Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

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Online publication date: 23 April 2010

To cite this Article Kiser, Mehlika A. , Oppenheimer, Joan , DeCarolis, Jay , Hirani, Zakir M. and Rittmann, Bruce E.(2010) 'Quantitatively Understanding the Performance of Membrane Bioreactors', Separation Science and Technology, 45: 7, 1003 — 1013

To link to this Article: DOI: 10.1080/01496391003667146

URL: http://dx.doi.org/10.1080/01496391003667146

Separation Science and Technology, 45: 1003–1013, 2010

ISSN: 0149-6395 print/1520-5754 online
DOI: 10.1080/01496391003667146

Quantitatively Understanding the Performance of Membrane Bioreactors

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The membrane bioreactor (MBR) is a special form of activated sludge in which a membrane separator allows perfect solids retention. This offers obvious benefits for effluent COD and attaining a large ratio of solids retention time to hydraulic retention time (SRT/HRT). However, these benefits come with trade-offs. This work explores the trade-offs with a mechanistic model based on the unified theory for the biomass and soluble components in microbiological processes and adapted for the special features of MBRs. In particular, only large biomass-associated products (BAP_L) are retained by the membrane, while a high concentration of mixed liquor suspended solids (MLSS) lowers the oxygen-transfer rate and the critical trans-membrane flux. According to the model results, effluent COD is sensitive to the influent COD and to the ability of the membrane to retain BAP_L. While the ability of an MBR to achieve high MLSS and volumetric loading has cost benefits, high MLSS increases the required aeration power and decreases the trans-membrane flux. These strong trends point out the areas in which MBR research ought to yield a large benefit.

Keywords aeration power; membrane bioreactor; microbial products; trans-membrane flux; water quality

INTRODUCTION

Membrane bioreactors (MBRs), a marriage of microbiology and membrane technologies, are taking an increasingly large share of the wastewater-treatment market. A survey of the eight major MBR vendors shows that the number of MBRs in operation worldwide increased from 6 in 2000 to 166 in 2011, while the treatment capacity increased from about 38,000 to 250,000 m^3/day (10 MGD to 650 MGD) (1). These represent average growth rates of 30% and 38% per year for number and capacity, respectively.

Received 1 November 2009; accepted 31 December 2009.
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Although the MBR is a normal activated sludge process in most ways, utilizing low-pressure membranes to replace the gravity settler in activated sludge offers significant advantages in terms of operations simplicity, economics, and performance (1,2). The greater reliability of membrane separation allows MBRs to be operated with higher solids retention time (SRT), but lower hydraulic retention time (HRT), compared with conventional activated sludge. This advantage leads to a smaller footprint and capital-cost savings. Operations flexibility, automation capability, and the potential for retrofits and expansion also are enhanced with the MBR. Furthermore, membrane filtration improves effluent quality, since the membrane consistently provides an effluent with no suspended solids. In addition, some of the larger soluble macromolecules are removed from the effluent (3,4), which enhances effluent quality further, particularly if the retained molecules are more completely biodegraded.

While the MBR offers many benefits, they come with a set of trade-offs. For example, the membranes add significant capital cost and also operating cost for keeping them from fouling (1,5). Operation with a higher SRT, lower HRT, or both increases the concentrations of mixed liquor volatile suspended solids (MLVSS) and mixed liquor suspended solids (MLSS), and this can reduce aeration efficiency and increase the trans-membrane pressure needed to produce the effluent flow (1,6).

Our focus is on the performance aspects of MBRs. We take advantage of a series of recent advances in the quantitative modeling of microbiological processes immediately relevant to MBRs.

1. A unified model of active biomass, inert biomass, soluble microbial products (SMP), and extracellular polymeric substances (EPS) (7,8) makes it possible to sub-divide the biomass into its basic components, which behave quite distinctly with SRT. This allows an accurate description of the biomass concentration, its components, and its wasting rate.

2. A meta-analysis of MBR performance data (6) quantifies when and how the MLVSS concentration affects aeration efficiency and the trans-membrane flux.

In this work, we create and utilize a comprehensive, mechanistic model of the microbiological phenomena that affect effluent water quality, aeration efficiency, excess solids wasting, and trans-membrane flux in MBRs. The specific goals are to:

1. Develop a mechanistic model that incorporates the new advancements for the MBR setting.
2. Use the model to predict MBR performance in terms of effluent chemical oxygen demand (COD), MLVSS, excess sludge production, O_2 supply required, aeration power needed, and trans-membrane flux.
3. Define trends in MBR performance with controllable or variable design/operation factors: e.g., SRT, HRT, influent COD, and membrane removal of organic macromolecules.

To the degree possible, we compare model results with measurements in field-scale and pilot-scale MBRs to interpret why we see experimental results and to identify when fundamental modeling advances are needed.

MODELING METHODS

Model Overview

The framework of our model is based upon the analysis and design of a conventional activated sludge (CAS) process by Rittmann and McCarty (2001). Because MBRs replace gravitational settling with membrane separation, the CAS design was modified to accurately represent processes of an MBR. Four important changes were made from the basic CAS model:

1. The membrane accomplishes perfect retention of solids in the system. Thus, MBR effluent contains no active biomass, residual inert biomass, or EPS. Solids are removed from the system only by sludge wasting.
2. Active and inert biomass, EPS, and SMP (i.e., utilization-associated products (UAP) and biomass-associated products (BAP)) are described by a set of nonsteady-state mass balance equations that represent the unified theory of (7,8), who made the pathways of electron flow from the donor substrate to the range of microbial products consistent and comprehensive.
3. BAP are composed of macromolecules that range in size (10), and the larger molecules cannot pass through the membrane. In the model, the large-BAP fraction (BAP_L) is wasted with solids, but does not pass through the membrane to the effluent. The small-BAP fraction (BAP_S) passes through the membrane, leaving the system in effluent and waste streams. Also passing through the membrane are the original substrate (S) and UAP.
4. Membrane separation allows MBRs to operate at much higher MLSS concentrations than those used in conventional activated sludge reactors. Because increasing MLSS affects the oxygen transfer efficiency and trans-membrane flux within a system, the model includes MLSS-specific adjustments to these parameters based on the analysis of MBR performance by Schwarz et al. (2006).

