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The optimum operational condition of membrane bioreactor (MBR): cost estimation of aeration and sludge treatment

Seong-Hoon Yoon[a,]*, Hyung-Soo Kim[b], Ik-Tae Yeom[b]

[a] *Global Research Center, Nalco Company, Naperville, IL 60563-1198, USA*

[b] *Department of Civil and Environmental Engineering, SungKyunKwan University, Suwon 440-746, South Korea*

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Abstract

A methodology to obtain the most economical operational condition of membrane bioreactor (MBR) is developed. In order to achieve the optimum design parameters of MBR with which operational costs are minimized, aeration and sludge treatment costs were estimated for various operational conditions. Generally sludge treatment cost and aeration cost were inversely proportional to each other, which means sludge treatment cost is minimized when aeration cost is maximized and vice versa. Therefore, there might exist an optimum point between the two extreme cases. However, sludge treatment cost turned out to overwhelm the aeration cost over the reasonable operational conditions. Therefore, sludge minimization was considered to be a key for the economical operation of MBR. In the case of typical municipal wastewater of which COD was $400\,\mathrm{mg\,L^{-1}}$, steady-state MLSS was expected to increase from 11,000 to 15,000 mg/L without sludge removal when HRT was decreasing from 16 to 12 h. For the range of operational conditions considered in this study, economically optimum HRT and target MLSS were turned out to be 16 h and 11,000 mg/L, respectively. Under this condition, aeration for the biodegradation of organic matters would be $13.3\,\mathrm{m^3}$ air/min when influent was $1000\,\mathrm{m^3}$/day.

Keywords: Membrane bioreactor; Sludge reduction; Optimum operational condition

1. Introduction

Membrane bioreactor (MBR) process for the separation and retention of sludge has been one of the alternatives to the conventional activated sludge process since the late 1960s. Membrane process coupled with an activated sludge process not only replaces the secondary clarifier for solid–liquid separation, but also serves as an advanced treatment unit for coliform bacteria and suspended solids, which cannot be removed completely by conventional processes [1–7].

In MBR, complete retention of sludge by membrane process makes it possible to maintain high MLSS in bioreactor, which causes long sludge retention time (SRT) and low food-to-microorganism (F/M) ratio. The long SRT also causes less sludge production while low F/M ratio gives a chance to reduce hydraulic retention time (HRT). Consequently, it has been known that less sludge production can be achieved while short HRT is applied in MBR process [8].

However, sludge production is obviously inversely proportional to HRT when MLSS is fixed. Therefore, the shortest HRT and the minimum sludge production cannot be achieved simultaneously. When sludge production is minimized, aeration cost would be maximized and vice versa. Therefore, there may exist an optimum point between the two extreme cases, in which total operational cost is minimized.

The purpose of this study was to develop a methodology for obtaining design parameters with

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*Corresponding author. Tel.: +1-630-305-1012; fax: +1-630-305-2982.

E-mail address: syoon21@lycos.co.kr (S.-H. Yoon).

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Nomenclature

k_d	sludge decay rate constant, day^{-1} (= 0.028)
K_s	half saturation constant, mg L^{-1} (= 100)
m	reactor depth, m (= 3)
O_2	oxygen consumption, kg O_2 day^{-1}
P	power demand, kW
q	sludge removal rate, m^3 day^{-1}
Q	influent flow rate, L day^{-1} (= 1×10^6)
Q_{air}	air flow rate, m^3 min^{-1}
S	soluble COD in bioreactor, mg L^{-1}
S_e	soluble COD in effluent, mg L^{-1}
S_i	soluble COD in influent, mg L^{-1} (= 400)
t	time, days
V	aeration tank volume, m^3
x	MLSS, mg L^{-1}
x_e	suspended solid in effluent, mg L^{-1} (= 0)
x_i	suspended solid in influent, mg L^{-1} (= 0)
X	sludge production rate, ton day^{-1}
Y	yield coefficient, mg MLSS mg COD^{-1} (= 0.5)
Y_{obs}	observed yield coefficient, mg MLSS mg COD^{-1}
β	mg COD mg MLSS^{-1} (= 1.2)
ε	water content in cake (= 0.8)
μ_m	maximum specific growth rate, day^{-1} (= 3.0)
$\Pi_{L,Q}$	minimum air input rate, m^3 min^{-1} 1000 m^{-3} (= 20)
η	specific oxygen transfer efficiency, m^{-1}

which operational costs are minimized. All of the cost items were divided into "fixed cost" and "variable cost", where only "variable cost" was affected by the change of operational condition. The "variable cost" included aeration cost for the biodegradation of pollutant and sludge treatment cost, while aeration for membrane scouring was excluded. In this study total variable cost was estimated according to operational parameters in order to obtain the optimum operational conditions.

