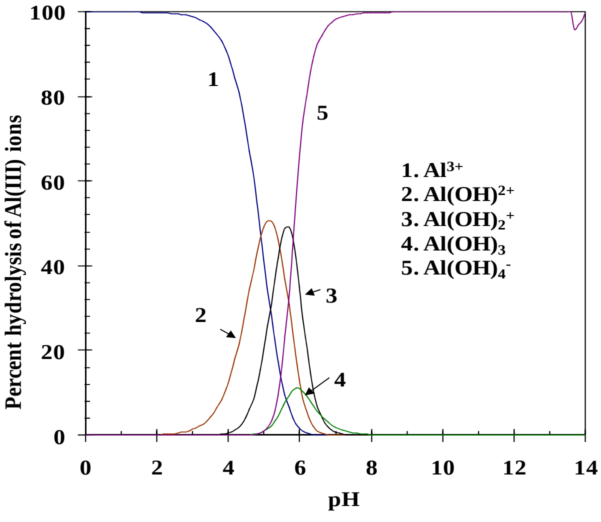

Figure 3.5.2. Speciation diagram of Al^{3+}

It can be seen from speciation diagram of Fe(II) ions that the dominant soluble species are Fe^{2+} and $Fe(OH)_3^-$ at low and high pH, respectively. The hydrolysis constants for aluminum cover a very narrower range, and all of the aluminum deprotonations are 'squeezed' into an interval of less than 2 unit. Therefore, apart from a narrow pH region approximately 5.5–6.5, the dominant soluble species are Al^{3+} and $Al(OH)_4^-$ at low and high pH, respectively [8].

Adsorption of the metal hydrolysed products on the colloid surface causes charge neutralization, which brings about van der Walls forces become dominant [9]. Charge neutralization alone will not necessarily produce macro-flocs (flocs that can be seen with the naked eye). Micro-flocs (which are too small to be seen) may form but will not aggregate quickly into visible flocs. The polymeric hydrolyzed species possess high positive charges, and adsorbed to the surface of the negative colloids. This results in a reduction of the zeta potential to a level where the colloids are destabilized. The destabilized particles, along with their adsorbed hydro-metallic hydroxometallic complexes, aggregate by interparticulate Van der Waals forces. These forces are aided by the gentle mixing in water [10]. When a coagulant forms threads or fibers which attach to several colloids, capturing and binding them together, this phenomenon is known as bridging. Some synthetic polymers and organic polyelectrolytes, instead of metallic salts, are used to assist interparticle bridging [9].

Adsorption sites on the colloidal particles can adsorb a polymer molecule. A bridge is formed when one or more particles become adsorbed along the length of the polymer. Bridge particles intertwined with other bridged particles during the process.

3. Sweep coagulation: Addition of relatively large doses of coagulants, usually aluminum or iron salts, which results in precipitation as hydrous metal oxides. Most of the colloids and some of dissolved solids are literally swept from the bulk of the water by becoming enmeshed in the settling hydrous oxide floc. This mechanism is often called sweep flocculation. Sweep floc is achieved by adding so much coagulant to the water that the water becomes saturated and the coagulant precipitates out. Then the particles get trapped in the precipitant as it settles down [7].

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Lecture 6

Pre-treatment & Physical treatment: Coagulation and flocculation – Part 2

COAGULATION REAGENTS

Numerous chemicals are used in coagulation and flocculation processes. There are advantages and disadvantages associated with each chemical. Following factors should be considered in selecting these chemicals:

- Effectiveness.
- Cost.
- Reliability of supply.
- Sludge considerations.
- Compatibility with other treatment processes.
- Secondary pollution.
- Capital and operational costs for storage, feeding, and handling.

Coagulants and coagulant aids commonly used are generally classified as inorganic coagulants and polyelectrolytes. Polyelectrolytes are further classified as either synthetic-organic polymers or natural-organic polymers. The best choice is usually determined only after jar test is done in the laboratory.

Following table lists several common inorganic coagulants along with associated advantages and disadvantages.

Table 3.6.1: Advantages and disadvantages of alternative inorganic coagulants

Name	*Advantages*	*Disadvantages*
Aluminum Sulphate (Alum) $Al_2(SO_4)_3.18H_2O$	Easy to handle and apply; most commonly used; produces less sludge than lime; most effective between pH 6.5 and 7.5	Adds dissolved solids (salts) to water; effective over a limited pH range.
Sodium Aluminate $Na_2Al_2O_4$	Effective in hard waters; small dosages usually needed	Often used with alum; high cost; ineffective in soft waters
Polyaluminum Chloride (PAC) $Al_{13}(OH)_{20}(SO_4)_2.Cl_{15}$	In some applications, floc formed is more dense and faster settling than alum	Not commonly used; little full scale data compared to other aluminum derivatives
Ferric Sulphate	Effective between pH 4–6 and	Adds dissolved solids (salts) to

$Fe_2(SO_4)_3$	8.8–9.2	water; usually need to add alkalinity
Ferric Chloride $FeCl_3.6H_2O$	Effective between pH 4 and 11	Adds dissolved solids (salts) to water; consumes twice as much alkalinity as alum
Ferrous Sulphate (Copperas) $FeSO_4.7H_2O$	Not as pH sensitive as lime	Adds dissolved solids (salts) to water; usually need to add alkalinity
Lime $Ca(OH)_2$	Commonly used; very effective; may not add salts to effluent	Very pH dependent; produces large quantities of sludge; overdose can result in poor effluent quality

Polyelectrolytes

Polyelectrolytes are water-soluble polymers carrying ionic charge along the polymer chain and may be divided into natural and synthetic polyelectrolytes. Important natural polyelectrolytes include polymers of biological origin and those derived from starch products, cellulose derivatives and alginates. Depending on the type of charge, when placed in water, the polyelectrolytes are classified as anionic, cationic or nonionic.

- Anionic—ionize in solution to form negative sites along the polymer molecule.
- Cationic—ionize to form positive sites.
- Non-ionic—very slight ionization.

Common organic polyelectrolytes are shown in following table.

Table 3.6.2 : Common organic polyelectrolytes [1]

Polymer Type	**Name**	**Mol.wt.**	**Available form**	**Typical use**
Nonionic	Polyacrylamide	1×10^6 to 2×10^6	Powder, emulsion, solution	As flocculent with inorganic or organic polymers

Anionic	Hydrolyse Polyacrylamide	1×10^6 to 2×10^7	Powder, emulsion, solution	As flocculent with inorganic or organic polymers
Cationic	Poly(DADMAC) or Poly(DADMAC) polymers	200 to 500×10^3	Solution	Primary coagulant alone or in combination with inorganics.
Cationic	Quaternized Polyamines	10 to 500×10^4	Solution	Primary coagulant alone or in combination with inorganics.
Cationic	Polyamines	10^4 to 10^6	Solution	Primary coagulant alone or in combination with inorganics.

Polyelectrolytes versus Inorganic Coagulants

Although they cannot be used exclusively, polyelectrolytes do possess several advantages over inorganic coagulants. These are as follows.

- During clarification, the volume of sludge produced can be reduced by 50 to 90%.
- The resulting sludge is more easily dewatered and contains less water.
- Polymeric coagulants do not affect pH. Therefore, the need for an alkaline chemical such as lime, caustic, or soda ash is reduced or eliminated.
- Polymeric coagulants do not add to the total dissolved solids concentration.
- Soluble iron or aluminum carryover in the clarifier effluent can result from inorganic coagulant use. By using polymeric coagulants, this problem can be reduced or eliminated [1].

Coagulant Aids [2]

- In some waters, an even large dose of primary coagulant does not produce a satisfactory floc size and hence good settling rate. In these cases, a polymeric coagulant aid is added after the coagulant, to hasten reactions, to produce a denser floc, and thereby reducing the amount of primary coagulant required.

- Because of polymer bridging, small floc particles agglomerate rapidly into larger more cohesive floc, which settles rapidly.
- Coagulant aids also help to create satisfactory coagulation over a broader pH range.
- Generally, the most effective types of coagulant aids are slightly anionic polyacrylamides with very high-molecular weights.
- In some clarification systems, non-ionic or cationic types have proven effective.

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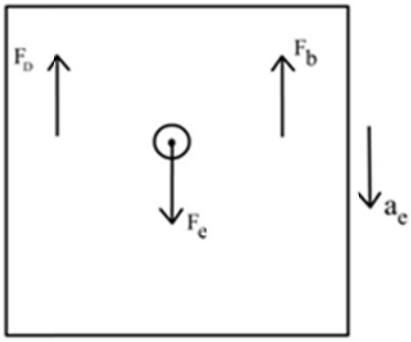
Lecture 7

Setting and sedimentation: Part 1

PARTICLE SETTLING THEORY

A particle settling in a fluid experiences following force balance:

$$m\frac{du}{dt}=F_e-F_D-F_b$$



Where, m is the mass of the particle, u is the settling velocity of the particle in the fluid, $F_e(=ma_e)$ is the acceleration force, a_e =g for Gravitational settling and a_e =rw^2 for settling under Centrifugal action. F_D is the drag force and F_b is the buoyancy force and they are given as:

$$F_D=C_D\frac{\rho_f u^2}{2}A_p \tag{3.7.1}$$

$$F_b=m\frac{\rho_f}{\rho_p}a_e \tag{3.7.2}$$

Where, C_D is the drag coefficient, ρ_f and ρ_p are the density of fluid and particle, respectively. A_P is projected area of the particle and m is the mass of particle. For spherical particles having diameter (D_P), value of A_P and m is given as:

$$A_P=\frac{\pi D_P^2}{4}, m=\frac{\pi D_P^3}{6}\rho_p \tag{3.7.3}$$

For particles settling with terminal velocity (u_t) under the force of gravitational force (a_e =g), (du/dt)=0. Putting the values of different forces, the terminal velocity (u_t) by **Newton's method** is given as:

$$u_t=\sqrt{\frac{2mg}{A_pC_D}\frac{(\rho_P-\rho_f)}{\rho_P\rho_f}} \tag{3.7.4}$$

$$u_t=\sqrt{\frac{4}{3}\frac{(\rho_P-\rho_f)}{\rho_f}\frac{gD_p}{C_D}} \text{ (for Spherical particle)} \tag{3.7.5}$$

Variation of C_D (Drag-coefficient)

In laminar zone, **Stoke's law** is applicable

$$C_D=\frac{24}{Re}; \quad 0.01 \le Re\left(=\frac{\rho_f u_t D_P}{\mu_f}\right) \le 0.1 \tag{3.7.6}$$

$$u_t=\frac{g(\rho_p-\rho_f)D_P^2}{18\mu_f} \tag{3.7.7}$$

For transition zone, $0.1 \le Re \le 1000$

$$C_D=\frac{a}{Re^n}=\frac{18.5}{Re^{0.6}} \tag{3.7.8}$$

For turbulent zone, C_D is independent of Re and $\mathbf{C_D=0.4}$

For non-spherical particles, formula for Reynold number and settling velocity calculation are modified using the shape factor (ϕ) [1]:

$$Re=\phi\frac{\rho_f u_t D_P}{\mu_f} \tag{3.7.9}$$

$$u_t=\sqrt{\frac{4}{3}\frac{(\rho_P-\rho_f)}{\rho_f}\frac{gD_p}{\phi C_D}} \tag{3.7.10}$$

Problem 3.7.1: A sand particle has an average diameter of 1 mm and a shape factor of 0.90 and a specific gravity of 2.1, determine the terminal velocity of the particle settling in water at 20 ^oC (kinematic viscosity of water=1.003×10^{-6} m^2/s and specific gravity=1). Drag coefficient can be computed using the following equation:

$$C_D=\frac{24}{Re}+\frac{3}{\sqrt{Re}}+0.34$$

Solution: Kinematic viscosity$(\nu)=\mu_f/\rho_f=1.003\times10^{-6}$

$$\mu_f=1.003\times10^{-6}\times10^{3}=1.003\times10^{-3}\ \mathrm{kg/ms}$$

Settling velocity using stokes law is:

$$u_t=\frac{g(\rho_p-\rho_f)D_P^2}{18\mu_f}=\frac{9.81\times\left((2.1\text{-}1)\times1000\right)\times\left(1\times10^{-3}\right)^2}{18\times1.003\times10^{-3}}=0.597\ \mathrm{m/sec}$$

$$\mathrm{Re}=\phi\frac{\rho_f u_t D_P}{\mu_f}=0.90\frac{10^3\times0.597\times\left(1\times10^{-3}\right)}{1.003\times10^{-3}}=536.32$$

Since Re>1, therefore, Newton's law should be used for finding terminal velocity in transition zone. For initial assumption of settling velocity, stoke's law is used. This initially assumed velocity is used to determine the Reynold number which is further used to find settling velocity. This iterative procedure is repeated till initial assumed velocity is approximately equal to settling velocity calculated from Newton's equation.

Initial drag coefficient is calculated as:

$$C_D=\frac{24}{\mathrm{Re}}+\frac{3}{\sqrt{\mathrm{Re}}}+0.34=0.5142$$

$$u_t=\sqrt{\frac{4}{3}\frac{\left(\rho_P\text{-}\rho_f\right)}{\rho_f}\frac{gD_p}{\phi C_D}}=0.1763\ \ \mathrm{m/s}$$

Now, iterative procedure is continued:

u_t (previous calculated)	Re	C_D	u_t	Difference
0.5977	536.3272	0.5143	0.1763	0.4214
0.1763	158.2037	0.7302	0.1480	0.0283
0.1480	132.7684	0.7811	0.1431	0.0049
0.1431	128.3690	0.7917	0.1421	0.0010
0.1421	127.5052	0.7939	0.1419	0.0002
0.1419	127.3315	0.7943	0.1419	0.0000

Final settling velocity=0.1419 m/s.

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Lecture 8

Setting and sedimentation: Part 2

TYPES OF GRAVITATIONAL SETTLING PHENOMENON

(i) **Discrete particle settling:** Applicable for very low concentration solids
  - Particles settle as individual entities
  - No interaction between particles

(ii) **Flocculation settling**: Applicable for dilute suspension of particles that coalesce or flocculate
  - By flocculation, particle size increases and terminal velocity increases.
  - Settling can be increased by addition of some ballasting agent such as polymers.

(iii) **Hindered settling**
  - For suspension of intermediate settling.
  - In this case, particles are such close together that the inter-particle force due to one hinders the settling of other particle.
  - The particles remain in fixed position with respect to each other and particles settles as a whole.

(iv) **Compression settling**
  - Case in which particles are in such high concentration that a whole structure is formed.
  - Compression takes place due to weight of whole mass which continuously increases.
  - A clear water is formed above compression zone

CLASSIFICATION OF SEDIMENTATION TANKS

- **Grit chamber**: For removal of sand, grits, etc.
- **Plain sedimentation tank**: For removal of settleable solids.
- **Chemical precipitation tank**: for removal of very fine suspended particles by adding coagulants, etc
- **Septic tanks**: For doing sedimentation and sludge digestion together in households
- **Secondary settling tanks**: After activated sludge or trickling filter treatment systems.

SCOUR VELOCITY

Maximum horizontal velocity though the tank which does not allows resuspension (scouring) of settled particles. It is given as [1]:

$$V_H = \sqrt{\frac{8k}{f}\frac{(\rho_p - \rho_f)}{\rho_f} gD_p} \tag{3.8.1}$$

Where, f is the Darcy–Weisbach friction factor (unit-less) and its value varies in the range 0.02- 0.03; k is cohesion constant that depends upon the type of material being scoured (unit-less). Its value varies in the range of 0.04- 0.06. For sticky interlocking matter k=0.6 whereas for ungrounded sand k=0.4.

Important point in design of sedimentation tank

Assume t is the detention time for which a suspension is detained in the settling tank having height H, length L and width W. Also assume, V_H is the horizontal velocity and u_t is the terminal settling velocity of the target particle. Now,

Cross-sectional area of tank (A_C)=H×W

Surface area of tank (A)=L×W

If Q is the flow rate of wastewater into the tank,

$$Q = A_C V_H = HWV_H \tag{3.8.2}$$

Since the target particle should not re-suspend during its flow along the length of the tank, therefore, detention time

$$t = \frac{L}{V_H} \tag{3.8.3}$$

Also, the target particle should settle down before it reaches the outlet, therefore,

$$t = \frac{H}{u_t} \tag{3.8.4}$$

Combining,

$$u_t = \frac{H}{L} V_H = \frac{W \times H}{W \times L} V_H = \frac{Q}{A} = \begin{pmatrix} \text{Surface loading} \\ \text{of the tank} \end{pmatrix} \text{OR} \begin{pmatrix} \text{Overflow} \\ \text{rate, } v_o \end{pmatrix} \tag{3.8.5}$$

This expression gives following important points:

- The terminal velocity should be ≥ surface loading of the tank.
- Surface area is more important than the height of the settling tank.
- Higher the surface area, higher will be the removal efficiency and more will be the removal of finer particles.
- All particles having settling velocity $u_t \geq v_o$ will be completed removed.
- For particles having $u_t < v_o$, only u_t/v_o only fraction will be removed.

Problem 3.8.1: A municipal wastewater plant is to be designed to treat maximum flow rate of 60000 m^3/d. Target particle for settling has the following characteristics: $D_P=200\times10^{-6}$ m, k=0.05, f=0.025, $\rho_P=1.25\times10^3$ kg/m^3. For a rectangular classifier having ratio of length to width>6, overflow rate is at-least four times the settling velocity and horizontal velocity at-most one-third of the scour velocity.

(a) Find the dimensions of the rectangular tank

(b) Determine detention time

Solution:

$$V_H = \sqrt{\frac{8k}{f}\frac{(\rho_p - \rho_f)}{\rho_f} g D_p} = \sqrt{\frac{8\times0.05(1.25\times10^3\text{-}10^3)}{0.025\times10^3} 9.81\times200\times10^{-6}} = 0.08853 \text{ m/s}$$

Actual horizontal velocity=V_H/3=0.02951 m/s.

$$u_t = \frac{g(\rho_p - \rho_f)D_P^2}{18\mu_f} = 5.44\times10^{-3} \text{m/s}$$

$$\text{Re} = \frac{\rho_f u_t D_P}{\mu_f} = 1.088$$

Overflow rate=3×u_t $= 21.76\times10^{-3}\,\text{m}/\text{s}$

If W is the width, L is the length and H is the height of the rectangular settling basin,

$$W\times H = \frac{\text{Flow rate}}{\text{Harizontal velocity}} = \frac{\left(60000/(24\times60\times60)\right)}{0.02951} = 23.54\ \text{m}^2$$

$$L\times W = \frac{\text{Flow rate}}{\text{Overflow rate}} = \frac{\left(60000/(24\times60\times60)\right)}{21.76\times10^{-3}} = 31.905\ \text{m}^2$$

Also given: $\frac{L}{W}=6$

$$\frac{L}{W}=\frac{31.905/W}{W}=6$$

W=2.305 m,

L=6×2.305=13.83 m

H=23.54/2.305=10.21 m

Volume of tank, V=LWH=325.47 m^3

Detention time, $t=\frac{325.47\times24\times60}{60000}=7.811\ \text{min}$

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Lecture 9

Settling chamber design

HINDERED (ZONE) SETTLING

During settling of high concentration slurries, both hindered or zone settling and compression settling usually occur in addition to discrete (free) and floculent settling. Various zones that get formed during settling of high concentration slurries are shown in following figure:

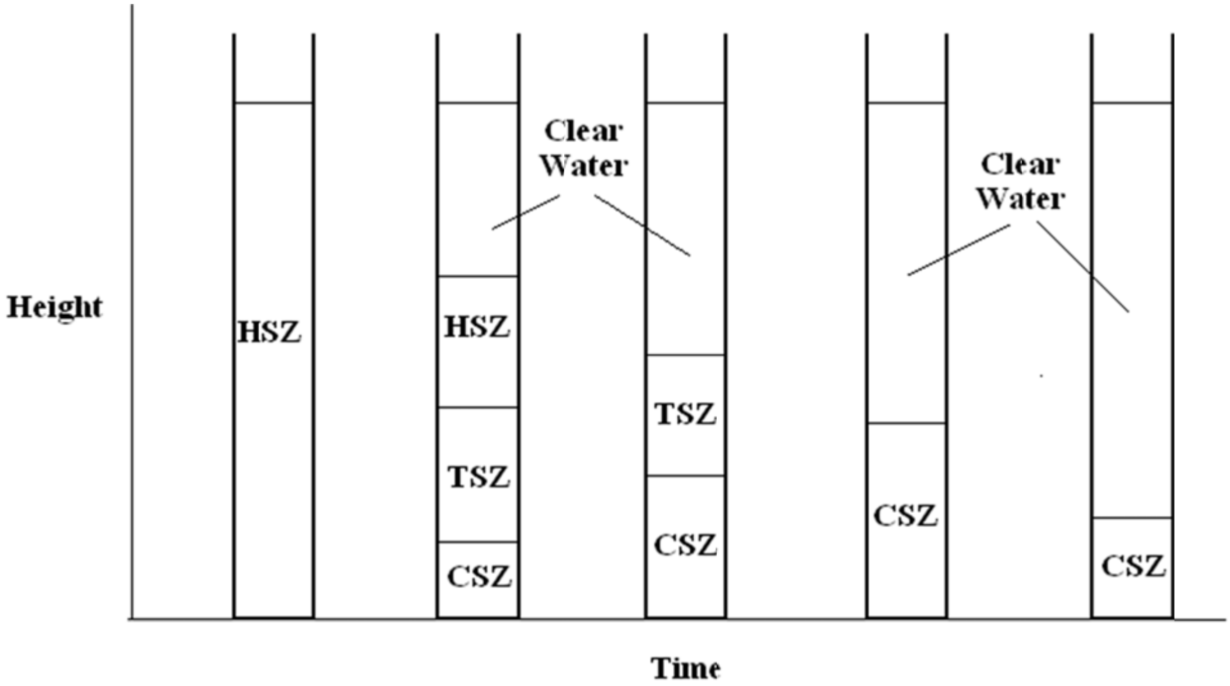


Figure 3.9.1. Phases of settling during hindered (zone) settling in a settling column, HSZ: hindered settling zone; TSZ: transtion settling zone; CSZ: compressive settling zone.

During this type of settling, the liquid tends to move up through the interstices of the contacting particles and therefore, the contacting particles tend to settle as a zone maintaing the same relative position with respect to each other. The phenomenon is known as hindered settling (HSZ). The rate of settling in the hindered settling region is a function of the concentration of the solids and their characteristics.

As the particles settle, a relatively clear layer of water is produced above the particles in the settling region. Remaining light particles usually settle as discrete or flocculant particles. An interface usually develops between the upper region and the hindered settling region.