The model contains seven nonsteady-state equations to quantify relationships among three solid and four soluble species according to the unified theory as modified for the MBR setting. Active biomass (X_a), residual inert biomass (X_{res}), and EPS are the solid species; soluble species are S, UAP, BAP_L, and BAP_S. Figure 1 summarizes all electron flows in the model. Donor electrons from original substrate are used to synthesize active biomass, manufacture UAP and EPS, and respire an electron acceptor (O_2) to generate energy (7). When active biomass is oxidized through endogenous respiration, energy is generated for cell maintenance, and residual inert biomass is generated. When UAP is produced, it is released directly into the aqueous solution. BAP is produced from the hydrolysis of EPS. Because UAP and BAP are biodegradable, a portion of their electrons can be used as "recycled" substrate by bacteria for biomass synthesis, while the remainder of electrons is devoted to the acceptor for energy generation. The model is constructed such that electrons from UAP and BAP can only be used for synthesis or energy generation, not for the formation of new UAP or EPS.

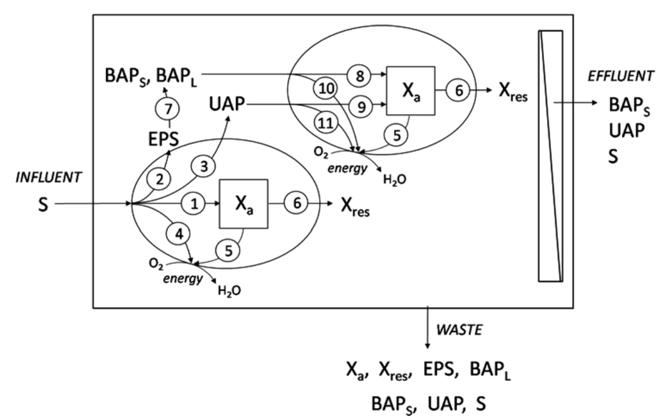

FIG. 1. Primary electron pathways in an MBR. The numbered pathways for electron flow represent (1) biomass synthesis, (2) EPS formation, (3) UAP formation, (4) substrate respiration, (5) endogenous biomass respiration, (6) formation of inert biomass from decay, (7) BAP formation from EPS hydrolysis, (8) biomass synthesis by utilization of donor substrate BAP, (9) biomass synthesis by utilization of donor substrate UAP, (10) donor substrate BAP respiration, and (11) donor substrate UAP respiration.

Substrate, UAP, and BAP_S are the only components of the system that can permeate the membrane and affect the quality of effluent. The remaining species (X_a, X_{res}, EPS, and BAP_L) constitute wasted sludge, as they are too large to pass through the membrane.

The model also relates the concentrations of these components to performance parameters commonly measured in an activated sludge process: effluent COD, MLVSS, MLSS, aeration power required, and the trans-membrane flux.

Jang et al. (2006) published an MBR model that captures some of the features of the unified model. In particular, it determines X_a, X_{res}, EPS, UAP, and fractions of BAP that will and will not permeate the membrane. In addition, the model calculates a modified fouling index used to predict biofouling potentials. It does not include the effects of MLSS on trans-membrane flux and k_La. Furthermore, (4) define MLSS and MLVSS differently from the definitions used in our model.

Mass Balance Equations

The seven mass balance equations (Eqns. 2 and 4–9) described in this section are patterned after those developed by Laspidou and Rittmann (2002b), but with adaptations made for an MBR. Each mass-balance equation is composed of rate and advection terms. The underlying bases for each rate term are provided in Laspidou and Rittmann (2002b). The definitions, values, and units of each parameter used in the mass balance equations are given in Table 1. Parameter values were taken from the literature (8,9,11).

The advection term is of the form

$$\frac{Q^0 Z^0}{V} - \frac{Q^e Z}{V} - \frac{Q^w Z}{V} \tag{1}$$

Q^0, Q^e, and Q^w represent the influent, effluent, and waste-biosolids flow rates, respectively (L/d). Z^0 and Z are the influent and reactor concentrations of the species of interest (mg/L), and V is the liquid volume (L). All concentrations are in units of mg COD/L, and terms are in mg COD/L-d. When a species is not present in a stream, i.e., X_a in the membrane permeate, its Z value is zero.

Original donor substrate (S). The first term in Eq. (2) is the rate at which substrate is consumed by active biomass.

$$\frac{dS}{dt} = -\hat{q}_S\left(\frac{S}{K_S+S}\right)X_a + \frac{Q^0 S^0}{V} - \frac{Q^e S}{V} - \frac{Q^w S}{V} \tag{2}$$

The specific rate of utilization, r_s, is part of the consumption term:

$$r_s = -\hat{q}_s\left(\frac{S}{K_S+S}\right) \tag{3}$$

Active biomass (X_a). In Eq. (4), the first term describes the synthesis rate of new active biomass from utilization of original substrate. The second term represents the synthesis rate of active biomass using electrons from UAP and BAP.

TABLE 1
Parameters for nonsteady-state mass balance and aeration equations in the MBR model

Variable	Definition	Value and Units
b	First-order endogenous decay rate coefficient	0.10 d^{-1}
f_d	Biodegradable fraction of active biomass	0.80 [unitless]
k_1	UAP formation rate constant	0.05 mg COD_P/mg COD_S
k_{EPS}	EPS formation coefficient	0.18 mg COD_P/mg COD_S
k_{hyd}	First-order hydrolysis rate coefficient	0.17 d^{-1}
K_{BAP}	Half-maximum-rate concentration for BAP utilization	85 mg COD_P/L
K_s	Half-maximum-rate concentration for utilization of original substrate	10.0 mg COD_S/L
K_{UAP}	Half-maximum-rate concentration for UAP utilization	100 mg COD_P/L
q_s	Maximum specific substrate utilization rate for original substrate	10 mg COD_S/mg COD_x-d
q_{BAP}	Maximum specific BAP utilization rate	0.07 mg COD_P/mg COD_x-d
q_{UAP}	Maximum specific UAP utilization rate	1.27 mg COD_P/mg COD_x-d
x_{BAPS}	Fraction of small BAP produced	0.5 [unitless]
Y_s	True yield for substrate utilizations	0.4 mg_X/mg_S
Y_P	True yield for SMP utilization	0.45 mg_x/mg_P
β	Wastewater oxygen solubility correction factor	0.95 [unitless]
$c_1{}^*$	Liquid phase equilibrium oxygen concentration	8.70 mg O_2/L
c_1	Liquid phase bulk oxygen concentration	2.0 mg O_2/L
SOTE	Standard oxygen transfer efficiency	2.0 kg O_2/kWh

