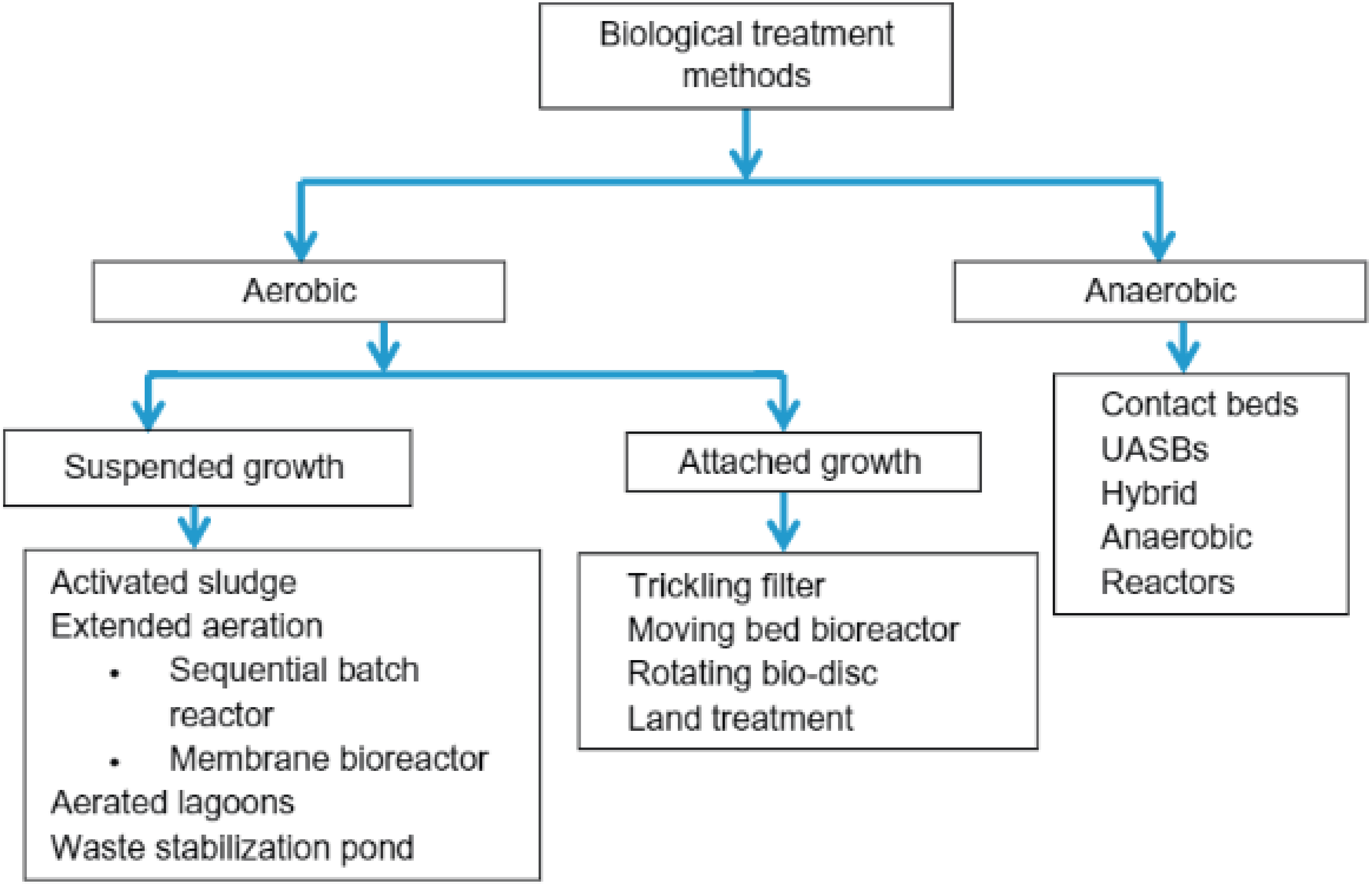
CHAPTER (5)

Aeration & OXYGEN TRANSFER IN AERATED BIOREACTORS



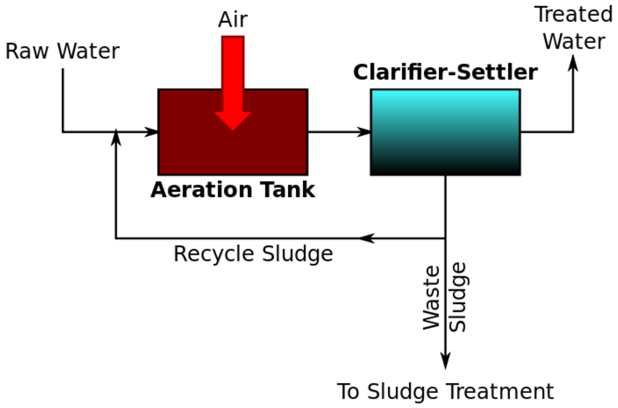
Refer to Environmental Engineering Course Notes

Introduction: Biological Treatment

1) Biological treatment is an important and integral part of any wastewater treatment plant that treats wastewater from either municipality or industry having soluble organic impurities or a mix of the two types of wastewater sources.
2) Biological treatment of organic component in wastewater can be performed either aerobically (in the presence of oxygen) or anaerobically (in the absence of 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.
3) By aerobic treatment organic compound would be degraded to CO_2 and H_2O and about 50% of the carbon is used to form new biomass.
4) Aerobic processes normally are applied for wastewater with a BOD < 5000 mg/L. Under optimal aeration conditions and a proper retention time, nitrogenous compounds are converted to nitrate after the carbon respiration was finished.

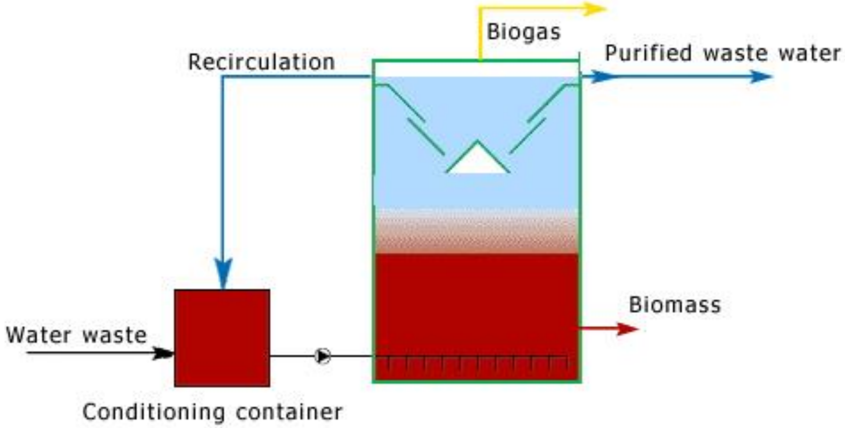
Aerobic Biological Treatment

- Microorganisms convert organics into carbon dioxide and new biomass in the presence of oxygen.
- These systems can act as stand-alone systems, or polish anaerobically pretreated wastewater.
- <u>General Features:</u>
  - Best for wastewater with **lower concentrations of organics**
  - Often used after primary treatment
  - Low effluent values can be attained
  - Nitrogen and phosphorous removal possible
  - Produce excess sludge
  - High operating costs
    - Requires aeration (power)
    - Nutrients (nitrogen and phosphorous)
    - Sludge disposal handling