As settling continues, a compressed layer of particles begins to form on the bottom of the cylinder. In this compression setting region, particles remain in close physical contact and form a structure. A transition region of settling between the hindered and compression settling zones gets formed. As the time progresses, first hindered and then transtion settling zones get removed and finally only clear water zone and compressed settling layer are only obtained [1].

These methods are, however, seldom used in the design of treatment plants because of less concentration of slurries.

Area requirement based on single-batch test results. For purposes of design, the final overflow rate selected should be based on a consideration of the following factors:

1) The area needed for clarification
2) The area needed for thickening, and
3) The rate of sludge withdrawal.

Column settling tests can be used to determine the area needed for the settling region directly. However, because the area required for thickening is usually greater than the area required for the settling, the rate of free settling rarely is the controlling factor. In the case of the activated-sludge process, where light fluffy floc particles are present, the free flocculant settling velocity of these particles could control the design.

AREA REQUIRED FOR THICKENING [1]

Assume that a column of height H_o is filed with a suspension of solids of uniform concentration (C_o). The rate at which the interface subsided is then equal to the slope of the curve at that point in time. According to the procedure, the area required for thickening is given by [2]:

$$A = \frac{Qt_u}{H_o} \tag{3.9.1}$$

Where, A is area required for sludge thickening $(m)^2$, Q is the flow rate into tank (m^3/s), H_o is the initial height of interface in column (m), t_u is the time to each desired underflow concentration (s). The critical concentration controlling the solids handling capability of the tank occurs at a height H_2 where the concentration is C_2. This point is determined by extending the tangents to the hindered settling and compression regions of the subsidence curve to the point of intersection and bisecting the angle thus formed.

The time t_u can be determined as follows:

(a) Construct a horizontal line at the depth H_u that corresponding to the depth at which the solids are at the desired underflow concentration C_u. The value of H_u is determined using the following expression [2]:

$$H_u = \frac{C_o H_o}{C_u} \tag{3.9.2}$$

(b) Construct a tangent to the settling curve at the point indicated by C_2.

(c) Construct a vertical line from the point of intersection of the two lines drawn in steps 1 and 2 to the time axis to determine the value of t_u .

With this value t_u , the area required for the thickening is computed using equation earlier. The area required for clarification is then determined. The larger of the two areas is the controlling value.

Problem 3.9.1: The settling curve shown in the following diagram was obtained for an activated sludge with an initial solid concentration C_o of 3000 mg/l. The initial height of the interface in the settling column is 1 m. Determine the area required to yield a thickened solids concentration (C_u) of 15000 mg/l with a total flow of 3 m^3/min. Also determine the solids loading (kg/m^2.d) and the overflow rate (m^3/m^2.d).

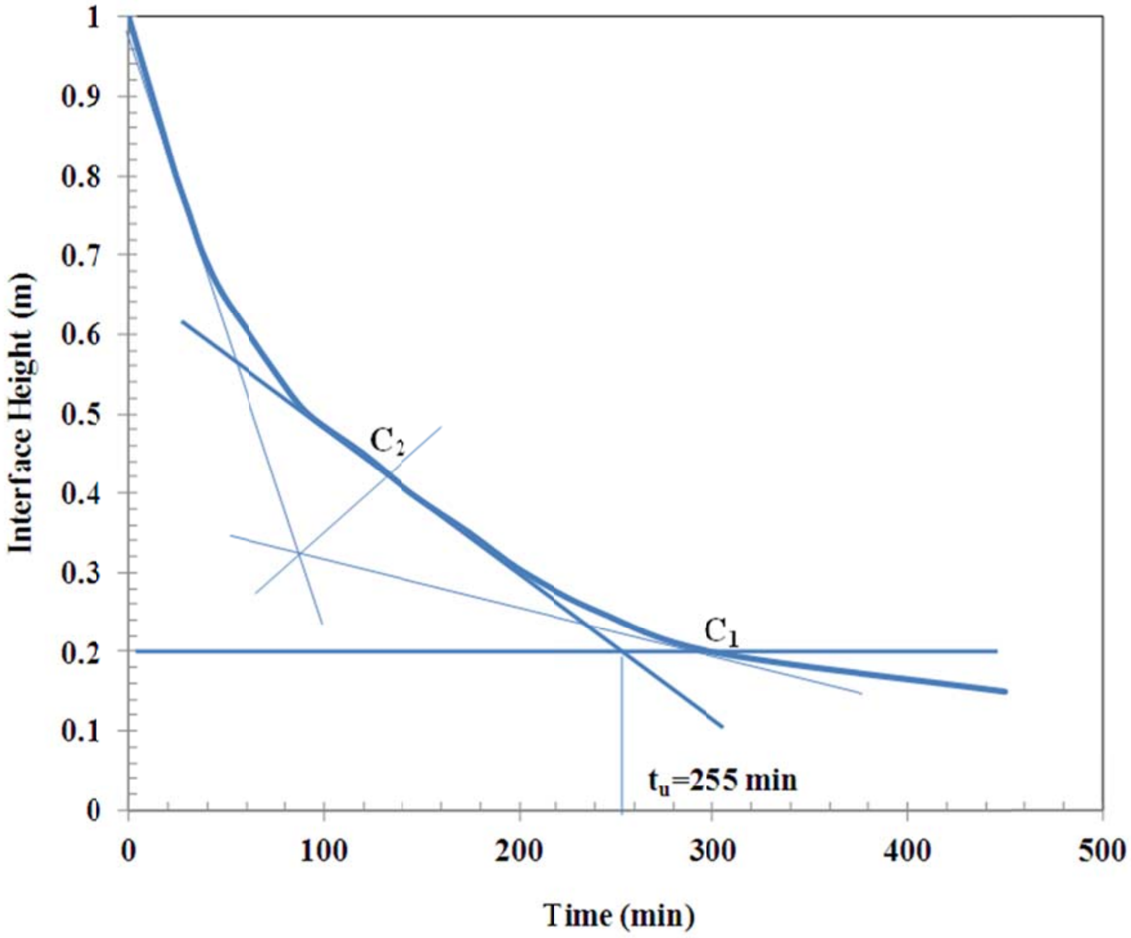
Solution: [A] Determination of the area required for thickening

$$H_u = \frac{C_o H_o}{C_u} = \frac{3000 \times 1}{15000} = 0.2 \text{ m}$$

A horizontal line is constructed at H_u=0.2 m which meets the settling curve at point C_1. Tangents are drawn to the curve at point C_1 and as well as at time t=0. Line bisecting the angle formed between the tangents meet the settling curve at point C_2. A tangent is further drawn to the settling curve at C_2 (the mid-point of the region between hindered and compression settling). The intersection of the tangent at C_2 and the line H_u=0.2 m determines t_u=255 min.

Thus for t_u=255 min, and the required area is

$$\mathrm{A} = \frac{\mathrm{Qt_u}}{\mathrm{H_o}} = \left(\frac{3 \times 255}{1}\right) = 765 \, \mathrm{m}^2$$



[B] Determination of the clarification area

a. *Determination of the interface subsidence velocity* ν *:* The subsidence velocity is determined by computing the slope of the tangent drawn from the initial portion of the interface settling curve. The computed velocity represents the unhindered settling rate of the sludge.

$$\nu = \left(\frac{1-0.7}{38}\right) = 0.007895 \text{ m/min}$$

b. *Determination of the clarification rate:* Since, the clarification rate is proportional to the liquid volume above the critical sludge zone, it may be computed as:

$$Q_c = 3\left(\frac{1-0.25}{1}\right) = 2.25 \text{ m}^3\text{/min}$$

c. *Determination of the clarification area:* The required area is obtained by dividing the clarification rate by the settling velocity.

$$A = \frac{Q_c}{\nu} = \frac{2.25}{0.007895} = 285 \ m^2$$

The controlling area is the thickening area (765 m^2) because it exceeds the area required for clarification (285 m^2).

[C] Determination of the solids loading: The solids loading is computed as follows:

$$\text{Solids, kg/d} = \frac{3 \times 3000 \times (24 \times 60)}{10^3} = 12960 \ \mathrm{kg/d}$$

$$\text{Solids loading} = \frac{12960}{765} = 16.94 \ \mathrm{kg/m^2.d}$$

[D] **Determination of the hydraulic loading rate:**

$$\text{Hydraulic loading rate} = \frac{3 \times (24 \times 60)}{765} = 5.65 \ \mathrm{m^3/m^2.d}$$

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Lecture 10

Filtration

FILTRATION

Water filtration is a mechanical or physical process of separating suspended and colloidal particles from fluids (liquids or gases) by interposing a medium through which only the fluid can pass. Medium used is generally a granular material through which water is passed. In the conventional water treatment process, filtration usually follows coagulation, flocculation, and sedimentation.

Filtration process

- During filtration in a conventional down-flow depth filter, wastewater containing suspended matter is applied to the top of the filter bed.
- As the water passes through the filter bed, the suspended matter in the wastewater is removed by a variety of removal mechanisms.
- With passage of time, as material accumulates within the interstices of the granular medium, the head-loss through the filter starts to build up beyond the initial value.
- After some period of time, the operating head-loss or effluent turbidity reaches a predetermined head loss or turbidity value, and the filter must be cleaned (backwashed) to remove the material (suspended solids) that has accumulated within the granular filter bed.
- Backwashing is accomplished by reversing the flow through the filter. A sufficient flow of wash water is applied until the granular filtering medium is fluidized (expanded), causing the particles of the filtering medium to abrade against each other.

Filtration is classified into following three types [1]:

1) Depth filtration
    a) Slow sand filtration
    b) Rapid porous and compressible medium filtration
    c) Intermittent porous medium filtration
    d) Recirculating porous medium filtration
2) Surface filtration
    a) Laboratory filters used for TSS test
    b) Diatomaceous earth filtration
    c) Cloth or screen filtration
3) Membrane flirtation

DEPTH FILTRATION

In this method, the removal of suspended particulate material from liquid slurry is done by passing the liquid through a filter bed composed of granular or compressible filter medium.

- Depth filtration is the solid/liquid separation process in which a dilute suspension or wastewater is passed through a packed bed of sand, anthracite, or other granular media.
- Solids (particles) get attached to the media or to the previously retained particles and are removed from the fluid [2].
- This method is virtually used everywhere in the treatment of surface waters for potable water supply.
- Depth filtration is also often successfully used as a tertiary treatment for wastewater.
- Failure of depth filtration affects the other downstream processes significantly and most of the times results in overall plant failure.
- Performance of a filter is quantified by particle removal efficiency and head loss across the packed bed.
- The duration of a filter run is limited by numerous constraints: available head, effluent quality or flow requirement.
- The head loss and removal efficiency of a filter are complicated functions of suspension qualities (particle size distribution and concentration, particle surface chemistry, and solution chemistry), filter design parameters (media size, type, and depth), and operating conditions (filtration rate and filter runtime) [2].

Slow sand filtration (SSF):

- It is very effective for removing flocs containing microorganisms such as algae, bacteria, virus, etc.
- Slow sand filtration (SSF), with flow rates ranging between 0.1 and 0.2 $m^3 h^{-1}$, has been a standard biofiltration treatment for decades in the wastewater industry [3].

Rapid sand filtration (RSF)

- The major difference between SSF and RSF is in the principle of operation; that is, in the speed or rate at which water passes through the media.
- In Rapid sand filtration (RSF), water passes downward through a sand bed that removes the suspended particles [4].

- RSF is used today as an effective pretreatment procedure to enhance water quality prior to reverse osmosis (RO) membranes in desalination plants [3].

SURFACE FILTRATION

- Surface filtration involves removal of suspended material in a liquid by mechanical sieving. In this method, the liquid is passed through a thin septum (i.e., filter material).
- Materials that have been used as filter septum include woven metal fabrics, cloth fabrics of different weaves, and a variety of synthetic materials [4].

MEMBRANE FILTRATION

- Membrane filtration can be broadly defined as a separation process that uses semi-permeable membrane to divide the feed stream into two portions: a permeate that contains the material passing through the membranes, and a retentate consisting of the species being left behind [5].
- Membrane filtration can be further classified in terms of the size range of permeating species, the mechanisms of rejection, the driving forces employed, the chemical structure and composition of membranes, and the geometry of construction [6].
- The most important types of membrane filtration are pressure driven processes including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO).

MECHANISMS INVOLVED IN THE FILTRATION PROCESSES

The process of filtration involves several mechanisms listed in the table. Straining has been identified as the principal mechanism that is operative in the removal of suspended solids during the filtration of settled secondary effluent from biological treatment processes. Other mechanisms including impaction, interception, and adhesion are also operative even though their effects are small and, for the most part, masked by the straining action.

Table 3.10.1 Mechanisms involved in the filtration processes [1]

Mechanism/ phenomenon	**Description**
Straining a) Mechanical b) Chance contact	Particles larger than the pore space of the filtering medium are strained out mechanically. Particles smaller than the pore space are trapped within the filter by chance contact
Sedimentation	Particles settle on the filtering medium within the filter
Impaction	Heavy particles do not follow the flow streamlines
Interception	Particles get removed during contact with the surface of the filtering medium
Adhesion	Particles become attached to the surface of the filtering medium as they pass through.
Flocculation	It can occur within the interstices of the filter medium.
Chemical adsorption a) Bonding b) Chemical interaction	Once a particle has been brought in contact with the surface of the filtering medium or with other particles, either one of these mechanisms, chemical or physical adsorption or both, may occur.
Physical adsorption a) Electrostatic forces b) Electrokinetic forces c) Van der Waals forces	
Biological growth	Biological growth within the filter reduces the pore volume and enhances the removal of particles with any of the above removal mechanisms

FILTER-MEDIUM CHARACTERISTICS

Grain size is the principle filter-medium characteristic that affects the filtration operation. Grain size affects both the clear-water head loss and the buildup of head loss during the filter run. If too small a filtering medium is selected, much of the driving force will be wasted in overcoming the frictional resistance of the filter bed. On the other hand, if the size of the medium is too large, many of the small particles in the influent will pass directly through the bed. The size distribution of the filter material is usually determined by sieve analysis using a series of decreasing sieve sizes.

CLASSIFICATION OF FILTERS

Filters that must be taken off-line periodically to be backwashed are classified operationally as semi-continuous.

Filters in which is filtration and backwash operations occur simultaneously are classified as continuous.

Within each of these two classifications, there are a number of different types of filters depending on bed depth (e.g., shallow, conventional, and deep bed), the type filtering medium used (mono-, dual-, and multi-medium), whether the filtering medium is stratified or unstratified, the type of operation (down-flow or upflow), and the method used for the management of solids (surface or internal storage). For the mono- and dual-medium semi-continuous filters, a further classification can be made based on the driving force (e.g., gravity or pressure) [7].

TYPES OF DEPTH FILTERS

The five types of depth filters used most commonly for wastewater filtration are

(a) Conventional down-flow filters: Single-, dual-, or multimedium filter materials are utilized in conventional down-flow depth filters. Typically sand or anthracite is used as the filtering material in single-medium filters. Dual-medium filters usually consist of a layer anthracite over a layer of sand. Dual- and multimedium and deep-bed mono-medium depth filters were developed to allow the suspended solids in the liquid to be filtered to penetrate farther into the filter bed, and thus use more of the solids-storage capacity available within the filter bed.

(b) Deep-bed down-flow filters: The deep-bed down-flow filter is similar to the conventional down-flow filter with the exception that the depth of the filter bed and the size of the filter medium are greater than corresponding values an conventional filter. Because of the greater depth and larger medium size, more solids can be stored within the filter bed and the run length can be extended.

(c) Deep-bed upflow continuous-backwash filters: In this filter the wastewater to be filtered is introduced into the bottom of the filter where it flows upward through a series of riser tubes and is distributed evenly into the sand bed through the open bottom of an inlet distribution hood. The water then flows upward through the downward-moving sand. The clean filtrate exits from the sand bed, overflows a weir, and is discharged from the filter. Because the sand has higher settling velocity than the removed solids, the sand is not carried out of the filter.

(d) Pulsed-bed filter: The pulsed-bed filter is a proprietary down-flow gravity filter with an unstratified shallow layer of fine sand as the filtering medium. The shallow bed is used for solids storage, as opposed to other shallow-bed filters where solids are principally stored on the sand surface. An unusual feature of this filter is the use of an air pulse to disrupt the sand surface and thus allow penetration of suspended solids into the bed.

(e) Travelling-bridge filters: The travelling-bridge filter is a proprietary continuous down-flow, automatic backwash, low-head, granular medium depth filter. The bed of the filter is divided horizontally into long independent filter cells. Each filter cell contains approximately 280 mm of medium. Treated wastewater flows through the medium by gravity.

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Lecture 11

Water pollution control by membrane based technologies

MEMBRANE

Membrane can be described as a thin layer of material that is capable of separating materials as a function of their physical and chemical properties when a driving force is applied across the membranes. Physically membrane could be solid or liquid.

In membrane separation processes, the influent to the membrane module is known as the feed stream (also known as the feed water), the liquid that passes through the semipermeable membrane is known as permeate (also known as the product stream or permeating stream) and the liquid containing the retained constituents is known as the concentrate also known as retained phase.

MEMBRANE PROCESS CLASSIFICATION

Membrane processes can be classified in a number of different ways [1]:

- The type of material from which the membrane is made
- The nature of the driving force
- The separation mechanism
- The nominal size of the separation achieved

Table 3.11.1. General characteristics of membrane processes [2]

Membrane process	**Driving force**	**Method of separation**	**Operating structure (pore size)**	**Typical operating range, µm**	**Permeate description**	**Range of application**
Microfiltration	Hydrostatic pressure difference	Sieving mechanism	Macropores (>50 nm)	0.08 - 2.0	Water + dissolved solutes	Sterile filtration clarification
Ultrafiltration	Hydrostatic pressure difference	Sieving mechanism	Mesopores (2 -50 nm)	0.005 – 0.2	Water + small molecules	Separation of macromolecular solutions
Nanofiltration	Hydrostatic pressure difference	Sieving mechanism + solution/diffusion	Micropores (<2 nm)	0.001 – 0.01	Water + very small molecules, ionic	Removal of small molecules, small

					solutes	harness, viruses
Reverse osmosis	Hydrostatic pressure difference	Solution diffusion mechanism + exclusion	Dense (<2 nm)	0.0001 – 0.001	Water + small molecules	Separation of salts and microsolutes from solutions
Dialysis	Concentration gradient	Diffusion in convection free layer	Mesopores (2 -50 nm)	-	Water + ionic solutes	Separation of salts and microsolutes from macromolecular solutions
Electrodialysis	Electrical potential gradient	Electrical charge of particle and size	Micropores (<2 nm)	-		Desalting of ionic solution

Table 3.11.2. Advantages & disadvantages of membrane technologies [1, 3, 4].

Advantages	**Disadvantages**
Microfiltration and ultrafiltration	
➢ Can reduce the amount of treatment chemicals	➢ Uses more electricity; high-pressure systems can be energy-intensive
➢ Smaller space requirements (footprint); membrane equipment requires 50 to 80 percent less space than conventional plants	➢ May need pretreatment to prevent fouling; pretreatment facilities increase space needs and overall costs
➢ Reduced labour requirements; can be automated easily	➢ May require residuals handling and disposal of concentrate
➢ New membrane design allows use of	➢ Require replacement of membranes

lower pressures; system cost may be competitive with conventional wastewater-treatment processes	about every 3 to 5 years
➢ Remove protozoan cysts, oocysts, and helminth ova; may also remove limited amounts of bacteria and viruses	➢ Scale formation can be a serious problem. Scale-forming potential difficult to predict without field testing ➢ Flux rate (the rate of feedwater flow through the membrane) gradually declines over time. Recovery rates may be considerably less than 100 percent ➢ Lack of a reliable low-cost method of monitoring performance
Reverse osmosis	
➢ Can remove dissolved constituents	➢ Works best on ground water or low solids surface water or pretreated wastewater effluent
➢ Can disinfect treated water	➢ Lack of a reliable low-cost method of monitoring performance
➢ Can remove NDMA and other related organic compounds	➢ May require residuals handling and disposal of concentrate
➢ Can remove natural organic matter (a disinfection by-product precursor) and inorganic matter	➢ Expensive compared to conventional treatment

MEMBRANE MATERIALS & CONFIGURATIONS

- Membranes can be made from a number of different organic and inorganic materials. The membranes used for wastewater treatment are typically organic. The principle types of membranes used include polypropylene, cellulose acetate, aromatic polyamides, and thin-film composite (TFC).

- Membranes used for the treatment of water and wastewater typically consist of a thin skin having a thickness of about 0.20 to 0.25 µm supported by a more porous structure of about 100 µm in thickness.
- Term ‘module’ is used to describe a complete unit comprised of the membranes, the pressure support structure for the membranes, the feed inlet and outlet permeate and retentate ports, and an overall support structure.
- The principle types of membrane modules used for wastewater treatment are 1) tubular, 2) spiral wound, 3) hollw fibre,4) flat.

Table 3.11.3. Comparison of different membrane configurations [5]

Membrane geometry	**Suspended solids tolerance**	**Control of fouling**	**Cleaning easiness**	**Packing density**	**Cost for unit of volume**
Tubular	Good	Excellent	Excellent	Low-medium	Medium-high
Spiral-wound	Low	Limited	Medium	High	Low
Hollow fibre (external feed)	Scant (good)	Scant (good)	Scant (good)	Excellent	High (low)
Flat	Medium	Good	Medium	Medium	Medium-low

MEMBRANE FOULING

Membranes can be seen as sieves retaining part of the feed. As a consequence, deposits of the retained material will accumulate at the feed side of the membrane. In time this might hamper the selectivity and productivity of the separation process. This process is called fouling. koros et al gave the definition of fouling as “The process resulting in loss of performance of a membrane due to deposition of suspended or dissolved substances on its external surfaces, at its pore openings, or within its pores”. Membrane fouling is an important consideration in the design and operation of membrane systems as it affects pretreatment needs, cleaning requirements, operating conditions, cost, and performance [6].

Three approaches are used to control membrane fouling:

1) Pretreatment of the feed water: pretreatment is used to reduce the TSS and bacterial content of the feed water
2) Membrane backflushing: to eliminate the accumulated material from the membrane surface with water and/or air.
3) Chemical cleaning of the membranes: Chemical treatment is used to remove constituents that are not removed during conventional backwashing. Chemical precipitates can be removed by altering the chemistry of the feed water and by chemical treatment.

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Lecture 12

Water pollution control by adsorption: Part 1

ADSORPTION

- Adsorption can be simply defined as the concentration of a solute, which may be molecules in a gas stream or a dissolved or suspended substance in a liquid stream, on the surface of a solid [1].
- In an adsorption process, molecules or atoms or ions in a gas or liquid diffuse to the surface of a solid, where they bond with the solid surface or are held there by weak inter-molecular forces. The adsorbed solute is called the adsorbate, and the solid material is the adsorbent.
- Activated clays, activated carbons, fuller earths, bauxite, alumina, bone char, molecular sieves, synthetic polymeric adsorbents, silica gel, etc. are the main types of adsorbents used in the industry.
- There are basically two types of adsorption processes: one is physical adsorption (physisorption) and the second is chemisorption.

