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MEMBRANE BIOREACTORs

Week 4th: Membranes, Modules, and Cassettes

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CEV4362 MEMBRANE BIOREACTORS

2018-2019 Spring Semester

Time and Room: Wednesday 11:00 - 11:50 FZ-82

12:00 - 12:50 FZ-82

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Week 4th: Membranes, Modules, and Cassettes

3.5. Membrane Performance

- Permeability
- Rejection
- Compaction
- Fouling Property

3.6. Membrane Modules

- Chemistry
- Morphologies
- Membrane Effective Area
- Packing Density
- Operation Types

3.7. Membrane Cassettes

- Components and Materials
- Setup and Maintenance
- Membrane Effective Area and Packing Density
- Aeration

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3.5. Membrane Performance

There are two main performance criteria for membranes;

- ✓ Permeated performance (How much clean water is permeated)
- ✓ Contaminants rejection efficiency

Permeate performance is interested in permeability. Permeability is affected negatively from **“hydraulic pressure of permeation”** and **“Fouling of the membrane”**, during operation.

3.5.1. Permeability

The definition of permeability is as follows:

$$L_p = \frac{J}{\Delta P}$$

where

L_p is the water permeability of the membrane, LMH/bar
J is the water flux of the membrane, LMH, L/m^2 h
ΔP is the transmembrane pressure (TMP), bar

3.5. Membrane Performance (2/9)

TMP is calculated from pressures measured during membrane operation (In Figure 3.26).

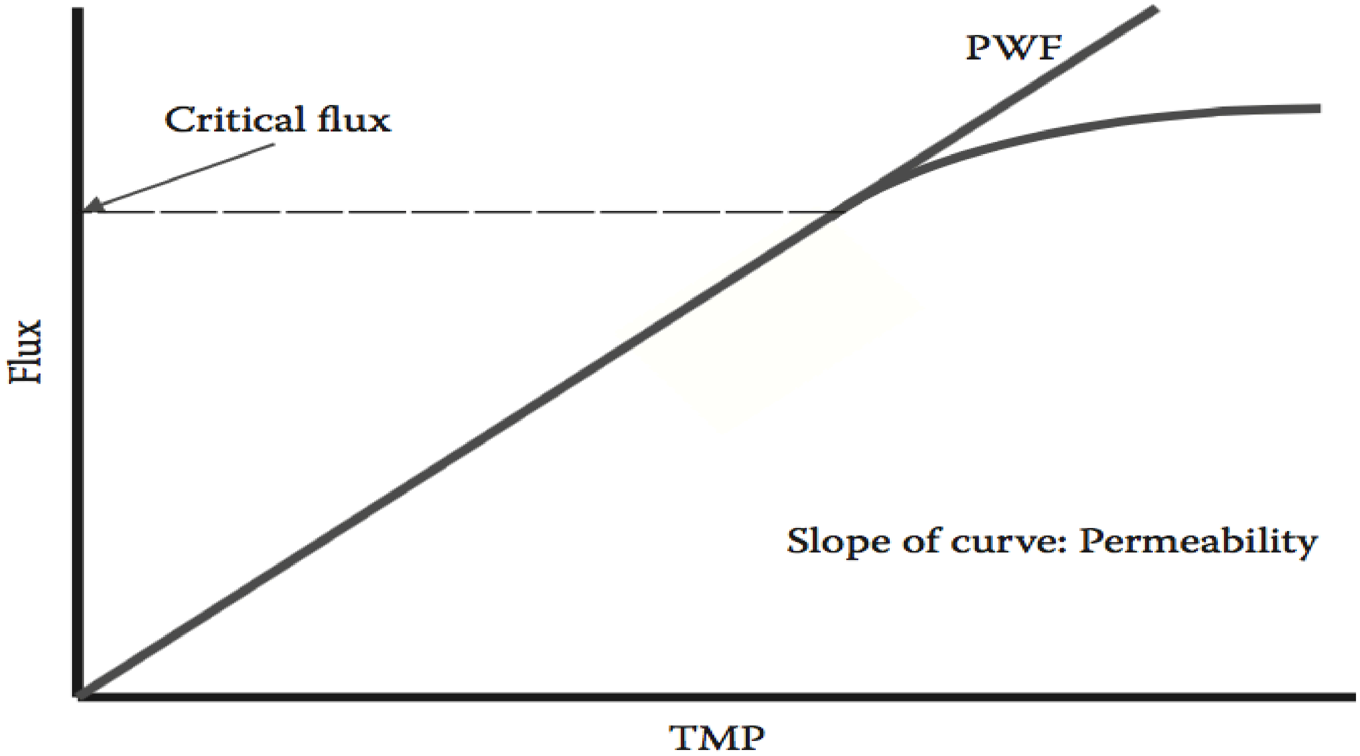

Figure 3.26. Flux versus ΔP at constant temperature

3.5. Membrane Performance (3/9)

TMP is defined using the following equation:

$$TMP = \Delta P = P_{perm} - P_{source\text{-}water\text{-}side} = P_{perm} - \frac{(P_{in} + P_{conc})}{2}$$

where

P_{perm} is the pressure measured at the permeate water side of the membrane

$P_{source\text{-}water\text{-}side}$ is the pressure measured at the source water side of the membrane

