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Critical Review on the Effects of Mixed Liquor Suspended Solids on Membrane Bioreactor Operation

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Abstract: One of the characteristics of MBRs is that they typically operate with higher mixed liquor suspended solids (MLSS) concentration than activated sludge with a conventional settling tank. While higher MLSS has obvious benefits in terms of increasing the volumetric loading or the solids retention time, it can have negative impacts on system operation and economics. We critically evaluate three hypotheses on how high MLSS may adversely affect MBR operation:

(1) reduced membrane flux with high MLSS,
(2) decreased aeration alpha (α) value with high MLSS, and
(3) poorer thickening characteristics of excess sludge wasted from an MBR based on the Sludge Volume Index (SVI) and the Capillary Suction Time (CST).

The results support the first and second hypotheses, but not the third. Increasing MLSS decreases the critical permeate flux, but the effect is strong only for MLSS $< \sim 5$ g/L. For the typical MLSS zone ($> \sim 5$ g/L), flux-management

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techniques to prevent serious cake formation are more important than MLSS. The aeration α decreases with increasing MLSS concentration, although the strength of the correlation depends on system-specific factors that are poorly understood. Thickening properties of IMBR sludge are not significantly poorer than those of traditional activated sludge, based on available CST tests.

Keywords: Aeration alpha, MBR, MLSS, permeate flux, thickening, viscosity

INTRODUCTION

The membrane bioreactor (MBR) is gaining widespread acceptance due to technology advancements that significantly reduce construction and operating costs and to the performance advantages inherent to replacing gravity settling with membrane separation. Research and practical experience generally demonstrate that the biological characteristics of MBRs are similar to those of traditional activated sludge. For instance, the kinetics and stoichiometry of the MBR process are essentially the same as for normal activated sludge (1).

In spite of many similarities between the MBR and traditional activated sludge (TAS), important differences exist. Perhaps the most profound is that substituting membrane separation for gravity sedimentation allows much higher mixed liquor suspended solids (MLSS) concentrations. Elevated MLSS reduces bioreactor volume for the same BOD load and solids residence time (SRT); and it allows a higher SRT or BOD load for the same volume. However, elevated MLSS may produce adverse effects: e.g., a lower oxygen-transfer rate or hydraulic capacity (referred to as permeate flux for membrane systems). Moreover, elevated MLSS and other environmental conditions within the MBR may result in a waste sludge with poorer thickening characteristics that impede the performance of subsequent sludge-processing steps.

The authors participated in the assembly of an extensive computerized literature database on MBRs by the Water Environment Research Foundation (WERF) (2). Assembling the database motivated us to address these critical issues about the role of MLSS in MBR operation (3) and also gave us access to most of the refereed and gray literature. Here, we report the results of our critical evaluations of the following three hypotheses concerning the effects of MBR operation versus using a conventional settling tank:

1. Increased MLSS concentration reduces the membrane operating flux.
2. The aeration alpha value decreases with increasing MLSS concentration.
3. The thickening characteristics of excess sludge wasted from an MBR are poorer than those of traditional activated sludge based on the Sludge Volume Index (SVI) and the Capillary Suction Time (CST).

For each hypothesis, we provide essential background information, report the results we obtained by exploiting information obtained mainly via the

WERF database, conclude about the truth of the hypothesis, and suggest important directions for practice and research.

HYPOTHESIS 1: INCREASED MLSS REDUCES PERMEATE FLUX

Background

MBR technology was first introduced for use in small applications, such as for trailer parks, ski resorts, and office complexes. Operated at long SRT (>50 days), high MLSS (15,000–25,000 mg/L), and low permeate flux (<20 m^2-h, or <0.02 m/h), these package systems achieve high effluent quality, complete nitrification with infrequent sludge wasting, and minimal membrane fouling and cleaning (4). Subsequently, designers reduced the SRT and MLSS in an attempt to increase permeate flux and reduce membrane surface area (4). These systems operate at relatively low SRT (10–15 days), low MLSS (10,000 mg/L), and high flux (>26 L/m^2-h, or >0.026 m/h). A key assumption underlying this MBR development is that membrane flux improves at lower MLSS, reducing the cost of membrane equipment (4). Additionally, lower MLSS may allow higher peak-to-average flow ratios. Despite its obvious significance, an MLSS-flux relationship has not been quantified so that it can be used to optimize MBR design and operation.

