MEMBRANE BIOREACTORs

Week 7th: Membrane Fouling

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Time and Room: Wednesday 11:00 - 11:50 FZ-82
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Week 7th: Membrane Fouling

4.5. Quantitative Determination of Fouling

- Resistance in the Series Model
- TMP Buildup

4.6. Fouling Control Strategy

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4.5. Quantitative Determination of Fouling

Quantitatively determining the fouling propensity is an important step to set up a fouling control strategy. Continuous and precise monitoring of how fouling advances in MBR can allow the operator to anticipate future troubles and to take appropriate antifouling or cleaning action. There are several ways to express the degree of fouling both theoretically and practically.

4.5.1. Resistance in the Series Model

Analyzing filtration resistances makes it easy to understand the fouling phenomena in MBRs. The most frequently used method to analyze fouling mechanisms in laboratory-scale MBR studies is **The RIS Model**. The basic idea of this model is that the permeate flux, J, is proportional to the driving force for membrane filtration and inversely proportional to the sum of all the resistances:

$$J = \frac{\text{driving force}}{\sum \text{resistances}}$$

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4.5.1. Resistance in the Series Model (Cont.)

This model states that the driving force for membrane filtration is the TMP, and the resistance to permeation is the sum of resistances and the permeate viscosity:

$$J = \frac{\Delta P_T}{(\eta \cdot R_t)}$$

where

J is the permeation flux, $L/m^2\ h$

ΔP_T is the TMP, $kg\ m/s^2\ cm^2$

η is the viscosity of the permeate, kg/m s ($= N\ s/m^2$)

R_T is the total resistance, m^{-1}

Total resistance (R_T) consists of intrinsic(R_m) and resistance arising from all kinds of fouling ($R_{fouling}$). Dividing the fouling resistance ($R_{fouling}$) into two resistances (R_c + R_f) is very easy to understand, and it is convenient to get each resistance value by conducting a series of filtration experiments.