P_{in} is the pressure measured at the inlet of the source water

P_{conc} is the pressure measured at the concentrate water

3.5. Membrane Performance (4/9)

3.5.2. Rejection

The main target of MF and UF membranes are colloidal solids and microbial flocs. Colloidal solids are frequently turbidity (NTU) or suspended solids (SSs, mg/L). The permeate water quality from the MBR process (<0.2 NTU) is 5–10 times better than that of the conventional type (1–10 NTU).

Sometimes conventional plants suffer from sludge bulking resulting in discharging reduced water quality, but MBR plants guarantee permeate water qualities such as turbidity and SSs under any trouble conditions.

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3.5.3. Compaction

Commercial membranes are supplied after full compaction to guarantee constant permeation performance. Nevertheless when the membrane meets a higher hydraulic pressure or a membrane deteriorates after long operation times, further compaction occurs (Figure 3.27).

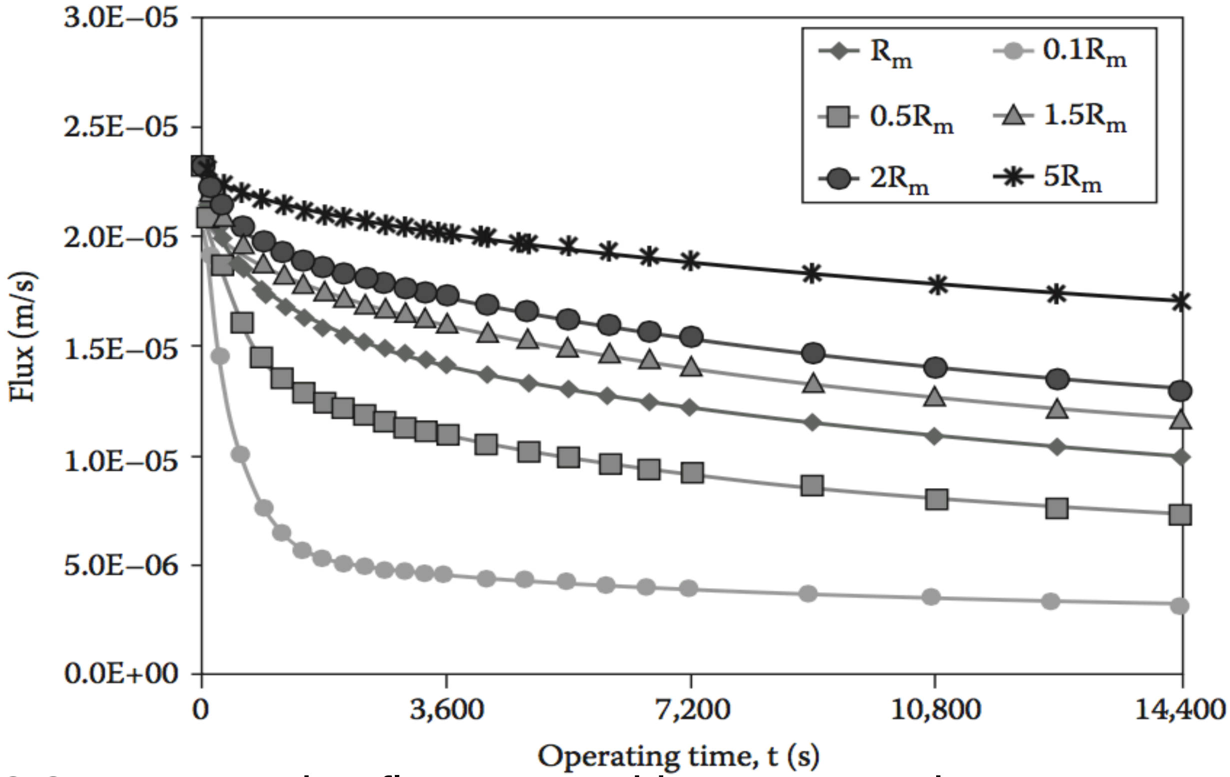

Figure 3.27. Permeation flux curve with respect to time at constant TMP

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3.5.4. Fouling Property

When a membrane is fouled, permeate flux reduce at the same temperature and TMP. To recover the shortage, TMP should be increased. All membranes have their own TMP limitation for sustainable operation, and their TMP limit stimulates **irreversible fouling**, which is not easily cleaned by normal processes. Most irreversible fouling can be removed by high concentrations of chemicals with intense physical flushing. Some irreversible fouling, which is called **irrecoverable fouling**, cannot be removed. Moreover, frequent chemical recovery cleaning reduces the life span of membranes.