Quantitative flux-MLSS relationships should be system-specific, because MBR systems differ in fundamental ways. Membranes are either operated under pressure and located external to the tank containing the mixed liquor (i.e., external MBRs, or EMBRs) or operated under vacuum and immersed directly into the tank containing the mixed liquor (i.e., internal MBRs, or IMBRs). The external configuration uses tubular or modified plate-and-frame membranes. Types of immersed membranes are hollow fiber, oriented either vertically or horizontally, or flat sheet. Additionally, membranes differ in their pore size and the types of raw material (e.g., cellulose acetate, ceramics, or organic polymers). Importantly, the two basic MBR types rely on different flux-management strategies. Water cross flow (for EMBRs) or air sparging beneath the membrane (for IMBRs) provides the shear forces that minimize the buildup of solids at the membrane surface. Hence, the key operating parameters to maintain adequate flux for EMBRs are cross-flow velocity and pressure provided by a recirculation pump, while they are the rate of coarse bubble aeration and suction pressure for the IMBR. While IMBRs have a more restricted differential pressure and, hence, must operate at a lower flux, EMBRs are considerably more energy-intensive. Additionally, both systems typically depend on intermittent physical cleaning, such as by frequent back pulsing of the membranes with clean permeate, to produce stable fluxes.

Mechanisms of Membrane Fouling

Membrane fouling is the systematic accumulation of suspended solids, colloids, and macromolecules on the membrane surface or inside the pores, causing a reduction in membrane permeability. Adsorption of solutes and colloids narrows and blocks pores. This type of fouling is considered irreversible, causes the characteristic slow permeability decline, and generally must be removed by chemical cleaning (5). The deposition of microbial aggregates, or flocs, on membranes often produces a compact "cake layer," which is generally viewed as reversible and removed by physical cleaning. The cake layer, which often controls overall fouling resistance, depends on several factors, such as trans-membrane pressure (TMP), MLSS concentration, particle size, cake compressibility, and shear forces at the membrane surface.

Figure 1 illustrates how the fouling mechanisms control the relationship between permeate flux (J) and TMP. Irreversible fouling by pore blocking and narrowing reduces the slope of the linear portion of the curve over time. The initial reduction is fast, but gradually slows. Eventually, irreversible fouling becomes so great that chemical cleaning is needed to restore membrane capacity, which moves the linear curve from situation (b) to close to situation (a).

The critical condition, defined by the critical flux (J_c) and the critical TMP (P_c), occurs at the onset of particle deposition to form a cake. As TMP increases past P_c, the cake layer thickens and compresses, which prevents the flux from

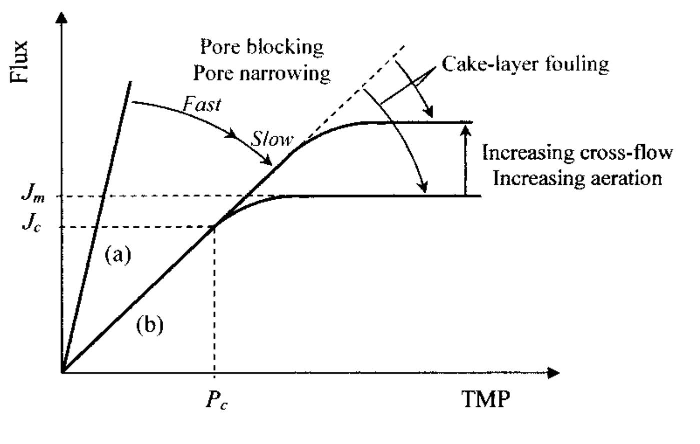

Figure 1. Flux-TMP curves for filtration of (a) pure water and (b) mixed liquor (6). The linear part of the curve is lower for the mixed-liquor because of irreversible pore blocking and narrowing by colloids and macromolecules. In the sub-critical zone, flux increases linearly with TMP, but the line moves from (a) to (b). Above the critical flux (J_c), in the supra-critical zone, flux becomes independent of TMP. Shear from cross-flow velocity (EMBR) or air scour (IMBR) extends the sub-critical operation to higher TMPs.

increasing linearly with TMP. For somewhat higher TMP, the flux curve flattens, and the maximum flux J_m is reached. Then, TPM increases are fully neutralized by greater cake-layer resistance. Increasing cross-flow velocity (EMBR) or increasing air-scour intensity (IMBR) is effective in increasing J_c and J_m, thereby extending the zone of linear operation.