4.5. Quantitative Determination of Fouling (3/28)

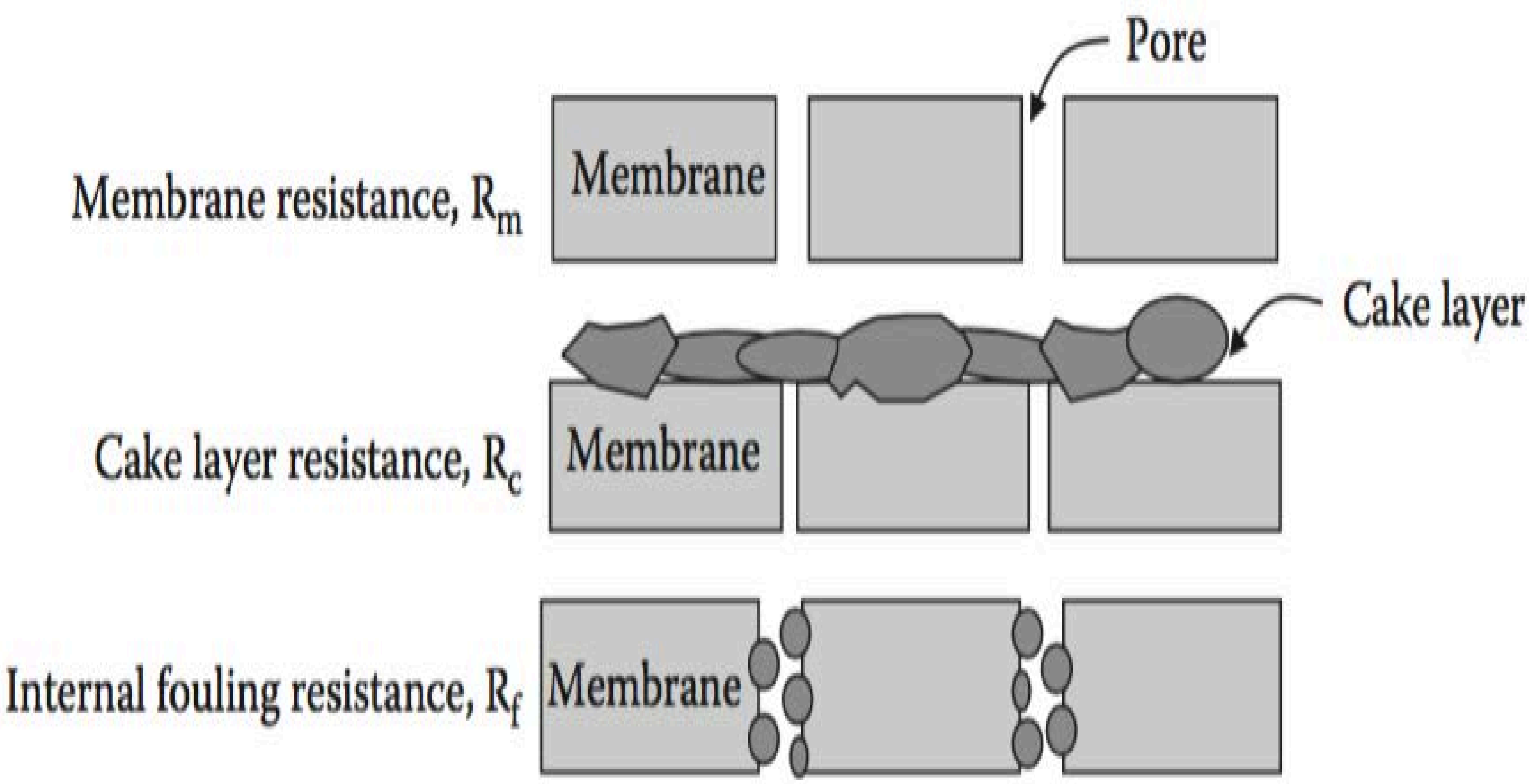

Figure 4.28. Schematic of the RIS model.

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4.5.1. Resistance in the Series Model (Cont.)

In light of this information, the RIS model equation is expressed as follows:

$$J = \frac{\Delta P_T}{\eta \cdot R_T} = \frac{\Delta P_T}{\eta \cdot (R_m + R_c + R_f)} \qquad (4.27)$$

where

R_c is the cake layer resistance on the membrane surface, m^{-1}

R_f is the internal fouling resistance caused by solute adsorption onto the membrane pores and walls, m^{-1}

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4.5.1. Resistance in the Series Model (Cont.)

The basic equation (J) of this model has an analogy to the well-known Ohm's law, which states that the rate of flow of electrical charge through an electrical resistor is proportional to the difference in voltage (V) measured across the resistor:

$$I = \frac{V}{R} \tag{4.28}$$

where

I is the electric current, ampere, representing the flow rate of the electrical charge

V is the potential, volt, which is the difference in voltage across the resistor

R is the resistance, Ω

Figure 4.30 clearly shows the analogy presented between Ohm's law and the RIS model. Each resistance value (R_m, R_c, and R_f) can be obtained through Equations 4.28 through 4.30 and can be determined experimentally utilizing J_{iw}, Jf_w, and J:

4.5. Quantitative Determination of Fouling (7/28)

Current, I, is the rate expression, coulomb/time		Flux, J, is the rate expression, volume/time
Voltage, V, is the driving force of circuit	*vs.*	TMP is the driving force of filtration
Resistance to electrons flow		Resistance to fluids flow

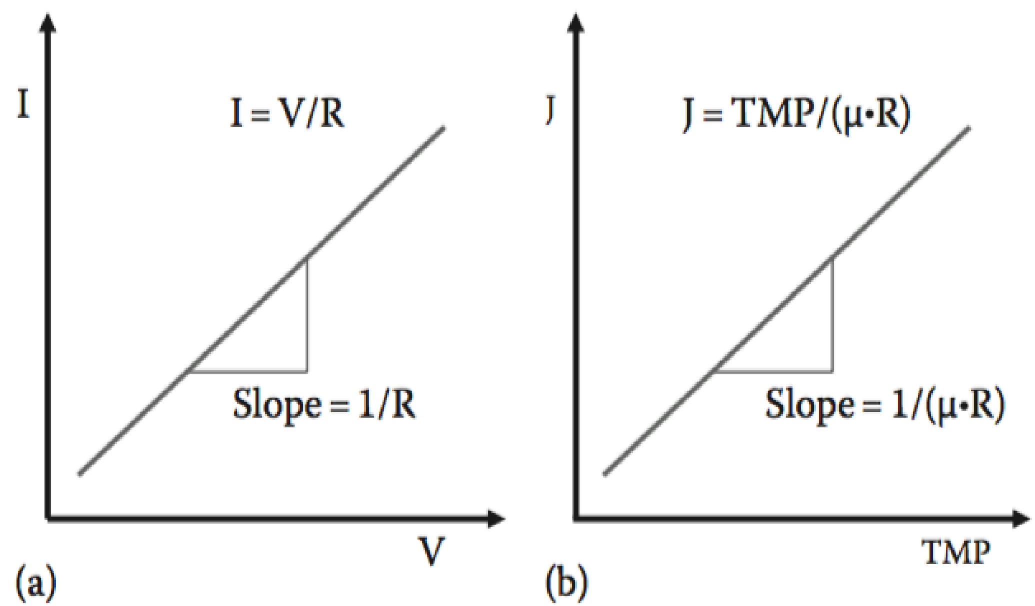

Figure 4.30. Analogy of (a) Ohm's law and the (b) RIS model.

