



MEMBRANE BIOREACTORs

Week 8th: MBR Operation

Part I

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CEV4362 MEMBRANE BIOREACTORS

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Week 8th: MBR Operation

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5.1. Operation Parameters (1/18)

5.1. Operation Parameters

MBR systems are biological wastewater treatment processes except membrane unit, which plays the role of solid–liquid separation just like the secondary setting tank in conventional activated sludge (CAS), replaces the secondary setting tank. CAS and MBR systems are similar. So, the operational parameters related to the microbial operation currently used in CAS can be directly applied to MBR operation.

Dissolved oxygen (DO) and nutrient concentrations are important parameters for CAS systems, but these parameters are not recognized as membrane operation parameters. Therefore, important operation parameters with respect to microbial characteristics should be monitored in MBR operation in terms of membrane fouling.

5.1. Operation Parameters (2/18)

5.1.1. HRT (Hydraulic Retention Time)

HRT is a measure of the average length of time that water remains in a storage unit. Average HRT values in CAS for domestic wastewater treatment ranges from 4 to 10 h (hours) depending on the characteristics of the influent wastewater. Longer HRT will be required if industrial wastewaters including recalcitrant molecules or nonbiodegradable substances inflow to the wastewater treatment plant (WWTP) or biological nutrient removal (BNR) processes are employed.

The concentration of microorganisms (MLVSS) in MBR is much greater than that of CAS, so reduced HRT operation can be possible in MBR. Organic removal in MBR is faster and more stable than CAS due to the high concentrations of biomass. If the designed f/m ratio [$F/M = \{S_o/HRT\} \cdot X$] remains constant, the HRT could be reduced because the biomass concentration (X) in MBR is greater than that of the CAS.

5.1. Operation Parameters (3/18)

5.1.2. SRT (Sludge Retention Time)

SRT is a measure of the average length of time that sludge remains in a storage unit. Average SRT values in CAS ranges from 4 to 10 days. However, the perfect retention of microorganisms in MBR by membranes makes the SRT quite longer, typically over 30 days of SRT. Without sludge being withdrawn in membrane tank, the SRT of MBR will be infinite (this is not possible in CAS systems).

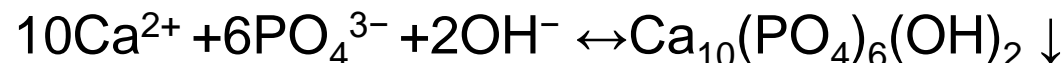
Wastewater treatment engineers want their system to be operated under short HRT and long SRT without loss of system performance. However, it is a difficult goal to achieve in CAS operation due to the imperfect separation capabilities of secondary clarifiers (HRT and SRT are closely coupled). On the other hand, HRT and SRT can be decoupled in MBR operation because the membrane separates the microorganisms perfectly.

5.1. Operation Parameters (4/18)

5.1.2. SRT (Cont.)

The longer SRT operation in MBR produces less excess sludge than CAS. But it makes the microorganisms in the aeration tank old, which means the microbial growing state shifts to endogenous phase. **The older the sludge, the more oxygen it requires.** However, extensive coarse aeration is commonly practiced in membrane tanks for fouling control in MBR, is enough for aeration.

In CAS systems, phosphorus is stored inside the cells and the cells removed with the excess sludge withdrawals. However, the sludge in MBR is not removed at a high rate, **so P removal is limited.** MBR plants employ extra treatment facilities for P removal. For example, **lime ($\text{Ca}(\text{OH})_2$)** can be added to the MBR effluent to precipitate the P out as hydroxylapatite, $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$, as shown in the following equation:



5.1. Operation Parameters (6/18)

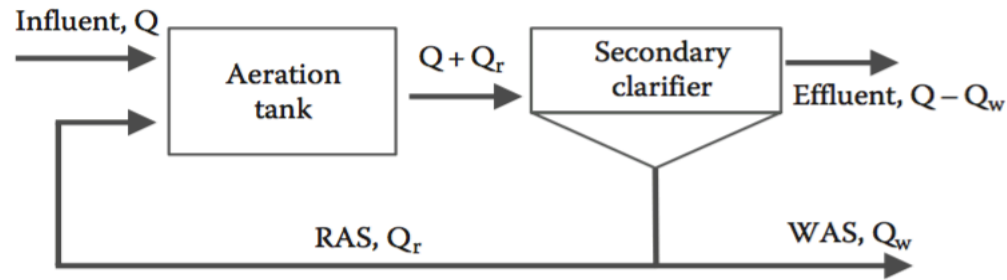
5.1.3. Recirculation Ratio, α

The recirculation ratio, $\alpha = Q_r/Q$, is defined as the ratio of the recirculation flow rate from the secondary clarifier to the bioreactor (Q_r) and the influent flow rate (Q). SRT and α are important parameters to control WWTP performance.

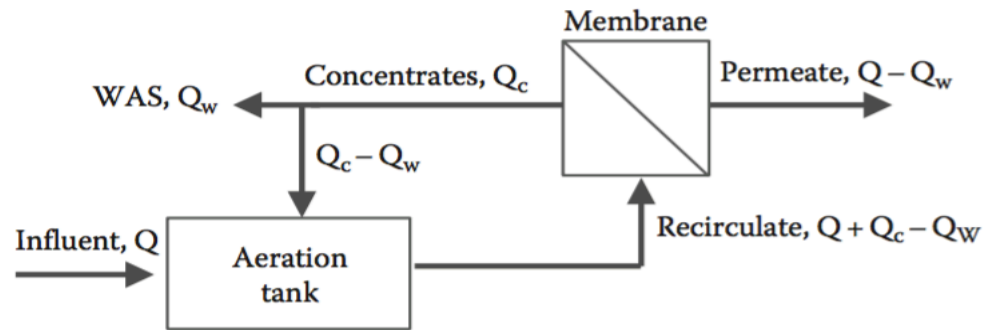
Obviously, there is no concept of α in submerged MBR where sludge return is not necessary. However, there is an analogy of α in sidestream MBR because a membrane unit outside an aeration tank in sidestream MBR plays the exact same role as a secondary clarifier as shown in Figure 5.1.

If there is sludge withdrawal in sidestream MBR (Figure 5.1b), the flow rate of the returning stream to the aeration tank is $Q_c - Q_w$, which corresponds to Q_r of CSA. Thus, the recirculation ratio, α , in a sidestream MBR with the same flow configuration, as shown in Figure 5.1b, is $(Q_c - Q_w)/Q$.

5.1. Operation Parameters (7/18)

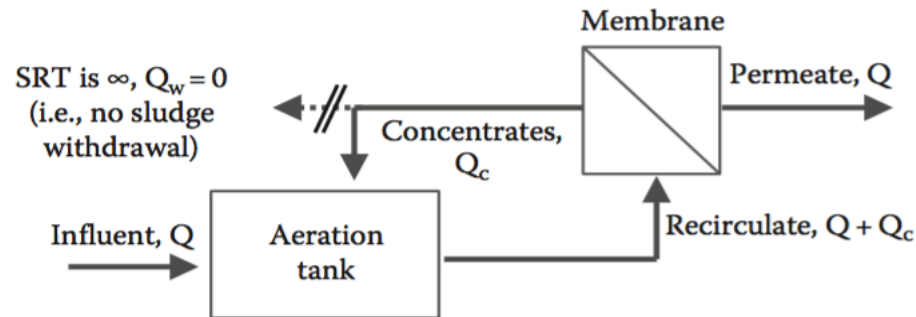


(a)



(b)

$$\alpha = (Q_c - Q_w) / Q \text{ in sidestream MBR}$$



(c)

Figure 5.1. Analysis of flow: (a) CAS, (b) sidestream MBR, and (c) sidestream MBR with infinite SRT (no sludge withdrawal).