Endogenous decay of active biomass is given by the third term. Because active biomass is a solid, it is retained by the membrane and has a concentration of 0 mg COD/L in the effluent. Thus, the effluent concentration rate term for X_a disappears from the advection equation.

$$\frac{dX_a}{dt} = Y_S r_S (1 - k_1 - k_{EPS}) X_a + Y_p \left(\frac{\hat{q}_{UAP} UAP}{K_{UAP} + UAP} + \frac{\hat{q}_{BAP} BAP}{K_{BAP} + BAP} \right) X_a - bX_a + \frac{Q^0 X_a^0}{V} - \frac{Q^w X_a}{V} \quad (4)$$

True residual inert biomass (X_{res}). The rate of formation of residual inert biomass is described by the first term in Eq. 5. Like active biomass, inert biomass does not permeate the membrane and only leaves the system in the waste-solids stream.

$$\frac{dX_{res}}{dt} = b(1 - f_d) X_a + \frac{Q^0 X_{res}^0}{V} - \frac{Q^w X_{res}}{V} \quad (5)$$

Extracellular polymeric substances (EPS). The first term in Eq. 6 is the rate at which a fraction of substrate electrons are used for EPS formation. The second term provides the rate of EPS loss due to hydrolysis, which forms BAP. EPS advects out only in the waste-solids stream.

$$\frac{dEPS}{dt} = k_{EPS} r_S X_a - k_{hyd} EPS + \frac{Q^0 EPS^0}{V} - \frac{Q^w EPS}{V} \quad (6)$$

Small biomass-associated products (BAP_S). The formation of small BAP from the hydrolysis of bound EPS is given by the first term in Eq. 7. The fraction of total BAP formed that is small, x_{BAPS}, is a variable input in the model. Biodegradation of BAP_S is given by the second term. BAP_S is present in waste-solids and effluent streams.

$$\frac{dBAP_S}{dt} = x_{BAPS} k_{hyd} EPS - \frac{\hat{q}_{BAP} BAP_S}{K_{BAP} + BAP_S} X_a + \frac{Q^0 BAP_S^0}{V} - \frac{Q^e BAP_S}{V} - \frac{Q^w BAP_S}{V} \quad (7)$$

Large biomass-associated products (BAP_L). The terms for BAP_L are the same as those for BAP_S, except that $(1 - x_{BAPS})$ of total BAP produced is too large to pass through the membrane and is, therefore, not in the effluent stream.

$$\frac{dBAP_L}{dt} = (1 - x_{BAPS}) k_{hyd} EPS - \frac{\hat{q}_{BAP} BAP_L}{K_{BAP} + BAP_L} X_a + \frac{Q^0 BAP_L^0}{V} - \frac{Q^w BAP_L}{V} \quad (8)$$

Utilization-associated products (UAP). The rates of UAP formation and degradation are given in the first and second terms, respectively, of Eq. 9. UAP is soluble and, like substrate and BAP_S, affects effluent quality.

$$\frac{dUAP}{dt} = k_1 r_s X_a - \frac{\hat{q}_{UAP} UAP}{K_{UAP} + UAP} X_a + \frac{Q^0 UAP^0}{V} - \frac{Q^e UAP}{V} - \frac{Q^w UAP}{V} \quad (9)$$

Model Solution and Performance Parameters

We made three assumptions to simplify the model solution without sacrificing important phenomena.

1. All influent soluble COD is biodegradable; it contains no refractory soluble COD.
2. Any particulate COD entering the reactor is either biodegradable or refractory. The biodegradable fraction is completely hydrolyzed to soluble COD in the MBR, and the soluble COD is utilized by the active biomass. The refractory COD passes through the system unchanged.
3. The reactor is completely mixed, which means that concentrations of all species are uniform and mass transport resistances are not considered.

We discretized the set of nonsteady-state mass balance equations and, using a small time step and constant input, solved the equations until the results reached steady-state values. Mass balance verification was completed following the verification method of (12), and the model gave near-perfect ($<0.1\%$ difference) mass balance closures for all COD. Steady-state values of S, X_a, X_{res}, EPS, BAP_L, BAP_S, and UAP were subsequently used as input for the remainder of model calculations.

MLVSS is the sum of the steady-state values of X_a, X_{res}, and EPS determined by solving the discretized equations. MLSS, estimated following the method given by Rittmann and McCarty (2001), is the sum of MLVSS, inorganic solids associated with MLVSS, and input inorganic solids. We assumed 10 parts inorganics per 90 parts organics in the MLVSS; thus, inorganic solids associated with MLSS are (10/90) MLVSS. Since only S, BAP_S, and UAP permeate the membrane, we computed effluent COD as the sum of these values.

Along with effluent water quality, the required aeration power and trans-membrane flux are key indicators of MBR performance. The required aeration power was determined by first calculating the oxygen supply rate (kg O_2/d), which is the difference between the input and output oxygen demand of the reactor.

$$O_2^{in} = Q^0 (O_2^0 + S^0 + X_a^0 + X_{res}^0 + EPS^0 + UAP^0 + BAP_S^0 + BAP_L^0) \quad (10)$$

$$Q_2^{out} = (Q^e + Q^w)(S + UAP + BAP_S) + \frac{(X_a + X_{res} + EPS + BAP_L)V}{\theta_x} \quad (11)$$

To determine the aeration power requirement of an MBR in kilowatts (kW), the oxygen supply rate was divided by the field oxygen transfer efficiency (FOTE) (kg O_2/kWh):

$$FOTE = SOTE \times 1.035^{T-20} \times \frac{\alpha(\beta c_1^* - c_1)}{9.2} \quad (12)$$

where SOTE is the standard oxygen transfer efficiency (kg O_2/kWh), T is the reactor temperature (C), c_1^* is the liquid phase oxygen concentration (mg/L) in equilibrium with the bulk gas phase, c_1 is the liquid phase bulk oxygen concentration (mg/L), β is a correction factor to better represent wastewater oxygen solubility, and α is a correction factor to better describe the aeration capacity in a volume of wastewater (9). Pilot- and full-scale studies of MBR aeration have shown that α decreases as the MLSS concentration increases (6). The following equation, developed from a pilot-scale study of internal and external MBRs, describes the relationship between α and MLSS (6):

$$\alpha = e^{-0.088 MLSS} \quad (13)$$

where MLSS is in units of grams per liter (g/L). Values of the other factors in the FOTE equation, given in Table 1, were selected for typical wastewater conditions and do not vary with MLSS. Once α was determined and FOTE calculated, we computed the power requirement by dividing the oxygen supply rate by FOTE.