Anaerobic Biological Treatment

- ❑ Energy-efficient process in which microorganisms convert organic matter into biogas in the absence of oxygen.
- ❑ <u>General Features:</u>
  - Ideal for **medium and highly concentrated** wastewater
  - Better for warm wastewater (> 20°C)
  - Typically low effluent values can only be obtained with additional aerobic polishing
  - No significant nitrogen or phosphorous removal
  - Valuable, money-saving biogas
  - Very little excess sludge
  - Low operating costs:
    - Low power consumption
    - Low or no nutrient addition
    - Low excess waste sludge

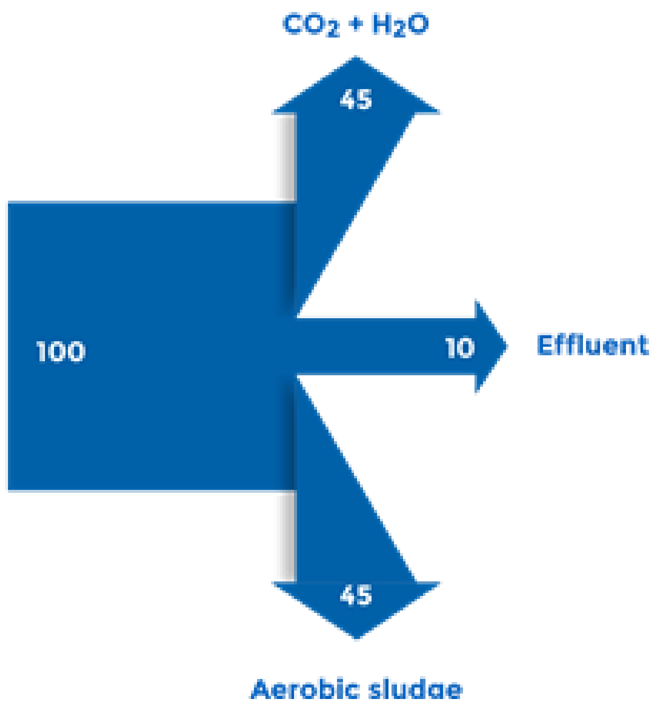


Biological Methods

AEROBIC VS. ANAEROBIC

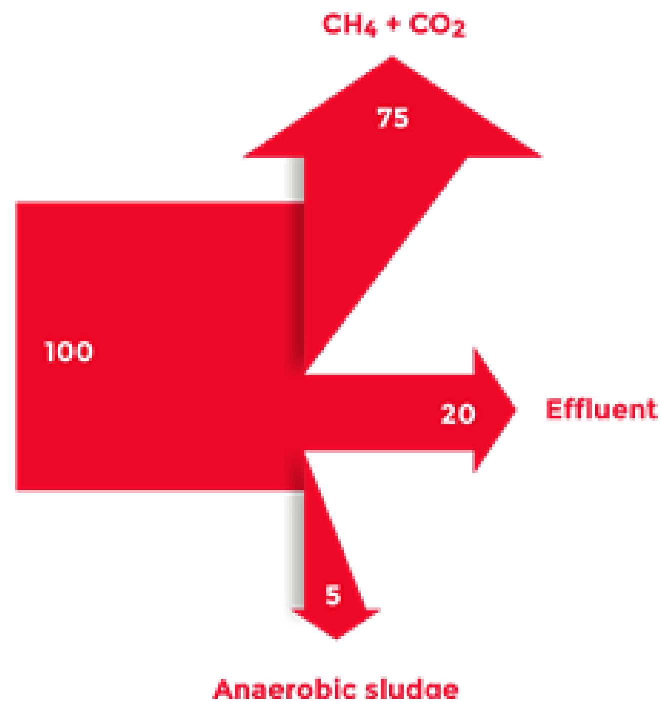
AEROBIC PROCESS

$COD + O_2 \rightarrow H_2O + CO_2 + BIOMASS$

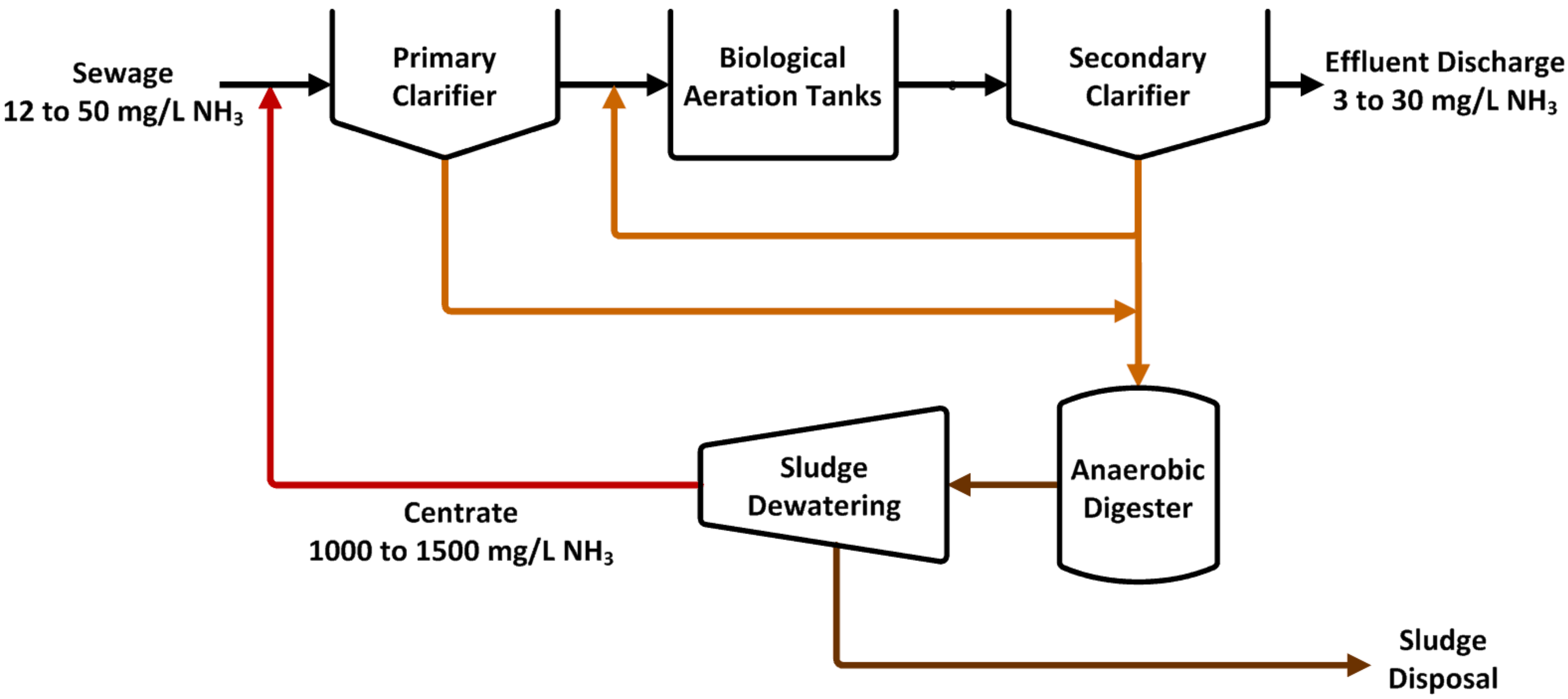


ANAEROBIC PROCESS

$COD \rightarrow CH_4 + CO_2 + BIOMASS$