5.1. Operation Parameters (9/18)

5.1.4. Temperature

Temperature is not classified as an operational parameter. However, temperature is an important factor determining MBR system performance (affect **microbial metabolism and gas dissolved in water**).

The **low temperature severely deteriorates** the biological system performance. Particularly, the slow-growing nitrogen-oxidizing bacteria and denitrification bacteria are very vulnerable to low temperature, so that nitrogen removal efficiency drops in winter.

Temperature **also related with dissolved gasses in water**, so that the saturated oxygen concentration in water decreases during summer. On the contrary, the mass transfer “rate” of gases to water increases as temperature increases.

5.1. Operation Parameters (10/18)

5.1.4. Temperature (Cont.)

For example, the overall gas transfer rate coefficient ($K_{L,a}$) determining the gas transfer rate follows the van't Hoff–Arrhenius equation, which is used to model the effect of temperature on reaction rate as follows:

$$k_{L,a(T)} = k_{L,a(20)} \times \theta^{T-20}$$

where

$k_{L,a(T)}$ is the overall gas transfer rate coefficient at temperature $T^{\circ}\text{C}$ (s^{-1})

$k_{L,a(20)}$ is the overall gas transfer rate coefficient at 20°C (s^{-1})

θ is the temperature activity coefficient, typically ranged from 1.013 to 1.040

T is the temperature, $^{\circ}\text{C}$

5.1. Operation Parameters (11/18)

5.1.5. Temperature Dependence of Flux

Temperature effect the viscosity of the feed solution, so permeation flux strongly depend on temperature (**3°C temperature change can effect viscosity**). Instead of the common van't Hoff–Arrhenius equation, the flux at temperature T_1 can be converted to the flux at temperature T_2 using the following equation, because the viscosity is reciprocally proportional to the temperature:

$$J_{T1} = J_{T2} \left(\frac{\eta_{T2}}{\eta_{T1}} \right)$$

where

J_{T1} is the ux at temperature T_1

J_{T2} is the ux at temperature T_2

η_{T1} is the viscosity at temperature T_1

η_{T2} is the viscosity at temperature T_2

5.1. Operation Parameters (11/18)

Example 5.1

New membranes arrive and the initial water flux is tested in a laboratory. The initial water flux is measured at 100 LMH. The water temperature is equilibrated with the room temperature of the laboratory, which is maintained at 25°C for the filtration period. The water temperature of the outside MBR plant is 15°C. Estimate the initial water flux at 15°C.

Solution

Temperature and the flux are reciprocally proportional to each other. Using the viscosity presented in Table 5.1, calculate the water flux at 15°C:

$$J_{T1} = J_{T2} \left(\frac{\eta_{T2}}{\eta_{T1}} \right)$$

$$J_{15} = J_{25} \cdot \frac{\eta_{25}}{\eta_{15}}$$

$$J_{15} = 100 \text{ LMH} \cdot \frac{0.8949 \text{ mPa} \cdot \text{s}}{1.1447 \text{ mPa} \cdot \text{s}} = 78.2 \text{ LMH}$$

The initial water flux at 15°C is calculated to be 78.2 LMH.

5.1. Operation Parameters (12/18)

5.1.6. TMP and Critical Flux

Transmembrane pressure (TMP) is the most important parameter for operation of a submerged MBR under constant flux mode. Only after TMP monitoring can operators make an appropriate diagnosis for a TMP jump or other kinds of abnormal TMP behaviors and can take immediate and proper action for the ongoing fouling phenomena.

Flux and TMP are linearly dependent of each other in water filtration (i.e., no fouling conditions). This is called the **pressure controlled region**. In filtration of activated sludge suspension, flux increases along with TMP within a certain range of TMP; thereafter, the rate of flux increase drops. This is due to the fouling on the membranes, where the flux is mainly controlled by the mass transfer of foulants (solutes) toward the membranes. This is called the **mass transfer controlled region** (or the TMP independent region).