Trans-membrane flux is the water throughput capacity of a membrane, expressed in units of volume of permeate passing through a unit of membrane surface area per day. Critical permeate flux (J_c) is the flux value above which the deposition of microbial aggregates begins, forming a "cake layer." For steady-state operation, flux should be maintained at or below the critical flux to reduce fouling from cake layer formation. Based on findings of how critical flux is affected by hydrodynamics and MLSS concentration, (6) developed relationships to quantify flux for given MLSS and cross-flow velocities (CFVs). Because the majority of MBRs currently in full-scale operation are internal MBRs (1), we used the equation for the critical flux of internal MBRs (IMBRs):

$$J_c = 31.85 MLSS^{-0.17} \quad (14)$$

Modeling Strategy

In order to define trends in MBR performance with respect to operational parameters, we ran numerous scenarios with different combinations of values of S^0, SRT, and HRT. We first defined a range of values for each parameter. For S^0, the minimum value of the range was 100 mg COD/L, the maximum was 1000 mg COD/L, and the typical value was defined as being 550 mg COD/L. SRT ranged from 2 to 60 days, with a typical value of 12.5 days. HRT varied from 1 to 10 hours, and we chose 5.5 hours as the typical HRT. (1) surveyed the operating conditions and performance of full-scale MBR facilities. They found that the influent COD ranged from 110 to 600 mg COD/L, the SRT was from 3 to 50 days, and the HRT was from 3 to 20 hours. Thus, the ranges of values we selected are consistent with current practice. The fraction of small biomass produced, x_{BAPS}, also was a variable parameter. The range for x_{BAPS} is 0 to 1.0, and we used 0.35 as a typical value, as this is close to what (3) found to be appropriate for modeling MBR results.

Each individual input was varied across its designated range of values, while the other inputs were fixed at either minimum, typical, or maximum values of their ranges. We present combinations of inputs that yield a comprehensive array of operation scenarios and provide insight into relationships between different features of MBR performance and S^0, SRT, HRT, and x_{BAPS}. The performance features include effluent COD, MLVSS, solids wasting rate, required aeration power, and critical trans-membrane flux.

RESULTS AND DISCUSSION

Effluent COD

Figure 2 shows the effect of influent donor substrate (S^0), SRT, and HRT on effluent COD. This figure illustrates the format in which we highlight the results and main trends. We show three curves to create a "performance envelope" for the range of parameter combinations we tested. The top and bottom curves are the highest and lowest values for the output parameter (y-axis), and the legend indicates what combinations of parameters give those curves. The middle curve is for the typical values of the parameter ranges. A significant slope to a curve means that the dependent parameter (the x-axis) has a strong impact on the output parameter. Having the curves close together indicates that the other input parameters have little impact.

Figure 2a shows that S^0 has a pronounced impact on effluent COD, but HRT and SRT have minimal effects. COD in the effluent rises steadily when the influent COD concentration increases: from ~6 mg COD/L for $S^0 =$ 100 mg COD/L to ~20 mg/L for $S^0 = 1{,}000$ mg COD/L. However, the increase in effluent COD is not proportional to the increase in S^0, and the percentage COD removal goes from ~94% to ~98%. The very narrow band of curves, reflecting small differences in effluent COD concentrations despite very different operation regimes for SRT and HRT, means that the effluent COD is not sensitive to SRT or HRT, which is confirmed by the flat slopes in Figs. 2b and 2c.

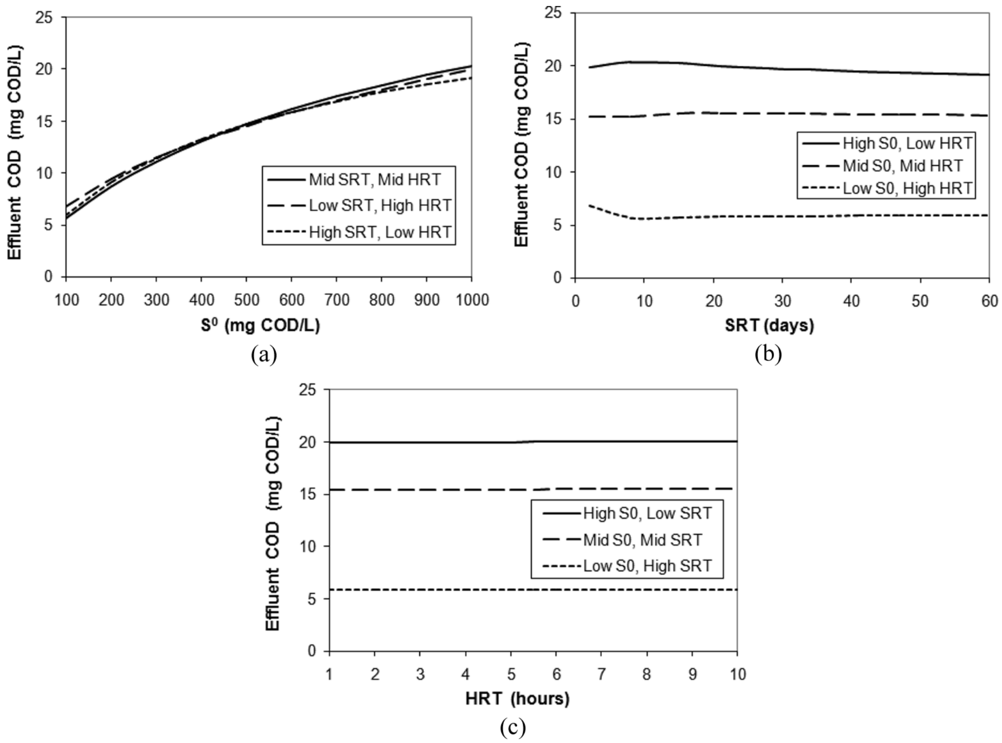

FIG. 2. Effect of (a) S°, (b) SRT, and (c) HRT on effluent COD.