2. Theory

2.1. Sludge production in MBR

Fig. 1 shows a schematic of separated type MBR in which separation tank is installed separately. In this study, bioreaction in the separation tank was neglected because separation tank is much smaller than the bioreactor. Moreover, the maintenance cost of the separation tank, which includes electricity fees for an air pump and a suction pump, was not considered for the cost evaluation because the costs for the separation tank were hardly affected by operational parameters of MBR. Here, soluble COD in mixed liquor (S) is assumed to be equal to the effluent COD (S_e) because the submerged membranes used in MBR are mostly micro- or ultrafilters which rarely remove dissolved materials. Additionally, all organic material in feed solution was assumed to be soluble.

In activated sludge process, microorganisms in bioreactor are growing with the consumption of organic substrate contained in wastewater. In addition the microorganisms are doing endogenous respiration consuming themselves. These phenomena can be described by Eq. (1), where the microbial growth is expressed by Monod equation, and the endogenous respiration, by first-order kinetic equation

$$\frac{dx}{dt} = \frac{\mu_m S_e}{K_s + S_e} x - k_d x \tag{1}$$

Here, μ_m is a maximum specific growth rate (day^{-1}), K_s is a half saturation constant (mg L^{-1}), k_d is a endogenous decay constant (day^{-1}), S_e is a substrate constant in mixed liquor (mg L^{-1}), x is an MLSS in bioreactor (mg L^{-1}) and t is a time (days).

While microorganisms are growing, majority of the substrate (organic pollutant in influent) is consumed by microorganisms and some substrate is discharged with effluent. This balance can be described by Eq. (2) where the first term on the right side expresses the COD balance between influent and effluent and the second term expresses the substrate consumption by

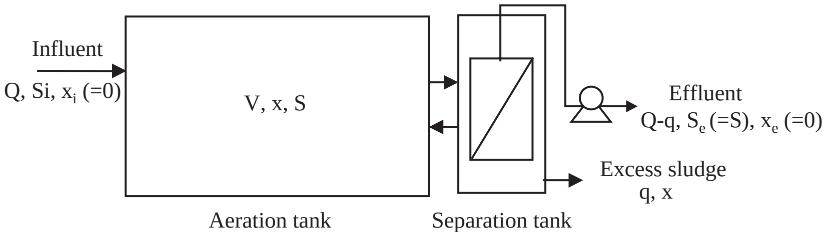

Fig. 1. Schematic of typical membrane bioreactor (MBR) process, where influent and effluent SS are zero.

microorganisms:

$$\frac{dS_e}{dt} = \frac{Q}{V}(S_i - S_e) - \frac{1}{Y}\frac{\mu_m S_e}{K_s + S_e}x \tag{2}$$

Here, Q is an influent flow rate ($m^3\,day^{-1}$) and Y is a yield coefficient (kg MLSS kg COD^{-1}).

2.2. Sludge production

The MLSS increasing rate can be obtained using the time derivative of MLSS (x) as shown in Eq. (1). By the way, the sludge production rate at a certain MLSS can also be calculated by multiplication of reactor volume (V) with the MLSS increasing rate. Assuming the water content in cake is ε, total cake production rate (X) is calculated below when MLSS in bioreactor is controlled to a target value as follows:

$$X = \frac{V}{(1-\varepsilon)\times 10^9}\left(\frac{dx}{dt}\right)_{x=x_{target}} \tag{3}$$

Inserting Eq. (1) into Eq. (3), following equation is obtained:

$$X = \frac{V}{(1-\varepsilon)\times 10^9}\left(\frac{\mu_m S_e}{K_s + S_e} - k_d\right)x_{target} \tag{3'}$$

2.3. Aeration requirement

In biological wastewater treatment, organic materials contained in influent are converted into new biomass while some of them are converted to carbon dioxide with the consumption of oxygen. Therefore, the oxygen requirement can be calculated by subtracting the amount of COD converted to biomass from the total COD removed.

The total oxygen consumption rate $\overset{\bullet}{O}_2$ can be expressed as follows where the first term on the right side describes the COD balance between influent and effluent and the second term describes the amount of COD converted to biomass:

$$\overset{\bullet}{O}_2 = \frac{dO_2}{dt} = \frac{Q}{V}(S_i - S_e) - \beta\frac{dx}{dt} \tag{4}$$

where β is a conversion factor of biomass to COD.