The relationship between flux and TMP during the filtration of activated sludge suspension, and factors affecting the mass transfer of foulants in bulk solution to the membranes are shown in Figure 5.2.

5.1. Operation Parameters (13/18)

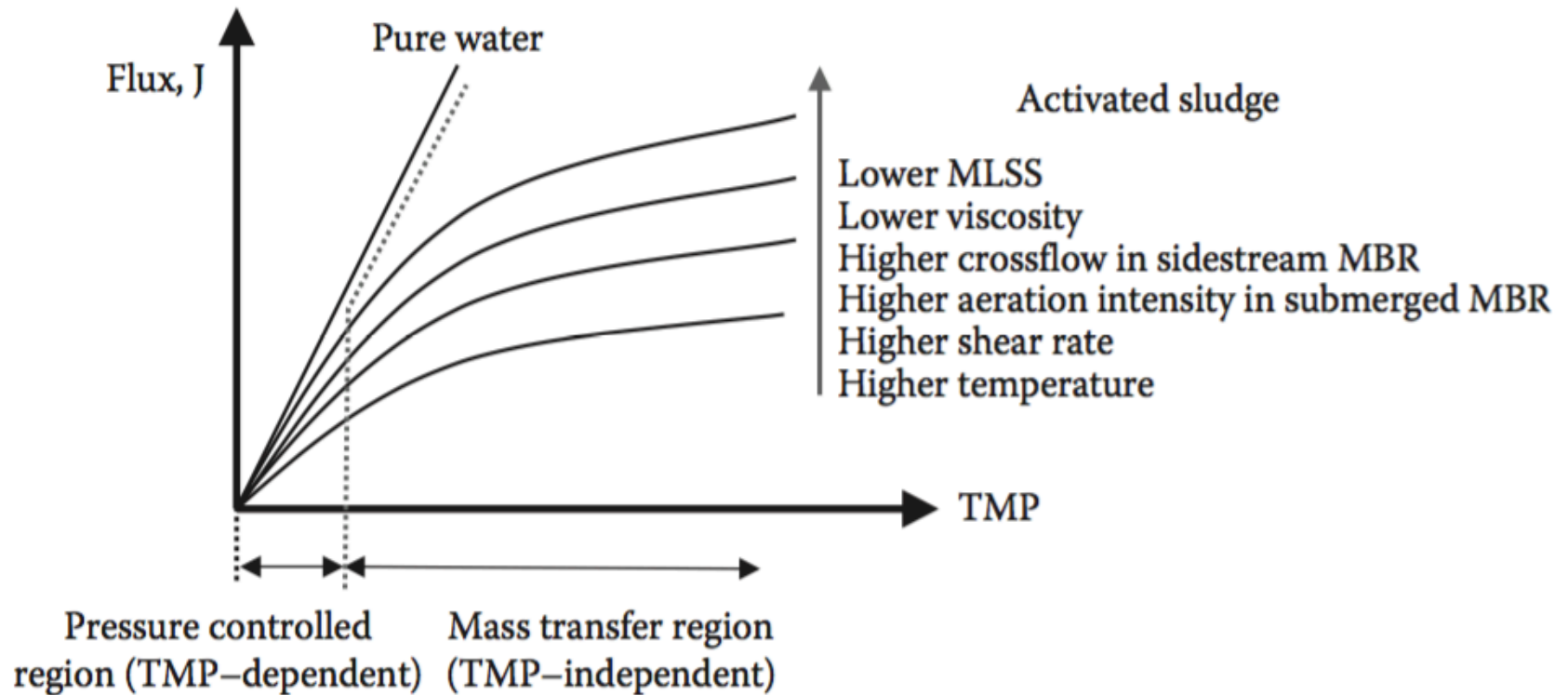


Figure 5.2. Relationship of TMP and flux: the pressure controlled region and the mass transfer controlled region.