The components comprising effluent COD are shown in Fig. 3. Plots of effluent COD against S^0 and SRT highlight that BAP_S dominates the effluent COD for SRT greater than about 8 days (81 to 91%), which is in good agreement with the experimental finding by Jang et al. (2007) that SMP accounts for 83–91% of COD in MBR effluents. In Fig. 3, UAP comprises 7 to 15%, while S is only 2 to 4% of COD in the effluent. BAP_S makes up a larger fraction of the effluent COD as S^0 increases, but it becomes a smaller fraction of S^0. This explains why the percentage removal of COD goes up as S^0 is larger.

Since BAP_S controls effluent COD, the effluent quality is changed if the membrane retains more or less BAP. In the model, this is reflected by the ratio of BAP_S to total BAP (i.e., x_{BAPS}). We used a typical value of $x_{BAPS} = 0.35$ (3,13) to generate the results in Figs. 2 and 3. Having $x_{BAPS} = 1$ is the same as having activated sludge with a settler instead of a membrane, and a value of 0 reflects retention of all BAP. Figure 4 quantifies the importance of x_{BAPS} on effluent COD. The effluent COD could decline to as low as 2 mg COD/L if all BAP were retained by the membrane. The value for achieving our typical retention of BAP_L ($x_{BAPS} = 0.35$) is apparent, since the effluent COD (~15 mg COD/L) is only about 35% of that for no BAP retention.

Oppenheimer et al. (2010) tabulated the effluent COD values from the full-scale MBR facilities and found that the range was 8 – 30 mg COD/L. The modeling results in Figs. 2 and 3 correspond to the observed values. Seeing some observed values well above 15 mg COD/L suggests that x_{BAPS} may have been larger than 0.35 in some cases. Since x_{BAPS} is poorly understood, but has a strong impact on effluent quality, it deserves attention as a means to characterize membranes used in MBRs.

Mixed Liquor Volatile Suspended Solids

Figure 5 illustrates the impact of S^0, SRT, and HRT on MLVSS. Note that the concentrations are plotted logarithmically. As is well known for all activated sludge processes (9), MLVSS increases when the influent substrate increases (Fig. 5a), the SRT increases (Fig. 5b), and the HRT decreases (Fig. 5c). The fact that the top curve in Fig. 5a has MLVSS concentrations so much higher than the other curves demonstrates that the combination of high SRT and low HRT can allow a very high MLVSS. This is reflected by the bioconcentration factor, SRT/HRT, which is 1,440 for the top curve in Fig. 5a, but only 55 for the intermediate curve. In the high-extreme case, the MLVSS curve extends from about 20,000 to about 220,000 mg VSS/L, making volumetric loading 4 – 25 kg COD/m^3-d, which is much higher than typical MBR loading rates (1.2 – 3.6 kg COD/m^3-d) (Metcalf and Eddy 2003; Oppenheimer et al. 2010). Clearly, the MLVSS and volumetric loading values for the high-extreme case are unrealistic, and it is not

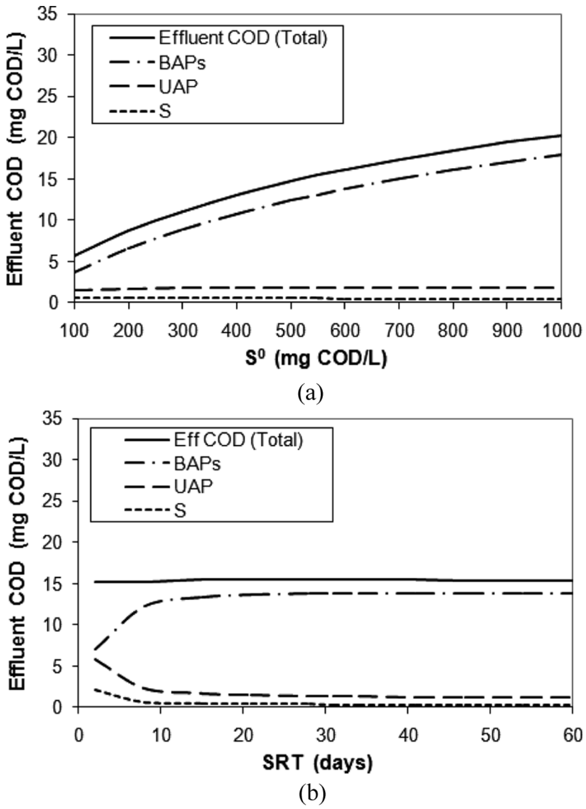

FIG. 3. Constituents of effluent COD with respect to (a) influent COD and (b) SRT. Non-varied parameters are fixed at typical values ($S^\circ = 550$ mg COD/L; SRT = 12.5 days; HRT = 5.5 hours; $x_{BAPS} = 0.35$).

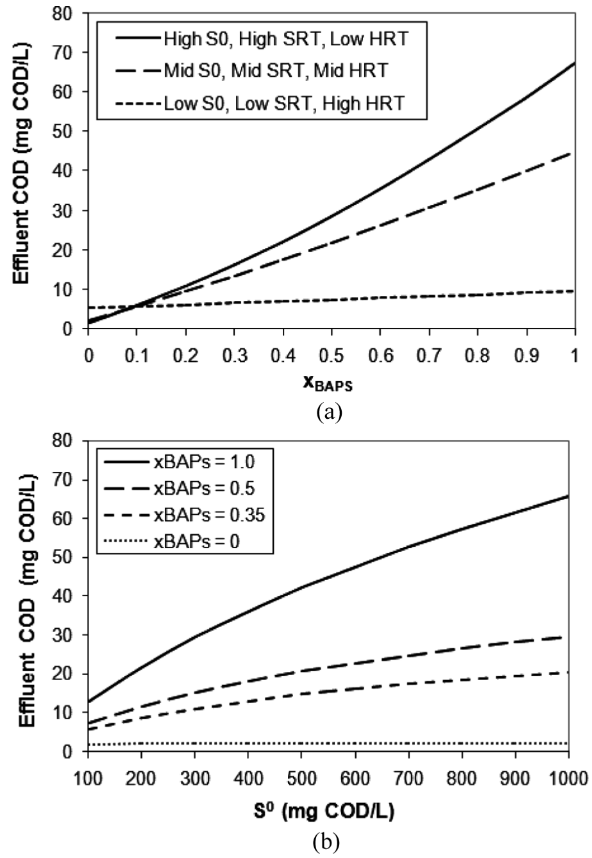

FIG. 4. (a) Effect of varying x_{BAPS} of three different scenarios on effluent COD. (b) Effluent COD as a function of S° and x_{BAPS}; SRT and HRT are typical values (12.5 days and 5.5 hours, respectively).

feasible to have an SRT/HRT ratio close to 1,400. For the typical case, the MLVSS is in the range of 1,300 to 13,000 mg/L, which corresponds reasonably well to the values tabulated by Oppenheimer et al. (2010) in their survey of full-scale MBR facilities: 4,200 to 20,000 mg/L. The generally higher values from the field survey probably reflect that SRT/HRT ratios were somewhat larger than the value for our typical case (55).