4.5. Quantitative Determination of Fouling (8/28)

4.5.1. Resistance in the Series Model (Cont.)

$$R_m = \frac{\Delta P_T}{(\eta \cdot J_{iw})} \qquad (4.29)$$

$$R_f = \frac{\Delta P_T}{(\eta \cdot J_{fw}) - R_m} \qquad (4.30)$$

$$R_c = \frac{\Delta P_T}{(\eta \cdot J) - (R_m + R_f)} \qquad (4.31)$$

Jiw is the measured initial water flux of a new (or cleaned) membrane before the feed filtration experiments, J is the measured permeate flux of the feed solution, and J_{fw} is the final water flux measured after removing the cake layer of the fouled membrane.

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4.5.1.1. Stirred-Batch Filtration Cell

The best way to understand current fouling propensity in an MBR plant is to make them determine each resistance value in their laboratory. Each resistance is obtained by a series of membrane filtration tests with pure water and samples of the activated sludge suspension delivered from the aeration basin to the laboratory using a stirred-batch filtration cell as depicted in Figure 4.31.

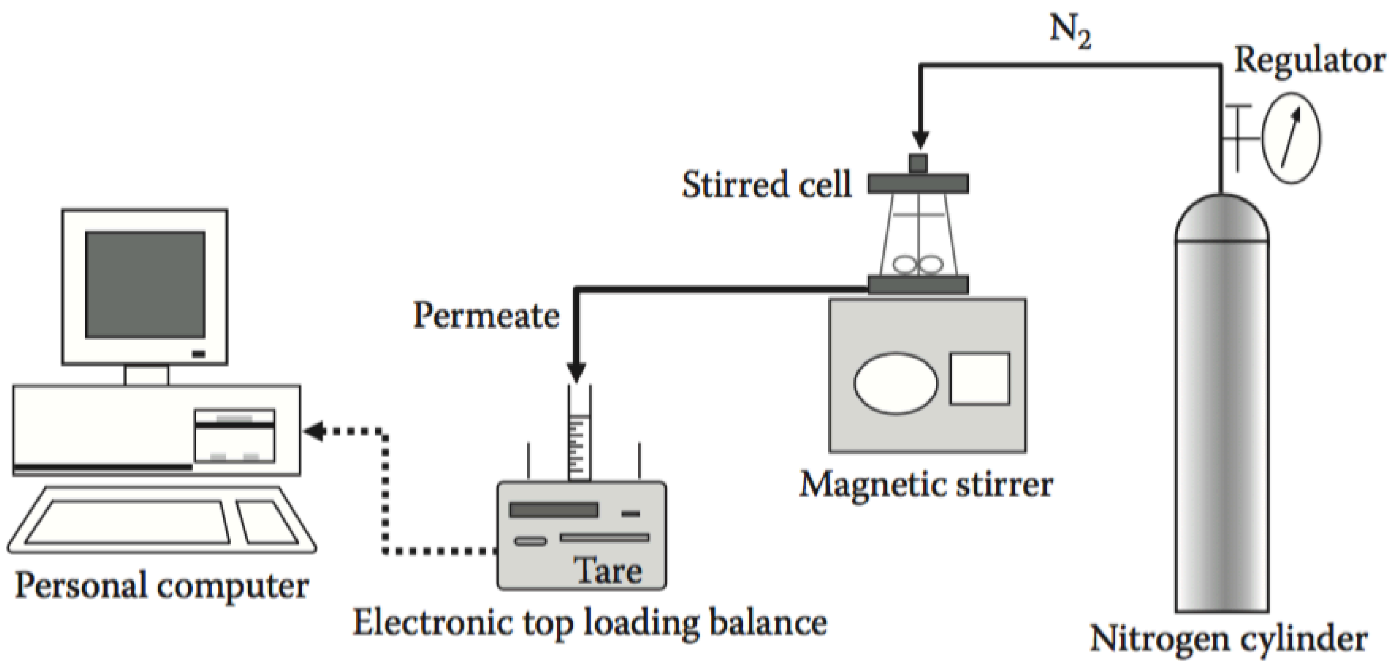

Figure 4.31. Schematic of stirred-batch filtration cell system in laboratory use.