DIFFUSION OF ADSORBATE

There are essentially four stages in the adsorption of an organic/inorganic species by a porous adsorbent [2]:

1. Transport of adsorbate from the bulk of the solution to the exterior film surrounding the adsorbent particle;
2. Movement of adsorbate across the external liquid film to the external surface sites on the adsorbent particle (film diffusion);
3. Migration of adsorbate within the pores of the adsorbent by intraparticle diffusion (pore diffusion);
4. Adsorption of adsorbate at internal surface sites.

All these processes play a role in the overall sorption within the pores of the adsorbent. In a rapidly stirred, well mixed batch adsorption, mass transport from the bulk solution to the external surface of the adsorbent is usually fast. Therefore, the resistance for the transport of the adsorbate from the bulk of the solution to the exterior film surrounding the adsorbent may be small and can be neglected. In addition, the adsorption of adsorbate at surface sites (step 4) is usually very rapid and thus offering negligible resistance in comparison to other steps, i.e. steps 2 and 3. Thus, these processes usually are not considered to be the rate-limiting steps in the sorption process [3].

In most cases, steps (2) and (3) may control the sorption phenomena. For the remaining two steps in the overall adsorbate transport, three distinct cases may occur:

Case I:	external transport	>	internal transport.
Case II:	external transport	<	internal transport.
Case III:	external transport	≈	internal transport.

In cases I and II, the rate is governed by film and pore diffusion, respectively. In case III, the transport of ions to the boundary may not be possible at a significant rate, thereby, leading to the formation of a liquid film with a concentration gradient surrounding the adsorbent particles [3].

Usually, external transport is the rate-limiting step in systems which have (a) poor phase mixing, (b) dilute concentration of adsorbate, (c) small particle size, and (d) high affinity of the adsorbate for the adsorbent. In contrast, the intra-particle step limits the overall transfer for those systems that have (a) a high concentration of adsorbate, (b) a good phase mixing, (c) large particle size of the adsorbents, and (d) low affinity of the adsorbate for adsorbent [4].

The possibility of intra-particle diffusion can be explored using the intra-particle diffusion model [5, 6].

$$q_t = k_{id} t^{1/2} + I \qquad (3.12.1)$$

Where, q_t is the amount of the adsorbate adsorbed on the adsorbent (mg/g) at any t and k_{id} is the intra-particle diffusion rate constant, and values of I give an idea about the thickness of the boundary layer.

In order to check whether surface diffusion controls the adsorption process, the kinetic data can be analyzed using Boyd kinetic expression which is given by [7]:

$$F = 1 - \frac{6}{\pi^2}\exp(-B_t) \text{ or } B_t = -0.4977 - \ln(1-F) \qquad (3.12.2)$$

Where, $F(t) = q_t / q_e$ is the fractional attainment of equilibrium at time t, and B_t is a mathematical function of F.

However, if the data exhibit multi-linear plots, then two or more steps influence the overall adsorption process. In general, external mass transfer is characterized by the initial solute uptake and can be calculated from the slope of plot between C/C_o versus time. The slope of these plots can be calculated either by assuming polynomial relation between C/C_o and time or it can be calculated based on the assumption that the relationship was linear for the first initial rapid phase [8].

ADSORPTION KINETIC

Pseudo-first-order and pseudo-second-order model: The adsorption of adsorbate from solution to adsorbent can be considered as a reversible process with equilibrium being established between the solution and the adsorbate. Assuming a non-dissociating molecular adsorption of adsorbate molecules on adsorbent, the sorption phenomenon can be described as the diffusion controlled process.

Using first order kinetics it can be shown that with no adsorbate initially present on the adsorbent, the uptake of the adsorbate by the adsorbent at any instant t is given as [9].

$$q_t = q_e\left[1-\exp\left(-k_f t\right)\right] \tag{3.12.3}$$

where, q_e is the amount of the adsorbate adsorbed on the adsorbent under equilibrium condition, k_f is the pseudo-first order rate constant.

The pseudo-second-order model is represented as [10,11]:

$$q_t = \frac{tk_S q_e^2}{1+tk_S q_e} \tag{3.12.4}$$

The initial sorption rate, h (mg/g min), at t –> 0 is defined as

$$h = k_S q_e^2 \tag{3.12.5}$$

ADSORPTION ISOTHERM

Equilibrium adsorption equations are required in the design of an adsorption system and their subsequent optimization [12]. Therefore it is important to establish the most appropriate correlation for the equilibrium isotherm curves.

Srivastava et al. [9,13] have discussed the theory associated with the most commonly used isotherm models. Various isotherms namely Freundlich, Langmuir, Redlich-Peterson (R-P) and Tempkin which are given in following table are widely used to fit the experimental data:

Table 3.12.2. Various isotherm equations for the adsorption process

Isotherm	**Equation**	**Reference**
Freundlich	$q_e = K_F C_e^{1/n}$	[14]
Langmuir	$q_e = \dfrac{q_m K_L C_e}{1 + K_L C_e}$	[15]
R-P	$q_e = \dfrac{K_R C_e}{1 + a_R C_e^{\beta}}$	**[16]**
Tempkin	$q_e = B_T \ln(K_T C_e)$	**[17]**

K_R: R–P isotherm constant (l/g), a_R: R–P isotherm constant (l/mg), β: Exponent which lies between 0 and 1, C_e: Equilibrium liquid phase concentration (mg/l), K_F: Freundlich constant (l/mg), 1/n: Heterogeneity factor, K_L: Langmuir adsorption constant (l/mg), q_m: adsorption capacity (mg/g), K_T: Equilibrium binding constant (l/mol), B_T: Heat of adsorption.

The Freundlich isotherm is derived by assuming a heterogeneous surface with a non-uniform distribution of heat of adsorption over the surface, whereas in the Langmuir theory the basic assumption is that the sorption takes place at specific homogeneous sites within the adsorbent. The R-P isotherm incorporates three parameters and can be applied either in homogenous or heterogeneous systems. Tempkin isotherm assumes that the heat of adsorption of all the molecules in the layer decreases linearly with coverage due to adsorbent-adsorbate interactions, and the adsorption is characterized by a uniform distribution of binding energies, up to some maximum binding energy [13].

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Lecture 13

Water pollution control by adsorption: Part 2

FACTORS CONTROLLING ADSORPTION

The amount of adsorbate adsorbed by an adsorbent from adsorbate solution is influenced by a number of factors as discussed below:

Nature of Adsorbent

The physico-chemical nature of the adsorbent is important. Adsorbents differ in their specific surface area and affinity for adsorbate. Adsorption capacity is directly proportional to the exposed surface. For the non-porous adsorbents, the adsorption capacity is inversely proportional to the particle diameter whereas for porous material it is practically independent of particle size. However, for porous substances particle size affects the rate of adsorption. For substances like granular activated carbon, the breaking of large particles to form smaller ones open up previously sealed channels making more surface accessible to adsorbent.

Pore sizes are classified in accordance with the classification adopted by the International Union of Pure and Applied Chemistry (IUPAC) [1], that is, micro-pores (diameter (d) <20 Å), meso-pores (20 Å < d < 500 Å) and macro-pores (d > 500 Å). Micro-pores can be divided into ultra-micropores (d < 7 Å) and super micro-pores (7 Å < d < 20 Å).

pH of Solution

The surface charge as well as the degree of ionization is affected by the pH of the solution. Since the hydrogen and hydroxyl ions adsorbed readily on the adsorbent surface, the adsorption of other molecules and ions is affected by pH. It is a common observation that a surface adsorbs anions favorably at low pH and cations in high pH range.

Contact Time

In physical adsorption most of the adsorbate species are adsorbed within a short interval of contact time. However, strong chemical binding of adsorbate with adsorbent requires a longer contact time for the attainment of equilibrium. Available adsorption results reveal that the uptake of adsorbate species is fast at the initial stages of the contact period, and thereafter, it becomes slower near the equilibrium. In between these two stages of the uptake, the rate of adsorption is found to be nearly constant. This may be due to the fact that a large number of active surface sites are available for adsorption at initial stages and the rate of adsorption is a function of available vacant site. Concentration of available vacant sites decreases and there is repulsion between solute molecules thereby reducing the adsorption rate [2].

Initial Concentration of Adsorbate

A given mass of adsorbent can adsorb only a fixed amount of adsorbate. So the initial concentration of adsorbate solution is very important. The amount adsorbed decreases with increasing adsorbate concentration as the resistance to the uptake of solute from solution of adsorbate decreases with increasing solute concentration. The rate of adsorption is increased because of the increasing driving force [3].

Temperature

Temperature dependence of adsorption is of complex nature. Adsorption processes are generally exothermic in nature and the extent and rate of adsorption in most cases decreases with increasing temperature. This trend may be explained on the basis of rapid increase in the rate of desorption or alternatively explained on the basis of Le-Chatelier's principle.

Some of the adsorption studies show increased adsorption with an increase in temperature. This increase in adsorption is mainly due to an increase in number of adsorption sites caused by breaking of some of the internal bonds near the edge of the active surface sites of the adsorbent. Also, if the adsorption process is controlled by the diffusion process (intraparticle transport-pore diffusion), than the sorption capacity increases with an increase in temperature due to endothermicity of the diffusion process. An increase in temperature results in an increased mobility of the metal ions and a decrease in the retarding forces acting on the diffusing ions. These result in the enhancement in the sorptive capacity of the adsorbents [4, 5].

ADSORPTION OPERATIONS

Fixed bed adsorbers

- These are used for the adsorption of dyes and colorants, refractory pollutants from wastewater.
- The size of the bed depends on the gas flow rate and the desired cycle time.
- The bed length usually varies from 0.3 to 1.3 m.
- The gas is fed downward through the adsorbent particles in the bed.
- Inside the bed, the adsorbent particles are placed on a screen, or performed plate.
- Upflow of feed is usually avoided because of the tendency of fluidization of the particles at high rates. When the adsorption reaches the desired value, the feed goes to the other bed through an automatic valve and the regeneration process starts.

- Regeneration process is usually carried out by steam, provided the solvent is immiscible with water. It may also be carried out by a hot or inert gas.
- The adsorption cycle usually varies from 2 to 24 h. for a large bed, the adsorption cycle is high, but the pressure drop and capital cost are also high.
- For a small bed, the pressure drop is less, but the separation is incomplete and more energy is required for regeneration.

The concentration of solute in the fluid phase and of the solid adsorbent phase change with time and with position in the fixed bed as adsorption proceeds. At the inlet to the bed, the solid is assumed to contain no solute at the start of the process. As the fluid first comes in contact with the inlet of the bed, most of the mass transfer and adsorption takes place here. As the fluid passes through the bed, the concentration of the fluid drops very rapidly with the distance in the bed and reaches zero well before the end of the bed of the reached [6].

After the short time, the solid near the entrance is almost saturated, and most of the mass transfer and adsorption now takes place at a point slightly farther from the inlet. Following figure shows the breakthrough concentration profile in the fluid at outlet of bed.

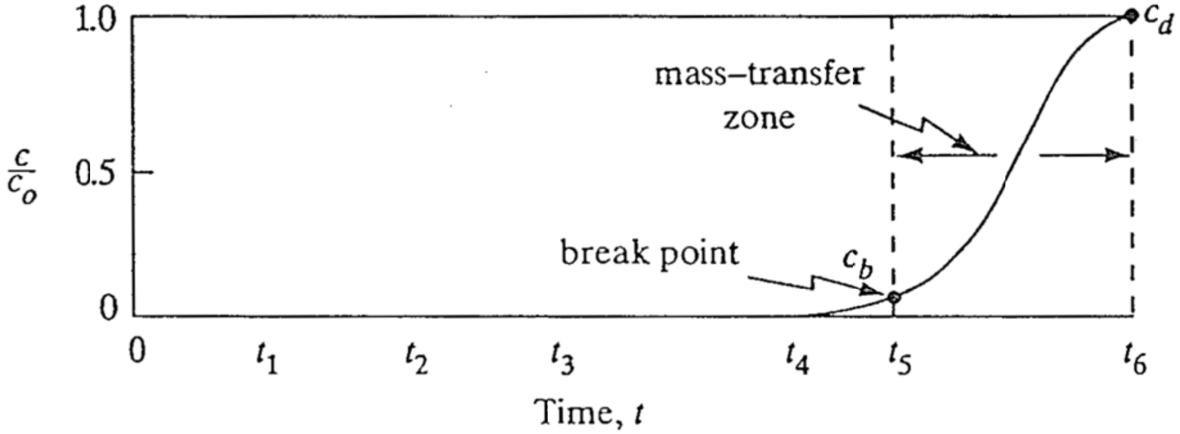

Figure 3.13.1. Breakthrough concentration profile in the fluid at outlet of bed.

In the figure, the outlet concentration remains near zero until the mass transfer zone starts to reach the tower outlet at time t_4. Then the outlet concentration starts to rise, and at t_5 the outlet concentration has risen to c_b, which is called the break point. The service time of the bed is given by the Bohart Adams equation [7].

$$t = \frac{N_o}{C_o \cdot v}\left[X - \frac{v}{K \cdot N_o}\ln\left(\frac{C_o}{C_B} - 1\right)\right] \tag{3.13.1}$$

Where, t is the service time of the bed, V is the linear flow rate of the solution, X is the depth of the bed, K is the rate constant, N_o is the adsorption capacity, C_o is the concentration of the solute entering into the bed, C_B is the allowable effective concentration.

Stirred tank adsorbers

- Stirred tank adsorbers are generally used for the removing pollutants from the aqueous wastes.
- Such an adsorber consists of a cylindrical tank fitted with a stirrer or air sparger.
- The stirrer or air-sparger keeps the particles in the tank in suspension.
- The spent adsorbate is removed by sedimentation or filtration.
- The mode of operation may be batch or continuous.

Continuous adsorbers

- The solid and the fluid move through the bed counter currently and come in contact with each other throughout the entire apparatus without periodic separation of the phrases.
- The solid particles are fed from the top and flow down through the adsorption and regeneration sections b gravity and are then returned to the top of the column by an air lift or mechanical conveyer.
- Multi-stage fluidized beds, in which the fluidized solids pass through down comers from stage to stage, may be used for fine particles.

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Lecture 14

Electrochemical Treatment

ELECTROCHEMICAL TREATMENT (ECT)

ECT process can be another alternative process for treating various wastewaters.

The major methods for ECT are: electro-coagulation (EC), electro-flotation (EF) and electro-oxidation (EO).

An ECT unit consists of anodes and cathodes in parallel mode. When electric power is applied from a power source, the anode material gets oxidized and the cathode is subjected to reduction of elemental metals and due to further reactions depending on conditions applied, removal of various pollutants takes place by EC and/or EF and/or EO mechanisms [1].

Electro-flotation (EF)

EF is a simple process in which buoyant gases bubbles generated during electrolysis take along with them the pollutant materials to the surface of liquid body. The bubbles of hydrogen and oxygen which are generated from water electrolysis move upwards in the liquid phase. A layer of foam, containing gas bubbles and floated particles is formed at the surface of water. The rate of flotation depends on several parameters such as surface tension between the water particles and gas bubbles; the bubble size distribution and bubble density; size distribution of the particles; the residence time of the solution/liquid in the EC cell and the flotation tank; the particle and gas bubble zeta potentials; and the temperature, pH of the solution [2,3].

Electro-oxidation (EO)

Decomposition of organic materials through EO treatment means the oxidation of organics present in wastewater to carbon dioxide and water or other oxides. The electrochemical oxidation of wastewater is achieved in two ways. First, by direct anodic oxidation, in which organics are adsorbed at the electrode and oxidized at the surface of the electrode and second, by indirect oxidation in which some oxidizing agents are generated electrochemically which are responsible for oxidation of organics present in the solution [2].

Organic pollutants are adsorbed on the anode surface in direct anodic oxidation process, where active oxygen (adsorbed hydroxyl radicals) or chemisorbed “active oxygen” is accountable for the oxidation of adsorbed Organics pollutants. The mechanism of oxidation of organic matter on oxide anode (MO_X) was suggested by Comninellis [4]. The reactions involve are as follows:

$$H_2O + MO_X \longrightarrow MO_X[OH] + H^+ + e^- \qquad (3.14.1)$$

The adsorbed hydroxyl radicals may form chemisorbed active oxygen

$MO_X[OH] \longrightarrow MO_{X+1} + H^+ + e^-$ (3.14.2)

The liberated chemisorbed active oxygen is responsible for the oxidation.

During the EO treatment process, two types, of oxidation is possible. In one way, toxic and non-biocompatible pollutants are converted into bio-degradable organics, so that further biological treatment can be initiated. In contrast, in other way, pollutants are oxidized to water and CO_2 and no further purification is necessary.

In an indirect oxidation process, strong oxidant such as hypochlorite/chlorine, ozone, and hydrogen peroxide [5] are regenerated during electrolysis. Following reaction shows the formation of hypochlorite:

$H_2O + Cl^- \longrightarrow HOCl + H^+ +2e^-$ (3.14.3)

High voltage can led to formation of hydrogen peroxide and other molecules as follows:

$H_2O \longrightarrow OH, O, H^+, H_2O_2$ (3.14.4)

These oxidants oxidize many inorganic and organic pollutants in the bulk solution.

Electro-coagulation (EC)

EC, like coagulation, is the process of destabilization of colloidal particles present in wastewater and can be achieved by two mechanisms: one in which an increase in ionic concentration, reduce the zeta potential, and adsorption of counter-ions on colloidal particles neutralises the particle charge; and other by well known mechanism of sweep flocculation [6,7].

Various reactions take place in the EC reactor during its operation. As the current is applied, the anode material undergoes oxidation and cathode gets reduced. If iron or Al electrodes are used, Fe^{2+} and Al^{3+} ion generation takes place at anode by the following reaction [8,9]

$Fe\,(S) \rightarrow Fe^{2+}\,(aq) + 2e^-$ (3.14.5)

$Al\,(S) \rightarrow Al^{3+}\,(aq) + 3e^-$ (3.14.6)

In addition, oxygen evolution can compete with iron or aluminum dissolution at the anode via the following reaction:

$2H_2O\,(l) \rightarrow O_2\,(g) + 4H^+\,(aq) + 4e^-$ (3.14.7)

At the cathode, hydrogen evolution takes place via the following reaction:

$3H_2O\,(l) + 3e^- \rightarrow 3/2H_2\,(g) + 3OH^-\,(aq)$ (3.14.8)

Liberated Fe^{2+}/Al^{3+} and OH^- ions react to form various monomeric and polymeric hydrolyzed species. The concentration of the hydrolyzed metal species depends on the metal concentration, and the solution *pH*. These metal hydrolysed products are responsible for the coagulation of pollutants from solution [7].

FACTORS AFFECTING ECT PROCESS

Current density (*J*), electrolysis time (*t*) and anodic dissolution: Faraday's law describes the relationship between current density (*J*) and the amount of anode material that dissolves in the solution. It is given as [7-9]:

$$w = \frac{MJt}{ZF} \qquad (3.14.9)$$

Where, w is the theoretical amount of ion produced per unit surface area by current density J passed for duration of time, t. Z is the number of electrons involved in the oxidation/reduction reaction, M is the atomic weight of anode material and F is the Faraday's constant (96486 C/mol).

The pollutants removal efficiency depends directly on the concentration of aluminum ions produced by the metal electrodes, which in turn as per Faradays law depends upon the t and J. When the value of t and J increases, an increase occurs in the concentration of metal ions and their hydroxide flocs. Consequently, an increase in t and J increases the removal efficiency.

Theoretically, according to the Faraday's law when 1 F of charge passes through the circuit, 28 g of iron is dissolved at each electrode individually connected to the positive node of the power supply unit. During the coagulation process with iron electrodes, the valency of the coagulant increases, with Fe^{3+} being much more effective than the Fe^{2+}.

pH: The initial *pH* (pH_i) of the wastewater will have a significant impact on the efficiency of the ECT. The effects of pH_i on the ECT of wastewater can be reflected by the solubility of metal hydroxides. The effluent pH after ECT would increase. The incremental increase in pH with an incremental increase in the amount of current applied tends to decrease at higher current [10,11]. The general cause of the pH increase can be explained from the following equation:

$$2\,H_2O + 2e^- \longrightarrow H_{2(g)} + 2OH^- \text{ (cathode)} \qquad (3.14.9)$$

At the cathode, generated hydrogen gas (which attaches to the flocculated agglomerates, resulting in flocs floation to the surface of the water) and this causes the pH to increase as the hydroxide-ion concentration in the water increases. This reaction is one of the dominant reactions that occur in the electro-flocculation system [3, 12].

Also, due to the following reaction, pH is affected:

$$2\ H_2O \longrightarrow O_2\,(g) + 4H^+ + 4\ e^- \qquad (3.14.10)$$

These two reactions tend to neutralize pH. This is the reason, which, however, prevents larger pH increases due to larger hydroxides formations at higher current densities.

Conductivity and the effect of salts: Feed conductivity is an important parameter in ECT, since it directly affects the energy consumed per unit mass of pollutants removed. If conductivity is low, higher amount of energy is consumed per unit of mass of pollutants removed and vice versa. Due to this, some salts (commonly NaCl) are added to increase the conductivity of feed. When, salt is added to the solution, it reduces the solution resistance and hence, voltage distribution between the electrodes reduces. However, a too high conductivity may lead to secondary parasite reactions, diminishing the main reaction of the electrolytic decomposition. Additionally, the presence of chlorides can enhance the degradation of organic pollutants in the wastewaters due to the formation of various species (Cl_2, HOCl and ClO^-) formed as function of the pH. ClO^-, which is dominating at higher pH, has been reported as better oxidant among all chlorine species [13]. Moreover, the type and concentration of salt also influences the effectiveness of the treatment. Salts of bi- and tri-valent metals are more effective than monovalent salts because of their high ionic strengths. Cl_2 and OH^- ions are generated on the surface of the anode and the cathode, respectively, when NaCl is used as an electrolyte in ECT. The organics are destroyed in the bulk solution by oxidation reaction of the regenerated oxidant. In an ECT cell, Cl_2/hypochlorite formation may take place because chloride is widely presented in many wastewaters [14].