5.2. Aeration for Biotreatment and Membrane Aeration (1/15)

5.2. Aeration for Biotreatment and Membrane Aeration

Aeration serves a number of useful purposes in WWTP. For example;

- odor control (such as H_2S removal)
- aeration to aerobic microorganisms
- dissolved air flotation (DAF)
- aerated grit chamber
- removal of volatile organic compounds (VOC), etc.

In MBR plants, aeration might be the most important unit operation, supplying **the oxygen to microorganisms** for their metabolism as well as to the **membrane surface for fouling control**. **Fine bubbles with** extended surface areas are beneficial for effective oxygen transfer to cells whereas **coarse aeration with large-sized bubbles** is adequate for effectively vibrating and scouring the membrane bundles.

5.2. Aeration for Biotreatment and Membrane Aeration (2/15)

5.2.1. Fine Bubble Aeration

Because the extended surface area of fine bubbles is favorable to accelerate the mass transfer of oxygen, fine bubble aeration is practiced in WWTP. Although there are many types of aerators, compressed air supply through diffusers underneath the water surface is the most widely used for aeration tanks in MBR, because of fouling control.

Delivered air is first dissolved in the wastewater by diffusion or mechanical aeration. Then the DO is taken up by the microorganisms. Although the oxygen demand depends on the amounts of organics and ammonia present in the wastewater, at least 1 mg/L of oxygen should be maintained in the aeration basin, typically 2–3 mg/L.

5.2. Aeration for Biotreatment and Membrane Aeration (3/15)

5.2.1. Fine Bubble Aeration (Cont.)

Oxygen consumption by the microorganisms should be considered important in determining oxygen transfer rate in the aeration tank. The rate of oxygen transfer is as follows:

$$\frac{dC}{dt} = k_{L,a} (C_s - C) - r_m$$

where

C is the oxygen concentration in wastewater (mg/L)

C_s is the saturated oxygen concentration given by Henry's law (mg/L)

$k_{L,a}$ is the overall oxygen transfer coefficient (s^{-1})

r_m is the rate of oxygen consumed by microorganisms (mg/L s)

5.2. Aeration for Biotreatment and Membrane Aeration (4/15)

5.2.1. Fine Bubble Aeration (Cont.)

If the oxygen concentration is maintained at a constant level (i.e., steady-state condition, $dC/dt=0$), this equation is simplified as follows:

$$r_m = k_{L,a}(C_s - C)$$

In this case, C_s is constant and not variable with time, so that r_m can be obtained by the determination of $K_{L,a}$. The overall oxygen transfer coefficient, $K_{L,a}$, can be obtained by simple experiments as the following example demonstrates.

5.2. Aeration for Biotreatment and Membrane Aeration (4/15)

Example 5.2

An aeration system has been monitored to determine $K_{L,a}$. The monitored data for dissolved oxygen versus time is shown in the following table. Assume that the saturation dissolved oxygen concentration (C_s) is 9.0 mg/L at this temperature. Use the data to determine $K_{L,a}$.

<i>Time (min)</i>	<i>C_t (mg/L)</i>
0	1.20
4	2.68
8	3.92
12	4.89
16	5.71
20	6.35
24	6.88
28	7.32
32	7.66
36	7.93
40	8.14
44	8.31
48	8.45
52	8.56
56	8.65
60	8.72

5.2. Aeration for Biotreatment and Membrane Aeration (4/15)

Solution

The oxygen transfer rate in clean water without oxygen consumption by microorganisms is expressed as follows:

$$\frac{dC}{dt} = k_{L,a}(C_s - C) \quad (\text{E2.1})$$

Separating the variable and integrating the previous equation yields

$$\int_{C_0}^{C_t} \frac{1}{C_s - C} dC = \int_0^t k_{L,a} dt \quad (\text{E2.2})$$