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4.5.1.2. Cautious Use of the Resistance in the Series Model

The RIS model is very convenient and is an easy method to evaluate and predict membrane fouling quantitatively, but there is a need to be cautious when using the RIS model:

$$J = \frac{\Delta P_T}{\eta \cdot R_T} = \frac{\Delta P_T}{\eta \cdot (R_m + R_c + R_f)} \quad (4.27)$$

The total resistance, R_T, is taken as the sum of each resistance ($R_T = R_m + R_c + R_f$). However, this summation is only possible if each resistance is additive. In order to be additive, the individual resistances (R_m, R_c and R_f) must work independently without interferences.

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Example 4.7

A bench-scale submerged MBR is running in a laboratory under a constant flux mode (Table 4.5). Determine each resistance value, R_m, R_c and R_f, using the following dataset that was obtained from a series of filtration experiments with pure water and activated sludge suspension (assume that the permeate density is 1 g/mL):

- MLSS concentration, 3500 mg/L
- The membrane surface area, 0.05 m^2
- The pore size of the hollow membrane, 0.4 μm
- Initial water flux (J_{iw}), 30 L/m^2 h
- Flux (J), 20 L/m^2 h (LMH)
- Final water flux (J_{fw}), 24 L/m^2 h
- Temperature, 20°C
- Permeate viscosity, 1.009×10^{-3} kg/m s

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Example 4.7 (Cont.)

Table 4.5. TMP versus Filtration Time Data

Time (s)	*Monitored Pressure (bar)*		
	Pure Water Filtration before the MBR Run	*MBR Run with Activated Sludge*	*Pure Water Filtration after Cleaning the Cake Layer on the Membrane Surface*
15	0.020	0.656	0.039
30	0.042	1.675	0.045
45	0.046	2.389	0.068
60	0.061	3.199	0.079
75	0.063	3.918	0.091
90	0.070	4.631	0.121
105	0.071	5.348	0.137
120	0.073	5.953	0.145
135	0.073	6.361	0.149
150	0.073	6.662	0.191
165	0.076	6.863	0.192

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Example 4.7 (Cont.)

Table 4.5. TMP versus Filtration Time Data (Cont.)

Time (s)	*Monitored Pressure (bar)*		
	Pure Water Filtration before the MBR Run	*MBR Run with Activated Sludge*	*Pure Water Filtration after Cleaning the Cake Layer on the Membrane Surface*
180	0.077	6.862	0.195
195	0.077	6.861	0.198
210	0.077	6.862	0.199
225	0.078	6.862	0.201
240	0.078	6.863	0.203
255	0.078	6.863	0.204
270	0.078	6.862	0.204
285	0.078	6.861	0.203
300	0.078	6.863	0.203
315	0.078	6.862	0.204
330	0.078	6.863	0.203

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Solution (Cont.)

Table 4.6. Determination of Each TMP Value Using the Filtration Data

Time (s)	*TMP*		
	Pure Water Filtration before the MBR Run	*MBR Run with Activated Sludge*	*Pure Water Filtration after Cleaning the Cake Layer on the Membrane Surface*
	Pressure ($kg\ m/s^2\ cm^2$)	*Pressure ($kg\ m/s^2\ cm^2$)*	*Pressure ($kg\ m/s^2\ cm^2$)*
15	0.151999	6.5574	0.3898
30	0.4198	16.7433	0.4498
45	0.4598	23.8804	0.6797
60	0.6098	31.9772	0.7897
75	0.6297	39.1643	0.9096
90	0.6997	46.2915	1.2095
105	0.7097	53.4586	1.3695
120	0.7297	59.5062	1.4494
135	0.7297	63.5846	1.4894
150	0.7297	66.5934	1.9092

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Solution (Cont.)

Table 4.6. Determination of Each TMP Value Using the Filtration Data (Cont.)

Time (s)	*TMP*		
	Pure Water Filtration before the MBR Run	*MBR Run with Activated Sludge*	*Pure Water Filtration after Cleaning the Cake Layer on the Membrane Surface*
	Pressure (kg m/s² cm²)	*Pressure (kg m/s² cm²)*	*Pressure (kg m/s² cm²)*
165	0.7597	68.6025	1.9192
180	0.7697	68.5926	1.9492
195	0.7697	68.5826	1.9792
210	0.7697	68.5926	1.9892
225	0.7797	68.5926	2.0092
240	0.7797	68.6025	2.0292
255	0.7797	68.6025	2.0392
270	0.7797	68.5926	2.0392
285	0.7797	68.5826	2.0292
300	0.7797	68.6025	2.0292
315	0.7797	68.5926	2.0392
330	0.7797	68.6025	2.0292
TMP	$TMP_i = 0.7797$ (kg m/s² cm²)	$TMP = 68.6025$ (kg m/s² cm²)	$TMP_f = 2.0292$ (kg m/s² cm²)