Fouling is the most important parameter for membrane processes, and it is tightly dependent on;

- the source water quality
- the membrane operation process

There are two criteria that can express fouling intensity;

- ✓ Permeate flux
- ✓ Fouling resistance

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3.5.4. Fouling Property (Cont.)

Fouling resistance is calculated from the permeate flux and TMP using the equation derived in the **resistance-in-series (RIS)** model:

$$J = \frac{\Delta P}{\eta \times R}$$

where

J is the permeation flux, LMH
ΔP is the TMP, bar
η is the viscosity of water, bar s
R is the resistance, m^{-1}

Resistance is directly related to the fouling intensity. Using the RIS model, fouling can be understood in more detail. Unlike flux, resistance is the sum of several numbers in series independently.

3.5. Membrane Performance (8/9)

3.5.4. Fouling Property (Cont.)

The relation among the resistances is as follows:

$$R_t = R_m + R_r + R_{ir}$$

where
R_t is the total fouling resistance
R_m is the membrane resistance
R_r is the reversible fouling resistance
R_{ir} is the irreversible resistance

Sometimes R_r is represented as R_c, cake layer resistance, and R_{ir} can be represented as R_p or R_b, resistance by pore plugging or resistance by pore blocking.

$R_r + R_{ir}$, $R_c + R_p$ or $R_t - R_m$ is sometimes called Rf, membrane fouling resistance (Figure 3.28).