Aeration requirement (Q_{air}) is calculated from the oxygen consumption rate $\overset{\bullet}{O}_2$ considering the specific oxygen transfer efficiency (η) and reactor depth (m) [9]. In this study, reactor depth was assumed to be 3 m as submerged membrane module's height was 2 m [10].

$$Q_{air} = \frac{\overset{\bullet}{O}_2}{4.0\,\eta m} \tag{5}$$

Table 1
Values of kinetic and stoichiometric parameters used in calculation

Parameter	Unit	Value	Reference
k_d	day^{-1}	0.028	Nagaoka et al. [11]
K_s	$mg\,L^{-1}$	100	Henze et al. [12] Grady et al. [9]
Y	mg MLSS mg COD^{-1}	0.5	Grady et al. [9]
β	mg COD mg $MLSS^{-1}$	1.2	Grady et al. [9]
μ_m	day^{-1}	3	Henze et al. [12] Grady et al. [9]

Table 2
Values of operational parameters used in calculation

Parameter	Unit	Values
Q	$L\,day^{-1}$	1×10^6
ε	—	0.8
M	M	3.0
$\Pi_{L,Q}$	$m^3\,min^{-1}\,1000\,m^{-3}$	20[a]
$S_e(t=0)$	$mg\,L^{-1}$	30
S_i	$mg\,L^{-1}$	400
$x_\ell(t=0)$	$mg\,L^{-1}$	5,000
Electricity	U\$ kW^{-1}	0.05
Sludge treatment	U\$ ton^{-1}	40

[a] Grady et al. [9].

By the way, aeration tank requires minimum aeration for mixing. This minimum requirement, which depends only on reactor volume, can be calculated as

$$Q_{min} = \frac{V\Pi_{L,Q}}{1000} \tag{6}$$

where $\Pi_{L,Q}$ is a minimum air input rate [9]. If Q_{min} exceeds Q_{air}, Q_{min} needs to be adapted as an aeration rate.

By the power requirement, P is directly obtained by multiplication of conversion factor with the aeration rate as shown in Eq. (7) [9]:

$$P = 0.7(Q_{air}\ \text{or}\ Q_{min}) \tag{7}$$

All constants and parameters used in this calculation are summarized in Tables 1 and 2.

3. Results and discussion

3.1. Sludge production rate

By solving Eqs. (1) and (2) simultaneously, sludge build-up curves are obtained, shown in Fig. 2. The parameters and constants used in this calculation are summarized in the Tables 1 and 2. According to this figure, steady-state MLSS in bioreactor was expected to decrease with longer HRT. In case the HRT increases over 12 h, MLSS in bioreactor will be stabilized at less

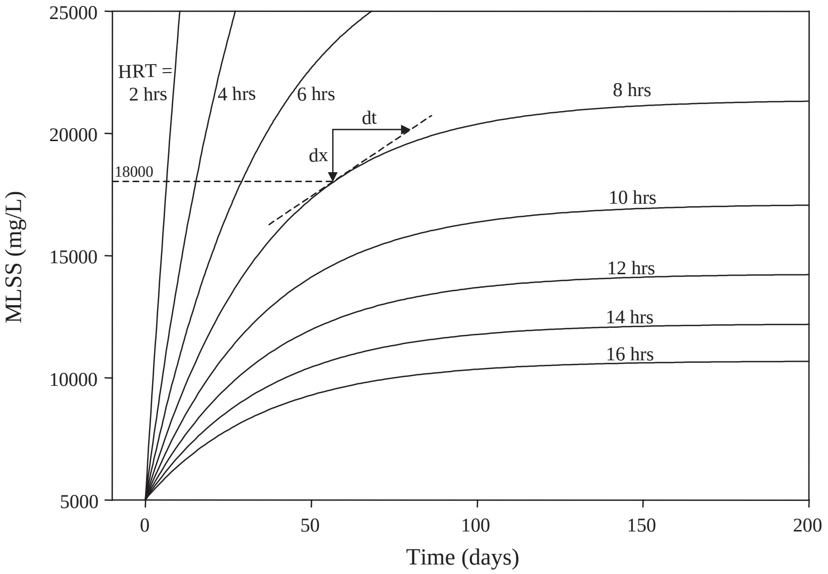

Fig. 2. Time curve of sludge concentration in the reactor as a function of HRT. Influent COD was assumed to be 400 mg L^{-1}.

than 15,000 mg/L, where stabilized MLSS means no further sludge production. Considering 15,000 mg/L is the maximum allowable MLSS in commercial MBRs to ensure low membrane fouling [10,13], stable MBR operation may be possible without sludge removal when HRT is more than 12 h.