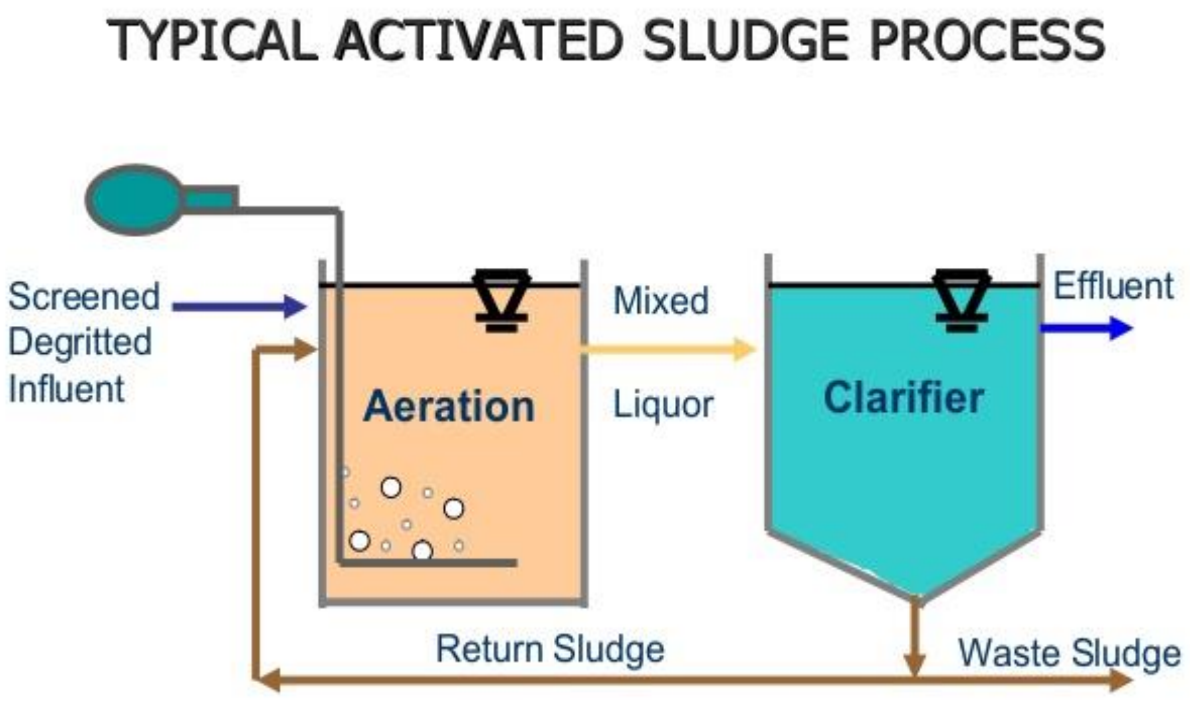
Biological Methods: ammonia removal



Introduction: Aeration

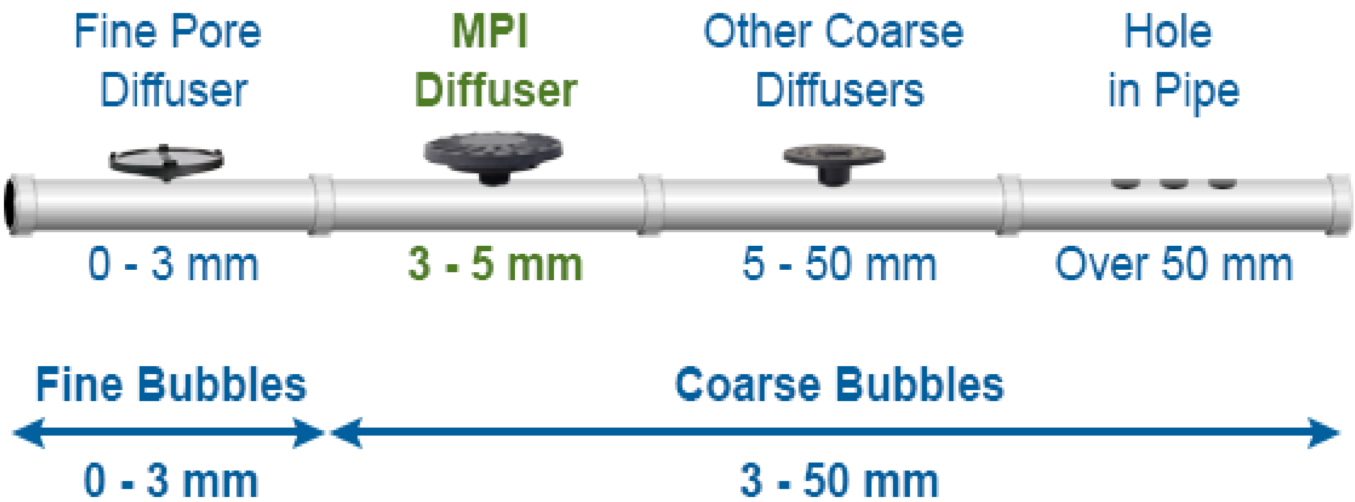
- In activated sludge, aerated lagoon, and aerobic digestion processes, oxygen must be supplied to the biological solids for aerobic respiration, and mixing must be sufficient to maintain the solids in suspension.
- Oxygen transfer and mixing are provided by two main types of aeration devices, depending on where they are located:
  1. Submerged (diffused) aerators: Air introduced below liquid surface by blowing air to diffusers. Air is provided by blowers
  2. Surface (mechanical) aerators: Mechanically agitate water to promote transfer of oxygen to the water from the atmosphere above the liquid.
  3. Combination of diffused compressed air and mechanical aeration (such as the submerged-turbine type of aerator).