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Module 4: WATER POLLUTION CONTROL BY BIOLOGICAL METHODS

Lecture	Topic	No. of Hours (7)
1	Introduction to Biological Treatment	1
2	Anaerobic and Aerobic Treatment Biochemical Kinetics	1
3	Activated Sludge and Lagoons	1
4	Trickling Filter	1
5	Sequential Batch Reactor	1
6	UASB Reactor	1
7	Sludge Separation and Drying	1

Lecture 1

Introduction to biological treatment

BIOLOGICAL TREATMENT

The physical processes that make up primary treatment are augmented with processes that involve the microbial oxidation of wastes. Such processes are biological or secondary processes that utilize microorganisms to oxidize the organics present in the waste. Main objectives of biological treatment are:

- To oxidize dissolved and particulate biodegradable constituents into non-polluting end products.
- To remove or transform nutrients such as nitrogen and phosphorous.
- To capture non-settleable and suspended solids into a biofilm.
- To remove specific trace organic compounds.

Biological treatment is basically divided into two main categories: a) aerobic processes, and b) anaerobic processes. Aerobic means in the presence of air (oxygen) while anaerobic means in the absence of air (oxygen). These two terms are directly related to the type of bacteria or microorganisms that are involved in the degradation of organic impurities in a given wastewater and the operating conditions of the bioreactor.

Aerobic Processes: Aerobic treatment processes take place in the presence of air and utilize those microorganisms (also called aerobes), which use molecular/free oxygen to assimilate organic impurities i.e. convert them in to carbon dioxide, water and biomass.

Anaerobic Processes: The anaerobic treatment processes take place in the absence of air (molecular/free oxygen) by those microorganisms (also called anaerobes) which do not require air (molecular/free oxygen) to assimilate organic impurities. The final products of organic assimilation in anaerobic treatment are methane and carbon dioxide gas and biomass [1].

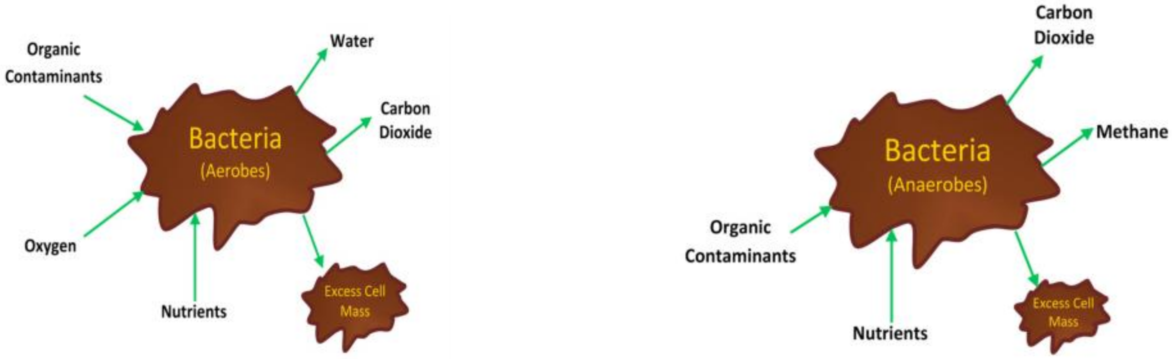

Figure 4.1.1. Mechanism of aerobic and anaerobic processes.

Table 4.1.1. Comparison of aerobic and anaerobic processes.

S.No.	Aerobic	Anaerobic
	Advantages	
1	50% carbon is converted into carbon di-oxide (CO_2). 40%-50% of carbon is converted into biomass	94% of carbon is converted into biogas (CH_4). 5% of carbon is converted into biomass
2	60% of energy is stored in biomass. Rest removed as process heat	90% of energy is retained as (CH_4). 3%-5% is wasted as heat and rest is converted to biomass.
3	High energy input for aeration	No external energy input
4	Nutrient addition requirement is substantial	Low nutrient requirement
5	Process requires large area	Process area required is less
	Disadvantages	
1	Small start time is required	Large start-up time is required
2	Technology is well established.	Under development with research in progress.

ANAEROBIC PROCESSES

Anaerobic process has two major stages

(1) Acid fermentation stage.

(2) Methane fermentation stage.

For every complex material there are many sub stages [2]:

(a) Hydrolysis of complex organic material

(b) Fermentation of amino acids and sugars

(c) Anaerobic oxidation of long chain fatty acids and alcohols

(d) Anaerobic oxidation of intermediate products (such as short chain fatty acids except acetate)

(e) Acetate production from CO_2 and H_2 (homo acetogenesis)

(f) Conversion of acetate to CH_4

(g) Methane production by reduction of CO_2 by H_2 (Reductive methanogenesis)

Following group of bacteria are required for anaerobic degradation

(a) Fermentation bacteria.

(b) H_2 Producing acetogenic bacteria.

(c) H_2 Consuming acetogenic bacteria.

(d) CO_2Reducing bacteria.

(e) Aceticlasticmethanogenesis.

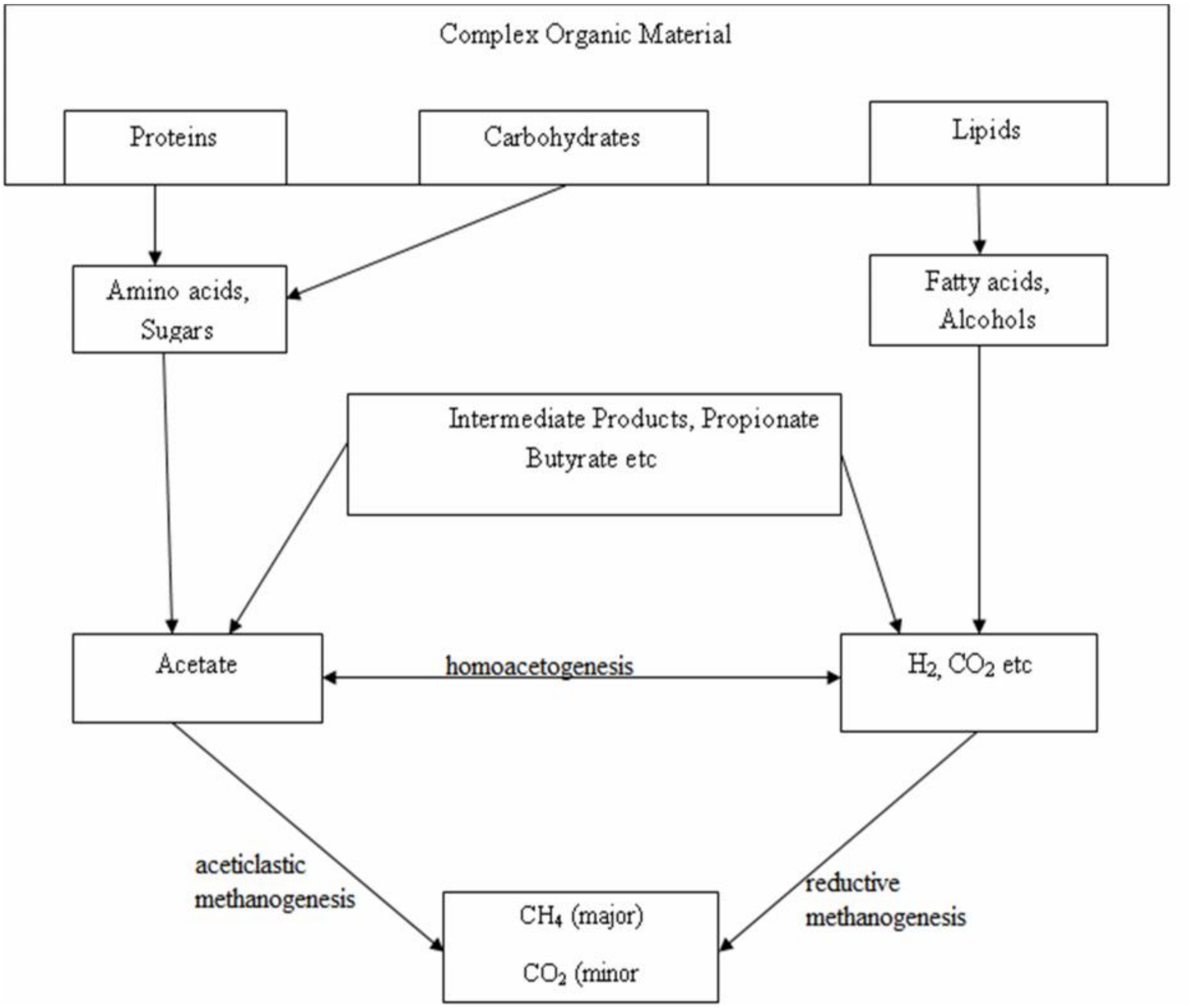

Figure 4.1.2. Reaction scheme for anaerobic complex organic material [2].

Table 4.1.2. Major biological treatment processes used for wastewater treatment [3]

Type	Common Name
Aerobic Processes	
Suspended Growth	Activated Sludge Processes
	Aerated Lagoons
	Stabilization Ponds
	Aerobic Digestion
Attached Growth	Trickling Filters
	Rotating Biological Contactors
	Packed Bed reactors
Hybrid (suspended + attached growth)	Trickling filter/ Activated Sludge
Anaerobic Processes	
Suspended Growth	Anaerobic Contact Process
	Anaerobic Digestion
Attached Growth	Anaerobic Packed or Fluidized Bed
Sludge Blanket	Upflow Anaerobic Sludge Blanket
Lagoon Processes	
Aerobic Lagoons	Aerobic Lagoons
Maturation Lagoons	Maturation Lagoons
Faculative Lagoons	Faculative Lagoons
Anaerobic Lagoons	Anaerobic Lagoons

TYPES OF BIOLOGICAL PROCESSES FOR WASTEWATER TREATMENT

For the treatment of wastewater the principle biological processes are divided into two categories: suspended growth and attached growth processes.

[A] Suspended Growth Processes

In this process the microorganisms responsible for treatment are maintained in liquid suspension by mixing methods. The following section describes the two most widely used suspended growth processes activated sludge and aerated lagoons and one recently introduced membrane bioreactors.

Activated Sludge Process: It is the most widely used process for wastewater treatment. It consists of two sets of basins. In the first, air is pumped through perforated pipes at the bottom of the basin, air rises through the water in the form of many small bubbles. These bubbles provide oxygen from the air to the water and create highly turbulent conditions that favor intimate contact between cells, the organic material in the water and oxygen. The second basin is a settling tank where water flow is made to be very quiet so that the cellular material is removed by gravitational settling. Some of the cell material collected at the bottom is captured and fed back into the first basin to seed the process. The rest of the sludge is taken for anaerobic digestion.

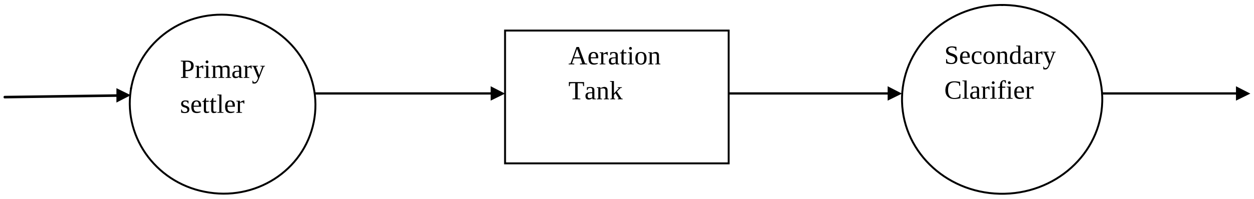

Figure 4.1.3. Activated Sludge Process

Aerated Lagoons and Oxidative Pond: Oxidative ponds are shallow ponds with a depth of 1 to 2 m where primary treated waste is decomposed by the microorganisms. Oxidative ponds maintain aerobic conditions, the decomposition near the surface is aerobic whereas near the bottom is anaerobic. They have a mix of conditions and are called facultative ponds. The oxygen required for decomposition is derived from either surface aeration or the photosynthesis of algae.

Membrane Bioreactors: These membranes have been designed to reduce the size of secondary treatment tanks and improve the separation efficiency. They draw water from mixed liquor into hollow fiber membranes which have a pore size of about 0.2μm. The membranes are submerged in the activated sludge aeration tank and there is no need of a secondary clarifier or they may be present outside the aeration zone.

[B] Attached Growth Treatment

In this treatment, the microorganisms that are used for the conversion of nutrients or organic material are attached to the inert packing material. The organic material is removed from the wastewater flowing past the biofilm or the attached growth. Sand, gravel, rock and a wide variety of plastic and other synthetic material is used as the packing material. They can be used both as aerobic when partially submerged in wastewater or as anaerobic when fully submerged and no air space above it.

Trickling Filter: This is the most widely used attached growth process. It consists of a rotating distribution arm that sprays wastewater above the bed of plastic material or other coarse material. The spacing between the packing allows air to easily circulate so that aerobic conditions are present. The media in the bed is covered by a layer of biological slime containing bacteria, fungi etc that adsorbs and consumes the waste trickling through the bed.

Rotating Biological Contactors: It consists of a series of closely spaced circular plastic disks that are attached to a rotating hydraulic shaft. 40% of the bottom of each plate is dipped in the wastewater and the film which grows on the disk moves in and out of the wastewater.

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Lecture 2

Anaerobic and aerobic treatment biochemical kinetics

BASIC EQUATION FOR BIOLOGICAL TREATMENT OF WASTEWATER [1, 2]

According to Monod kinetics,

$$\mu = \mu_{\max}\left[\frac{s}{k_s + s}\right] \tag{4.2.1}$$

Where, s is the substrate concentration, k_s is the substrate concentration when $\mu(=\mu_{max}/2)$, μ_{max} is the maximum μ when substrate is not limiting.

Also, solid production rate $\left(\frac{dX}{dt}\right)$ is related to substrate utilization rate $\left(\frac{dS}{st}\right)$ by following relationship:

$$\left(\frac{dX}{dt}\right) = Y\left(\frac{dS_r}{st}\right) \tag{4.2.2}$$

Where, S_r is the mass of soluble substrate (i.e. BOD), Y is the yield coefficient (kg of new cells formed/kg BOD removed). However owing to large treatment time in many of the large treatment units, substantial number of cells may die because of endogenous respiration. Therefore,

$$\text{Net production rate } \left(\frac{dX}{dt}\right) = Y\left(\frac{dS_r}{dt}\right) - K_d X \tag{4.2.3}$$

Where, K_d is the endogenous respiration decay rate constant.

For growth phase only,

$$\left(\frac{dS_r}{dt}\right) = Y\frac{dX}{dt} = \frac{\mu}{Y}X = \frac{\mu_{\max}}{Y}X\left(\frac{s}{K_s + S}\right) \tag{4.2.3}$$

Case 1- $S >> K_s$

$$\frac{dS_r}{dt} \approx KX \quad \text{where } K = \frac{\mu_{\max}}{Y} \tag{4.2.4}$$

i.e. removal rate is independent of substrate concentration and that the removal rate depends on X only.

Case 2: $S << K_S$

$$\frac{dS_r}{dt} = K \times \frac{S}{K_s} \approx K' \times S, K' = \frac{K}{K_S} = \frac{\mu_{\max}}{YK_S} \tag{4.2.5}$$

Here, removal rate depends both upon X and S. Where, X is the mass of biomass in the system (usually represented by MLSS i.e. Mixed Liquor Suspended Solid), μ is the specific growth rate constant (time^{-1}).

Major Terms

[a] Hydraulic detention time, $t_{HRT} = \frac{V}{Q} = \frac{\text{volume}}{\text{flowrate}}$ (4.2.6)

[b] Sludge age or mean residence time (θ_C)

$$\theta_C = \frac{\text{Mass of solid in the system}}{\text{Mass of solid leaving system per day}} = \frac{xV}{x'Q} = \frac{x}{x'} t_{HRT} \tag{4.2.7}$$

Where, x (=X/V) the concentration of microbial solution in the system, x' is the concentration of solids withdrawn.

For the flow through system, $x' = x$ and $\theta_C = t_{HRT}$

For the flow system with recycling, $x' < x$ and $\theta_C \to t_{HRT}$

[c] Food to microorganism ratio

$$\frac{F}{M} = \frac{\text{Substrate removal rate}}{\text{Solids (microorganisms) in the system}} = \frac{(S_O - S)/t}{X} = \frac{S_O - S}{xVt} \tag{4.2.8}$$

Problem 4.2.1: An aerated activated sludge tank is being operated under following conditions: Q=4400 m^3/d, MLSS=3500 mg/l, Y=0.5, tank volume =770 m^3, Endogeneous decay rate constant k_d=0.09 d^{-1}.

(a) Estimate weight of solids produced per day for the conditions in which BOD is reduced from 350 mg/l to 130 mg/l.

(b) Estimate θ_c.

(c) Estimate F/M ratio.

Solution:

$$t_{HRT} = \frac{V}{Q} = \frac{770}{4400} = 0.175\text{day}$$

$$\left(\frac{dX}{dt}\right) = Y\left(\frac{dS_r}{dt}\right) - K_d X = 0.5\frac{(350-130)}{0.175} - 0.09\times 3500 = 313.57\frac{mg}{l\,d} = 313.57\times V \text{ mg.m}^3\text{/l.d}$$

=241.4 kg/d.

$\theta_C =$ mass of solid in the system/ mass of solid leaving the system per day= $\dfrac{X}{\Delta x / \Delta t_{net}}$

$$\left(\frac{dX}{dt}\right)\frac{1}{X} = Y\frac{(S_O - S)/t}{X} - K_d$$

$$\frac{1}{\theta_C} = Y\left(\frac{F}{M}\right) - K_d$$

$\dfrac{F}{M} = \dfrac{S_O - S/t}{X}$ = 0.359 (kg BOD/kg MLSS)

$\theta_C =$ 11.17 day.

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Lecture 3

Activated sludge and lagoons

ACTIVATED SLUDGE PROCESS

Activated sludge process is used during secondary treatment of wastewater. Activated sludge is a mixture of bacteria, fungi, protozoa and rotifers maintained in suspension by aeration and mixing [1].

In this process, a biomass of aerobic organisms is grown in large aerated basins. These organisms breakdown the waste and use it as their food to grow themselves.

Activated sludge processes return settled sludge to the aeration basins in order to maintain the right amount of organisms to handle the incoming "food".

Activated sludge processes have removal efficiencies in the range (95-98%) than trickling filters (80-85%). [2]

WORKING OF ACTIVATED SLUDGE SYSTEM [3]

- A primary settler (or primary clarifier) may be introduced to remove part of the suspended solids present in the influent and this reduces the organic load to the activated sludge system.
- The biological reactor or aeration tank is filled with a mixture of activated sludge and influent, known as “mixed liquor”. It is necessary to maintain certain mixed liquor suspended solid (MLSS) in the aerated tank maintain good removal efficiency.
- The aeration equipment transfers the oxygen necessary for the oxidation of organic material into the reactor, while simultaneously introducing enough turbulence to keep the sludge flocs in suspension.
- The continuous introduction of new influent results in a continuous discharge of mixed liquor to the secondary settler where separation of solids and liquid takes place.
- The liquid leaves the system as treated effluent, whereas some part of the sludge is recirculated to the aeration tank called as ‘return sludge’ and rest of sludge is taken for anaerobic digestion.

DESIGNING OF ACTIVATED SLUDGE SYSTEM

Suppose, Q is the flow rate of influent (m^3/d), Q_W is the flow rate of waste sludge (m^3/d), Q_r is the flow rate of return activated sludge (m^3/d), V is the volume of aeration tank (m^3), S_0 is the influent soluble substrate concentration (BOD g/m^3), S is the effluent soluble substrate concentration (BOD g/m^3), X_o is the concentration of biomass in influent (g VSS/m^3), X_R is the concentration of biomass in return line from clarifier (g VSS/m^3), X_r is the concentration of biomass in sludge drain (g VSS/m^3) and X_e is the concentration of biomass in effluent (g VSS/m^3) [4]. VSS stands for volatile suspended solids.

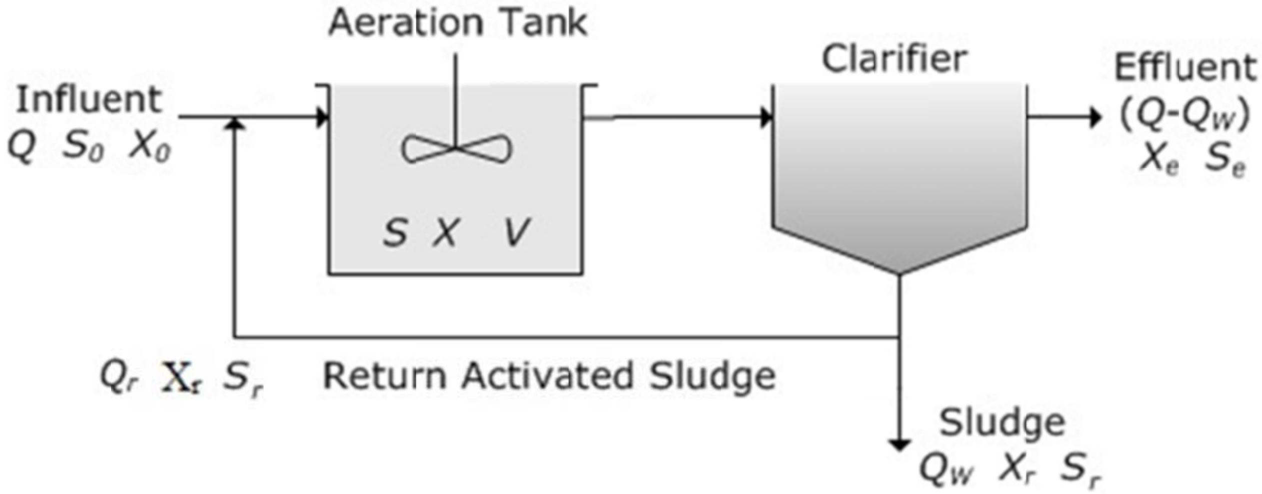


Figure 4.3.1. Activated sludge process

(a) Equations used for design of aeration tank

$$\theta_C = \frac{VX}{Q_W X_r}$$

$$\frac{1}{\theta_C} = \frac{QY(S_0 - S)}{VX} - k_d$$

(b) Mass balance around clarifier

$$X(Q+Q_r) = (Q-Q_W)X_e + (Q_W + Q_r)X_r$$

For $X_e = 0$

$$X(Q+Q_r) = (Q_r + Q_W)X_r$$

$$Q_r = \frac{QX - Q_W X_r}{X_r - X}$$

$$\text{Recycle ratio} = \frac{Q_r}{Q}$$

Problem 4.3.1: An activated-sludge system is to be used for secondary treatment of 15,000 m^3/d of municipal wastewater. After primary clarification, the BOD is 170 mg/L, and it is desired to have not more than 25 mg/L of soluble BOD in the effluent. A completely mixed reactor is to be used, and pilot-plant analysis has established the following values: hydraulic detention time (θ_C)=10 d yield coefficient (Y)=0.5 kg/kg, k_d=0.05 d^{-1}. Assuming an MLSS concentration of 4500 mg/L and an underflow concentration of 12,000 mg/L from the secondary clarifier, determine (1) the volume of the reactor, (2) the mass and volume of solids that must be wasted each day, and (3) the recycle ratio.