4.5. Quantitative Determination of Fouling *(21/28)*

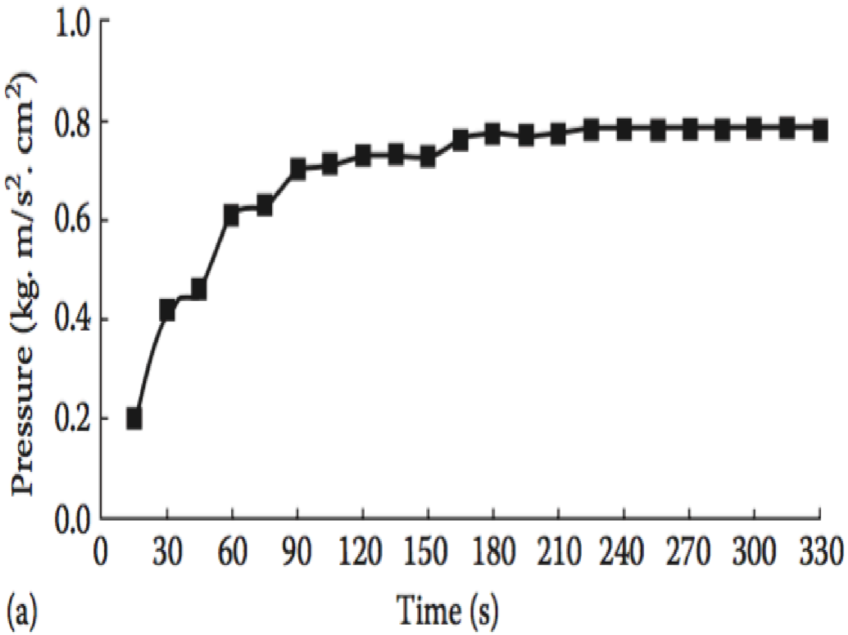

Figure 4.35. TMP_i profile of the pure water filtration

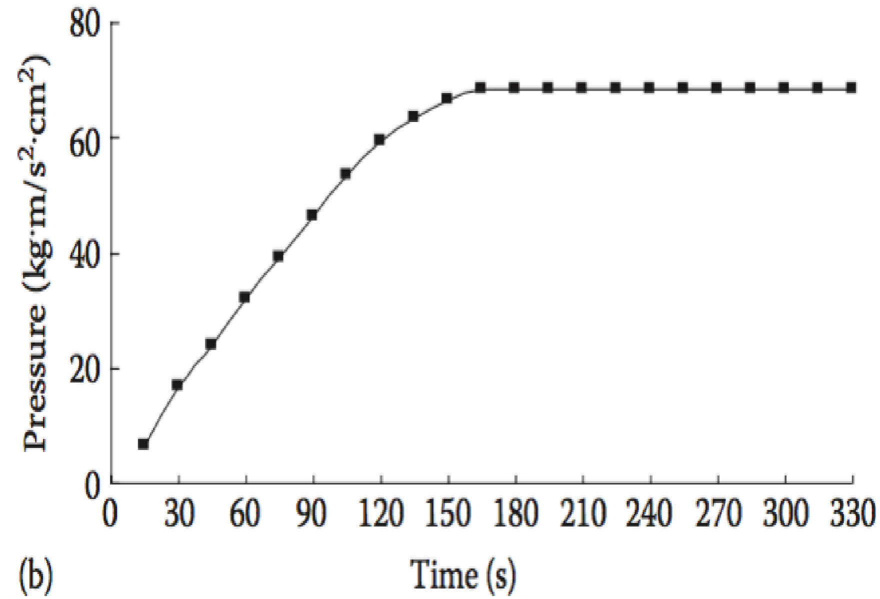

Figure 4.36. TMP profile of the filtration of activated sludge

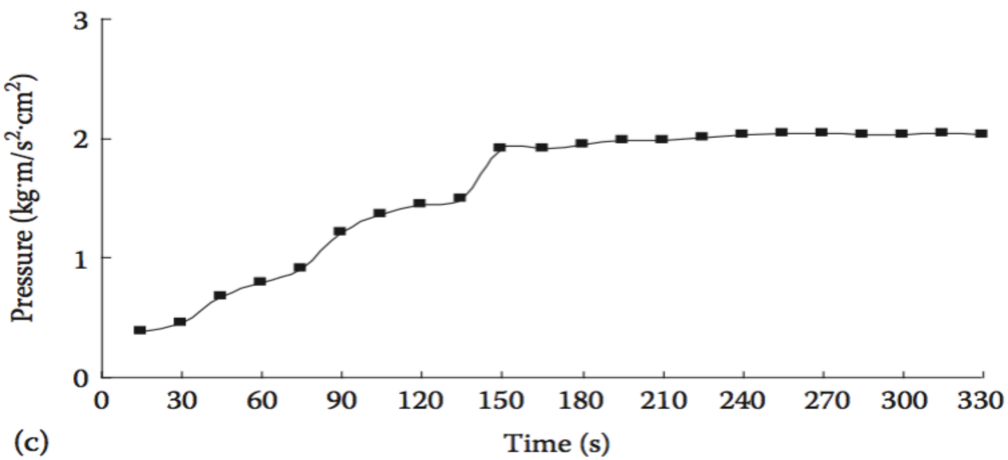

Figure 4.37. TMP_f profile of the pure water filtration after removing the cake layer.

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Solution (Cont.)

The fourth column in Table 4.6 shows the calculated TMP obtained after proper cleaning of the fouled membrane surface, for example, after backwashing. Figure 4.37 shows the plot of time versus the calculated TMP using the spreadsheet in Table 4.6. The stabilized TMP is calculated to be 2.0292 kg m/s^2 cm^2.

Through the procedure earlier, the three TMP values that were required to calculate the resistance values were obtained: $TMP_i = 0.7797$ kg m/s^2 cm^2, TMP = 68.6025 kg m/s^2 cm^2, and $TMP_f = 2.0292$ kg m/s^2 cm^2. The next step is the calculation of each resistance value using the RIS model and the TMP data:

1. Determination of membrane resistance (R_m) using the following equation: $R_m = \Delta P/\eta \cdot J_{iw}$
   a. Insert each value, $J_{iw} = 30$ L/h m^2, $TMP_i = 0.7797$ kg m/s^2 cm^2, and $\eta = 1.009 \times 10^{-3}$ kg/m s, into the following equation and calculate it:

$$R_m = \frac{0.7797\ \mathrm{kg \cdot m}}{\mathrm{s^2 \cdot cm^2}} \times \frac{\mathrm{m \cdot s}}{1.009 \times 10^{-3}\ \mathrm{kg}} \times \frac{\mathrm{m^2 \cdot h}}{30\ \mathrm{L}} \times \frac{3600\ \mathrm{s}}{\mathrm{h}} \times \frac{100^2\ \mathrm{cm^2}}{\mathrm{m^2}} \times \frac{10^3\ \mathrm{L}}{\mathrm{m^3}}$$

$$R_m = 0.09 \times 10^{13}\ \mathrm{m^{-1}}$$

4.5. Quantitative Determination of Fouling (22/28)

Solution (Cont.)

2. Determination of fouling resistance (R_f) using the following equation: $R_f = \Delta P/\eta \cdot J_{fw} - R_m$
   a. Insert each value, $J_{fw} = 24$ L/h m², $TMP_f = 2.0292$ kg m/s² cm², and $\eta = 1.009 \times 10^{-3}$ kg/m s, into the following equation:

$$R_f = \frac{2.0292\ \text{kg}\cdot\text{m}}{\text{s}^2\ \ \text{cm}^2} \times \frac{\text{m}\cdot\text{s}}{1.009\ \ 10^{-3}\ \text{kg}} \times \frac{\text{m}^2\cdot\text{h}}{24\ \text{L}} \times \frac{3600\ \text{s}}{\text{h}}$$

$$\times \frac{100^2\ \text{cm}^2}{\text{m}^2} \times \frac{10^3\ \text{L}}{\text{m}^3} - 0.09 \times 10^{13}$$

$$R_f = 0.3 \times 10^{13}\ \text{m}^{-1} - 0.09 \times 10^{13}\ \text{m}^{-1}$$

$$\therefore R_f = 0.21 \times 10^{13}\ \text{m}^{-1}$$

3. Determination of cake resistance (R_c) using the following equation: $R_c = (\Delta P/\eta \times J) - (R_m + R_f)$
   a. Insert each value, $J_{fw} = 20$ L/h m², $TMP = 68.6025$ kg m/s² cm², and $\eta = 1.009 \times 10^{-3}$ kg/m s, into the following equation:

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Solution (Cont.)