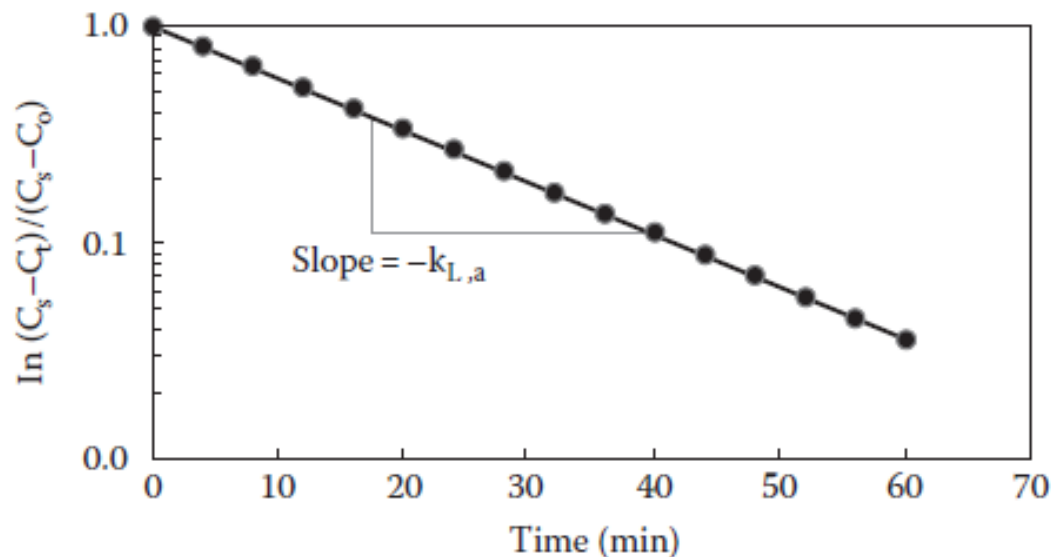
5.2. Aeration for Biotreatment and Membrane Aeration (4/15)

$$\frac{C_s - C_t}{C_s - C_0} = e^{-k_{L,a} \cdot t} \quad (E2.3)$$

$$\ln \left(\frac{C_s - C_t}{C_s - C_0} \right) = -k_{L,a} \cdot t \quad (E2.4)$$

C_0 is the initial concentration, which is 1.2 mg/L (time at zero), and C_t is the concentration at time t . The results of the calculations are shown in the spreadsheet table as follows.

A plot of $\ln (C_s - C_t) / (C_s - C_0)$ versus t is shown in the figure. The slope, which is equal to $K_{L,a}$, is calculated to be 0.055 per min or 3.3 per h.



5.2. Aeration for Biotreatment and Membrane Aeration (5/15)

5.2.2. Oxygen Transfer

The oxygen transfer coefficient, $K_{L,a}$, depends on;

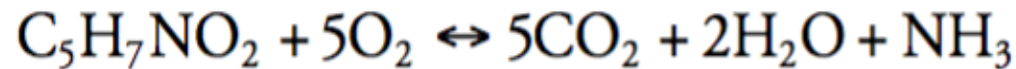
- mixing intensity
- geometry of the aeration basin
- temperature, altitude (\propto atmospheric pressure)
- surface tension
- characteristics of the wastewater

All factors affecting the coefficient ($K_{L,a}$) **except temperature** are difficult to generalize and express mathematically on a theoretical basis. Instead, correction factors that can be obtained experimentally are used. The actual amount of oxygen required in plants should be calculated with the corrected equation, which will be discussed further in Chapter 6.4.