Solution: Given that Q=10,000 m^3/d, θ_C=10 d

Using

$$\frac{1}{\theta_C} = \frac{QY(S_0 - S)}{VX} - k_d$$

$$0.1\ d^{-1} = \frac{15,000\ \mathrm{m^3/d}\left(0.17\ \mathrm{kg/m^3} - 0.025\ \mathrm{kg/m^3}\right)}{V \times 4.5\ \mathrm{kg/m^3}} - 0.05\ \mathrm{d^{-1}}$$

V=1611 m^3

Using $\theta_C = \dfrac{VX}{Q_W X_r}$ =10

$$Q_W X_r = 724.95\ \mathrm{kg/d}$$

If the concentration of solids in the underflow is 12,000 mg/L

$$Q_W = \frac{724.95\ \mathrm{kg/d}}{12\ \mathrm{kg/m^3}} = 60.41\ \mathrm{m^3/d}$$

For X_e=0

$$Q_r = \frac{QX - Q_W X_r}{X_r - X} = \frac{15,000\ \mathrm{m^3}/d \times 4.5\ \mathrm{kg/m^3} - 724.95\ \mathrm{kg/d}}{12\ \mathrm{kg/m^3} - 4.5\ \mathrm{kg/m^3}} = 8903.34\ \mathrm{m^3/d}$$

$$\text{Recycle ratio} = \frac{Q_r}{Q} = \frac{8903.34}{15,000} = 0.59$$

PONDS AND LAGOONS

Other than activated sludge processes, ponds and lagoons are most common suspended-culture biological systems used for the treatment of wastewater.

A wastewater pond, alternatively known as a stabilization pond, oxidation pond, and sewage lagoon, consists of a large, shallow earthen basin in which wastewater is retained long enough for natural purification processes.

Classification of lagoons is based on degree of mechanical mixing provided.

Aerobic lagoon: The reactor is called an aerobic lagoon, when sufficient energy is supplied to keep the entire contents, including the sewage solids, mixed and aerated. To meet suspended-solids effluent standards, solids are removed from the effluent coming from an aerobic lagoon.

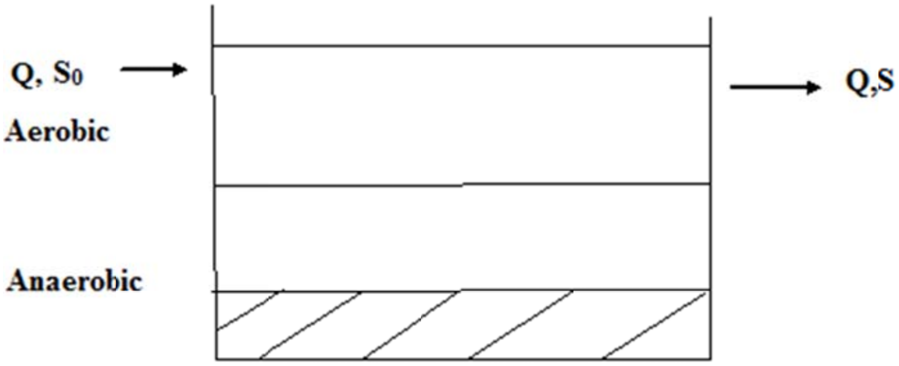
Facultative lagoon: In facultative lagoon, only enough energy is supplied to mix the liquid portion of the lagoon, solids settle to the bottom in areas of low velocity gradients and proceed to degrade anaerobically and this process is different from facultative pond only in the method by which oxygen is supplied. Facultative lagoons are assumed to be completely mixed reactors without biomass recycle [5].

Aerobic lagoons with solid recycle: The aerobic lagoon with solids recycle is same as extended aeration activated-sludge process, but an earthen (typically lined) basin is used in place of a reinforced-concrete reactor basin. It is necessary that the aeration requirement for an aerobic lagoon with recycle must be higher than the values for an aerobic flow-through lagoon to maintain the solids in suspension.

DESIGN OF LAGOONS

Process design considerations for flow-through lagoons [6]

- BOD removal
- Effluent characteristics
- Temperature effect
- Oxygen requirement
- Energy requirement for mixing
- Solids separation



Applying mass balance on lagoon given in above figure

$BOD_{in} = BOD_{out} + BOD_{consumed}$

$$QS_0 = QS + V(kS)$$

$$\frac{S}{S_0} = \frac{1}{1+k(V/Q)} = \frac{1}{1+k\theta}$$

Where, S/S_0=fraction of soluble BOD remaining, k=reaction rate coefficient (d^{-1}), θ=hydraulic detention time (d^{-1}), V= reactor volume (m^3), and Q= flow rate (m^3/d).

If several reactors are arranged in series, the effluent of one pond becomes the influent to the next. A substrate balance written across a series of n reactors results in following equation:

$$\frac{S_n}{S_0} = \frac{1}{\left(1+(k\theta/n)\right)^n}$$

A wide range of values for k is available in the literature. Although many variables relating to both the reactor and wastewater affect the value of *k*, water temperature affects it most significantly. k value at any temperature can be find out by following equation:

$$k_T = k_{20}\ \varphi^{T-20}$$

Where, k_{20} = reaction rate constant at 20°C (ranges from 0.2 to1.0) and φ =temperature coefficient ranges from 1.03 to 1.12.

Problem 4.3.2: Wastewater flow from a small community averages 3400 m^3/d during the winter and 6600 m^3/d during the summer. The average temperature of the coldest month is 10°C, and the average temperature of the warmest month is 30°C. The average BOD_5 is 200 mg/L with

70% being soluble. The reaction coefficient k is 0.23 d^{-1} at 20°C, and the value of temperature coefficient is 1.06. Prepare a preliminary design for a facultative pond treatment system for the community to remove 90% of the soluble BOD.

a) Find volume of facultative lagoon to remove 90% of the soluble of BOD.
b) Find the dimensions of three square lagoons in series with depth 1.5 m.

Solution:

(a) Estimation of rate constants at given temperature

Summer: $k_{25} = 0.23(1.06)^{30-20} = 0.411\ \mathrm{d}^{-1}$

Winter: $\mathrm{k}_{10} = 0.23(1.06)^{10-20} = 0.128\ \mathrm{d}^{-1}$

(b) Estimation of volume of lagoon

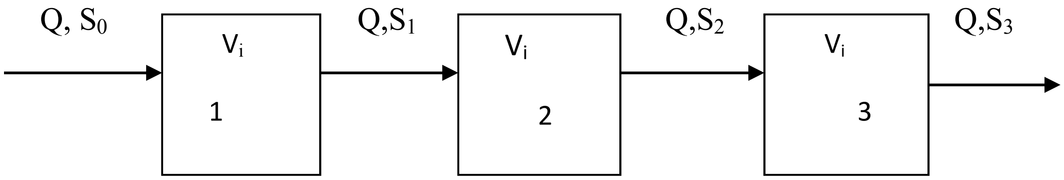
Summer: $$\frac{\mathrm{S}}{\mathrm{S}_0} = \frac{1}{1+\mathrm{k}\left(\mathrm{V}/\mathrm{Q}\right)} \Rightarrow \frac{20}{200} = \frac{1}{1+0.411\left(\mathrm{V}/6600\right)}$$

$\mathrm{V}=144525.5\ \mathrm{m}^3$

Winter: $$\frac{20}{200} = \frac{1}{1+0.128\left(\mathrm{V}/3400\right)}$$

$\mathrm{V}=239062\ \mathrm{m}^3$

(c) Estimation of dimensions of three square lagoons in series



$$\frac{\mathrm{S}_n}{\mathrm{S}_0} = \frac{1}{\left(1+\mathrm{k}\left(\frac{\mathrm{V}_i}{\mathrm{n}\times\mathrm{Q}}\right)\right)^n}$$

Summer : $$\frac{200}{20} = \left(1+\frac{0.411\times\mathrm{V}_i}{3\times 6600}\right)^3$$

$V_i = 55607.13\ \mathrm{m}^3$

Winter: $$\frac{200}{20} = \left(1+\frac{0.128\times V_i}{3\times 3400}\right)^3$$

$\mathrm{V}_i = 91980.8\ \mathrm{m}^3$

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Lecture 4

Trickling filter

TRICKLING FILTER

-
- Trickling filter is an **attached-growth** type of process in which microorganisms attached to a medium are used for removing organic matter from wastewater. that utilizes
- This type of system is common to a number of technologies such as rotating biological contactors (RBCs) and packed bed reactors (biotowers). These reactors are also called as non-submerged fixed film biological reactors.

COMPONENTS OF TRICKLING FILTER

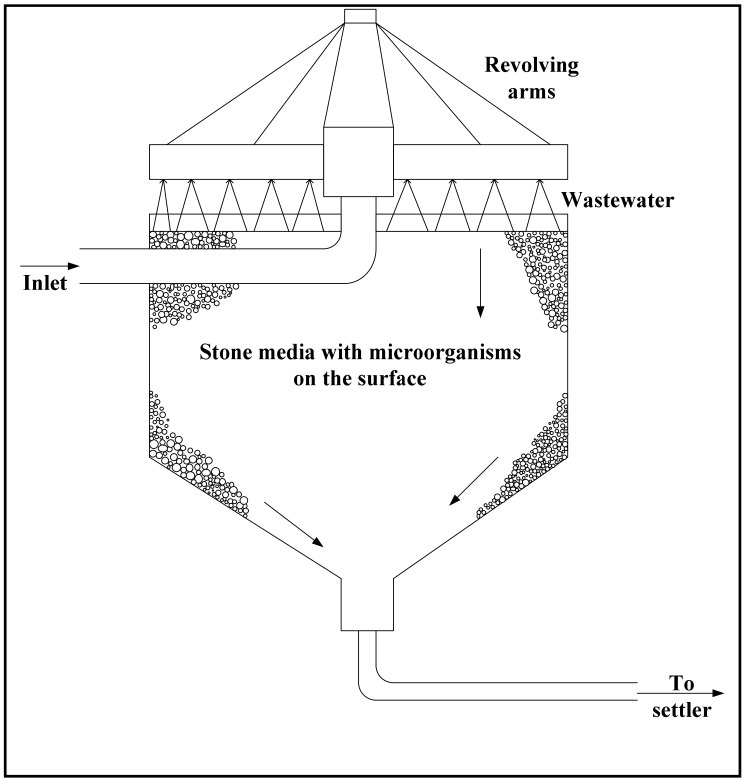


Figure 4.4.1 Trickling filter

[A] Packing

- Trickling filter uses packing medium composed of crushed stone, slag, rock or plastic over which wastewater is distributed continuously (Figure 4.4.1).
- The ideal medium should have the following properties: high specific surface area, high void space, light weight, biological inertness, chemical resistance, mechanical durability, and low cost.

- The important characteristics of medium includes-
  - **a) Porosity:** It is a measure of the void space available for passage of the wastewater and air and for ventilation of product gases.
  - **b) Specific surface area:** It refers to the amount of surface area of the media that is available for biofilms growth.
  - **c)** Size of the medium ranges from 50-100 mm having specific surface area in the range of 50-65 m^2/m^3 with porosities of 40-50 %.

[B] Wastewater dosing

- Influent wastewater is normally applied from the top of the trickling filter.
- Under a hydraulic head of about 1.0 m, jet action through the nozzles is sufficient to power the rotor.
- As the flow is intermittent, there is enough air circulation through the pores between dosing.
- The distributer arm distributes the wastewater continuously over the medium, which trickles down through the bed.

[C] Under-drain [1]

- It is used in trickling filters to support the filter medium, collect the treated effluent and the sloughed biological solids, and circulate the air through the filter**.**
- The liquid flow in under-drains and collection channels should not be more than half full for adequate air flows.

PROCESS DESCRIPTION OF TRICKLING FILTER

- A rotary or stationary distribution mechanism distributes wastewater from the top of the filter percolating it through the interstices of the film-covered medium [2].
- As the wastewater moves through the filter, the organic matter is adsorbed onto the film and degraded by a mixed population of aerobic microorganisms.
- The oxygen required for organic degradation is supplied by air circulating through the filter induced by natural draft or ventilation.
- As the biological film continues to grow, the microorganisms near the surface lose their ability to cling to the medium, and a portion of the slime layer falls off the filter. This process is known as **sloughing** [3].

- The sloughed solids are picked up by the under-drain system and transported to a clarifier for removal from the wastewater.
- Microorganisms used [1]
    - The microorganisms used are mainly facultative bacteria that decompose the organic material in the wastewater along with aerobic and anaerobic bacteria.
    - It includes *Achromobacter, Flavobacterium, Psudomonas,* and *alcaligenes*.
    - In the lower reaches of the filter, the nitrifying bacteria are usually present.

FACTORS AFFECTING THE OPERATION OF TRICKLING FILTER [2, 4, 5]

[A] Organic loading

- A high organic loading rate results in a rapid growth of biomass.
- Excessive growth may result in plugging of pores and subsequent flooding of portions of the medium.

[B] Hydraulic flow rates

- Increasing the hydraulic loading rate increases sloughing and helps to keep the bed open. Range of hydraulic and organic loading rates for trickling filters are shown in table 1.

[C] Relative temperature of wastewater and ambient air

- Cool water absorbs heat from air, and the cooled air falls towards toward the bottom of the filter in a concurrent fashion with the water.
- Warm water heats the air, causing it to rise through the underdrain and up through the medium.
- At temperature differentials of less than about 3 to 4^0C, relatively little air movement results, and stagnant conditions prevent good ventilation.
- Extreme cold may result in icing and destruction of the biofilms.

DESIGN EQUATIONS FOR TRICKLING FILTER

[A] Tentative method of ten states of USA [4]

The equation is given as follows:

$$E = \frac{(R/Q)+1}{(R/Q)+1.5} \tag{4.4.1}$$

where, Q is the flow rate, R is the recycle flow rate and E is the efficiency.

a) Loading rate

$$\text{(Raw settled domestic sludge)} < 102\,\text{kg BOD}/(\text{d.m}^3)$$

b) R/Q should be such that

$$\text{BOD entering filter (including recirculation)} \leq 3 \times \text{BOD expected in effluents}$$

[B] Velz equation [1]

The following equation is used for a single-stage system and in the first stage of a two-stage system:

$$S_{e1} = [(S_i + r_1 S_{e1})/(1 + r_1)]\exp[(-kDA^n / Q^n)(1.035^{T-20})] \qquad (4.4.2)$$

The following equation is used for the second stage of a two-stage system:

$$S_{e2} = [(S_e + r_2 S_{e2})/(1 + r_2)]\exp[(-kDA^n S_{e1} / Q^n S_i)(1.035^{T-20})] \qquad (4.4.3)$$

Where, S_e is the effluent BOD from the filter (mg/l), S_i is the influent BOD (mg/l), r is the ratio of recirculated flow to wastewater flow, D is the filter depth (m), A is the filter plan area (m^2), Q is the wastewater flow (m^3/min), T is the wastewater temperature (^oC), k and n are empirical coefficients (for municipal wastewaters, k = 0.02 and n = 0.5) and subscript i (i = 1, 2) repressent the stage number.

[C] NRC equations [1]

The following equation is used for a single-stage system and the first stage of a two-stage system:

$$1 - (S_{e1} / S_i) = 1/[1 + 0.532(QS_i / V_1 F_1)^{0.5}] \qquad (4.3.4)$$

$$F_1 = [(1 + r_1)/(1 + 0.1 r_1)^2] \qquad (4.3.5)$$

The following equation is used for the second stage of a two-stage system:

$$1 - (S_{e2} / S_{e1}) = 1/[1 + 0.532(QS_{e1} / V_2 F_2)^{0.5}] \qquad (4.3.6)$$

$$F_2 = [(1 + r_2)/(1 + 0.1 r_2)^2] \qquad (4.3.7)$$

Where, V is the filter volume (m^3) and F is the recirculation factor.

[D] Eckenfelder equation (Plastic media) [6]

The Eckenfelder equation used for plastic media is as follows:

$$S_e / S_i = \exp[-KD(QS_a^m / A)^{-n}] \qquad (4.3.8)$$

Where, K is the observed rate constant for a given filter depth (m/d), S_a is the specific surface area of the filter (m^2/m^3), D is the filter depth (m), Q is the wastewater flow rate (m^3/d), A is the filter plan area (ft^2), and m and n are empirical coefficients.

[E] Germain/Schultz equations (Plastic media) [1]

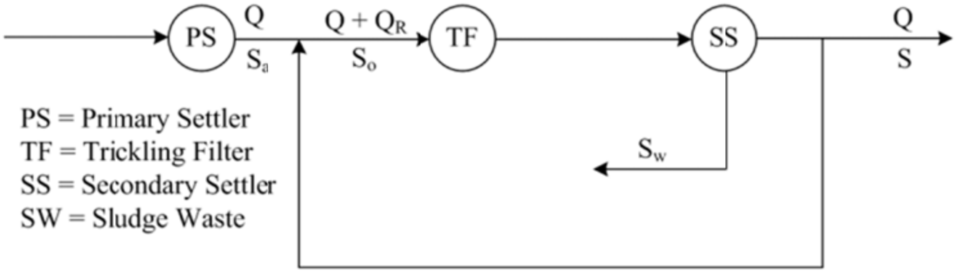
The Germain/Schultz equations used for plastic media are as follows:

$$S_e / S_i = \exp[-K_{20,i} D_i (Q/A)^{-n}] \tag{4.3.9}$$

$$k_{20,2} = k_{20,1} (D_1 / D_2)^x \tag{4.3.10}$$

Where, $k_{20,I}$ is the treatability constant corresponding to a specific filter depth D_i at 20^0C, $(m^3/min)^n$ m, Q is the wastewater flow (m^3/min), n and x are empirical constants (n is usually 0.5; x is 0.5 for rock and 0.3 for cross-flow plastic media)

Problem 4.4.1: Calculate the values of k_f and influent BOD (S_o) to trickling filter for R/Q (ratio of recycle flow rate to hydraulic loading) value of 1.65. Given that: raw settled BOD after primary settling (S_a)=220 mg/l; hydraulic loading (Q)=30 $m^3/(d.\ m^2)$; depth of filter (D)=1.5 m; n=0.5 and effluent BOD after secondary settling (S)=35 mg/l.



Solution:

$$QS_a + Q_R S = (Q + Q_R) S_o$$

$$S = \frac{(Q + Q_R)S_o - QS_a}{Q_R} = \frac{(1 + (Q_R/Q))S_o - S_a}{(Q_R/Q)}$$

Also,

$$S_o = \frac{QS_a + Q_R S}{Q + Q_R} = \frac{S_a + (Q_R/Q)S}{1 + (Q_R/Q)}$$

On putting values in last equation, we get,

$$S_o = \frac{220 + 1.63 \times 35}{1 + 1.65} = 104.81 \text{ mg/l}$$

From Eckenfelder equation,

$$\frac{S}{S_o} = \exp\left[-\frac{k_f D}{Q^n}\right]$$

$$\frac{35}{104.81} = \exp\left[-\frac{k_f \times 1.5}{30^{0.5}}\right]$$

$$k_f = 4.004 \text{ m}^{-1/2}\text{d}^{-1/2}$$

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Lecture 5

Sequential Batch Reactor

SEQUENTIAL BATCH REACTOR (SBR)

It is a fill and draw type activated sludge system. In this system, wastewater is added to a single batch reactor, treated to remove undesirable components, and then discharged. The conventional activated sludge systems and SBR processes are the same but the difference between the two technologies is that the SBR performs equalization, biological treatment, and secondary clarification in a single tank using a time controlled sequence. Equalization, aeration, and clarification can all be achieved using a single batch reactor [1]. Figure 4.5.1 shows cycle of sequential batch reactor.

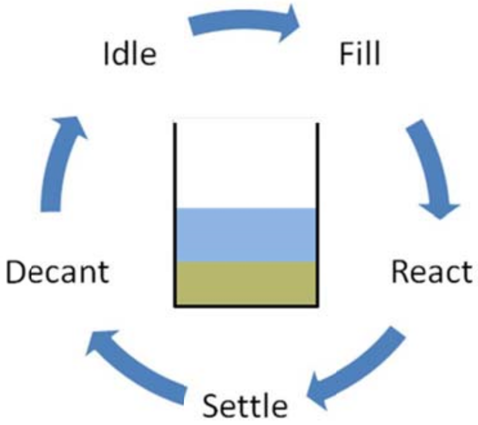

Figure 4.5.1 Cycle of sequential batch reactor

All the SBR systems have five steps in common, which are carried out in sequence as follows [1]:

Fill: Wastewater flows in to the reactor and mixes with the biomass already present in the reactor. Filling of influent can be varied to create the following three different conditions:

- **Static Fill:** Under a static-fill condition, influent wastewater enters into the reactor with no mixing and/or aeration. Static fill is used when there is no need to nitrification or denitrification.
- **Mixed Fill**: Under the condition of mixed-fill, influent is mixed with biomass present in the reactor but the aeration remains off. As there is no aeration, an anoxic condition appears. Anaerobic conditions can also be achieved during the mixed-fill phase. Denitrification may occur under these anoxic conditions. Denitrification is the biological conversion of nitrate-nitrogen to nitrogen gas [2].
- **Aerated Fill**: In condition of aerated-fill, both the aeration and the stirrer are switched on. Aerobic and anoxic environment are created inside the reactor by

keeping on/off oxygen supply to the reactor. During the aerobic condition nitrification takes place. Aerated Fill can reduce the aeration time required in the react step.

React: Depending on the conditions applied: anaerobic, anoxic or aerobic reactions, substrate present in the waste water are consumed by the biomass.

Settle: After sufficient time of reaction, aeration and mixing is stopped and biomass is allowed to settle from the liquid resulting in clear supernatant.

Decant: Clear supernatant (treated waste water) is removed from the reactor.

Idle: This is the time between cycles which is used to prepare the SBR for next cycle. It is also used to adjust the cycle time between the SBR reactors. Sludge wasting is also performed during this phase.

OPERATING PARAMETERS IN SBR PROCESS

The treatment efficiency of SBR depends on the operating parameters such as phase duration, hydraulic retention time (HRT) and organic loading, Sludge retention time (SRT), temperature, mixed liquor suspended solids (MLSS), mixed liquor volatile suspended solids (MLVSS), dissolved oxygen (DO) concentration and the strength of wastewater.

Cycle time: A cycle in SBR comprises of fill, react, settle, decant and idle phase. The total cycle time (t_C) is the sum of all these phases.

$$t_C = t_F + t_R + t_S + t_D + t_I \tag{4.5.1}$$

Where, t_F is the fill time (h), t_R is the react time (h), t_S is the settle time (h), t_D is the decant time (h), and t_I is the idle time (h).