$$R_c = \frac{68.6025\ \text{kg}\cdot\text{m}}{\text{s}^2\cdot\text{cm}^2} \times \frac{\text{m}\cdot\text{s}}{1.009\times10^{-3}\ \text{kg}} \times \frac{\text{m}^2\cdot\text{h}}{20\ \text{L}} \times \frac{3600\ \text{s}}{\text{h}} \times \frac{100^2\ \text{cm}^2}{\text{m}^2} \times \frac{10^3\ \text{L}}{\text{m}^3}$$

$$-(0.09+0.21)\times10^{13}$$

$$R_c = 12.2\times10^{13}\ \text{m}^{-1} - (0.09+0.21)\times10^{13}\ \text{m}^{-1}$$

$$\therefore R_c = 11.9\times10^{13}\ \text{m}^{-1}$$

Summarizing each resistance, the membrane resistance, $R_m = 0.09\times10^{13}\ m^{-1}$; the cake layer resistance, $R_c = 11.9\times10^{13}\ \text{m}^{-1}$ and the fouling resistance, $R_f = 0.21\times10^{13}\ \text{m}^{-1}$:

$$\therefore \text{Total resistance, } R_T = R_m + R_c + R_f$$

$$= 0.09\times10^{13}\ \text{m}^{-1} + 11.9\times10^{13}\ \text{m}^{-1} + 0.21\times10^{13}\ \text{m}^{-1}$$

$$= 12.2\times10^{13}\ \text{m}^{-1}$$

4.5.1.3. Cautious Use of the Resistance in the Series Model to Determine Cake Layer Resistance (R_c)

The calculated R_c values are very dependent upon the cleaning methods used for removing the cake layer from the membranes.

According to the study of Han and Chang (2014), there are big differences in R_c depending on the cake layer removal method. After a series of batch filtrations of the activated sludge suspensions, four different cleaning methods were employed to remove the cake layer on the membrane surface:

1. Water rinsing in a vibrating shaker
2. Manual water rinsing
3. Sponge scrubbing
4. Ultrasonications at different power levels

The ratio of the cake layer resistance to the total fouling resistance, $R_c/(R_c + R_f)$, was calculated and compared in Figure 4.38.

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4.5.1.3. Cautious Use of the Resistance in the Series Model to Determine Cake Layer Resistance (R_c)

The total fouling resistance, $R_c + R_f$, should be identical regardless of the removal options. The decisive parameter for comparing the removal efficiencies between each removal option is not the individual resistance values but the ratio of R_c to the total fouling resistance (i.e., $R_c/(R_c + R_f)$). This ratio decreases in the case of incomplete cake layer removal but increases with proper cake layer removal.

For YM30 membranes, sponge scrubbing removed the cake layer completely ($R_c/(R_c + R_f$ =100%), whereas other methods showed removal efficiencies ranging from 79% to 99%. **For the PM30 membrane**, none of the options achieved complete cake layer removal. In addition, sponge scrubbing was not the best option for cake removal, indicating that even a method with the potential to completely remove the cake layer on a specific membrane is not universal for every kind of membrane.

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4.5. Quantitative Determination of Fouling *(25/28)*