Introduction



Air Blowers

Diffused Aeration

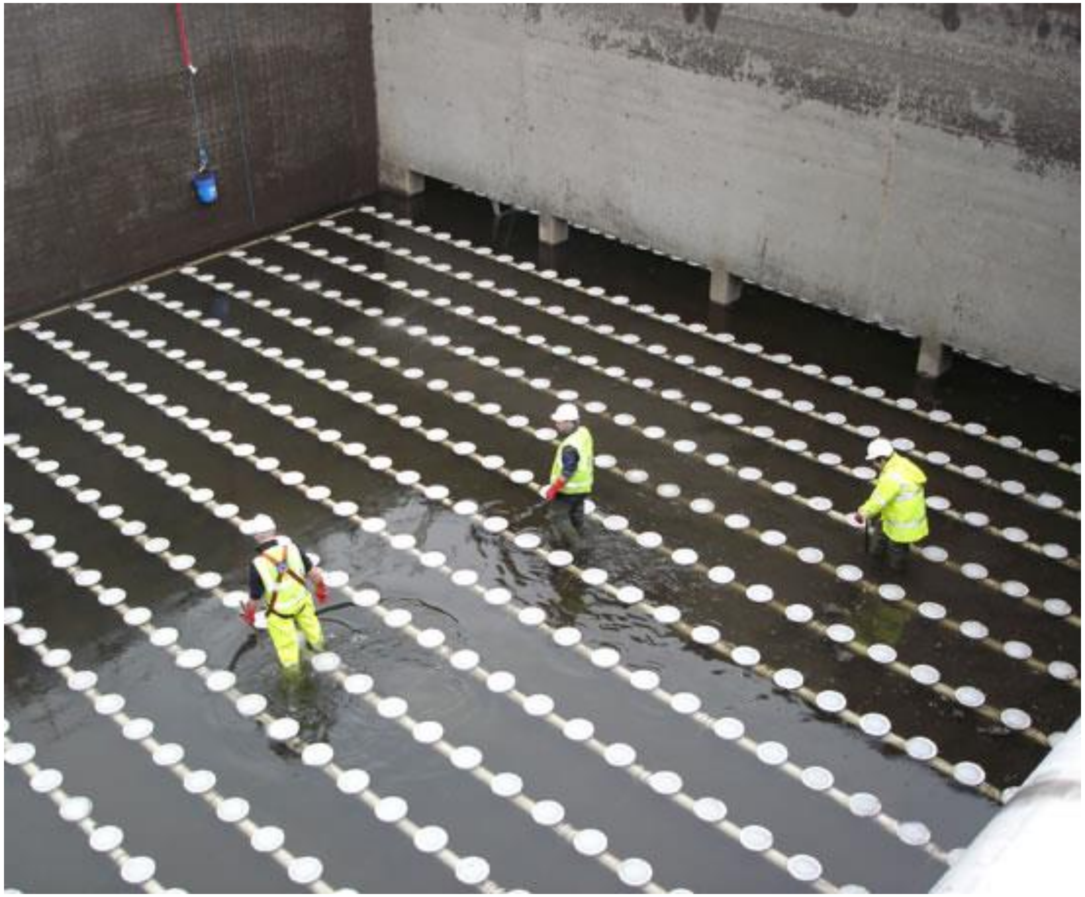


Diffused Aeration

1. Aeration devices for diffused compressed air may be classified as coarse or fine bubble diffusers.
2. The efficiency of oxygen transfer depends primarily upon:
    a) *the design of the diffuser,*
    b) *the size of the bubbles produced, and*
    c) *the depth of submergence.*
3. The field transfer efficiency for coarse bubble diffusers is usually from 4 to 8%, while that of fine bubble type is from 8 to 12% ***(which indicates % of oxygen supplied by the air which will be transferred to liquid phase).***

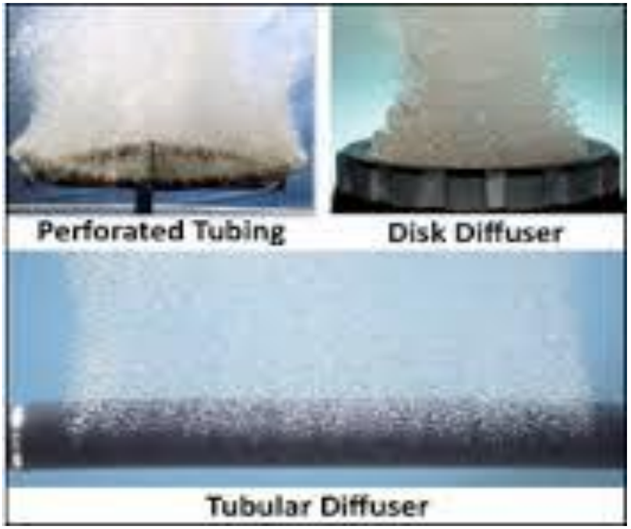
4. The coarse bubble type has a lower efficiency than the fine bubble type; however, it is less susceptible to clogging.
5. Diffusers are usually made of:
    A. *porous ceramic tubes or cylindrical metal frames covered with a wrapping such as a Dacron cloth.*
    B. *Sometimes porous ceramic plates covering an air channel cast in the tank bottom are used.*