Moreover during the react phase, organic matters, nitrogen or phosphorus removal may be achieved by arresting aerobic, anoxic or anaerobic condition, respectively. Therefore, aerobic, anoxic or anaerobic time can be found in react time (t_R). Hence

$$t_R = t_{AE} + t_{AX} + t_{AN} \tag{4.5.2}$$

Where, t_{AE} is the aerobic react time (h), t_{AX} is the anoxic react time (h), and t_{AN} is the anaerobic react time (h).

Volume exchange ratio (VER) and hydraulic retention time (HRT): Due to filling and decanting phase during a cycle, SBR operate with varying volume. Volume exchange ratio (VER) for a cycle is defined as V_F/V_T, Where, V_F is the filled volume of wastewater and decanted effluent for a cycle and V_T is the total working volume of the reactor [3].

HRT for the continuous system is defined as

$$\text{HRT} = \frac{(V_T)}{Q} \qquad (4.5.3)$$

Where, Q is the daily waste water flow rate.

For SBR systems;

$$\text{Q} = V_F N_C \qquad (4.5.4)$$

Where, N_C is the number of cycles per day and defined as:

$$\text{N}_\text{C} = \frac{24}{t_C} \qquad (4.5.5)$$

Therefore, HRT for the SBR systems may be given as:

$$\text{HRT} = \frac{(t_C)}{V_F / V_T} \frac{1}{24} \qquad (4.5.6)$$

Solid Retention Time (SRT): In biological treatment of wastewater, excess sludge is withdrawn from the reactor to control the sludge age (SRT). SRT determines the time (d) for which the biomass is retained in the reactor.

$$\text{SRT} = \frac{V_T X\, t_C}{V_W X_W 24} \qquad (4.5.7)$$

Where, X is the MLSS in the reactor with full filled (mg/l), X_W is the MLSS in waste stream (mg/l), and V_W is the waste sludge volume (l).

NITRIFICATION AND DENITRIFICATION

Nitrogen is the main source of eutrophication. In this regard, the complete oxidation of nitrogen during the treatment is favorable. Biological nitrogen is removed in two stages: aerobic nitrification and anoxic denitrification. In the nitrification process, ammonia ($N\text{-}NH_4^+$) is oxidized to nitrite ($N\text{-}NO_2^-$) (equation 3.4.8) by autotrophic bacteria called Nitroso-bacteria and generated nitrite is oxidized to nitrate ($N\text{-}NO_3^-$) (equation 3.4.9) by another group of autotrophic bacteria called Nitro-bacteria under aerobic conditions and using oxygen as the electron acceptor.

$$2NH_4^+ + 3\,O_2 \longrightarrow 2\,NO_2^- + 2H_2O + 4\,H^+ \qquad (4.5.8)$$

$$2\,NO_2^- + O_2 \longrightarrow 2NO_3^- \qquad (4.5.9)$$

The autotrophic bacteria produce energy for their multiplication from the oxidation of inorganic nitrogen compounds, using inorganic carbon as their source of cellular carbon. During the nitrification, alkalinity of wastewater is used which reduces the pH of influent wastewater and required amount of alkalinity to carry out the reaction (equation 3.4.8, 3.4.9) in the $CaCO_3$ form, can be calculated by the following equation;

$$NH_4^+ + 2HCO_3^- + 2\ O_2 \longrightarrow NO_3^- + 3H_2O + 2CO_2 \qquad (4.5.10)$$

Biological denitrification involves the biological oxidation of many organic substrates in wastewater treatment using nitrate or nitrite as the electron acceptor under the anoxic condition or limited dissolved oxygen (DO) concentrations and nitrate is degraded to nitric oxide, nitrous oxide, and nitrogen gas [4-6] by following any of the two different routes. One of these routes predominates depending on the dissolved oxygen concentration [7].

$$NH_4^+ \longrightarrow NO_2^- \longrightarrow NO_3^- \longrightarrow NO_2^- \longrightarrow NO \longrightarrow N_2O \longrightarrow N_2$$

or

$$NH_4^+ \longrightarrow NO_2^- \longrightarrow NO \longrightarrow N_2O \longrightarrow N_2$$

During the denitrification process, pH of influent wastewater increases because of increase of alkalinity. Both heterotrophic and autotrophic bacteria are capable of denitrification. Most of these heterotrophic bacteria are facultative aerobic organisms with the ability to use oxygen as well as nitrate or nitrite, and some can also carry out fermentation in the absence of nitrate or oxygen [8].

ADVANTAGES AND DISADVANTAGES OF SBR [1, 2]

Advantages

- Equalization, primary clarification (in most cases), biological treatment, and secondary clarification can be achieved in a single reactor vessel.
- Operating flexibility and control.
- Potential capital cost savings by eliminating clarifiers and other equipments.

Disadvantages

- A higher level of sophistication, (compared to conventional systems), especially for larger systems, of timing units and controls is required.
- Higher level of maintenance (compared to conventional systems) associated with more sophisticated controls, automated switches and automated valves.
- Potential of discharging floating or settled sludge during the draw or decant phases with some SBR configurations.

- Potential plugging of aeration devices during selected operating cycles, depending on the aeration system used by the manufacturer.

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Lecture 6

UASB reactor

Design of upflow anaerobic sludge blanket reactor (UASB)

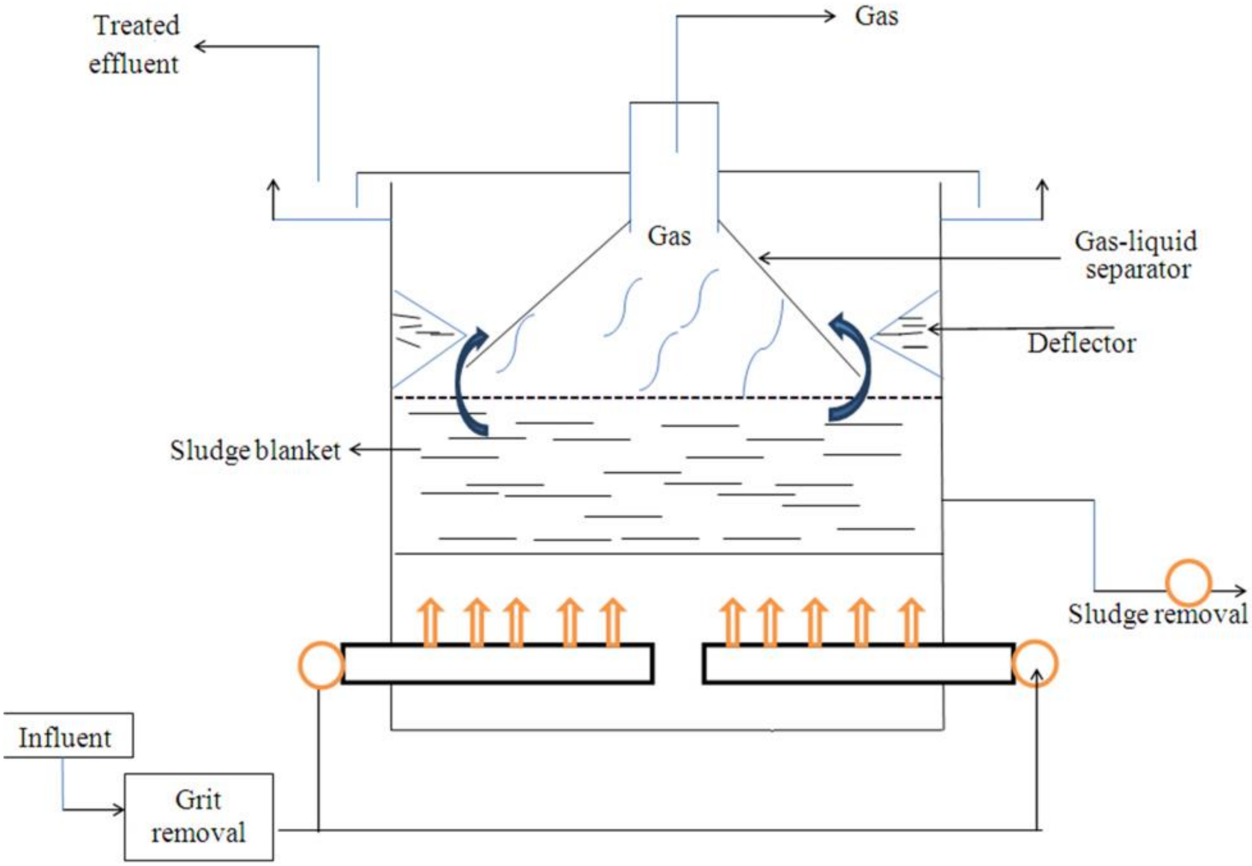

Figure 4.6.1: Schematic diagram of up flow anaerobic sludge blanket (UASB)

Table 4.6.1. Recommended loading on UASB reactor based on the COD concentration [1]

COD conc. (mg/l)	OLR $\frac{\text{kg COD}}{\text{m}^3\text{d}}$	SLR $\frac{\text{kg COD}}{\text{kg VSS} \times \text{d}}$	HRT (m)	Liquid upflow velocity (m/h)	Expected efficiency (%)
<750	1-3	0.1-0.3	6-18	0.25-0.7	70-75
750-3000	2-5	0.2-0.5	6-24	0.25-0.7	80-90
3000-10,000	5-10	0.2-0.6	6-24	0.15-0.7	75-85
>10,000	>10,000	0.2-1	>24	0.15-0.7	75-80

Where, COD: Chemical Oxygen Demand; OLR: Organic Loading Rate; SLR: Organic Loading on Sludge Blanket; HRT: Hydraulic Retention Time.

Important Design Points

- For temperature >20 ℃, SRT of around 30-50 days is used.
- At equilibrium, sludge produced per day = sludge withdrawn per day
- Average concentration of sludge in UASB reactor ≅ $70\ \frac{kg}{m^3}$
- Ration of height of sludge blanket to total height is ≈0.4-0.5.
- HRT (Hydraulic Retention Time) $= \frac{\text{Reactor Volume (V)}}{\text{Flow rate (Q)}}$
- Solid Retention Time (SRT) $= \frac{\text{Total sludge in the reactor (kg)}}{\text{Sludge wasted per day (kg/d)}}$

Where, total sludge in the reactor$=\left(\text{Average concentration of sludge in the reactor } \frac{\text{kg}}{\text{m}^3}\right)$ $\times\left(\frac{\text{sludge blanket height}}{\text{total reactor height}}\left(\frac{\text{m}}{\text{m}}\right)\right)\times$ Effective Coefficient × Reactor volume (m^3)

Problem 4.6.1: Given that the influent to UASB reactor has following characteristics: BOD = 350 mg/l; COD = 820 mg/l, TSS= 395 mg/l, VSS= 270 mg/l, flow rate=8000 m^3/d, depth of sludge blanket=2.2 m, reactor height (including settler)=5 m, effective coefficient (ratio of sludge to total volume in sludge blanket)= 0.85.

Determine HRT for sludge age of 30 days assuming 80% BOD removal efficiency; reactor area, and organic loading on reactor and the sludge blanket.

Solution:

$$\text{SRT} = 30 \text{ days} = \frac{70\frac{\text{kg}}{\text{m}^3}\times\frac{2.2}{5.0}\left(\frac{\text{m}}{\text{m}}\right)\times 0.85\frac{\text{m}^3}{\text{d}}\times\text{HRT}\frac{\text{h}}{24}}{315\left(\frac{\text{kg}}{\text{m}^3}\right)\left(\text{flowrate}\frac{\text{m}^3}{\text{d}}\right)}$$

$$\text{HRT} = \frac{30\times 315}{70\times\frac{2.2}{5.5}\times 0.85\times\frac{1000}{24}} = 8.66 \text{ h}$$

$$\text{Upflow velocity} = \frac{\text{Reactor height}}{\text{HRT}} = \frac{5}{8.66}\text{ m/h}$$

Reactor area required:

$$\text{Reactor area required} = \frac{\text{flow rate}\left(\frac{\text{m}^3}{\text{d}}\right)}{\text{Upflow rate}\left(\frac{\text{m}}{\text{d}}\right)} = \frac{8000\left(\frac{m^3}{d}\right)}{0.57\left(\frac{m}{h}\right)} = \frac{8000\left(\frac{m^3}{d}\right)}{0.57\left(\frac{m}{h}\right)\times 24\left(\frac{m}{d}\right)} = 577.7m^2$$

$$\text{Organic loading rate (OLR)} = \frac{\text{COD load}}{\text{volume of reactor}} = \frac{\text{influent COD}\times\text{flow rate}}{\text{volume of reactor}}$$

$$\text{Organic loading rate (OLR)} = \frac{820\frac{g}{m^3}\times 8000\frac{m^3}{d}}{1000\times(20\times 34\times 5)} = 1.93\ kg/m^3/day$$

Organic loading on sludge blanket (SLR)

$$= \frac{\text{influent COD}\times\text{flow rate}\left(\frac{\text{kg COD}}{d}\right)}{0.4\times\left(\frac{VSS}{TSS}\right)\times(Avg\text{ conc. of sludge in the reactor})\times(\text{sludge blanket volume})}$$

$$\text{SRT}=\frac{820\,\frac{\text{g}}{\text{m}^3}\times 8000\,\frac{\text{m}^3}{\text{d}}}{0.4\times 1000\times\left(\frac{\text{VSS}}{\text{TSS}}\right)\times\left(70\,\frac{\text{kg}}{\text{m}^3}\right)\times\left(20\times 34\times 2.2\right)}=0.156\text{kgCOD/kgVSS/day}$$

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Lecture 7

Sludge separation and drying

SLUDGE

- The polluted solid-liquid matter that is skimmed off or removed from wastewater during primary, secondary and tertiary treatment.
- It contains 0.25 to 12% organic to inorganic solid content
- Constituents
  - Organic material, nutrients, pathogens, metals, toxic substances

Goals of Sludge Management

- Stabilize sludge
- Kill pathogens
- Decrease water content from 0.5-2% solids to 6 to 12% solids

SLUDGE PROCESSING

(a) Thickening
(b) Conditioning, Stabilization, Disinfection
(c) Dewatering
(d) Drying
(e) Composting
(f) Incineration
(g) Final Disposal

[A] SLUDGE THICKENING

- Thickening: Capacity of sludge to increase concentration of solid in sludge
- Purpose: To decrease volume
- Benefits:
  - Reduces required capacity of downstream equipment
  - Reduce chemicals for conditioning
  - Reduce heat required by digesters
  - Reduce volume for transportation
- **Equipment types**
  - Gravity
  - Gravity Belt Thickener (GBT)

- Flotation
- Rotary drum
- Centrifuge

[B] SLUDGE CONDITIONING

- Sludge particles are negative (anionic) in surface charge
- The negative surface charge leads to electrostatic repulsive forces which hamper the settling process of the sludge particles.
- Cationic conditioning agents minimizes the electrostatic repulsive force and starts floc formation
- Chemical conditioning is similar to flocculation/coagulation process

[C] SLUDGE DEWATERING

- Mostly done in filtration type of units where solid particles from a fluid are retained on a filtering medium which allows the water to pass through it.
- Five types of equipment
  - Belt Filter Press (18-25%)
  - Centrifuge (30-35%)
  - Recessed Chamber Press
  - Vacuum Filtration
  - Drying Beds

[D] SLUDGE DRYING

- **Direct**: Sludge in contact with heat surface, e.g. fluidized bed dryer, revolving drum dryers
- **Indirect**: There is no direct contact between heat source and sludge, e.g. Disc dryer
- More expensive than mechanical methods such as pressing or centrifugation
- Yields greater volume reduction and a storable free flowing and hygienic product.
- End product can be used as
  - fertilizer/soil conditioner in agriculture and forestry
  - fuel in cement kilns, power plants and incinerators
  - top soil, landscaping, and landfilling use.

[E] SLUDGE COMPOSTING

- Can be applied to either digested or non-digested sludge

- Need to have sufficient mixture of organic matter content and water
- Carbon to nitrogen ratio: 25-30
- May be used as pretreatment to incineration
- Advantages
    - reduction in volume of materials to be transported for distribution in agricultural fields
    - allows the facilitation of storage
    - easier to spread
    - control in the nutrients in the compost
    - compost is more hygienic than raw sludge application
- Disadvantage
    - costly
    - requires aeration
    - requires a market

[F] SLUDGE INCINERATION

- A method used for drying and reducing sludge volume and weight. Since incineration requires auxiliary fuel to obtain and maintain high temperature and to evaporate the water contained in the incoming sludge, concentration techniques should be applied before incineration.
- Sludge incineration is a two-step process involving drying and combustion after a preceding dewatering process, such as filters, drying beds, or centrifuges.
- Multiple Hearths
    - Top – Drying
    - Middle – Incineration
    - Lower – Cooling
- Flue gas – need to be treated

[G] SLUDGE DISPOSAL

- Agriculture: For raw and treated sludge
    - Things to consider:
        - Heavy Metal content
        - Dry solid content

  - **Advantage**:
    - Utilization of nutrients in soil (organics, nitrogen, phosphorus)
    - Cheaper (raw sludge)
  - **Disadvantage**: need for storage facility (investment)
- Landfilling

DEWATERING FILTERS

- Filtration is the removal of solid particles from a fluid by passing the fluid through a filtering medium, or septum, on which the solids are deposited. However, the mechanical separation (filtration or clarification) of primary sludge is only partially effective as a treatment because 30 to 40 % of BOD and COD are water soluble and cannot be so removed.
- Filtration is generally complete in 1 to 2 days and results in solids concentration as high as 15 to 20%. The rate of filtration depends drainability of the sludge, which in turn is related to the specific resistance [1]

TYPES OF DEWATERING FILTERS [2]

[A] Rotary drum vacuum filters (RDVF)

- The filtration, washing, partial drying and discharge of the sludge all take place simultaneously.
- Process involves sucking of liquid through a moving septum to deposit a cake of solids.
- The cake is moved out of the filtering zone, washed, sucked dry, and dislodged from the septum, which then reenters the slurry to pick up another load of solids.

Table 4.7.1. Advantages and disadvantages of rotary drum filters

Advantages	**Disadvantages**
Filter is entirely automatic.	Maximum available pressure difference is limited as it being a vacuum filter.
Large capacity, hence large quantities can be filtered.	Difficulty in filtration of hot liquids because of their tendency to boil.

Cakes of varying thickness can be built by varying speed which results in removal of fine or coarser solids easily.	Initial cost of filter and vacuum equipment is high.
Low maintenance cost.	These are inflexible and do not perform well if their feed stream conditions are changing.

[B] Filter press

- It contains a set of plates designed to provide a series of chambers or compartments in which solids may collect.
- The plates are covered with a filter medium such as canvas.
- Slurry is admitted to each compartment under pressure; liquor passes through the canvas and out a discharge pipe, leaving a wet cake of solids behind.
- During operation, when the frames are full of solids and no more slurry can enter. The press is then said to be jammed.
- Wash liquid may then admitted to remove soluble impurities from the solids.

[C] Horizontal belt filter

- It is suitable for coarser particles as compared to rotary-drum filters.
- Feed slurry flows onto the belt from a distributor at one end of the unit; filtered and washed cake is discharged from the other.
- It is suitable for waste treatment as it is available in various sizes. They are available in sizes ranging from 0.6 to 5.5 m wide and 4.9 to 33.5 m long, with filtration areas up to 110 m^2.

[D] Rotating-leaf filter

- During filtration, the slurry enters, the filtrate exits, and solids are retained on leaves and covered with a filter cloth.
- Upon completion of filtration, the washing and drying bottom closure opens.
- The drive motor starts and rotates the stack of filter leaves.
- Centrifugal force causes the solids to move off the filter leaves, strike the inside wall of the tank and flow down to solid exit.
- Sizes are available up to 540 ft^2 per unit.

[E] Deep bed filter

- Filters with deep beds of sand, diatomaceous earth, coke, charcoal, and other inexpensive packing materials are normally used.
- Without preseparation the bed becomes loaded quickly.
- When the particle and bacteria in sizes smaller than the interstices of the bed, plus suspended BOD, are remove from the liquid, exceptional clarity is obtained.
- The dissolved substances, including dissolved BOD are not removed.

THERMAL DRYERS

Heat treatment followed by filtration is economical for dewatering sludge without using chemicals. Thermal drying of the sludge is economical only if a market for the product is available. Several types of thermal dryers used by the chemical process industry can be applied to sludge drying. The sludge is always dewatered prior to drying, regardless of the type of dryer selected.

TYPES OF DRYERS [2]

[A] Flash dryer

- It operates by promoting contact between the wet sludge and a hot gas stream.
- Drying takes place in less than 10 sec of violent action, either in a vertical tube or in a cage mill.
- A cyclone, with a bag filter or wet scrubber, if necessary, separates the solid from the gas phase.
- The vapors are returned through preheaters to the furnace, minimizing odor problems.
- A portion of the solid product is often returned to precondition the wet sludge.
- Being of only moderate thermal efficiency, this type of furnace is appropriate only for low sludge flows and where heat is available cheaply [3]

[B] Screw conveyor dryers

- It uses a hollow shaft and blades through which hot gas or water is pumped.
- The heat is transferred to the sludge as it is conveyed through the dryer.

[C] Multiple-hearth dryer

- These are converted multiple-hearth furnaces.
- The wet sludge can be mixed with dry product as it descends through the furnace.

- Fuel burners are located both on top and bottom.
- The outlet temperature of the gases is approximately 400 ^{0}C, while that of the wet sludge at the upper drying levels barely exceeds 70 ^{0}C.

[E] Rotary dryers

- It consists of a rotating cylinder through which the sludge moves.
- Various types of blades or flights are installed in the dryers depending on the type of material being dried.
- Drying takes place by direct contact with heated air.
- With a combustion temperature of 900 to 1000 ^{0}C and 50 % excess air, the outlet temperature of gases from sewage sludge is around 300 ^{0}C.

[F] Atomized spray dryers

- It has been used for many years in the chemical process industry.
- Spraying solids counter-currently into a downward draft of hot gas dries although concurrent spray dryers are also used in the chemical industry.

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Module 5: SOLID DISPOSAL

Lecture	Topic	No. of Hours (6)
1	Municipal and Solid Waste Disposal	1
2	Plastic Waste Management: Part I	1
3	Plastic Waste Management: Part II	1
4	Solids Waste Disposal – Composting	1
5	Landfilling	1
6	Gasification and Incineration	1

Lecture 1

Municipal and Solid Waste Disposal

MUNICIPAL SOLID WASTE

Municipal Solid Waste (MSW) is waste collected by or on behalf of a local authority. It mostly comprises of household waste, although it may also include some commercial and industrial wastes. MSW is more commonly known as trash or garbage, and it consists of everyday items such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, and batteries.