Sludge production rate at a certain MLSS (ex. 18,000 mg L^{-1}) can be obtained from the slope of a tangent line as shown in Fig. 2. This slope represents the rate of MLSS increasing when MLSS is controlled to be 18,000 mg L^{-1}. The total dry sludge production is obtained by multiplication of reactor volume with the MLSS increasing rate. Cake production rate is also calculated using Eq. (3). In this calculation, water content in cake was assumed to be 0.8 as shown in Table 2 because survey showed average water content in cake was 0.815 when centrifuges were used [14]. As a result of the slight underestimation of the water content in cake, sludge disposal cost might be slightly underestimated in this calculation.

Fig. 3 shows daily cake production from the plant of which flow rate is 1000 m^3 day^{-1}. According to this graph, cake production rate decreases with longer HRT and/or higher target MLSS in bioreactor. Finally, cake production can be completely prevented just by increasing the HRT and/or target MLSS.

In real MBR, however, increased sludge viscosity at high MLSS boosts up the membrane fouling. In this study the high limit of target MLSS in bioreactor was set to be 15,000 mg L^{-1} according to Husain and Côté [10]. In Fig. 3, the HRT corresponding to the target MLSS 15,000 mg L^{-1} while cake production is zero is 11.4 h. This means the minimum HRT to obtain zero sludge production is 11.4 h when target MLSS is less than 15,000 mg L^{-1}.

As shown above, sludge production can be reduced significantly by increasing HRT and/or target MLSS. If either HRT or MLSS increases, more sludge will be retained in bioreactor and this increases SRT. The SRT and the observed yield coefficient, Y_{obs} are expressed as in the following equations:

$$\mathrm{SRT} = \frac{x}{\left(\frac{\mathrm{d}x}{\mathrm{d}t}\right)_{x=x_{\mathrm{target}}}} \tag{7'}$$

$$Y_{\mathrm{obs}} = \frac{V\left(\frac{\mathrm{d}x}{\mathrm{d}t}\right)_{x=x_{\mathrm{target}}}}{QS_i} \tag{8}$$

Fig. 4 shows SRT and observed yield coefficient, Y_{obs}, as functions of HRT and target MLSS in bioreactor. Assuming the target MLSS of 10,000–15,000 mg L^{-1} and HRT 6 h, SRT was expected to be 20–40 days. This SRT is much longer than that in conventional activated system, i.e. mostly less than 6 days [15]. Consequently observed yield coefficient, Y_{obs}, also was expected to be as low as 0.23–0.32 kg MLSS kg COD^{-1} while Y_{obs} in activated sludge process was 0.4–0.5 kg MLSS kg COD^{-1}. In case HRT is more than 12 h and MLSS is 14,000 mg L^{-1}, SRT would be over 1000 days and Y_{obs} approaches to zero.

3.2. Oxygen requirement and aeration rate

In MBR process, sludge production is suppressed by long HRT and/or high MLSS as shown in Section 3.1.

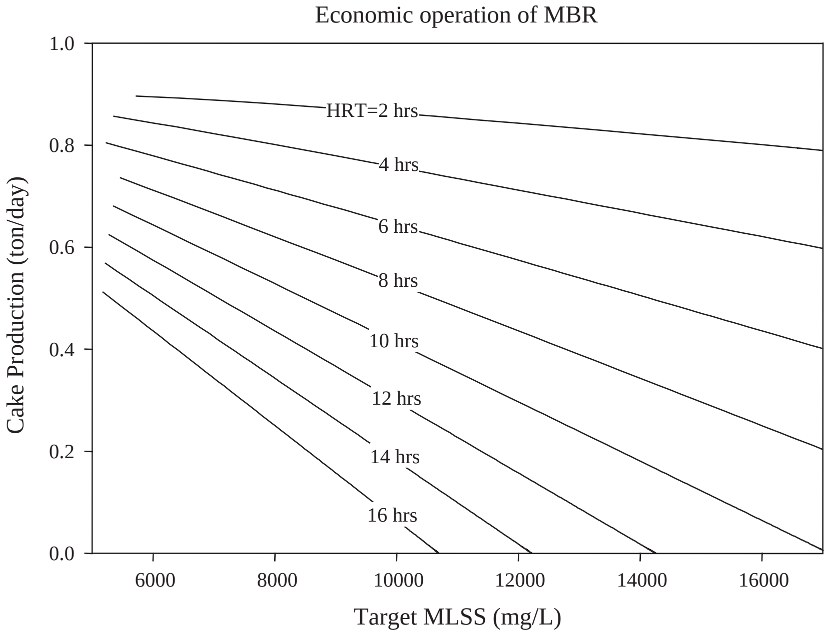

Fig. 3. Amount of cake production as functions of HRT and target MLSS. Water content of the cake was assumed to be 0.8.