5.2. Aeration for Biotreatment and Membrane Aeration (6/15)

5.2.3. Oxygen Demand

Since MBR is basically a biological processes, the oxygen demand should account for the biological oxygen demand (BOD) and ammonia demand. The oxygen demand in CAS is determined by the difference between the influent and effluent BOD, that is, $(BOD_i - BOD_e)$. The wasted sludge should be subtracted from the total oxygen demand because the cells consuming oxygen are wasted as excess sludge. The representative chemical formula of cell is $C_5H_7NO_2$, so that the cell oxidation can be described as the following reaction:



Since 5 mol of oxygen per 1 mol cell are required, 1.42 $(=5 \times 32/113)$ g of oxygen is required for oxidation of 1 g of sludge cell.

5.2. Aeration for Biotreatment and Membrane Aeration (7/15)

5.2.3. Oxygen Demand (Cont.)

Therefore, oxygen demand for carbonaceous biodegradation is

$$\text{O}_2 \text{ demand (kg O}_2 \text{/day)} = Q (\text{BOD}_i - \text{BOD}_e) - 1.42 (P_s)$$

where

O_2 demand is the carbonaceous oxygen demand (kg/day)

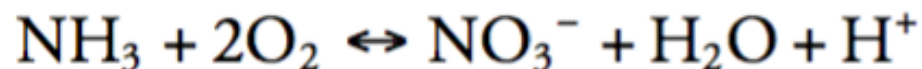
Q is the wastewater flow rate to the aeration basin (kg/day)

BOD_i is the influent BOD to aeration basin (mg/L)

BOD_e is the effluent BOD from the secondary clarifier (mg/L)

P_s is the rate of sludge waste (kg/day)

During the course of full nitrification, ammonia (NH_3) converts to nitrate (NO_3^-) consuming 2 mol of oxygen by nitrifying bacteria, as shown in the following:



5.2. Aeration for Biotreatment and Membrane Aeration (8/15)

5.2.3. Oxygen Demand (Cont.)

The oxygen demand corresponding to full nitrification is calculated to be 4.6 mg/L (=2 mol O₂/1 mol of nitrogen=2×32 g O₂/14 g-N). Therefore, the total oxygen demand for a biological process is as follows:

$$\text{O}_2 \text{ demand, kg O}_2/\text{day} = Q(\text{BOD}_i - \text{BOD}_e) - 1.42(P_s) + 4.6 \cdot Q \cdot (\text{NO}_x)$$

where NO_x is the total nitrogen concentration in influent (mg/L).

Sludge production (P_s) in MBR is significantly lower than CAS because MBR operates at long SRT. Therefore, the oxygen demand for MBR must be greater than that of the CAS. If the SRT of MBR is infinite, the oxygen demand in Equation 5.14 could be simplified as

$$\begin{aligned} \text{O}_2 \text{ demand in MBR with infinite SRT, kg O}_2/\text{day} \\ = Q(\text{BOD}_i - \text{BOD}_e) + 4.6 \cdot Q \cdot (\text{NO}_x) \end{aligned}$$

5.2. Aeration for Biotreatment and Membrane Aeration (9/15)

5.2.4. Coarse Aeration

Membrane aeration is primarily responsible for maintaining membrane permeability. The dual purposes of coarse aeration in membrane tanks are;

- ❖ vibrate the fiber bundles to prevent sludge clogging inside the module and
- ❖ scour the membrane surfaces to prevent deposition of sludge on the membranes

To achieve both effectively, intensive and big-sized air bubbles are needed. Orifices or nozzles are adequate for generating coarse bubbles instead of porous materials for fine bubbling.