Submerged Aeration: Fine Bubble Diffusers



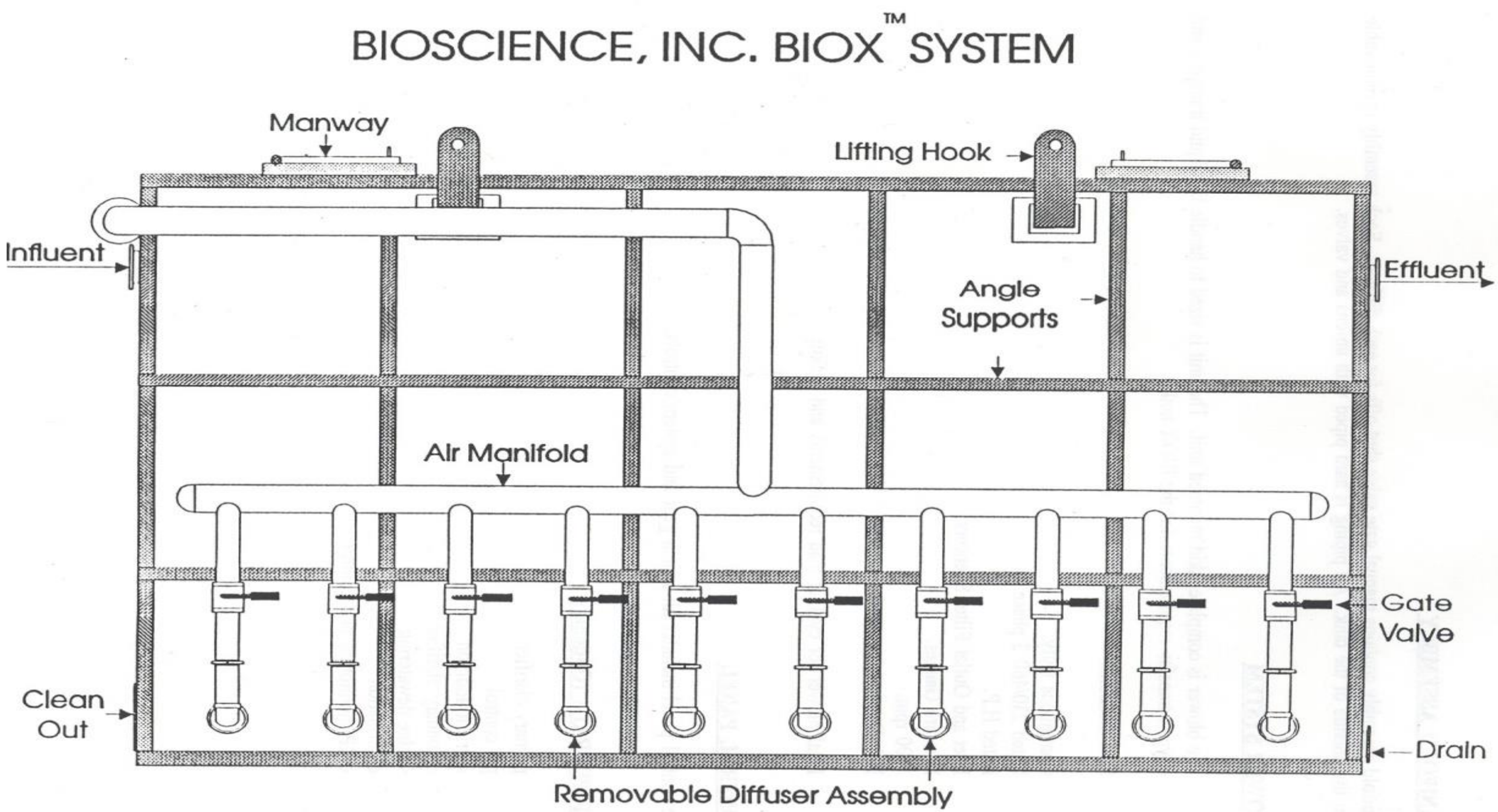
Coarse Bubble Aerators

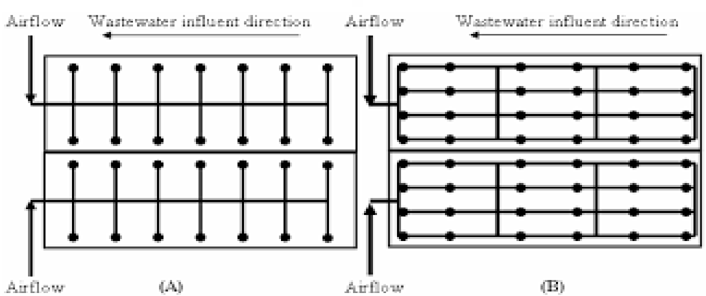
Fine Bubble Aerators



Membrane diffuser

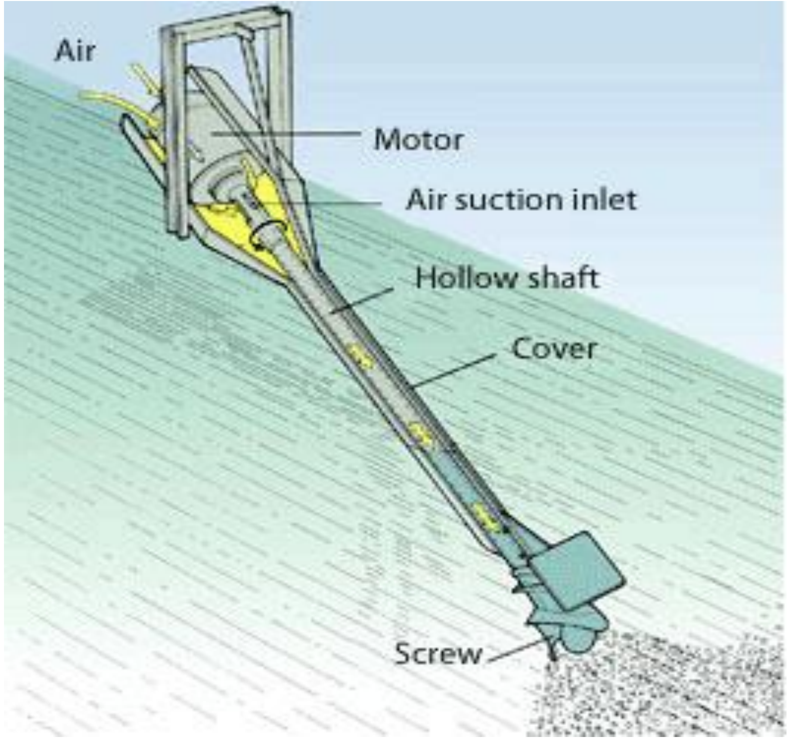
Bioreactor with Diffused Aeration

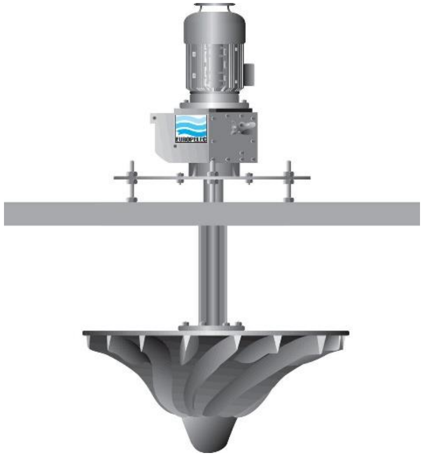




Surface Aeration: Rotor Brush Aerators

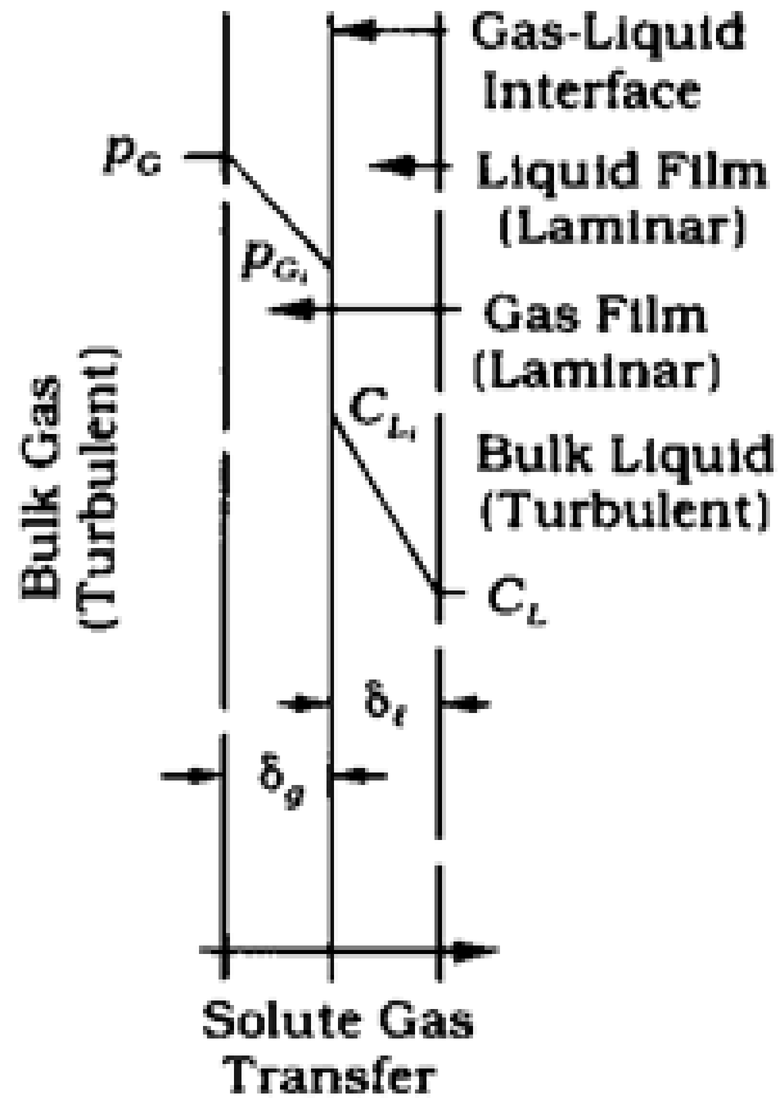
Surface Aerators: Other Mechanical





Oxygen Transfer Process

1. The transfer of a solute gas from a gas mixture into a liquid that is in contact with the mixture can be described by the **two-film theory of Lewis and Whitman (1924).**
2. The Figure shows a schematic drawing of the two phases in contact with each other.
3. The solute gas must diffuse through the gas film (laminar layer), pass through the interface, and then diffuse through the liquid film (laminar layer).
4. The interface offers no resistance to the solute gas transfer:



Oxygen Transfer Process

- For gases that are slightly soluble in the liquid, such as oxygen in water, the rate limiting step is the diffusion of the solute gas through the liquid film.
- The diffusion transfer coefficient, **K_L**, for oxygen diffusing through the water film is given by

$$K_L = D / \delta$$

  where **D** is the diffusivity coefficient of oxygen in water and **δ** is the film thickness.
- Multiplying **K_L** by **a** (the interfacial bubble area per unit volume of water), gives the overall mass transfer coefficient, **K_La**

Oxygen Transfer Process

$$\frac{dC}{dt} = K_L a(C_s - C)$$

where

dC/dt = rate of oxygen transfer, mass/(volume)(time) — for example, mg/ℓ-hr

$K_L a$ = overall liquid mass transfer coefficient, $time^{-1}$ — for example, $hour^{-1}$