3.5. Membrane Performance (9/9)

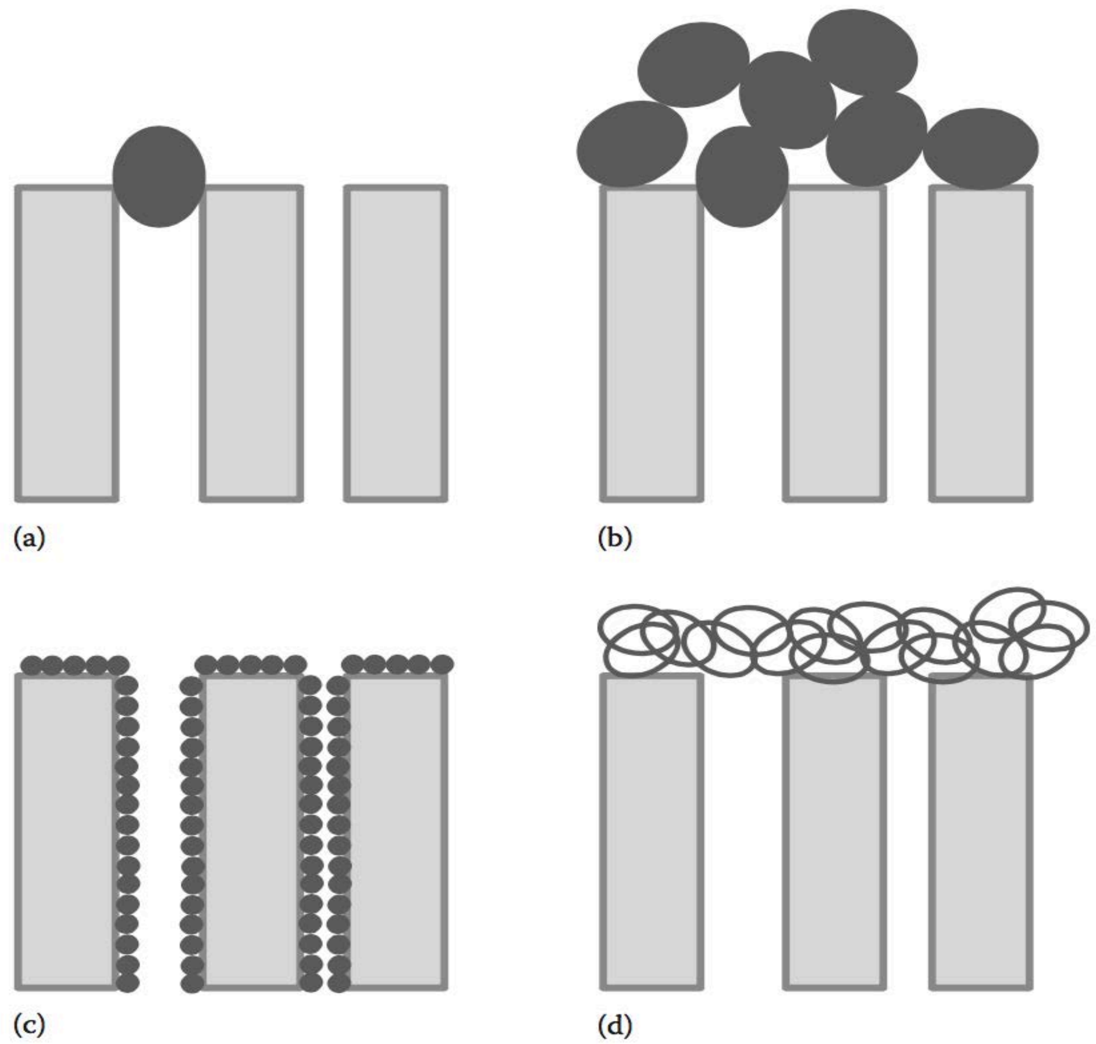

Figure 3.26. Hermia's membrane fouling mechanism: (a) complete blocking, (b) internal pore blocking, (c) intermediate blocking, and (d) cake formation.

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Example 3.21

When a fresh membrane is filtering (a) initially deionized water at 420 LMH and then (b) surface water in turn to produce drinking water at 60.0 LMH of permeate water flux, calculate (a) the membrane resistance and (b) fouling resistance of the surface water.

Assume viscosities of all kinds of waters have the same value and all operations are conducted at a constant temperature (20.0°C) and TMP is 1.00 bar.

3.5. Membrane Performance

Solution

(a) The membrane is not contaminated and the source water is deionized. So the total resistance only consists of the membrane resistance:

$$R_m = \frac{\Delta P}{\eta \times J} = \frac{1.00 \text{ bar}}{(1.002 \times 10^{-7} \text{ bar s})(420 \text{ LMH})(1 \text{ h}/3600 \text{ s})(1 \text{ m/h}/1000 \text{ LMH})}$$

$$= \frac{1}{0.000117 \times 10^{-7} \text{ m}} = 8.55 \times 10^{10} \text{ m}^{-1}$$

(b) The source water is not clean and so the permeate water flux will be lower than that of clean water. So we will use the total fouling resistance (R_t) at first:

$$R_t = \frac{\Delta P}{\eta \times J} = \frac{1.00 \text{ bar}}{(1.002 \times 10^{-7} \text{ bar s})(60.0 \text{ LMH})(1 \text{ h}/3600 \text{ s})(1 \text{ m/h}/1000 \text{ LMH})}$$

$$= \frac{1}{0.0000167 \times 10^{-7} \text{ m}} = 5.99 \times 10^{11} \text{ m}^{-1}$$

Because $R_t = R_m + R_f$, we can acquire R_f from R_m and R_t, which we already calculated:

$$R_f = R_t - R_m = 5.99 \times 10^{11} \text{ m}^{-1} - 8.55 \times 10^{10} \text{ m}^{-1} = 5.14 \times 10^{11} \text{ m}^{-1}$$

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3.6. Membrane Modules

When fabricating modules with membranes, there are several important parameters to consider:

- To minimize the loss of essential performance properties resulting from scaling up from single membrane operation to module operation.
- The membranes need to maintain integrity during long periods of operation.
- To optimize module performance, the membrane packing density must be considered.

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3.6.1. Chemistry

The main parts of modules are made of robust plastics such as polyvinylchloride (PVC), acrylonitrile–butadiene–styrene (ABS) copolymer, and polycarbonate (PC). They compose frameworks, permeation water channels, and connectors.

ABS is the cheapest material and easiest to mold into diverse shapes, but the mechanical and chemical durability is less than the other options. Potting resin (similar to glue) is another important part of membrane housing.

- ✓ For flat sheet membrane modules, potting resin acts as a glue to seal the two sheets together.
- ✓ For hollow fiber membrane modules, potting resin glues the ends of the fibers to the module to seal fibers.

Potting is a separation process to divide space between the inlet and permeate sides. Potting resin needs to be not only mechanically robust and chemically durable but also a strong adhesive between the membrane and module material.