5.2. Aeration for Biotreatment and Membrane Aeration (10/15)

5.2.4. Coarse Aeration (Cont.)

Shear intensity (often called the shear rate and denoted as σ), G (s^{-1}), induced by aeration is given by the following equation:

$$G = \sqrt{\frac{\rho \cdot g \cdot U_a}{\mu_s}}$$

where

ρ is the sludge density (kg/m^3)

g is the gravitational acceleration (m/s^2)

U_a is the aeration intensity ($L/m^2 s$)

μ_s is the viscosity of the sludge suspension ($kg/m s$, $Pa s$ or $N s/m^2$)

5.2. Aeration for Biotreatment and Membrane Aeration (11/15)

5.2.5. Aeration Demand and Energy

One of the important issues in MBR is the energy costs caused by **aeration** (membrane aeration usually counts for 30%–50% of the whole plant power consumption). Specific aeration demand (SAD) is a popularly accepted criteria for comparing aeration requirements in MBR. Two types of SAD (SAD_m and SAD_p) are used to express the aeration demands.

- SAD_m is the aeration demand based on membrane area, Nm^3 of air/(h m^2),
- SAD_p is the aeration demand based on permeate volume, Nm^3 of air/(m^3 of permeate)

Flux (J) has the unit of m^3 of permeate/(h m^2), the mutual relationship of both demands is as follows:

$$SAD_p = \frac{SAD_m}{J}$$

5.2. Aeration for Biotreatment and Membrane Aeration (12/15)

5.2.5. Aeration Demand and Energy (Cont.)

In most submerged MBR plants, SAD_p exceeds 10 and can be as high as 50 at some sites. Some plants even show over 90. This is because the SAD_p strongly depends on module configuration and packing density and frequency of chemical cleanings. The blower power consumed by aeration in submerged MBR is calculated as follows:

$$P_{\text{blower}} = \frac{p_a \times Q_{\text{air}}}{\eta}$$

where

P_{blower} is the power of blower (Watt = N m/s)

p_a is the air pressure (N/m²)

Q_{air} is the air flow rate (m³/h)

η is the efficiency of blower and pump (unitless)

5.2. Aeration for Biotreatment and Membrane Aeration (13/15)

5.2.5. Aeration Demand and Energy (Cont.)

The blower power can be rewritten as follows:

$$P_{\text{blower}} = \frac{p_a \cdot Q_{\text{air}}}{\eta} = \frac{(\delta p + \rho \cdot g \cdot h) \cdot Q_{\text{air}}}{\eta}$$

where

ρ is the water density (kg/m^3)

g is the gravity acceleration (m/s^2)

δp the pressure loss at the outlet of the blowers and diffusers

h the underwater pressure at depth (m)

Therefore, the energy required for aeration can be calculated as follows:

$$\text{Energy required for aeration (kW h or 3600 kJ)} = P_{\text{blower}} (\text{kW}) \times \text{operating time (h)}$$

5.2. Aeration for Biotreatment and Membrane Aeration (14/15)

5.2.5. Aeration Demand and Energy (Cont.)

Instead, specific energy consumptions of whole WWTPs employing MBR have been reported to be between **0.5 and 8 kWh/m³**, quite a broad span, depending on the influent characteristics and plant capacities. Although there have been many efforts to reduce the specific energy consumption by upgrading aeration modules and introducing cyclic aeration, MBR's energy consumption is still quite high compared to the specific energy consumption of CAS, which typically ranges from **0.2 to 0.4 kWh/m³**.

5.2. Aeration for Biotreatment and Membrane Aeration (15/15)

5.2.6. Packing Density

The packing density is defined by the membranes surface area per unit cross-section area of module header (m^2/m^2) or by the membrane surface area per module volume (m^2/m^3). It is important for systems with coarse aeration in membrane tanks. High membrane module packing densities reduce the footprint of membrane tanks but also lead to unfavorable hydrodynamic air conditions, requiring extensive aeration to put the air through the membrane bundles. Consequences of overpacked modules are increased fouling and sludge clogging within the module.

The average packing densities of commercial submerged hollow fiber and plate and frame membrane modules are 141 and 77 m^2/m^3 , respectively. But the standard deviation of the survey was relatively high, 41%–48%, indicating that diverse types of commercial modules compete in the market with unique configurations and packing densities.



Thank you...