Some facts & figures [1]

- In India, collection, segregation, transportation, and disposal of solid waste are often unscientific and chaotic. Uncontrolled dumping of wastes on the outskirts of towns and cities has created overflowing landfills, which have environmental impacts in the form of pollution to soil, groundwater, and air, and also contribute to global warming [2, 3]
- About 0.1 million tonne of municipal solid waste is generated in India every day. That is approximately 36.5 million tonne annually.
- Per capita waste generation in major Indian cities ranges from 0.2 kg to 0.6 kg.
- Difference in per capita waste generation between lower and higher income groups range between 180 to 800 g per day.
- The urban local bodies spend approximately Rs. 500 to Rs. 1500 per tonne on solid waste for collection, transportation, treatment and disposal. About 60-70% of this amount is spent on collection, 20-30% on transportation and less than 5% on final disposal.
- Calorific value of Indian solid waste is between 600 and 800 kcal/kg and the density of waste is between 330 and 560 kg/m^3.
- Out of the total MSW collected, on an average 94% is dumped on land and 5% is composted.
- Between 2000 and 2025, the waste composition of Indian garbage will undergo the following changes:[4]
    - *Organic* waste will go up from 40 percent to 60 percent
    - *Plastic* will rise from 4% to 6%
    - *Metal* will escalate from 1% to 4%
    - *Glass* will increase from 2% to 3%
    - *Paper* will climb from 5% to 15%

  - *Others* (ash, sand, grit) will decrease from 47% to 12%

Common problems associated with unsound MSW disposal

- The disposal of solid waste has always been a huge problem throughout India. The overwhelming majority of landfills in India are open dumps without leachate or gas recovery systems. Several are located in ecological or hydrologically sensitive areas. They are generally operated below the standards of sanitary practice. Municipal budgetary allocations for operation and maintenance are always inadequate [5]
- Careless and indiscriminate open dumping of wastes creates unsightly and unsanitary conditions within municipalities e.g. along the roads and highways [6]
- Delay in delivery of solid wastes to landfills (which are infact dump sites), resulting in nuisance dumps and unpleasant odours which attract flies and other vectors. Such dumps also lead to pollution of land/soils, ground and surface water through leachate and air through emission of noxious and offensive gases.
- Open solid waste dumps can also be a public health risk. Direct contact with refuse can be dangerous and unsafe to the public, as infectious diseases such as cholera and dysentery can be spread through contact with these wastes. In most municipalities, scavenging on refuse dumps is a common practice, and such people face danger of direct exposure to hazardous waste. Open solid waste dumps can also provide suitable breeding places for vermin and flies and other disease vectors, and can also contain pathogenic micro-organisms [6].
- Some categories of solid wastes block permeability of soils and drainage systems, including water courses, open drains and sewers, thus posing difficulties in the functioning and maintenance of such facilities;
- Due to the capital-intensive nature of solid waste handling and disposal operations, these can become an economic burden and constrain service delivery in other areas such as medical care, education and road construction.

Classification of MSW [7]

- MSW can be classified into recyclable waste, organic fraction, inert debris and hazardous waste.
- MSW can also be classified into "dry and "wet" materials on the basis of their moisture content.
- From the perspective of energy recovery, the non-recyclable "dry" fraction can be divided into combustible materials such as paper, plastics and wood; and non-combustible or "inert" materials such as metals and glasses.
- Medical or clinical waste from medical institutions can be classified into the following types: general waste, sharp objects such as used needles, blades and scissors; syringes, pathological wastes, including contaminated bandages, dressings, linens, dead tissues, organs etc; and radioactive wastes [8].
- Some of the industrial wastes generated by industrial processes may be hazardous also.
- Biodegradable waste include mainly organic wastes such as peelings of potatoes, bananas, saw dust and water hyacinth dumped within the municipal environs, etc.
- Non-biodegradable waste, e.g. polythene bags (buvera), plastic products, pesticide residues, process wastes, highly flammable and volatile substances, furniture, abandoned vehicles, used tyres; industrial wastes including metal scrap and medical wastes such as used needles, plastic and glass bottles and syringes.

Table 5.1.1. Classification of MSW.

Combustibles Wastes		**Non-combustibles Wastes**	
“Dry” Stream	**“Wet” Stream**	**“Dry” Non-combustibles**	**Other materials**
Paper : Corrugated Cardboard, Newspapers, All other papers **Plastics:** HDPE (clear & colored), Films and Bags, PET, Polypropylene, polystyrene, PVC, All other plastics **Other dry combustibles:** Wood, Textiles, Rubber &	Food Waste, Grass/ Leaves, Brush /Prunings /Stumps, Disposable Diapers, Miscellaneous Organics	Clear Glass Containers, All other glass, Aluminum, Ferrous Metal	Hazardous Waste, Bulk Items, (appliances, furniture, etc), Rubber & Leather, Fines, Other

Leather, Fines, Other			

STANDARD PROCESSES FOR MANAGING MUNICIPAL WASTE [7]

- **Incineration**: Energy is stored in chemical form in all MSW materials that contain organic compounds i.e. which can be used to generate electricity and steam. It is being done by a few major hospital for managing clinical wastes.
- **Composting**: The natural organic components of MSW (Food and plant wastes, paper, etc) can be composted aerobically to carbon dioxide, water, and a compost product that can be used as soil conditioner. Anaerobic digestion or fermentation produces methane, alcohol and a compost product.
- **Recovery/recycling**: Recovered paper, plastic, metal, and glass can be re-used. 18. In the absence of formalized waste segregation practices, recycling has emerged only as an informal sector using outdated technology, which causes serious health problems to waste–pickers [9].
- **Land filling**: MSW materials that cannot be subjected to any of the above three method, plus any residuals from these processes (e.g. ash from combustion) must be disposed in properly desinged landfills.

Almost all categories of waste may be disposed to better managed landfills directly. However, those types of wastes which will destroy the microbiological degradation processes within the landfill are unwelcome i.e. the non-biodegradable wastes. Management of these could include: incineration, recycling and reusing [10].

ENERGY RECOVERY FROM MSW

Energy recovery can also be achieved from different methods of managing waste including:

Advanced Thermal Treatment - production of electricity and/or heat by the thermal treatment decomposition of the waste and subsequent use of the secondary products (typically syngas)

Anaerobic digestion – production of energy from the combustion of the biogas which is produced from the digestion of biodegradable waste

Landfill - production of electricity from the combustion of landfill gas produced as biodegradable waste decomposes [11].

INTEGRATED SOLID WASTE MANAGEMENT [12]

Integrated solid waste management (ISWM) takes an overall approach to create sustainable systems that are economically affordable, socially acceptable and environmentally effective.

- **Economic affordability** requires that the costs of waste management systems are acceptable to all sectors of the community including householders, commerce, industry and government.
- **Social acceptability** requires that the solid waste management system meets the needs of the local community, and reflects the values and priorities of that society.
- **Environmental effectiveness** requires that the overall environmental burdens of managing waste are reduced both in terms of consumption of resources (including energy) and the production of emissions to air, water and land [13].
- The collection and sorting are at the epi-centre of any solid waste management system [5]. After this, various systems analysis techniques can be applied to handle MSW streams through a range of integrative methodologies. The methodologies are broadly classified as:

1) **System engineering models** including cost-benefit analysis (CBA), forecasting models (FM), simulation models (SM), optimization models (OM), and integrated modeling system (IMS), as well as

2) **System assessment tools** including management information system (MIS)/decision support system (DSS)/expert system (ES), scenario development (SD), material flow analysis (MFA), life cycle assessment or life cycle inventory (LCA or LCI), risk assessment (RA), environmental impact assessment (EIA), strategic environmental assessment (SEA), socioeconomic assessment (SoEA), and sustainable assessment (SA) [5].

Use of above methodologies facilitates the selection of the most appropriate waste management technologies and design of sustainable solid waste management systems. A range of treatment options including [13] materials recovery, biological treatment (composting/biogasification), thermal treatment (mass-burn incineration with energy recovery and/or burning of Refuse Derived Fuel (RDF) and land filling may additionally required to form an ISWM system. Implementation of appropriate solid waste management practices requires reliable waste statistics. The data should represent a sufficiently long time frame (usually more than a few years), with relatively short measurement frequencies, to be statistically acceptable [14].

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Lecture 2

Plastic Waste Management: Part I

PLASTIC WASTE MANAGEMENT

INTRODUCTION

- The first commercial plastic was developed over one hundred years ago, but the plastic became major consumer material only after the growth of the petrochemical industry in the 1920s [1].
- Now plastics have not only replaced many wood, leather, paper, metal, glass, and natural fiber products in many applications, but also have facilitated the development of entirely new types of products that [2] are so versatile in use that their impacts on the environment are extremely wide ranging Once hailed as a 'wonder material', plastic is now regarded as a serious worldwide environmental and health concern essentially due to its non-biodegradable nature [3]. Careless disposal of plastic bags chokes drains, blocks the porosity of the soil and causes problems for groundwater recharge [4, 5].
- Plastic disturbs the soil microbe activity, and once ingested, can kill animals. Plastic bags can also contaminate foodstuffs due to leaching of toxic dyes and transfer of pathogens. The rapid rate of urbanization in India has led to increasing plastic waste generation [6].
- In fact, a major portion of the plastic bags i.e. approximately 60-80% of the plastic waste generated in India is collected and segregated to be recycled. The rest remains strewn on the ground, littered around in open drains, or in unmanaged garbage dumps.

PLASTIC INDUSTRY PROFILE

- The plastics industry in India has made significant achievements ever since it made a modest but promising beginning by commencing production of Polystyrene in 1957.
- The growth of the Indian plastic industry has been phenomenal - the growth rate is higher than for the plastic industry elsewhere in the world [5].
- Per capita consumption of plastic in India is less as compared to China and other developed countries.
- Packaging presents a major growth area where there has been a spiraling demand for plastics.
- Among the commodity plastics, polyethylene and PET are predominantly used in packaging. Low density polyethylene (LDPE) is used in the manufacture of carry bags

and PET is used in packaging beverages like soft drink and mineral water. PET in particular presents a major growth area in the years to come.

SOURCES OF PLASTIC WASTE

Plastic wastes are generated from a variety of sources and can be broadly classified as consumer, industrial, computer and other wastes.

- Consumer waste generated from residential households, markets, small commercial establishments, hotels and hospitals include milk pouch, carry bags, cups/glasses, buckets/mugs, pens, mats, luggage, TV cabinets, footwear, etc.
- Industrial sector generates barrels, crates, films, jerry cans, tanks, cement bags, tarpaulins, etc. as plastic wastes.
- Floppy, CD, monitor, printers, etc. are included in computer wastes.
- Other sources of plastic wastes include automotive, agricultural and industrial wastes; and the construction debris.

PROBLEMS RELATED TO PLASTIC WASTE

- The plastic content of the municipal waste is picked up by rag pickers for recycling either at primary collection centers or at dumpsites.
- Moreover, since the rag-picking sector is not formalized, not all the recyclables, particularly plastic bags, get picked up and are found littered everywhere.
- Littering is a very common phenomenon in India. One of the offshoots of littering is the choking of drains, streams, etc.
- Plastic films, bags are not permeable, and so they tend to hold other type of wastes thus blocking the way. This gives rise to flooding of the streets in the urban low lying areas with wastewater emanating foul smell and causing breakthrough of serious health hazards.
- Recently, cow deaths have been reported due to the consumption of scattered plastic bags along with the organic matter [4].
- Plastics are recycled mostly in factories, which do not have adequate technologies to process them in a safe manner. This exposes the workers to toxic fumes and unhygienic conditions.

- Dioxin, a highly carcinogenic and toxic by-product of the manufacturing process of plastics, is one of the chemicals believed to be passed on through breast milk of the mother to the nursing infant. Burning of plastics, especially PVC releases this dioxin and also furan into the atmosphere [7].
- Since toxic dyes and chemicals are used as additives during the recycling, the workers engaged in the recycling of plastic are constantly exposed to various toxic compounds.
- Polybag recycling is carried out in shanties, this problem is compounded due to poor ventilation, as workers find themselves inhaling contaminated air [5, 8]. Child labour itself is a big issue. Indian collection sector employ children below the age of 15 to collect them because of the low wages to be paid to the child and the ease of availability of child labour [5].
- Backyard smelters and plastic recycling units dot India's suburban/urban sites, taking lead battery scrap and plastic waste imported from developed countries such as Australia and the United States. The dangerous toxins emitting from the smelters have affected human, animal and plant life.
- The current situation is that the plastic recycling in the country is creating more problems and with the influx of plastic waste import it is getting aggravated. If imported, India should also import the technology along with the waste.
    - Although plastics contribute only about 7% by weight to MSW, they may contribute 15% or more to the total heat content of MSW. Hydrogen chloride (HCl) gas is emitted during combustion of polyvinyl chloride (or other chlorinated polymers), and may result in corrosion of municipal waste combustor internal surfaces.

STATUES RELATING TO PLASTIC WASTE MANAGEMENT IN INDIA

In the last few years, state and central governments have started paying attention to the issues of plastic waste seriously. Consequently many legislations, acts and rules have been formulated to bring the situation under control. Responsibility to protect the environment and enforcing the existing regulation lies within the Ministry of Environment and Forests (MOEF).

- Government of Himachal Pradesh introduced HP Non-biodegradable Garbage (control) Act 1995 prohibiting throwing or deposing plastic articles in public places.

- The MOEF issued the criteria developed by Central Pollution Control Board (CPCB) in association with the Bureau of Indian Standards (BIS) for labeling 'plastic products' as 'Environment - friendly' under its 'Ecomark' scheme. One of the requirements for fulfilling this criterion is that the material used for packaging shall be recyclable or biodegradable.
- The Prevention of Food Adulteration Department of the Government of India issued directives to various catering establishments to use only ‘food-grade’ plastics while selling or serving food items. 'Food-grade' plastics meet certain essential requirements and are considered safe, when in contact with food. The intention is to preventing possible contamination, and to avert the danger from the use of the recycled plastics.
- **Recycled Plastics Usage Rules, 1998** were drafted in exercise of the powers conferred by clause (viii) of sub-section (2) of section 3 read with section 25 of the Environment (Protection) Act, 1986 (29 of 1986). It prohibits usage of carry bags made of recycled plastics for storing, carrying and packing the food stuffs. It allows the usage of carry bags, etc. [2] if the following conditions are satisfied, namely: -
    a) carry bags and containers made of recycled plastics conform to the specifications mentioned in the Prevention of Food and Adulteration Act, 1954 and the rules made there under;
    b) such carry bags and containers are not pigmented :
    c) the minimum thickness of carry bags made of recycled plastics shall not be less than 25 micron; and
    d) reprocessing or recycling of plastics is undertaken strictly in accordance with the Indian Standards, IS 14534 :1998 entitled " Guidelines for Recycling of Plastics" published by the BIS and the end product made out of recycled plastics is marked as "recycled" along-with the indication of the percentage of use of recycled material.
    e) The minimum thickness of carry bags made of virgin plastic shall not be less than 20 micron.
- **Recycled Plastic Manufacture and Usage Rule (1999)** addresses the issue of plastic bag. The rule prohibits the usage of carry bags and containers made of recycled plastic bags for storing, carrying and dispensing or packaging of foodstuffs. It mandates the use

of only virgin bags of 20 micron of natural colour without any dyes and pigments for packaging foodstuffs. The rule specifies minimum thickness of the carry bags of virgin [5] plastic to be of 20 micron and of the recycled plastic to be of 25 micron. It allows the use of recycled poly bags of a minimum thickness of 25 micron for non-food applications provided the dyes and pigments used conform to the specification in the Food Adulteration Act. The rule calls for recycling of plastics to be carried out according to the Guidelines for Recycling of Plastics

- **Guidelines for Plastics Packaging and Packaging Waste in India** aims to 4prevent the production of packaging waste, encourage reuse of packaging, recycling and other forms of recovering packaging waste thereby reducing the final disposal of such waste. The guidelines cover all plastic packaging used in the market today. They emphasize the need to think of recycling not when the product waste accumulates, but at the start of the development process [5]. The guidelines call for establishing an organized system for recycling, reuse and recovery of plastics along with appropriate incentives and penalties.
- **Guidelines for Recycling of Plastics** were published with a view to bring discipline to the recycling practices in the country. These guidelines not only prescribe standards for the segregation and processing of plastic wastes but also instruct the manufacturer of plastic products to mark the basic raw material on the finished product. Also, it is necessary to indicate the percentage of recycled content in the product [5, 8].

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Lecture 3

Plastic Waste Management: Part II

WAYS TO REDUCE THE IMPACTS OF PLASTICS WASTES

Source Reduction: There are number of ways of achieving source reduction. Examples include:

- Modify design of product or package to decrease the amount of material used.
- Utilize economies of scale with larger size packages.
- Utilize economies of scale with product concentrates.
- Make material more durable so that it may be reused.
- Substitute away from toxic constituents in products or packaging.

Potential plastic markets that may be considered for source reduction include packaging, building and construction, consumer products, electrical and electronic, furniture and furnishings, transportation, adhesives, inks, and coatings.

Recycling: India ranks highest in terms of plastic recycling percentage (60%) in the world, whereas the world average is only 20% [1]. Recycling methods could be classified by following types [2]

- **Primary Recycling:** Melting, molding and solidification.
- **Secondary recycling:** Melting and extrusion or injection.
- **Tertiary Recycling:** Physical and chemical methods that include thermolysis (pyrolysis, catalytic cracking, hydro cracking, etc.) and depolymerisation (alcoholysis, hydrolysis, acidolysis, aminolysis, etc.).
- **Quaternary Recycling:** Incineration with energy recovery

Phases of Plastic Recycling: Recycling plastics from MSW encompass four phases of activity collection, separation, processing/manufacturing and marketing [3].

Collection: Collection of plastics involves formal (municipal) sector and informal sector comprising of wastepickers, kabariwala, scrap dealers and bulk buyers. The municipality derives its funds for waste management either through funds designated by the Central Government and funds derived from property taxes.

Separation: It involves both formal and informal sector. Plastics segregated from MSW include a variety of resins. It is not necessary to separate plastics by resin type to allow their recycling, but separation by resin allows the production of the highest-quality recycled products.

Processing/Manufacturing: It may involve three different types of processes. *Primary processes* are defined as industrial recycling of manufacturing and processing scrap. Typically, such scrap is blended with virgin resins and reintroduced into plastics production processes. *Secondary processes* encompass a continuum of processing alternatives. One end of this continuum is defined by processes that consume clean, homogeneous resins that can be used to manufacture products interchangeable with those produced from virgin plastic resins. At the other end of this continuum are processes that consume mixed recycled plastics in the manufacture of products that do not replace or compete with virgin plastic products, but replace structural materials such as wood and concrete in product applications. *Tertiary processes* involve the chemical or thermal degradation of recycled plastics into chemical constituents that serve as fuels or chemical feedstocks. Tertiary processes may use either homogeneous or mixed plastics as inputs.

Marketing: This is the most important phase for the continuous recycling of plastics by informal sector. Homogeneous recycled resins are processed into products that compete in markets with virgin plastics. With currently available technologies, most mixed recycled plastics are processed into generally lower value products that compete in markets. Value addition of plastic waste across the informal sector is shown in following figure [4].

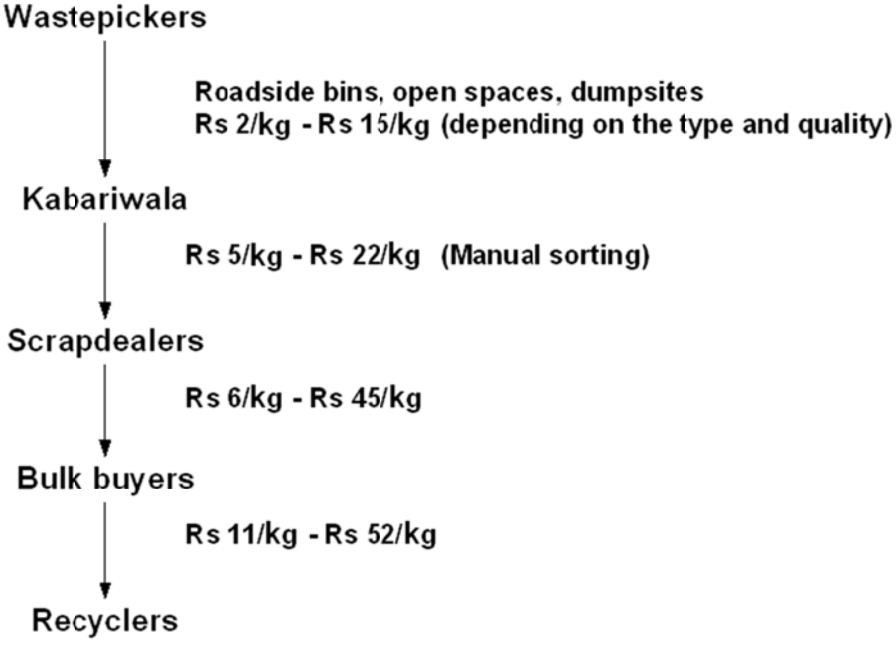

Figure 5.3.1. Value addition of plastic waste across the informal sector [4].

There are many problems for the plastic recycling industry in India. The supply of recovered plastic is rather volatile due to the decrease in the recovery rate year by year and the dependency on the fluctuating international market. Most plastic recycling enterprises are small and medium sized factories with obsolete equipment and technologies. Financial limitations are a constraint to the technical improvements needed to satisfy market demand. Plastic cannot be recycled indefinitely. In continuous recycling, plastic becomes too contaminated and degraded for use as a secondary material. Secondary pollution occurs during the recycling process. Some factories cannot afford to install pollution control facilities and must therefore discontinue production [5].

DEGRADABLE PLASTICS

Bioplastics are biodegradable plastics, whose components are derived from renewable raw materials. These plastics can be made from abundant agricultural/animal resources like cellulose, starch, collagen, casein, soy protein polyesters and triglycerides [6]. Large scale use of these would help in preserving non-renewable resources like petroleum, natural gas and coal and contribute little to the problems of waste management. Biodegradable plastics degrade over a period of time when exposed to sun and air [7]. Various types of plastic degradation processes and reasons for degradation are given in Table 2.

Table 5.3.1. Types of plastic degradation processes [3].