As shown in Fig. 5b, the MLVSS concentration changes most rapidly when SRT increases from 2 to 10 days. In Fig. 5c, the slopes of the curves are steepest with a 1- to 2-hour HRT, when small decreases in HRT yield significant increases in MLVSS concentration.

The trends in Fig. 5a underscore the potential to achieve high values of MLVSS and volumetric loading in an MBR by achieving a large bioconcentration factor. The advantages in terms of capital costs and areal footprint are obvious, but they come with trade-offs that we quantify in upcoming sections.

Figure 6 shows quantitatively how X_a, X_{res}, and EPS contribute uniquely to MLVSS as S^0 and SRT vary. The rate of change of all biomass concentrations is greatest for SRT less than about 10 days. All components increase with increasing S^0 (Fig. 6a) and increasing SRT (Fig. 6b), since they are solids. X_a increases relatively more strongly with S^0, because it is the direct result of substrate utilization. In contrast, X_{res} increases relatively more with SRT, since it is the result of biomass decay. X_a makes up the largest portion of MLVSS only until an SRT of about ~20 days, beyond which X_{res} becomes the dominant fraction. For an SRT of 60 days, X_{res} is 67% of the MLVSS, while X_a is only 25%. EPS generally follows X_a, but is more important at lower SRT: 48% of X_a at a SRT of 2 days versus 29% at 60 days.

Solids Wasting

Figure 7 presents the influences of S^0, HRT, and SRT on the rate of MLVSS wasting, expressed as kg COD/d. As is the case for any activated sludge process, increasing S^0 or decreasing the SRT requires more sludge wasting, while HRT has no effect.

Aeration Power

Figure 8 illustrates strong impacts of S^0, SRT, and HRT on the required aeration power. The results reflect

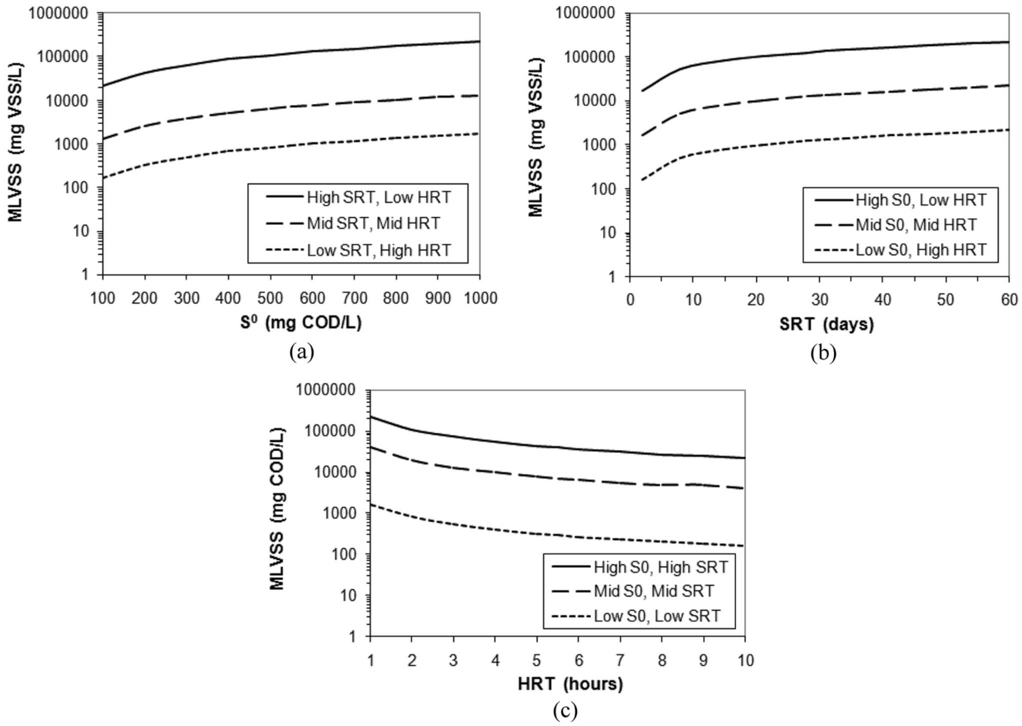

FIG. 5. Effect of (a) S°, (b) SRT, and (c) HRT on MLVSS. Note that the MLVSS concentrations are plotted on a logarithmic scale due to the very large range of values.

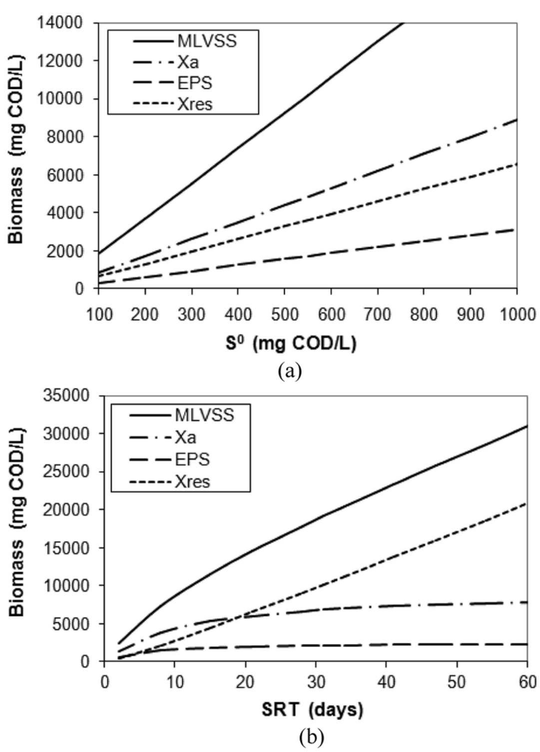

FIG. 6. Effect of (a) S° and (b) SRT on biomass components. Non-varied parameters are fixed at typical values ($S^\circ = 550$ mg COD/L; SRT = 12.5 days; HRT = 5.5 hours; $x_{BAPS} = 0.35$).

an interaction between the oxygen demand that must be met and the effect of MLSS on aeration efficiency. For a given reactor volume, the influent substrate loading is increased when S^0 goes up or HRT goes down. Thus, part of the strong trends in Figs. 8a and 8c are due to this loading effect. Likewise, a longer SRT allows more endogenous respiration of biomass components, and part of the rise in aeration power in Fig. 8b is from this effect.