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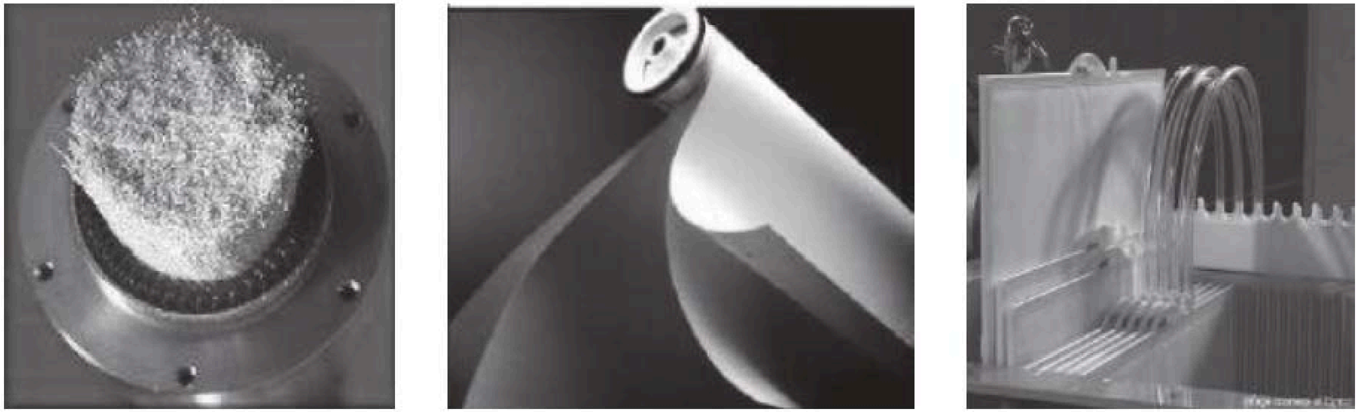
3.6.2. Morphologies

There are two types of morphologies of membrane modules:

- Cylindrical
- Rectangular

Cylindrical modules composed of flat sheet membranes are spiral wound modules. The advantage of cylindrical modules is tighter potting because of uniform distribution and easy connection to pipes. However, rectangular modules have higher packing density and are easier to expand to form larger cassettes (Figure 3.29).



(a) (b) (c)

Figure 3.29. (a) Cylindrical module of hollow fiber membrane,
(b) cylindrical (spiral wound) module of flat sheet membrane,
and (c) rectangular module of flat sheet membrane.

3.6. Membrane Modules (4/9)

3.6.3. Membrane Effective Area

We can then calculate the total membrane effective area of a membrane module as follows:

$$A = 2\pi \times r \times L \times N \text{ (hollow fiber or cylindrical type)}$$

$$A = W \times L \times N \text{ (flat-sheet type)}$$

where
A is the effective membrane surface area, m^2
r is the radius of the cross-sectional circle of the membrane, m
L is the length of the membrane, m
W is the width of the membrane, m
N is the number of membranes in the module, unitless

In general, membrane effective area of commercial membrane modules for MBR have;

- 5–100 m^2/module for hollow fiber membranes
- 0.4–1 m^2/module for flat sheet membranes

3.6. Membrane Modules

Example 3.22

Calculate the effective area of the two types of membrane modules:

(a) *Hollow fiber membrane module*: Inner diameter is 0.80 mm, outer diameter is 1.20 mm, and membrane length is 50 cm. The total number of membrane fibers is 3600. The membrane is operated with an out-to-in flow (the active layer is on the outer side of the membrane).

(b) *Flat sheet membrane*: Width is 0.50 m, length is 1.0 m, and thickness is 0.70 mm. Both sides can act as a membrane. The total number of membrane sheets is 100.

Solution

(a) For the hollow fiber membrane modules, the effective membrane area of each module (A) is as follows:

$$A = 2\pi \times r \times L \times N$$

where $r = 0.6$ mm, $L = 50$ cm, $N = 3600$.

Therefore, $A = (2\pi) \times (0.6 \times 10^{-3}\text{ m}) \times (50 \times 10^{-1}\text{ m}) \times (3600) = 6.8\text{ m}^2$.

(b) For flat sheet membrane modules, the effective membrane area of each modules (A) is as follows:

$$A = W \times L \times N \times 2$$

where $W = 0.50$ m, $L = 1.0$ m, $N = 100$. The multiple 2 is present because both sides of the membrane are used as active layers.

Therefore, $A = (0.50\text{ m}) \times (1.0\text{ m}) \times (100) \times (2) = 1.0 \times 10^2\text{ m}^2$.

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3.6.4. Packing Density

There are two types of parameters that represent the packing density of modules:

- Footprint
- The space a module occupies

The most ideal term that can express the exact packing density of a module is based on space, but in MBR the reactor is high enough to accommodate modules or cassettes, so the packing density based on footprint is more practical.

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3.6.5. Operation Types

The driving force separating liquids and particles via membranes is usually hydraulic pressure.

There are two operation types (Figure 3.30):

- **Pressurized modules:** Since permeate water is held at atmospheric pressure (if we can provide hydraulic pressure to the source water) a pressure differential will develop between the two sides, and flow from the source water side to the permeate water side will occur.

- **Submerged membrane modules:** A pump creates a slight vacuum on the permeate side, which induces the pressure difference also causing water to flow.