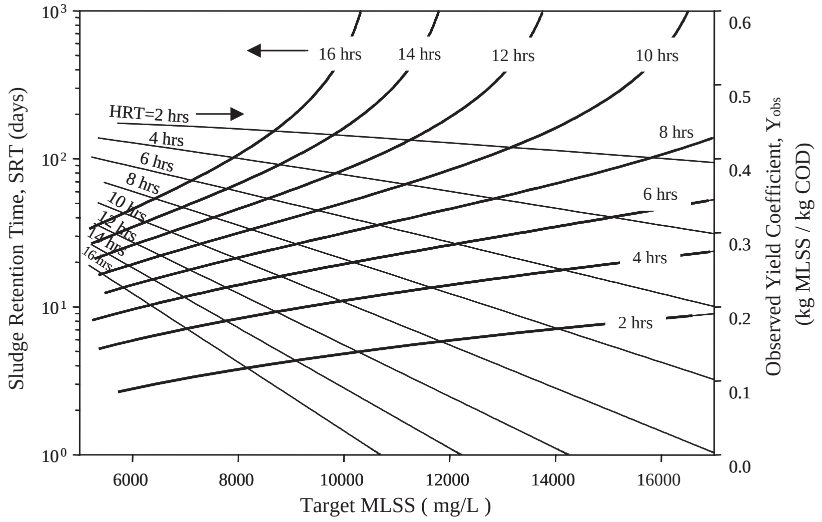

Fig. 4. Sludge retention time and observed yield coefficient as functions of HRT and target MLSS.

Along the sludge reduction, more oxygen is needed to oxidize the organic materials contained in wastewater, otherwise it turns into sludge. The oxygen requirement as functions of HRT and target MLSS can be calculated with Eq. (4). Solving Eq. (4) simultaneously with Eq. (1) and (2), oxygen requirement during the biodegradation can be calculated. The results are shown in Fig. 5. The dotted line indicates the maximum oxygen requirement when all influent organic materials turn to carbon dioxide.

In the figure, oxygen requirement is almost linearly proportional to the target MLSS and it is also proportional to HRT. A small change of target MLSS may cause more significant change of oxygen requirement when HRT is longer (slope is bigger for longer HRT). This means sludge production can be more reduced by increasing MLSS when HRT is high because high oxygen requirement directly means lower sludge production. For example, when MLSS increases from 6000 to 10,000 mg/L, oxygen requirement increases as

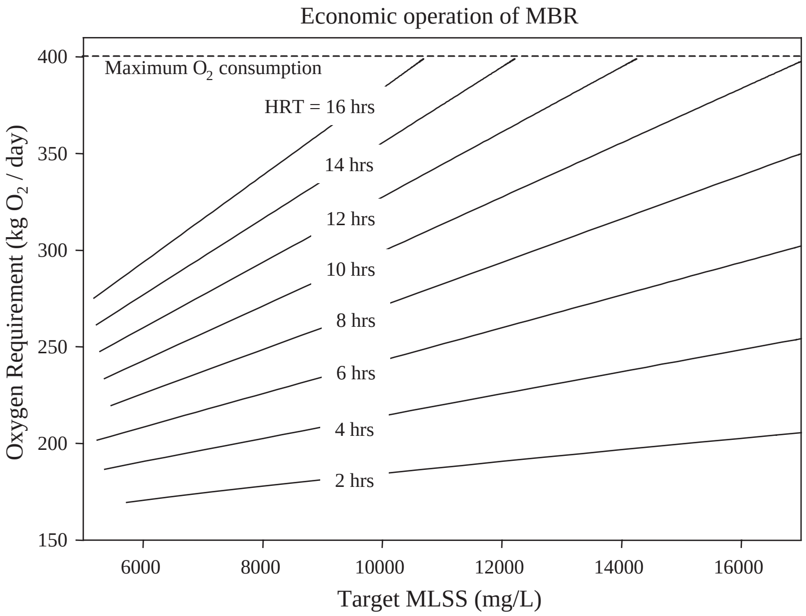

Fig. 5. Oxygen requirement during wastewater treatment as functions of HRT and target MLSS. The dotted line shows the maximum O_2 consumption when all influent COD is converted to carbon dioxide.