Photodegradation	Degradation caused through the action of sunlight on the polymer
Biodegradation	Degradation that occurs through the action of microorganisms such as bacteria, yeast, fungi, and algae etc.
Biodeterioration	Degradation that occurs through the action of microorganisms such as beetles, slugs, etc.
Autooxidation	Degradation caused by chemical reactions with oxygen.
Hydrolysis	Degradation that occurs when water cleaves the backbone of a polymer, resulting in a decrease in molecular weight and a loss of physical properties
Solubilization	Dissolution of polymers that occurs when a water-soluble link is included in the polymer.*

*Note: soluble polymers remain in polymeric form and do not actually “degrade.” They are included here because they are sometimes mentioned in the literature on degradable plastics.

Though the demand for biodegradable plastics is increasing, acceptance of biodegradable polymers is likely to depend on factors like [8]

- Customer response to costs.
- Possible legislation by Governments.
- The achievement of total biodegradability.

Immediate application areas identified in India for biodegradable plastics are agricultural mulch, surgical implants, industrial packaging, wrapping, milk sachets, foodservice, personal care, pharmaceuticals, medical devices, recreational, etc. However, the legal framework for the 4 utilisation of biodegradable materials is still very unclear. Within waste management, local authorities in many parts of the world including India don’t treat bioplastics as compostable material [9].

ADDITIONAL EFFORTS TO MITIGATE IMPACTS OF PLASTIC WASTE

- Environmental tax on plastic bags.
- Incineration with energy recovery.
- Landfilling, this will still be needed for disposal of plastic and other wastes.
- Reorganization of the recycling sector.
- Extended producer responsibility [10].
- Increasing educational initiatives.

Some of the potential strategies for minimization of plastic wastes and the effect on plastic pollution are given in following table:

Table 5.3.2. Plastic waste management strategies and its relationship to plastic waste pollution.

Potential strategies	Intended effect on plastic pollution
Source reduction	Reduces gross discards and toxicity of certain additives in plastic wastes
Recycling	Reduces net discards of plastics.

Degradable plastics	Reduces long-term impacts of improperly discarded plastics
Control of urban runoff and sewers	Reduces release of plastic floatable wastes generated from land sources
Control of emissions from incineration with energy recovery	Reduces emissions
Control of leachate from landfills	Prevents contamination of groundwater

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Lecture 4

Composting

COMPOSTING

- Composting is the biological reclamation of organic materials by natural decomposition process. Examples: decay of fallen leaves in forests, decay of wood in a stand and animal carcasses decaying in a preserve. These natural processes in nature return organic material to the ecosystem.
- Composting of agricultural waste and municipal solid waste has a long history and is commonly employed to recycle organic matter back into the soil to maintain soil fertility [1-3]. Composting is seen as an environmentally acceptable method of waste treatment [2].
- It is an aerobic, biological process which uses naturally occurring microorganisms to convert biodegradable organic matter into a humus-like product. The process destroys pathogens, converts N from unstable ammonia to stable organic forms, reduces the volume of waste and improves the nature of the waste [4, 5].
- Composting is a successful strategy for sustainable recycling of organic wastes [6]. It is an ecological alternative to mass burning and land-filling of MSW.
- Composting reduces the volume of waste to dispose to landfill and incineration and it recovers the useful organic matter for use as soil amendment. By contrast, odors, noise, vermin nuisance, bioaerosol (organic dust containing bacterial or fungal spores) generation and emissions, emission of volatile organic compounds (VOCs), and potential pathway from use on land for contaminants to enter food chain, are the disadvantages of composting [7-11].
- Composting is one element of an integrated solid waste management strategy that can be applied to mixed municipal solid waste (MSW) or to separately collected leaves, yard wastes, and food wastes. The three basic functions of composting are (1) preparation, (2) decomposition, and (3) post-processing [12].

PROCESS OF COMPOSTING [13]

- Compost results in a physical breakdown of organic matter layered with small amounts of soil by a process known as aerobic disintegration.
- Structure of the matter is broken down by bacteria and fungi of decay until it is part of the soil mass. For example, a piece of newspaper would, under ideal conditions, become a part of the humus in the soil within two to four weeks. A tin can biodegrades in about 100 years and an aluminum can in about 500 years.

- During composting, heat is generated because of interaction of organic material interaction with moisture, air, bacteria and fungi.

Phases of Composting [13]

The composting process can be divided into three phases determined by temperature and heat output.

a) During the first phase, the initial 24-48 hours, temperatures gradually rise to 40-50 ^{o}C. During this time, sugars and other easily biodegradable substances are metabolized mostly by bacteria and fungi.

b) During the second phase, which may occur over extended periods of time, temperatures between 40 and 65 ^{o}C prevails. 2Cellulose and other more difficult substances to biodegrade are destroyed at that time. Lignins, the darker, woody components in plant tissues, break down even more slowly. During this high temperature phase, plant pathogens, weed seeds and biocontrol agents (excepting Bacillus spp.) are killed by the heat. Turning compost piles ensures uniformly high temperatures and helps produce a homogeneous product.

c) The third stage is the curing phase when the concentrations of materials that readily decompose decrease. The rates of decomposition, heat output and temperature decline during this phase. A micro-flora, similar to that found in soil, now colonizes the compost. Mature compost has a dark color, consists largely of lignins, humus and biomass and has a distinctive soil or "earthy" odor. This odor is attributed to the soil microflora present in the compost [13].

Optimum Conditions for Composting [14]

Food:- organic waste containing water (moisture content between 30-80%) & added nutrients (Nitrogen, Phosphorous, Sulfur) present organic matter content in waste serves as a source of carbon, nutrients & energy for the metabolic reactions during bioremediation process.

Micronutrients in addition to N, P & S many other micronutrients are needed to a lower concentration such as K, Ca, Mg, Fe, Ni & others.

Oxygen if required (aerobic types): 2-5 kg of oxygen per kg of organic compound to be converted.

Moderate pH: between 6-9, neither too acidic nor too alkaline.

Moderate Temperatures: 50^{o} to 100^{o} F.

Enzymes: Chemical catalysts to break waste materials into smaller pieces.

Small Scale Composting

A households' compost pile includes such things as leaves, plant refuse, vegetables parings, weeds, wood shavings, lawn clippings, and non-greasy food wastes. Commercial nitrogen fertilizer are also included in the pile to expedite the decay process and ground limestone is added to balance the pH. The pile is kept moist and periodically is turned to aerate the mass and mix the materials for better decomposition.

Household compost is usually used as a soil conditioner. It helps aggregate soil particles, adds some nutrients, and increases water holding capacity.

Commercial Compost [13, 15]

Composting plants established globally and, in India also, have met with little success. The process of composting on a large scale differs from household composting. It is important to control the methane gas that develops during decomposition (as in a landfill) and prevent leaching. Yet, there are success stories.

The 'mass sorting processes' of most commercial composting provides a rough mix of grades of paper, wood, fiber, food scraps and miscellaneous other materials. The irregularity of the materials going into the compost process suggests that what comes out is also irregular. This irregularity of material is reflected in particle size, purity of the compost, and usability of the end product [13].

The downfall of most commercial compost facilities is the lack of markets for the end product. There appears to be consistent discrepancy between the quality and the perceived value of the compost.

Co-composting (mixing wastes with sludge from sewage treatment facilities) provides a high-quality soil additive but this product cannot be used on vegetable gardens and tuber, root or leafy crops. Use of co-compost in other fields is acceptable if the compost is monitored for heavy metal content. The irregular quality of the mass-sort compost makes it a difficult product to market. Greater effort is needed to create a sustainable quality and quantity of product and market match [13, 15].

HUMAN HEALTH RISKS DUE TO COMPOSTING [11]

MSW contains a number of chemical and biological agents, hence it contains a lot of harmful substances. These contaminants may expose different populations to health hazards, ranging from the composting plant workers to the consumers of vegetable products grown in soils treated with compost. Health risks are due to occupational exposure to organic dusts, bioaerosols and microorganisms in MSW composting plants. Potential health risks are due to volatile organic compounds (VOCs) released during composting **[11, 16].**

8With respect to the health risks of compost, three are three main exposure routes for the population: a) ingestion of soils treated with compost, b) contamination through the food chain by consumption of products cultivated in soils where compost has been applied, and c) dispersion of atmospheric dust of compost that transports microorganisms and toxicants susceptible of being inhaled [11].

ISSUES OF GHG EMISSIONS DUE TO COMPOSTING

Green house gas (GHG) emissions due to composting are often neglected. Aerobic decomposition from well managed composting results in the emission of CO_2 and H_2O. Due to the heterogeneous nature of a compost pile, some CH_4 may form in anaerobic pockets within the pile [17, 18]. However, studies have shown that the majority of this CH_4 emission oxidizes to CO_2 in aerobic pockets and near the surface of the compost pile, making CH_4 emission negligible [19, 20]. However, many investigators have reported considerable CH_4 emission even in well managed systems. This happens due to various variables controlling the nature of the compost piles [21-23].

There is other side of the coin also, the production of compost helps mitigate GHG emissions in following ways **[**24]:

1. Decreasing the need of chemical fertilizers and pesticides; thereby reducing GHG emissions from the use of fossil fuel associated with their production and application [25, 26].

2. Allowing for more rapid growth in plants, thereby increasing carbon uptake and storage within the plant [27-29]. This is a form of carbon sequestration which removes CO_2 from the atmosphere.

3. Sequestering carbon in soil that has receives the compost [28, 30]. It is estimated that approximately 50 kg carbon (183 kg CO_2) gets sequestered per ton of wet compost [31]. This figure is however specific to the US, and to a particular soil type **[**24].

4. Improving tillage and workability of soil (thereby reducing emissions from fossil fuel that would otherwise be used to work the soil) [26].

THE FUTURE FOR COMPOSTING

Composting of selected organic materials can be a valuable component of an integrated waste management system. It is a process as natural as nature and as technologically advanced as recycling [32]. Composting will be certainly important in the future. Generally, conditions in India are very conducive for composting in terms of waste composition and weather conditions. However, composting has never flourished as an option for refuse treatment and disposal. Most local authorities feel, based on local experience, that the running costs of composting plants are excessive and unjustifiable.

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Lecture 5

Land-filling

LANDFILL

Landfills include any site which is used for more than a year for the temporary storage of waste; and, any internal waste disposal site, that is to say a site where a producer of waste is carrying out its own waste disposal at the place of production.

Landfills does not include (a) any facility where waste is unloaded in order to permit its preparation for further transport for recovery, treatment or disposal elsewhere; (b) any site where waste is stored as a general rule for a period of less than three years prior to recovery or treatment; or, (c) any site where waste is stored for a period of less than one year prior to disposal [1].

MSW landfills represent the most widely accepted option for waste disposal in many parts of the world, particularly in underdeveloped and developing countries, due to its economic advantage over other methods [2]. Even highly developed countries also largely depend on landfilling. In USA, 54% of the 250×10^6 metric tons of MSW generated was landfilled in 2008, with recycling and composting accounting for about 33% of MSW management [3].

WASTE DECOMPOSITION PROCESS IN LANDFILL [4]

- MSW contains a large proportion of organic materials that naturally decompose when landfilled.
- This decomposition process initially is aerobic where the main byproducts are carbon dioxide, plus contaminated water. However, after the oxygen within the waste profile is consumed, it switches over to anaerobic processes. In the anaerobic process, carbon dioxide and methane are produced as waste decomposes. Liquid byproducts contain a large concentration of various contaminants that naturally move toward the landfill’s base.
- The decomposition process continues for many years. As this takes place, trace quantities of materials that may have significant impacts upon the environment can be contained in both the landfill gas and in the leachate. These trace materials are generated until the landfill becomes completely stabilized. Although it isn’t known how long this will take, some estimate between 300 and 1,000 years [5].

LANDFILL GAS RECOVERY

- The waste deposited in a landfill gets subjected, over a period of time, to anaerobic conditions and its organic fraction gets slowly volatilized and decomposed, leading to production of landfill gas which contains a high percentage of methane (about 50%).
- Typically, production of landfill gas starts within a few months after disposal of wastes and generally lasts for 10 years or even more depending upon mainly the composition of wastes and availability of moisture. As the gas has a calorific value of around 4500 kcal/m^3, it can be used as a source of energy either for direct heating/cooking applications or to generate power through IC engines or turbines [6].

Advantages of Landfill Gas Recovery

- Reduced GHG emissions;
- Low cost means for waste disposal; and
- The gas can be utilized for power generation or as domestic fuel.

Disadvantages of Landfill Gas Recovery

- Inefficient gas recovery process yielding only 30-40% of the total amount of gas actually generated. Balance gas escapes to the atmosphere (significant source of two major green house gases, carbon-dioxide and methane);
- Utilization of methane may not be feasible for remote sites;
- Cost of pre-treatment to upgrade the gas may be high; and
- Spontaneous ignition/explosions may occur due to possible build up of methane concentrations in atmosphere.

LANDFILL RECLAMATION

- An approach used to expand municipal solid waste (MSW) landfill capacity and avoid the high cost of acquiring additional land.
- The equipment used for reclamation projects is adapted primarily from technologies already in use in the mining industry, as well as in construction and other solid waste management operations [7].

Steps in Landfill Reclamation

(i) Excavation: An excavator removes the contents of the landfill cell. A front-end loader then organizes the excavated materials into manageable stockpiles and separates out bulky material, such as appliances and lengths of steel cable.

(ii) Soil Separation (Screening): A trommel (i.e., a revolving cylindrical sieve) or vibrating screens separates soil (including the cover material) from solid waste in the excavated material. The size and type of screen used depends on the end use of the recovered material. For example, if the reclaimed soil typically is used as landfill cover, a 2.5-inch screen is used for separation. If, however, the reclaimed soil is sold as construction fill, or for another end use requiring fill material with a high fraction of soil content, a smaller mesh screen is used to remove small pieces of metal, plastic, glass, and paper. Trommel screens are more effective than vibrating screens for basic landfill reclamation. Vibrating screens, however, are smaller, easier to set up, and more mobile [8].

Benefits of Landfill Reclamation

- Extending landfill capacity at the current site
- Generating revenues from the sale of recyclable materials
- Lowering operating costs or generating revenues from the sale of reclaimed soil
- Reducing landfill closure costs and reclaiming land for other uses
- Retrofitting liners and removing hazardous materials

Drawbacks of Landfill Reclamation

- Managing hazardous materials
- Controlling releases of landfill gases and odors
- Controlling subsidence or collapse
- Excavation of one landfill area can undermine the integrity of adjacent cells, which can sink or collapse into the excavated area.
- Increasing wear on excavation and MWC equipment

MANAGEMENT OF CLOSED LANDFILLS

Aftercare management of closed landfills typically includes monitoring of emissions (e.g. leachate and gas) and receiving systems (e.g. groundwater, surface water, soil, and air) and maintenance of the cover and leachate and gas collection systems [9].

Landfill Gas: Closed landfill sites pose a potential hazard because of their methane production. The greatest risk occurs at sites that are within 250 m of housing and/or industrial estates. Problems become more severe when there are no gas-control measures [10].

Landfill leachates: Landfill leachates are defined as the aqueous effluent generated as a consequence of rainwater percolation through wastes, biochemical processes in waste's cells and the inherent water content of wastes themselves. It contains many organic matters, minerals, heavy metals and has high concentration of ammonia-nitrogen, all these lead to the low biodegradability. The leachate qualities changes according to the landfill climate conditions and hydrology, it also varies according to the qualities of the garbage that has been buried in the landfill [11]. The removal of organic material based on chemical oxygen demand (COD), biological oxygen demand (BOD) and ammonium from leachate is the usual prerequisite before discharging the leachates into natural waters. Conventional landfill leachate treatments can be classified into three major groups [12-14]:

(a) leachate transfer: recycling and combined treatment with domestic sewage,

(b) biodegradation: aerobic and anaerobic processes and

(c) chemical and physical methods: chemical oxidation, adsorption, chemical precipitation, coagulation/flocculation, sedimentation/flotation and air stripping.

After the hardening of the standards of rejection, conventional landfill leachate treatment plants are not able to meet the desired standards. Today, the landfill leachate treatment consists of various combined processes such as coagulation and ammonia-nitrogen stripping, UBF anaerobic process and two stages of Anoxic/Oxic process filter, UF and RO deep treatment [11].

Landfill mining: Landfill mining could be described as a process for extracting minerals or other solid natural resources from waste materials that previously have been disposed of by burying them in the ground [14].

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Lecture 6

Gasification and incineration

THERMAL TREATMENT

In recent decades, industrialized countries also included the thermal treatment (incineration, pyrolysis, or gasification) of MSW as an important option for its management. Within thermal treatments, incineration has reached a great interest. However, although this process notably reduces the space required for the disposal of the same amount of residues in landfills (typically by a factor from 4 to 10) [1- 3], MSW incinerators (MSWI) have been questioned because of the atmospheric emissions of acid gases, heavy metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and especially by the emission of the potential carcinogenic agents polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) [1, 2, 4-6].

Thermal processes [7]

(a) Incineration (combustion): The term ‘incineration’ is used to describe processes that combust waste and recover energy. In mass burning systems, the refuse is burned in an "as received" condition. Generally, in mass burning systems all of the waste entering the facility is dumped into a large storage pit, with bulky items being removed prior to entering the combustion chamber [7]. To allow the combustion to take place a sufficient quantity of oxygen is required to fully oxidize the fuel. Incineration plant combustion temperatures are in excess of 850^{o}C and the waste is mostly converted into carbon dioxide and water and any noncombustible materials (e.g. metals, glass, stones) remain as a solid, known as incinerator bottom ash (IBA) that always contains a small amount of residual carbon. The direct combustion of a waste usually releases more of the available energy compared to pyrolysis and gasification [8, 9].

(b) Pyrolysis: Pyrolysis is thermal decomposition in the absence of oxygen. This process requires an external heat source to maintain the pyrolysis process. Typically, temperatures of between 300^{o}C to 850^{o}C are used during pyrolysis of materials such as MSW. The products produced from pyrolysing materials are a solid residue and syngas [9]. The solid residue (sometimes described as a char) is a combination of non-combustible materials and carbon. The syngas is a mixture of gases (combustible constituents include carbon monoxide, hydrogen and methane) and condensable oils, waxes and tars. The syngas typically has a net calorific value (NCV) of between 10 and 20 MJ/Nm^3. For comparison, natural gas has NCV of around 38 MJ/Nm^3 [9]. If required, the condensable (liquid) fraction can be collected, potentially for use as a liquid fuel or a feedstock in a chemical process, by cooling the syngas [10]. By manipulating the environmental conditions within the reactor, the yield of any desired product (gas of low calorific value, liquid oil and carbonaceous char) may be optimized [11-13].

Refuse-derived fuel (RDF): Fuel produced from combustible waste is called refuse derived fuel (RDF). RDFs are processed so that all non-combustible materials like recyclables (glass, metals) and inerts (stones, etc.), which do not contribute to the energy content of the waste are removed prior to burning. The waste going into the RDF mainly comprises wastes with significant energy content like plastics, dried biodegradable materials, textiles, etc [9]. In many instances, the waste remaining after processing is shredded into confetti-like particles [7, 8]. Raw MSW typically has an energy content of 9 – 11 MJ/kg, whereas an RDF can have an energy content of 17MJ/kg [8, 9].

(c) Gasification: When the heat for pyrolysis is provided by combustion of part of the waste in air or oxygen, the term "gasification" is used [7]. In gasification, air (oxygen) is added but the amounts are not sufficient to allow the fuel to be completely oxidized and full combustion to occur. The temperatures employed are typically above 650^{o}C. The process is largely exothermic but some heat may be required to initialize and sustain the gasification process. The main product is a syngas, which contains carbon monoxide, hydrogen and methane. Typically, the gas generated from gasification has a NCV of 4 – 10 MJ/Nm^3 [9]. The other main product of gasification is a solid residue of non-combustible materials (ash) which contains a relatively low level of carbon.

Necessary conditions for MSW incineration

The key requirements in the incineration of MSW are as follows:

- A minimum combustion temperature of 850^{o}C for 2 seconds of the resulting combustion products
- Specific emission limits for the release of SO_2, NOx, HCl, volatile organic compounds (VOCs), CO, particulate (fly ash), heavy metals, dioxins, etc. to the atmosphere.
- Bottom ash that is produced has a total organic carbon content of less than 3%.

USES OF ENERGY GENERATED FROM MSW [9, 10]

Energy recovered from waste can be used in the following ways:

(A) Generation of Power (electricity): The energy generation option selected for an incineration facility will depend on the potential for end users to utilize the heat and/or power available. In most instances power can be easily distributed and sold via the national grid and this is by far the most common form of energy recovery.

(B) Generation of Heat: For heat, the consumer needs to be local to the facility producing the heat and a dedicated distribution system (network) is required. Unless all of the available heat can be used the generating facility will not always be operating at its optimum efficiency.

(C) Generation of Heat and Power: The use of combined heat and power (CHP) combines the generation of heat and power (electricity). This helps to increase the overall energy efficiency for a facility compared to generating power only. In addition, as power and heat demand varies a CHP plant can be designed to meet this variation and hence maintain optimum levels of efficiency.

INCINERATION PROCESS [9, 10]

An incinerator with energy recovery comprises of the following process:

[A] Waste reception, sorting and preparation:

- It requires 1pre-sorting of MSW material to remove heavy and inert objects, such as metals, prior to processing in the furnace.
- The waste is then mechanically processed to reduce the particle size.
- Overall, the waste requires more preparation than if a moving grate was used.

[B] Combustion: The combustion is normally a single stage process and consists of a lined chamber with a granular bubbling bed of an inert material such as coarse sand/silica or similar bed medium. The bed is ‘fluidized’ by air (which may be diluted with recycled flue gas) being blown vertically through the material at a high flow rate. Wastes are mobilized by the action of this fluidized bed of particles. There are two main sub-categories of fluidized bed combustors:

- **Bubbling FB** – the airflow is sufficient to mobilize the bed and provide good contact with the waste. The airflow is not high enough to allow large amounts of solids to be carried out of the combustion chamber.
- **Circulating FB** – the airflow for this type of unit is higher and therefore particles are carried out of the combustion chamber by the flue gas. The solids are removed and returned to the bed.
- Rotary kilns are also used for incineration of MSW and hazardous wastes.

[C] Energy recovery plant: The standard approach for the recovery of energy from the incineration of MSW is to utilize 1the combustion heat through a boiler to generate steam. Up to 80% of the total available energy in the waste can be retrieved in the boiler to produce steam. The steam can be used for the generation of power via a steam turbine and/or used for heating [8].

[D] Emissions control: The combustion process must be correctly controlled and the flue gases must be cleaned prior to their release. Generally, ammonia is injected into the hot flue gases for control of NOx emissions. Lime or sodium bicarbonate is injected to control SO_2 and HCl. And finally, a filter bed consisting of adsorbents like activated carbon, fly ash and other solids (lime or bicarbonate) is used to control the release of heavy metals, CO, VOCs and dioxins.

[E] Residue handling: Finally, bottom ash and air pollution control residues should be properly handled and disposed off as per the regulations.

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