3.6. Membrane Modules (7/9)

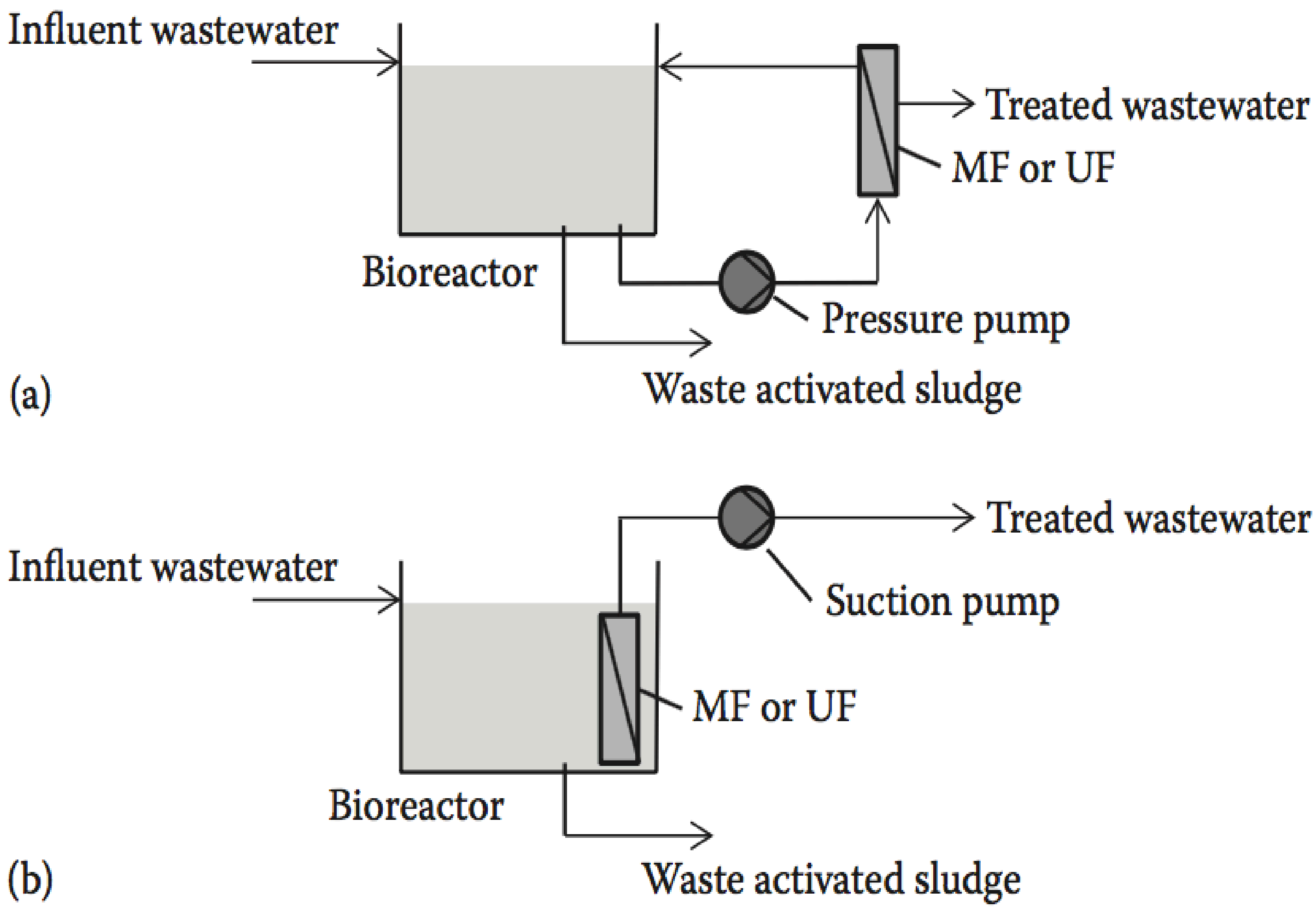

Figure 3.30. Membrane process schemes of (a) pressurized and (b) submerged membrane modules.

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3.6.5.1. Submerged Type

In MBR systems the modules are located in the bioreactor or in a separated membrane tank right after the bioreactor.

Submerged setups can reduce the footprint and the need for an extra source water tank. This setup is easy to maintain and experiences less fouling because of extra aeration provided from aerators installed below the modules.

The energy of the suction pump producing permeated water is lower than that of a pressurizing pump at the same permeability given constant temperature.

The only disadvantage of submerged membrane modules is a narrow permeate flux range.

3.6. Membrane Modules (9/9)

3.6.5.2. Pressurized Type

Most pressurized membrane modules are cylindrical and can have either flat sheet– or hollow fiber–type membranes.