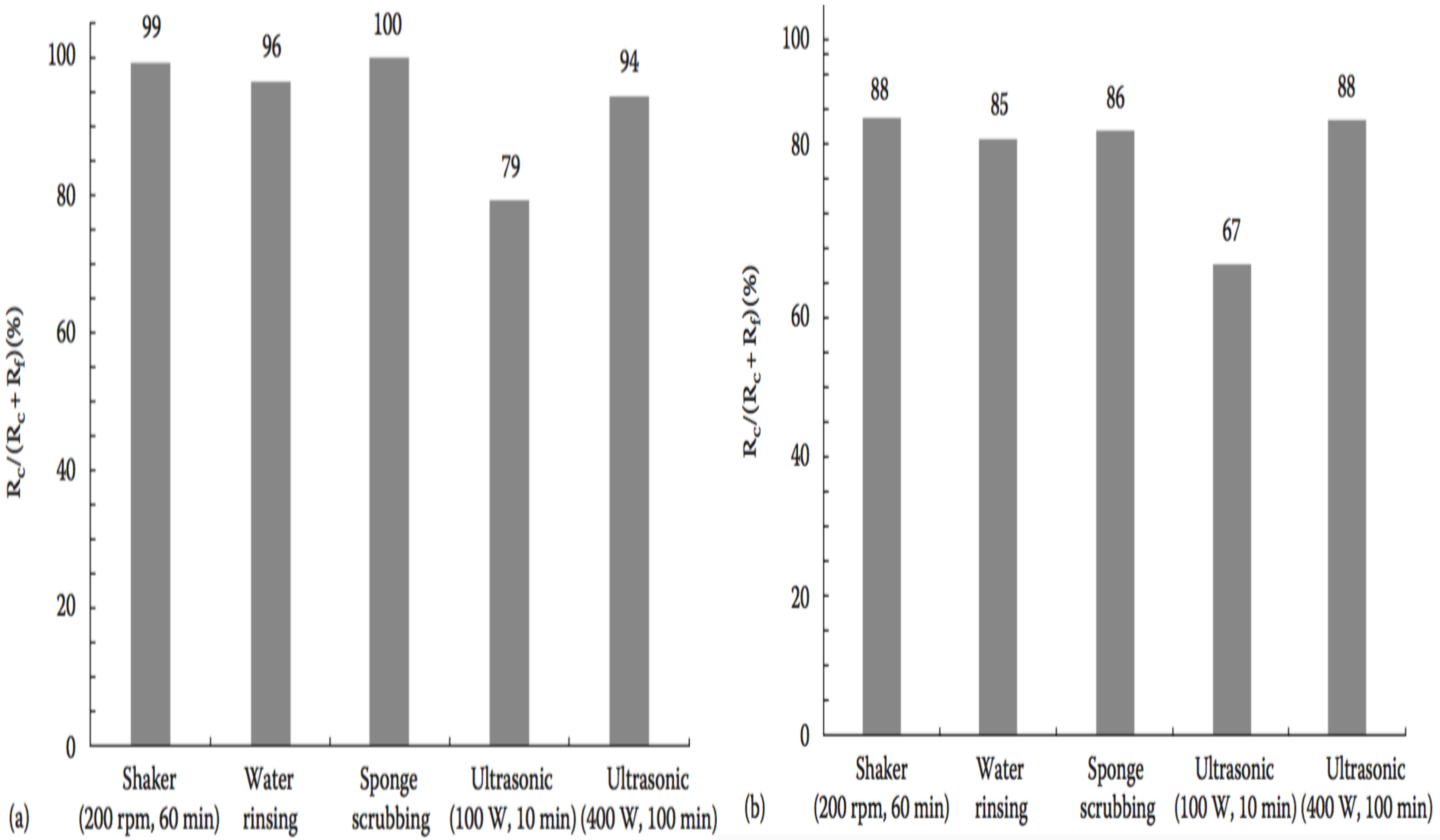

Figure 4.38. Comparison of the resistance ratio, $R_c/(R_c + R_f)$, for the five different cleaning methods using (a) the YM30 membrane and (b) the PM30 membrane.

4.6. Fouling Control Strategy (1/3)

4.6. Fouling Control Strategy

Recent developments and improvements in fouling control technologies have led to more favorable projections of membrane life and significantly reduced overall maintenance and operation costs.

There are numerous methods of fouling control that have been practiced in MBR plants. Most of the attempted methods can be categorized into chemical, physical, biological, or others (electric and membrane and module development).

Chemically cleaning membranes certainly restores membrane filtration performance. Strong acids, caustics, and/or oxidizing agents recover the membrane's deteriorated performance nearly completely.

However, chemical cleaning cannot avoid secondary contamination, which is the generated waste chemicals that require further treatment and eventual disposal. Moreover, safety regulations for the transport, storage, and usage of chemicals have become stringent nowadays, so that alternative cleaning options are encouraged instead of chemical cleaning.

4.6. Fouling Control Strategy (2/3)

4.6. Fouling Control Strategy (Cont.)

Therefore, physical cleaning methods are recommended because they do not produce secondary contaminants that require further treatment. However, this method has some disadvantages:

- Frequent backwashing leads to damages of the membrane structure and particularly collapses the anisotropic membrane structure.

- Physical cleaning such as coarse aeration that is widely practiced in submerged MBR systems consumes great amounts of energy. Most operation and maintenance (O&M) costs in MBR plants are attributed to the electrical energy consumption of the blower supplying coarse air to the membrane surfaces.

4.6. Fouling Control Strategy (3/3)

4.6. Fouling Control Strategy (Cont.)

Membrane fouling caused by biofilm formation and deposition on membrane surfaces by microorganisms could be inhibited by the addition of autoinducer-inhibiting chemicals.

Other types of biological control techniques besides quorum quenching are;

(1) nitric oxide to induce biofilm dispersal,

(2) Enzymatic disruption of EPSs,

(3) Disruption of biofilm formation by bacteriophages

Although these recent applications are still developing in the laboratory scale, they could arrive at mature stages soon.

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Thank you…