C_s = saturation dissolved oxygen concentration, mass/volume — for example, mg/ℓ

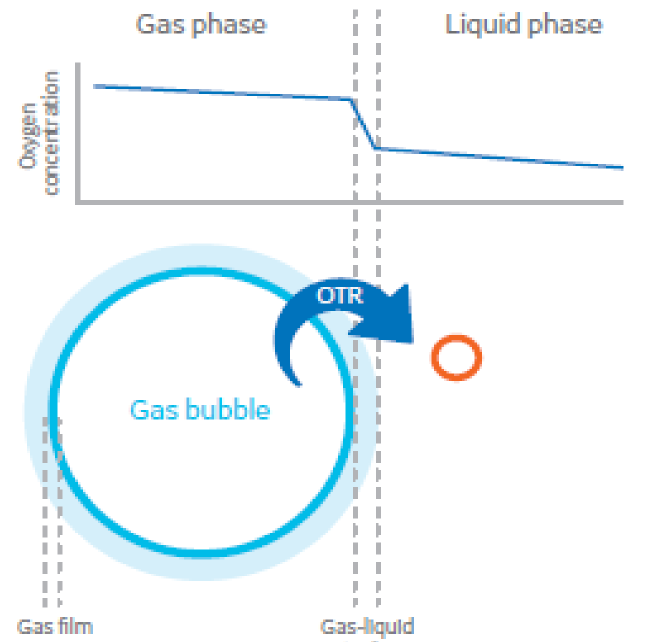
C = dissolved oxygen concentration in the liquid, mass/volume — for example, mg/ℓ

What We Need to Learn Regarding Aeration:

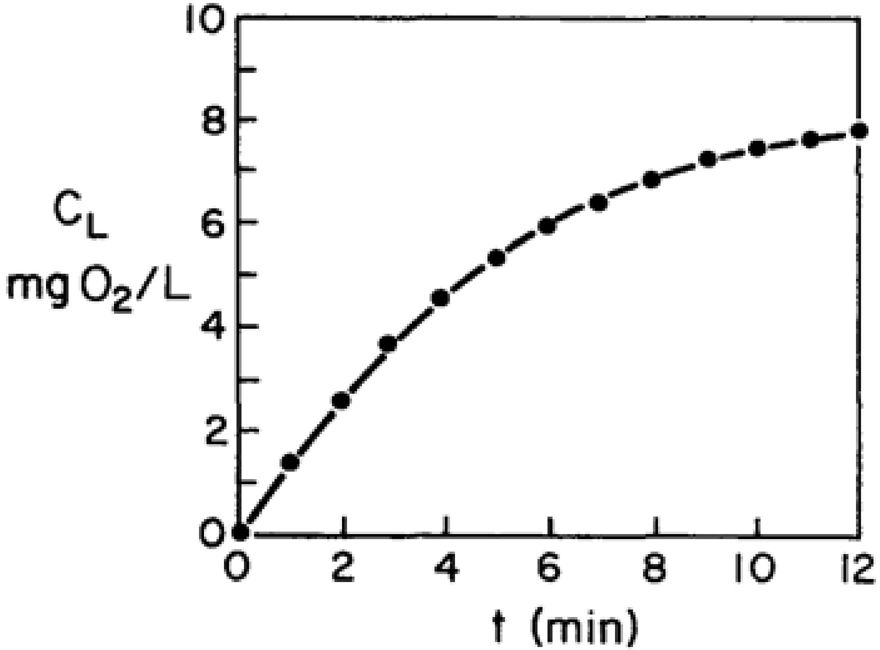
1. Calculate **oxygen requirement** for biological growth (carbon removal and nitrification).
2. This oxygen is going to be provided with **air and through a device** at a certain efficiency.
3. Need to know how **much air is required** to satisfy requirements and maintain a residual DO.

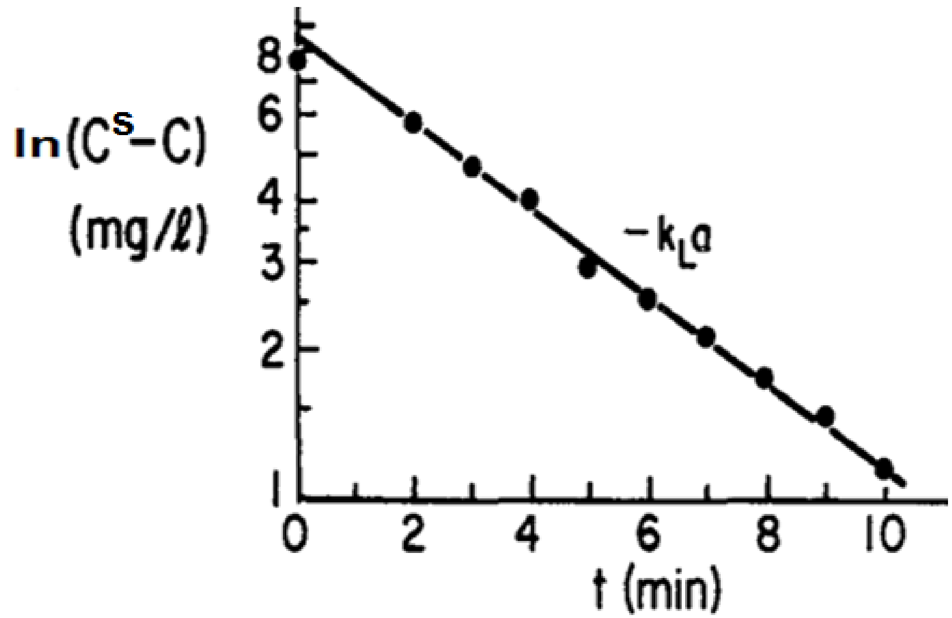
Determining Overall MTC, $\mathbf{K_La}$

1) Need a reactor with clean water and aeration equipment in it with *air being supplied at a given rate.*
2) Test started by *adding <u>sodium sulfite</u>* (Na_2SO_3) in the presence of *cobalt (Co)* catalyst to remove all oxygen from the water (zero oxygen at t = 0).
3) Then turn air on and measure oxygen concentration with time: *Unsteady state conditions*.



Determining Overall MTC, **K_La**





$C = Ct$ @ t

$C = Co$ @ $t = 0$

$$\frac{dC}{dt} = k_L a(C^s - C)$$

$$\ln(C^s - C) = -k_L a\, t$$ **+ constant**

$$C^s = \frac{p_{O_2}}{H(T)}$$ Henry's law

p_{O_2} is the partial pressure of oxygen

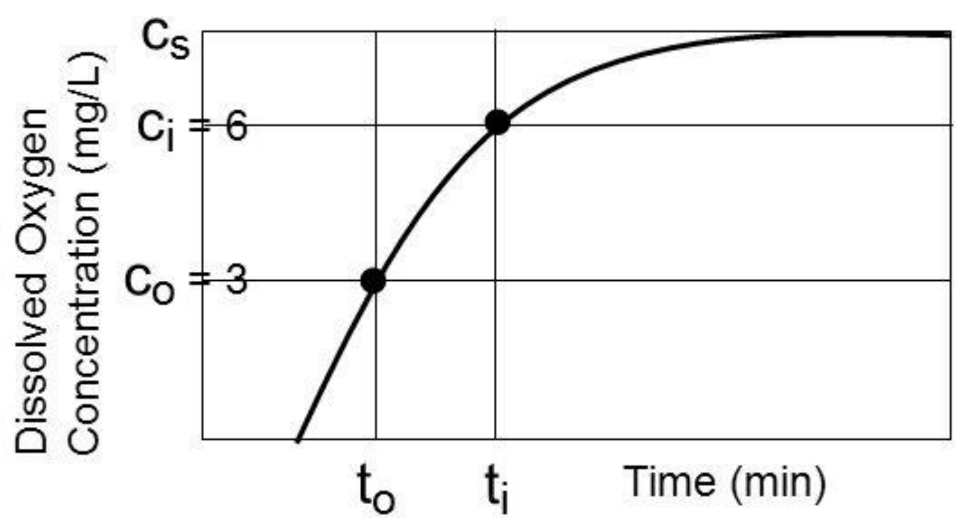
$H(T)$ is the Henry's law constant of oxygen