Pressurized modules have to endure higher hydraulic pressure and accommodate thousands of membrane fibers to satisfy larger effective membrane areas, and the cylindrical shape is the most adequate. Flat sheet membranes are wound tightly with spaces of proper thickness to secure source and permeate water channels inside. Finally, they are fabricated into spiral wound membrane modules and have a cylindrical shape.

The biggest advantage of pressurized membrane modules is higher permeate water flux rates. But, pressurized membranes cannot be scrubbed by aeration during permeation, so they tend to foul more quickly. This problem can solve higher cross flow, but higher cross flow consumes high energy (overdesigned cross flow pumps flow capacity is 5-15 times higher than the permeate flow).

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3.7. Membrane Cassettes

Because of scale-up and greater automation of the membrane module manufacturing processes, the price of membranes dramatically decreased over the last few decades from about 500 to 50 USD/m^2.

There should be a limitation on membranes and modules size, because of:

- To optimize the efficiency of manufacturing membranes and modules
- To save membrane footprints
- To encourage lots of automatic/manual valves and pipes including related components

But the market needs bigger cassettes coinciding with the trend of expanding the application of membrane plants to larger water and wastewater treatment plants (WTPs and WWTPs).

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3.7.1. Components and Materials

In case of submerged types, membrane cassettes consist of a mainframe, connectors to permeation pipe, aeration pipe, and, in the case of pressurized types, source water and concentrate pipe and aerators.

The major purposes of developing membrane cassettes are;

- to enlarge the effective membrane area
- to maintain operation during maintenance of a single membrane or module
- to promote robustness over long periods of operation.

In submerged membrane systems, aeration is one of the most important processes. So, we must optimize the hole size and its configuration for best performance and energy use. Major parameters for the optimization of the hole size are the space between holes, the angles of holes on the aerators, and the space between the holes and membranes (Figures 3.32 and 3.33).

3.7. Membrane Cassettes (3/10)

Figure 3.32. Schematic of the submerged membrane cassettes and the aerators.

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3.7. Membrane Cassettes (4/10)

Figure 3.33. Schematic of the pressurized membrane cassettes and the aerators.

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3.7.2. Setup and Maintenance

The setup of membrane cassettes is conducted on-site. This is because membrane cassettes are too big to deliver and handle from the manufacturing factory to the site.

After all parts are delivered, the mainframes are assembled, then the membrane modules are set up onto the mainframes, and finally the other parts are connected. Figures 3.34 and 3.35 show the pictures of assembled membrane cassettes.

A membrane module has hundreds to thousands of membranes, and there are dozens to hundreds of membrane modules in membrane cassettes.

If there are broken membranes in a membrane cassette, operators should find the exact module and then membrane and replace the module from the cassette with a new one and then fix the membrane while keeping membrane operation going. The recovery cleaning cycle is 3–6 months a year (for 10,000 m^3/day WWTP)