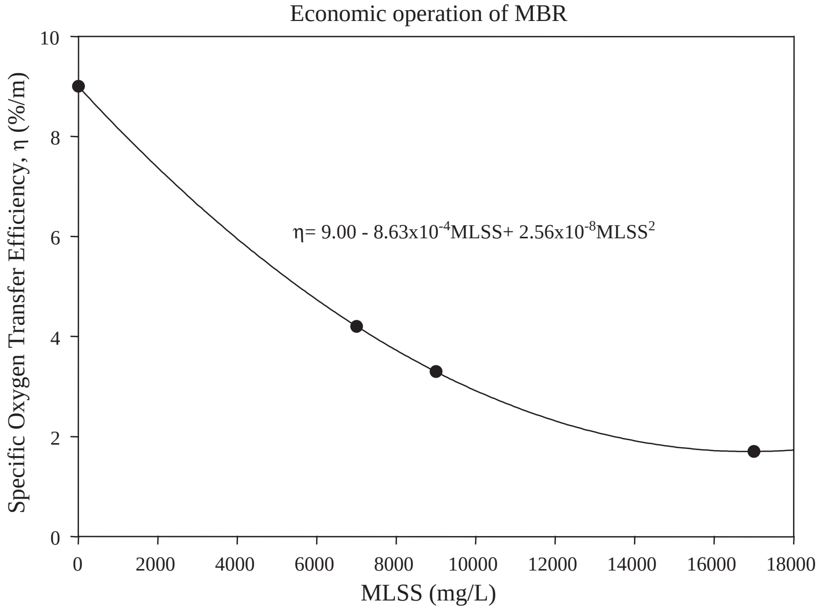

Fig. 6. Specific oxygen transfer efficiency (SOTE) as a function of MLSS [16,19].

much as 90 kg/day for the HRT of 16 h while it increases only by 13 kg/day for the HRT of 2 h, where higher oxygen requirement indicates lower sludge production.

The aeration requirement can be calculated with Eqs. (5) and (6), which are based on oxygen requirement and oxygen transfer efficiency. By the way oxygen transfer efficiency, η, is highly dependent on MLSS. Cornel et al. [16] measured a specific oxygen transfer efficiency in pure water and mixed liquor. Fig. 6 shows the specific oxygen transfer efficiency as a function of MLSS, which means an oxygen transfer efficiency per unit depth of aeration tank. The oxygen transfer efficiency was 9% m^{-1} in pure water but it decreases to 2% m^{-1} when MLSS increases to 17,000 mg L^{-1}. The relationship between MLSS and specific oxygen transfer efficiency was obtained through polynomial fitting and the following equation was obtained:

$$\eta = 9.00 - 8.63 \times 10^{-4}\,\mathrm{MLSS} + 2.56 \times 10^{-8}\,\mathrm{MLSS}^2. \quad (9)$$

In order to estimate the aeration demand for the biodegradation of pollutant organics, Q_{air} and Q_{min} were calculated using Eqs. (5) and (6); respectively, then larger value was adopted as a real aeration demand. As shown in Fig. 7, when HRT is 10 h and MLSS is less than 9800 mg/L, Q_{min} was adopted as an aeration demand because it is larger than Q_{air}. In Fig. 7, the end points of curves for HRT 12, 14 and 16 h mean maximum MLSS achievable without sludge production. The aeration demand was increasing with increase in target MLSS. On the other hand sludge production would decrease with the increase in target MLSS as shown in Fig. 3.

3.3. Total variable costs

The amount of cake production shown in Fig. 3 and the aeration requirement shown in Fig. 7 can be converted to costs by multiplying with unit costs for sludge treatment and aeration, respectively. The "total variable cost", which is affected by HRT and target MLSS, was estimated by summing up the two costs.

The electric power requirement for aeration can be calculated with Eq. (7) in which aeration requirement is directly converted to the electric power in kW unit. This electric power can be converted again to electricity fee by multiplying "operation time" and the "unit price of electricity". In this calculation an electricity price was assumed to be $0.05 per kWh.