Mathematical Determination of k_La

1. OTR is a change of c_L over time, thus = dc_L/dt

2. $k_La = \dfrac{dc_L/dt}{(c_S - c_L)}$ Integration gives

3. $k_La = \dfrac{\ln\left(\dfrac{c_S - c_O}{c_S - c_i}\right)}{t_i - t_o}$



$$k_La = \dfrac{\ln\left(\dfrac{8 - 3 \text{ ppm}}{8 - 6 \text{ ppm}}\right)}{10.5 - 6.1 \text{ min}} = \dfrac{\ln 2.5}{4.4 \text{ min}} = 0.21 \text{ min}^{-1} = 12.5 \text{ h}^{-1}$$

Determining Overall MTC, $K_l a$
Oxygen Solubility

Problem: The lowest level of oxygen gas dissolved in water that will support life is ~ 1.3×10^{-4} mol/L. At the normal atmospheric pressure of oxygen is there adaquate oxygen to support life?
Plan: We will use Henry's law and the Henry's law constant for oxygen in water with the partial pressure of O_2 in the air to calculate the amount.
Solution:

The Henry's law constant for oxygen in water is $1.3 \times 10^{-3} \frac{\text{mol}}{\text{liter} \cdot \text{atm}}$

and the partial pressure of oxygen gas in the atmosphere is 21%, or 0.21 atm.

$$S_{oxygen} = k_H \times P_{O2} = \frac{1.3 \times 10^{-3}\ \text{mol}}{\text{liter} \cdot \text{atm}} \times (0.21\ \text{atm})$$

$$S_{Oxygen} = \qquad\qquad \textbf{mol } O_2 \textbf{ / liter}$$

Factors Affecting Oxygen Transfer Rate

Consider the OTR Equation:

$$\text{Oxygen Transfer Rate} = \frac{dC}{dt} = K_L a(C_s - C)$$

A) Need to consider factors that affect C_S (concentration in liquid phase when at equilibrium with gas phase):

(T, P, composition of water or TDS)

B) Need to consider factors that affect K_La:

(T, depth, waste characteristics)

Factors Affecting Oxygen Transfer Rate

A) Factors Affecting C_S

1. **Temperature:**

   As temperature increases saturation concentration of dissolved oxygen decreases.

   At 0°C, C_s = 14.6 mg-O_2/L

   At 30°C, C_S = 7.6 mg-O_2/L.

   (Keeping pressure constant at 1 atm)

TABLE 5.1
Solubility of oxygen (mg/l) at various temperatures, elevations, and total dissolved solids levels

Temperature		Elevation, ft						TDS (sit sea level), ppm			
°C	0	1000	2000	3000	4000	5000	6000	400	800	1500	2500
0	14.6	14.1	13.6	13.1	12.6	12.1	11.7	—	—	—	—
2	13.8	13.3	12.8	12.4	11.9	11.5	11.1	13.74	13.68	13.58	13.42
4	13.1	12.6	12.2	11.8	11.4	10.9	10.5	13.04	12.98	12.89	12.75
6	12.5	12.0	11.6	11.2	10.8	10.4	10.0	12.44	12.38	12.29	12.15
8	11.9	11.4	11.0	10.6	10.2	9.9	9.5	11.85	11.80	11.70	11.58
10	11.3	10.9	10.5	10.1	9.8	9.4	9.1	11.25	11.20	11.12	11.00
12	10.8	10.4	10.1	9.7	9.4	9.0	8.6	10.76	10.71	10.64	10.52
14	10.4	10.0	9.6	9.3	8.9	8.6	8.3	10.36	10.32	10.25	10.15
16	10.0	9.6	9.2	8.9	8.6	8.3	8.0	9.96	9.92	9.85	9.75
18	9.5	9.2	8.9	8.5	8.2	7.9	7.6	9.46	9.43	9.36	9.27
20	9.2	8.8	8.5	8.2	7.9	7.6	7.3	9.16	9.13	9.06	8.97
22	8.8	8.5	8.2	7.9	7.6	7.3	7.1	8.77	8.73	8.68	8.60
24	8.5	8.2	7.9	7.6	7.3	7.1	6.8	8.47	8.43	8.38	8.30
26	8.2	7.9	7.6	7.3	7.1	6.8	6.6	8.17	8.13	8.08	8.00
28	7.9	7.6	7.4	7.1	6.8	6.6	6.3	7.87	7.83	7.78	7.70
30	7.6	7.4	7.1	6.9	6.6	6.4	6.1	7.57	7.53	7.48	7.40

Factors Affecting Oxygen Transfer Rate

$$C_S = C_{14.7}\left[\frac{P}{14.7}\right]$$

2. Partial pressure of oxygen:

- C_S = Oxygen saturation concentration at pressure P
- $C_{14.7}$ = Oxygen saturation concentration at 14.7 psi (1 atm) and actual WW temperature
- P = Pressure at oxygen transfer point
- For surface aerators, P = atmospheric pressure
- For submerged aerators, P = atmospheric pressure plus pressure at 1/3 of depth of the tank from the surface of the diffusers (in feet):

P = atmospheric pressure * depth * 0.434 psi/ft

If want to be conservative, use atmospheric pressure to calculate C_S

Factors Affecting Oxygen Transfer Rate

3. Composition of wastewater:

Presence of dissolved salts, particulates and surface active substances affect solubility of oxygen:

$$\beta = \frac{C_s^{Wastewater}}{C_S^{Pure\ Water}}$$

$$\beta = 0.95 \text{ for typical wastewater}$$

- Include factors affecting C_S into OTR equation

$$OTR = \frac{dC}{dt} = \mathrm{K_L} a (C_s - C)$$

$$OTR = \frac{dC}{dt} = \mathrm{K_L} a \left(\beta \, C_{14.7}^{T} \left[\frac{P}{14.7} \right] - C \right)$$

- *Next, we consider factors that affect **$K_L a$***

Factors Affecting Oxygen Transfer Rate

B) Factors Affecting kLa:

1. Temperature:

$$K_L a_{(T)} = K_L a_{(20^0 C)} 1.02^{(T-20)}$$

2. Liquid depth:

$$\frac{K_L a(H_1)}{K_L a(H_2)} = \left(\frac{H_1}{H_2}\right)^n, \ \mathrm{n} = 0.7$$

3. Waste characteristics:

$$\alpha = \frac{K_L a \text{ in wastewater}}{K_L a \text{ in tap water}}$$

TABLE 5.2
Values of α for different aeration devices

Aeration device	Alpha factor	Wastewater
Fine bubble diffuser	0.4–0.6	Tap water containing detergent
Brush	0.8	Domestic wastewater
Coarse bubble diffuser, sparger	0.7–0.8	Domestic wastewater
Coarse bubble diffuser, wide band	0.65–0.75	Tap water with detergent
Coarse bubble diffuser, sparger	0.55	Activated sludge contact tank
Static aerator	0.60–0.95	Activated sludge treating high-strength industrial waste
Static aerator	1.0–1.1	Tap water with detergent
Surface aerators	0.6–1.2	Alpha factor tends to increase with increasing power (tap water containing detergent and small amounts of activated sludge)
Turbine aerators	0.6–1.2	Alpha factor tends to increase with increasing power; 25, 50, 190 gal tanks (tap water containing detergent)

Factors Affecting Oxygen Transfer Rate

Notes on K_La:

1. ***Values for K_La in wastewater less than in tap water:***

   Reason for this is presence of surface active agents, which:

   - have *hydrophilic and hydrophobic* regions.
   - concentrate at interface, with hydrophilic end into water and hydrophobic end into gas phase, leading to retardation of molecular diffusion.