3.7. Membrane Cassettes (6/10)

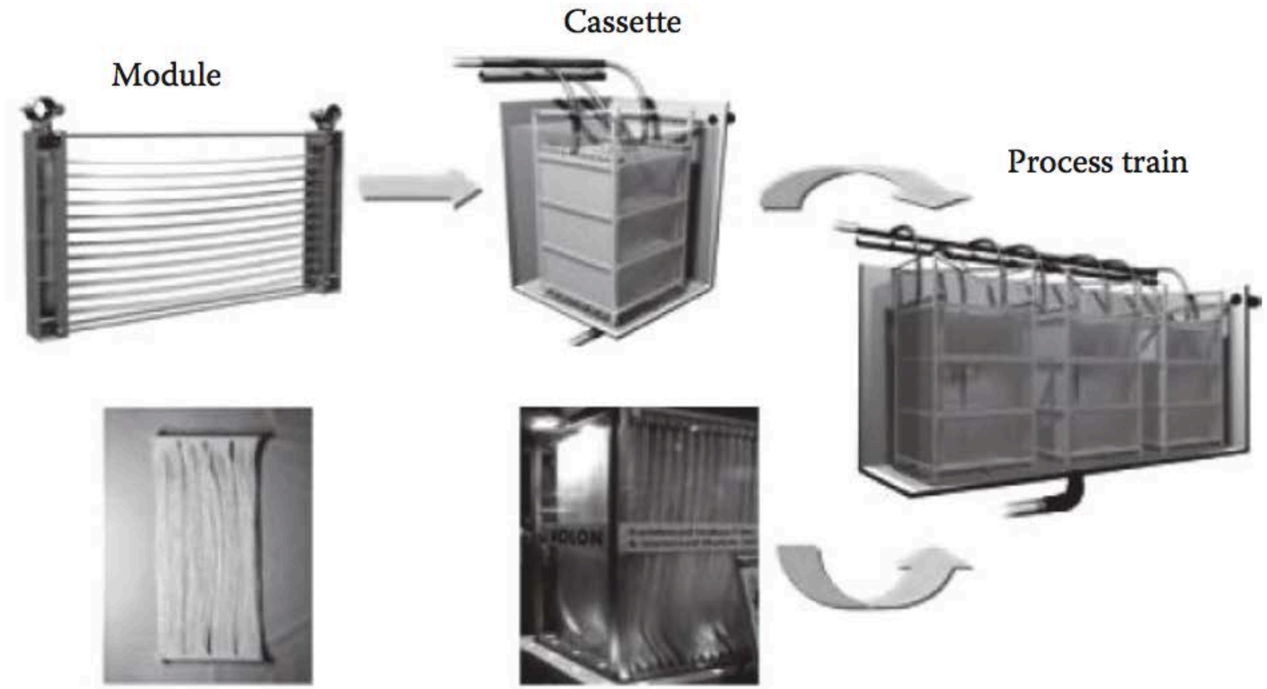

Figure 3.34. Installation of submerged membrane cassette.

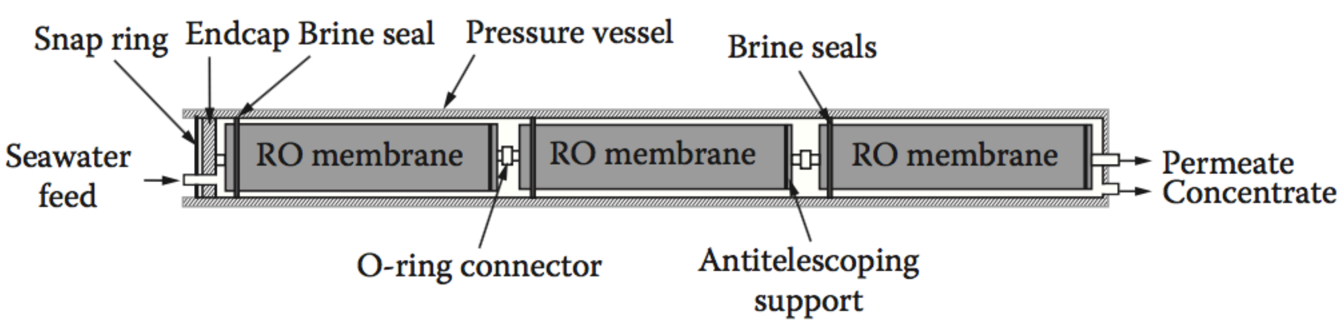

Figure 3.35. Installation of pressurized membrane modules (RO).

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3.7.3. Membrane Effective Area and Packing Density

The membrane effective area of a membrane cassette is easily acquired. We just consider one parameter, the number of membrane modules per membrane cassette.

Most of the membrane cassettes are rectangular. So, it can be easily measured the length, width, and height of the cassette to calculate the packing density of the membrane cassette.

3.7. Membrane Cassettes (8/10)

3.7.4. Aeration

3.7.4.1. Aerator

In MBR operation, there are several kinds of fouling inhibition processes; cross flow, backwash, relaxation, maintenance cleaning (or chemical enhanced backwash), recovery cleaning, and aeration.

When we compare the efficiency of fouling inhibition or removal of foulants from the membrane surface, chemical-based cleaning processes, maintenance, and recovery cleaning are the best. But among non-chemical-based cleaning processes, aeration is the most efficient because of the very effective scrubbing between two different phases (liquid and gas).

3.7. Membrane Cassettes (9/10)

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3.7.4.2. Air Demand

Generating and supplying air to membranes is one of the costly processes in MBR system. So, there should be some optimum range of air supplied, which is expressed by specific air demand (SAD).

There are two SAD values:

1) SAD_m (SAD per membrane area) whose units are N $m^3/(h\ m^2)$
2) SAD_p (SAD per permeate volume) whose units are m^3 air/m^3 permeate.

In general, membrane cassettes have a SAD_m in the range of 0.3–0.8 N $m^3/(h\ m^2)$ and a SAD_p in the range of 10–90 m^3 air/m^3 permeate.

3.7. Membrane Cassettes (10/10)

Example 3.24: When air is supplied to each module at 15 N m^3/h of flow, calculate SAD_m and SAD_p. Each membrane permeates 0.5 m^3/h of water. (Effective membrane area= 23 m^2)

$$SAD_m = \frac{Q_a}{A} = \frac{(15 \text{ N m}^3/\text{h})}{(23 \text{ m}^2)} = 0.65 \text{ N m}^3/(\text{h m}^2)$$

$$SAD_p = \frac{Q_a}{Q_w} = \frac{(15 \text{ N m}^3/\text{h})}{(0.5 \text{ m}^3/\text{h})} = 30 \text{ N m}^3/\text{m}^3$$

Thank you…