The impacts of MLSS on aeration efficiency are even stronger than those from oxygen demand. High MLSS concentration decreases the efficiency of oxygen transfer in wastewater (6), and this is reflected by the way in which the α factor is affected by MLSS in Eq. 13. When α decreases, Eq. 12 shows that the field oxygen transfer efficiency (FOTE) declines proportionally, and more aeration power is required for the same oxygen demand. Thus, the power requirements for the top curve are unrealistically high, another reason why operation with such a high SRT/HRT ratio is impractical. For the intermediate curve, the aeration power requirement is 1.2 to 5.2 kWh/kg COD removed, or 0.05 to 2.2 kWh/m^3 of wastewater treated. Oppenheimer et al. (2010) found that full-scale MBR facilities reported energy-use rates of $0.5 - 1.8\,kWh/m^3$. The negative impact of a low α value is so profound that research needs to be focused intensely on this topic.

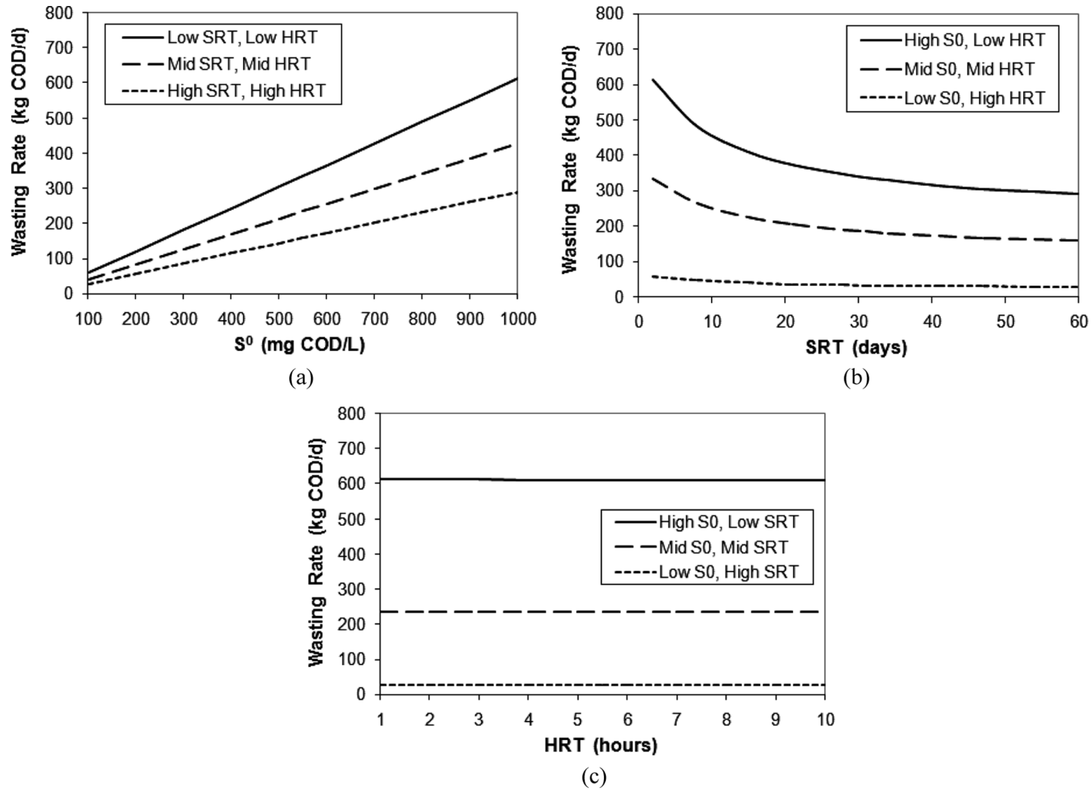

FIG. 7. Effect of (a) S°, (b) SRT, and (c) HRT on sludge wasting rate.

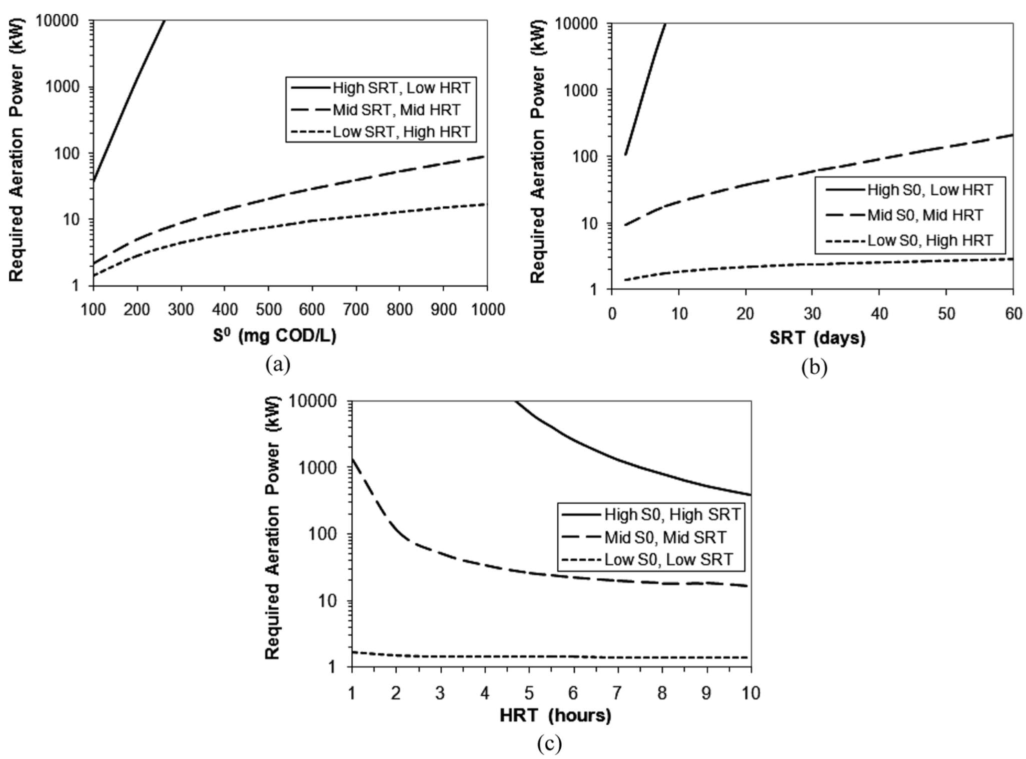

FIG. 8. Effect of (a) S°, (b) SRT, and (c) HRT on required aeration power.