2. ***Interfacial "*****a*****" depends on degree of turbulent mixing***. It also varies during bio-oxidation due to variation in *waste composition*.

3. Interfacial area "**a** " is determined by as part of evaluating "**K_La**" in both wastewater and tap water.

4. Normally, **K_La** determined under operational conditions and with suspended solids. Liquid depth can sometimes be neglected thus giving conservative readings.

Putting factors affecting $K_L a$ into Equation

- We had the following equation:

$$OTR = \frac{dC}{dt} = K_L a \left(\beta \, C_{14.7}^{T} \left[\frac{P}{14.7} \right] - C \right)$$

- Including the factors affecting **$K_L a$:**

$$OTR = \frac{dC}{dt} = \alpha K_L a_{\left(20^0 C\right)} \left(\beta \, C_{14.7}^{T} \left[\frac{P}{14.7} \right] - C \right) \left(1.02^{(T-20)} \right)$$

Factors Included In General Equation

- The Equation obtained was:

$$OTR = \frac{dC}{dt} = \alpha K_L a_{(20^0 C)} \left(\beta\, C^T_{14.7} \left[\frac{P}{14.7} \right] - C \right) \left(1.02^{(T-20)} \right)$$

$$\alpha = \frac{K_L a \text{ in wastewater}}{K_L a \text{ in tap water}}$$

$$C^T_S = C^T_{14.7} \left[\frac{P}{14.7} \right]$$

$$\beta = \frac{C_S^{Wastewater}}{C_S^{Pure\ Water}}$$

$$\beta = 0.95 \text{ for typical wastewater}$$

Oxygen saturation concentration at temperature T and 14.7 psi pressure (atmosphere)

How to Get Parameters for Equation

- Parameters used in equation for OTR are highly dependent on "environmental" conditions in the bioreactor.
  - This affects α and β.

- For standardization and comparison purposes:
  - manufacturers of aeration equipment report oxygen transfer rate of equipment tested at standard conditions.

Standard Conditions for Testing Aeration Equipment

- Temperature = 20° C
- Pressure = 14 psi = 1 atm
- Oxygen Concentration in Liquid Phase = 0 mg-O_2/L
- Standard Oxygen Transfer Rate = SOTR

$$SOTR = \frac{dC}{dt} = \alpha \mathrm{K_L} a_{\left(20^0 C\right)} \left(\beta\, C_{14.7}^{T} \left[\frac{P}{14.7} \right] - C \right) \left(1.02^{(T-20)} \right)$$

$$= \mathrm{K_L} a_{\left(20^0 C\right)} C_s^{20^0 C} = 9.17 \times \mathrm{K_L} a_{\left(20^0 C\right)}$$

Test For Determining SOTR: Determining K_La

- Need a reactor with clean water and aeration equipment in it with air being supplied at a given rate.

- Test started by adding sodium sulfite (Na_2SO_3) in the presence of cobalt catalyst to remove all oxygen from the water.

- Then turn air on and measure oxygen concentration with time: *Unsteady state conditions.*

Relating SOTR with AOTR

We can relate:

- Actual Oxygen Transfer Rate in the Field (AOTR) with
- Standard Oxygen Transfer Rate (SOTR)*

$$\frac{AOTR}{SOTR} = \frac{\alpha \mathrm{K_L} a_{(20^0 C)} \left(\beta \, C_{14.7}^{T} \left[\frac{P}{14.7} \right] - C \right) \left(1.02^{(T-20)} \right)}{9.17 \times \mathrm{K_L} a_{(20^0 C)}}$$

$$\frac{AOTR}{SOTR} = \frac{\alpha \left(\beta \, C_{14.7}^{T} \left[\frac{P}{14.7} \right] - C \right) \left(1.02^{(T-20)} \right)}{9.17}$$

**oxygen transfer rate @ standard conditions in clean water*

Example

- Nitrifying activated sludge system with actual oxygen requirements (AOR) of 1000 kg-O_2/day.
- Temperature is 20°C and pressure is 1 atm.
- Want to maintain a residual DO of 2 mg-O_2/L using ceramic discs for fine bubble aeration.
- How much air need to provide?

$$\frac{AOTR}{SOTR} = \frac{\alpha\left(\beta\, C_{14.7}^{T}\left[\frac{P}{14.7}\right] - C\right)\left(1.02^{(T-20)}\right)}{9.17}$$

How much Air Need to Supply?

- Step 1: Check with manufacturers, they typically give SOTE values for aeration equipment.

TABLE 10-7
Typical information on the clean water oxygen-transfer efficiency of various diffuser systems[a]

Diffuser type and placement	Air flowrate, $ft^3/min \cdot$ diffuser	SOTE (%) at 15 ft submergence[b]
Ceramic discs—grid	0.4–3.4	25–40
Ceramic domes—grid	0.5–2.5	27–39
Ceramic plates—grid	2.0–5.0[c]	26–33
Rigid porous plastic tubes		
Grid	2.4–4.0	28–32
Dual spiral roll	3.0–11.0	17–28
Single spiral roll	2.0–12.0	13–25
Nonrigid porous plastic tubes		
Grid	1.0–7.0	26–36
Single spiral roll	2.0–7.0	19–37
Perforated membrane tubes		
Grid	1.0–4.0	22–29
Quarter points	2.0–6.0	19–24
Single spiral roll	2.0–6.0	15–19
Jet aeration		
Side header	54.0–300	15–24
Nonporous diffusers		
Dual spiral roll	3.3–10.0	12–13
Mid-width	4.2–45.0	10–13
Single spiral roll	10.0–35.0	9–12

Assume SOTE= 0.30

How much Air Need to Supply?

- Then use the previously derived equation:

$$AOTE = \frac{\alpha SOTE}{9.17}\left(\beta\, C_{14.7}^{T}\left[\frac{P}{14.7}\right] - C\right)\left(1.02^{(T-20)}\right)$$

- Assume that β is 0.95.
  - This is very reasonable for typical municipal wastewater.
- Need a value for α: ***Use Tabulated data***

Aeration Device	**Typical α**
Coarse Bubble Diffusers	0.85
Fine Bubble Diffusers	0.50
Jet Aeration	0.75
Surface Mechanical Aerators	0.90
Submerged Turbines	0.85

How much Air Need to Supply?

- Can substitute all the values in equation:

$$AOTE = \frac{0.5\times 0.3}{9.17}\left(0.95\times 9.17\left[\frac{14.7}{14.7}\right]-2\right)\left(1.02^{(20-20)}\right)$$

$$= 0.11$$

- This means that 11% of the oxygen supplied by the air will be transferred to liquid phase.

- We know how much oxygen needs to be supplied to liquid phase = 1,000 kg-O_2/day. To calculate amount of air to be supplied to satisfy microbial oxygen demand and to provide a residual DO:

$$AOTE = \frac{AOR}{Q_{Air}\times \rho_{Air}\times f_{O_2,Air}}$$

$$0.11 = \frac{1{,}000}{Q_{Air}\times 1.295\times 0.232}$$

$$Q_{Air} = 30{,}258 m^3_{Air}/day$$