In this study, the sludge treatment cost includes (1) chemical cost, (2) labor cost, (3) disposal cost, etc. Though the sludge treatment cost significantly depends on the location of plant, it is assumed to be $40 per ton according to Rossi et al. [17] 's estimation, where cake treatment cost was 43 Euro per ton.

Fig. 8 shows the aeration cost, sludge treatment cost and total variable cost when HRT is 6 h. The sludge treatment cost is expected to be dominant for the reasonable range of MLSS. As a result, the condition in which sludge production was minimized was the most economical operational condition. It could be concluded that the economically optimum operation might be achieved at the maximum allowable MLSS assuming the conditions/parameters given in this study.

The calculations performed for obtaining Figs. 6 and 7 were repeated for another HRTs. Fig. 9 shows the 'variable operational costs' for some HRTs as a function of a target MLSS in aeration tank. The total variable operational costs decreased with increase in target MLSS, except in the case HRT 2 h. This may suggest that the most economical operation is achieved at a maximum allowable MLSS of membrane when

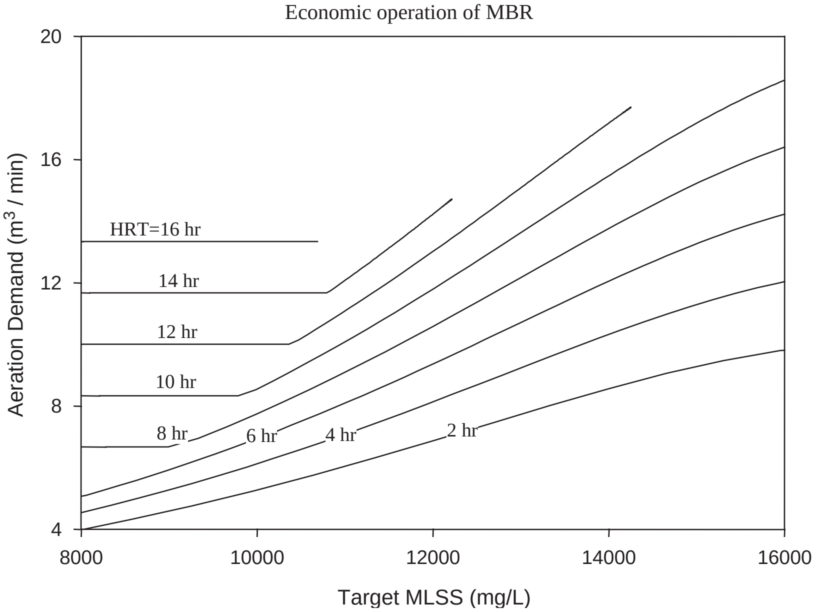

Fig. 7. Aeration demand for biodegradation of organic matters as a function of target MLSS and HRT. Flow rate and COD of influent were 1000 m^3/day and 400 mg/L, respectively.

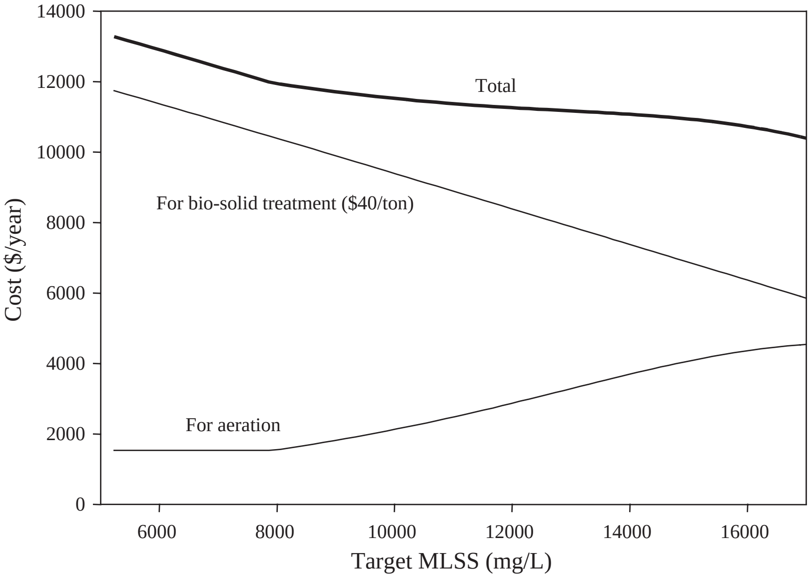

Fig. 8. Contributions of sludge treatment cost and aeration cost to total variable cost for MBR operation. Cake treatment cost was assumed to be $40 per ton.