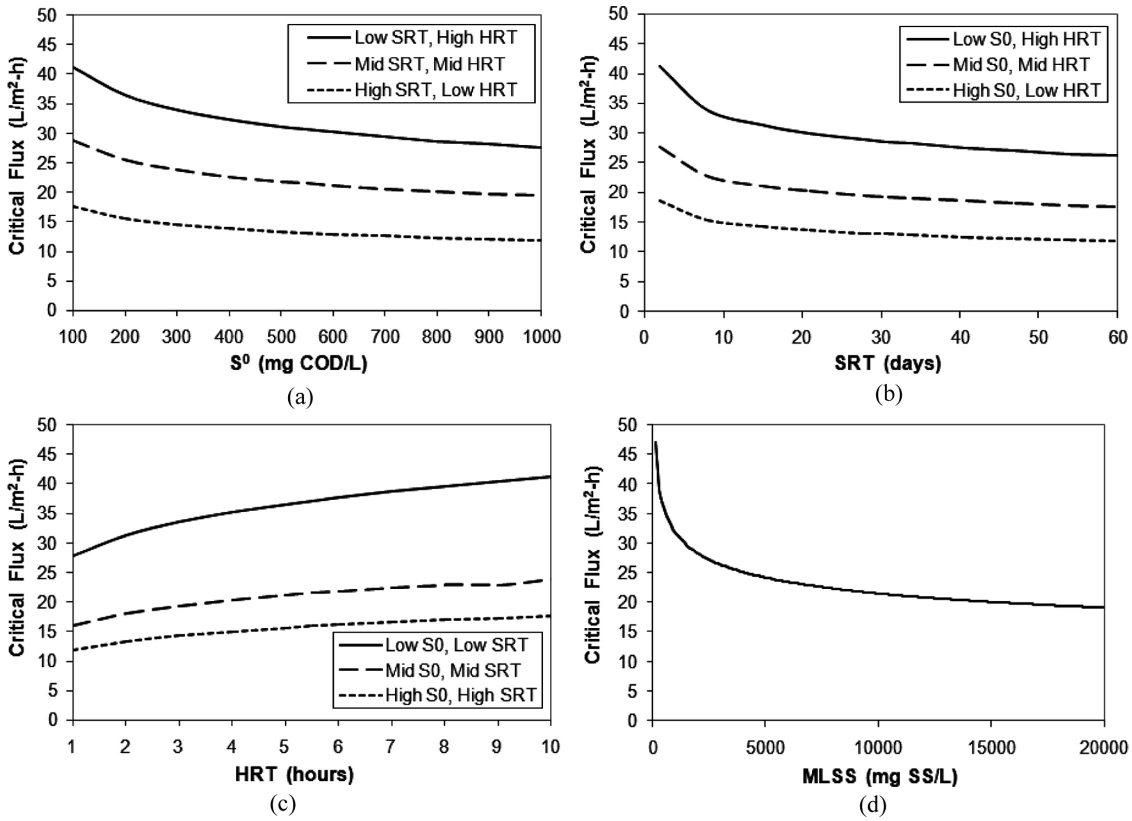

FIG. 9. Effect of (a) S°, (b) SRT, (c) HRT, and (d) MLSS concentration on critical trans-membrane flux.

Trans-Membrane Flux

High MLSS also results in greater membrane fouling, which decreases trans-membrane flux (6). Figure 9 shows how increasing S^0 or SRT/HRT ratio, both of which increase the MLVSS (Fig. 5) and MLSS (Fig. 9d), causes the critical flux to decline. The critical flux for the intermediate case is around $22\,L/m^2$-h, but the range is from 12 to $41\,L/m^2$-h. Oppenheimer et al. (2010) found a range of 12 to $42\,L/m^2$-h for operating fluxes, which is an amazing correspondence. The strong sensitivity of critical flux to MLSS presented here underscores that better quantification of the relationship could have an important impact on defining the trade-off inherent to MBRs.

CONCLUSIONS

While the MBR behaves like any activated sludge process in most ways, the membrane separator changes some factors that improve effluent quality and the ability to accumulate a high MLSS concentration. Based on the unified model for the key biomass and soluble components in all activated sludge processes, we created a mechanistic model that is directly relevant to the unique conditions of MBRs. Specifically, we divided the BAP into a large fraction that is retained by the membrane separator and a small fraction that passes through the membrane, included relationships for how high MLSS concentration lowers the oxygen-transfer rate and the trans-membrane flux, and solved the model for ranges of S^0, SRT, and HRT relevant to MBR operation.

The effluent COD is most sensitive to the influent COD concentration and to the ability of the membrane to retain BAP_L. High influent COD or a membrane that is relatively permeable to BAP (i.e., has a large x_{BAPS}) results in larger effluent COD. The ability of the membrane to retain biomass makes it possible to operate an MBR with a high SRT/HRT ratio, and that can make the MLVSS and MLSS quite high. The volumetric loading also increases proportionally. While high MLSS has obvious benefits in terms of lowering capital costs and land-area requirements, it leads to trade-offs, since high MLSS increases the aeration power required per unit COD and decreases the trans-membrane flux.

Several factors that strongly affect MBR performance are poorly understood. High marginal benefits should be obtained by research focused on quantifying how membranes retain BAP (i.e., what is x_{BAPS}?) and how α and the critical trans-membrane flux are affected by MLSS or a particular component of the mixed liquor (e.g., EPS or BAP_L). The components included in our model and the trends shown by it should help guide the MBR field towards the most productive areas for research and development.

ACKNOWLEDGEMENTS

We thank Aron Cummings for converting the program to FORTRAN and the Water Reuse Foundation for financial support. Funding was also provided by the U.S. Environmental Protection Agency through a grant/cooperative agreement (RD831713 and RD833322). This publication has not been subjected to the Agency's required peer and policy review. Therefore, it does not necessarily reflect the views of the Agency, and no official endorsement should be inferred.

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