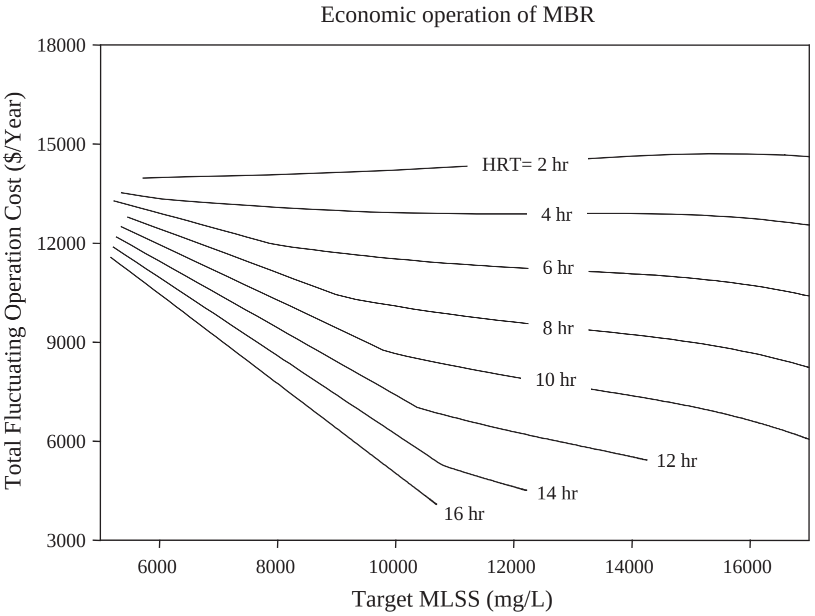

Fig. 9. Contributions of sludge treatment cost and aeration cost to total variable cost for MBR operation. Cake treatment cost was assumed to be $40 per ton.

HRT/bioreactor size is already fixed and HRT is not extremely low. At high MLSS, the cost reduction by sludge decrease exceeds the cost increase by decreased oxygen transfer efficiency.

The right ends of HRT 12, 14 and 16 h in Fig. 9 mean "zero sludge production" conditions, which correspond to the three end points in Fig. 7. From these two figures, the most economical operational condition out of all conditions considered in this study turns out to be HRT of 16 h and MLSS of 11,000 mg/L when aeration for the biodegradation of organic matters is 13.3 m^3 air/min to treat 1000 m^3 wastewater per day.

The operating cost for HRT 12 h is slightly higher than that for HRT 16 h because the higher steady-state

MLSS causes lower oxygen transfer efficiency for the case of HRT 12 h compared with HRT 16 h.

According to Lee et al. [3], Chang et al. [4], Nagaoka et al. [11] and Lee et al. [18], extracellular polymer (ECP) is one of the major membrane foulant and its concentration is affected by biological operational parameters such as HRT, MLSS and F/M ratio, etc. Therefore, membrane fouling propensity might be variable under different operational conditions. However, the relationship between those operational parameters and membrane cleaning frequency is not clear enough until now. As membrane-cleaning cost is not considered in this study, further research is needed to elucidate the relation between operational condition and membrane cleaning frequency.

4. Conclusions

This study provides a methodology for calculating the "total variable operational cost" of MBR and the following conclusions were drawn.

1. Sludge production rate can be quantitatively estimated as functions of HRT and MLSS. When either target MLSS in bioreactor or HRT increases, sludge production rate decreases and aeration requirement increase. By summing the decreasing sludge treatment cost and increasing aeration cost, total variable operational cost is obtained.
2. In the case of typical municipal wastewater of which COD is 400 mg L^{-1}, steady-state MLSS is expected to increase from 11,000 to 15,000 mg/L without sludge production when HRT decreases from 16 to 12 h.
3. The most economical operational condition out of all conditions considered in this study was turned out to be HRT of 16 h and MLSS of 11,000 mg/L when aeration for biodegradation was 13.3 m^3 air/min to treat 1000 m^3 wastewater per day.
4. For the reasonable ranges of HRT and MLSS, sludge treatment cost overwhelms aeration cost for biodegradation. Therefore, maintaining a low sludge production condition is most important for cost reduction of MBR operation.
5. When HRT/bioreactor size is already fixed and the HRT is not extremely low, the most economical operation is achieved at a maximum allowable MLSS of the membrane. At high MLSS, the cost reduction by sludge decrease exceeds the cost increase by decreased oxygen transfer efficiency.

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