The flux-step method is the most common procedure to measure critical flux. As illustrated in the left part of Fig. 2, the flux is increased step-wise while TMP is monitored. The critical flux is determined when TMP does not stabilize over the time step. A surrogate variable for J_c is the maximum or limiting flux (right part of Fig. 2), which is the steady-state flux after extended filtration at high TMP and after formation of a cake layer.

As Fig. 3 shows, MBRs can be operated either sub-critically (point 1) or supra-critically (points 2, 3, and 4). Sub-critical operation at steady state demands high shear forces to keep J_c high so that the operating J is below J_c to control fouling. Stable supra-critical operation, on the other hand, is not steady state, but only possible with additional flux-management action, such as back pulsing with permeate. Then, stable cyclical operation can be viewed as moving between two curves. After back pulsing, the flux-TMP line goes through points 2 and 4. This line is characterized by complete removal of deposited particles and, perhaps, partial removal of fouling due to pore narrowing and blocking. Subsequent filtration either at constant flux (from point 2) or constant pressure (from point 4) is supra-critical, and cake fouling builds up until point 3 is reached. Then, back pulsing is repeated to return to point 2 or 4.

Flux Modeling

Models frequently used to quantify the critical condition (7) focus on the polarization layer that forms as a consequence of the imposed permeate flux. At steady state, each point within the polarization layer is in a

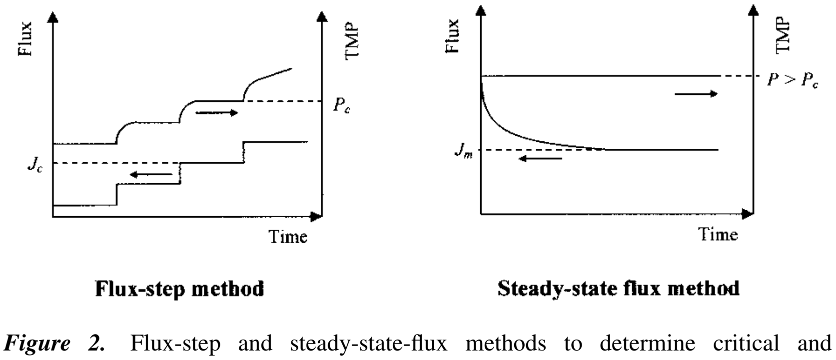

Figure 2. Flux-step and steady-state-flux methods to determine critical and maximum fluxes. Adapted from Chang et al. (5).

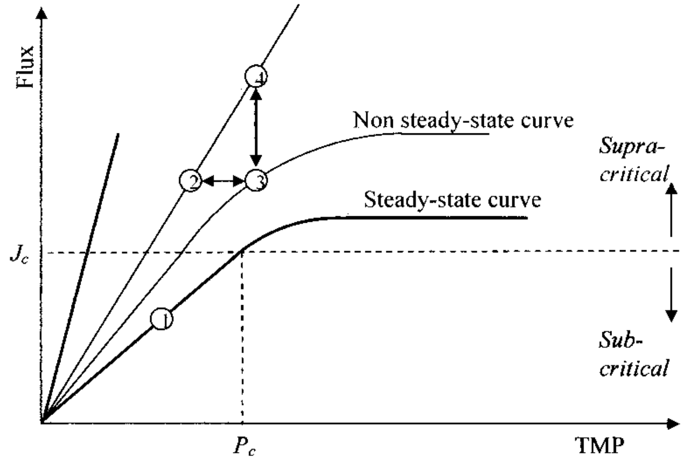

Figure 3. Sub-critical (point 1) and supra-critical (points 2, 3, and 4) operating strategies. Sub-critical operation is steady state, relying only on shear to keep $J < J_c$ at all times. Supra-critical operation is non-steady state and requires periodic back pulsing to remove cake resistance for constant-flux operation (between points 2 and 3) or constant-TMP operation (between points 4 and 3).

dynamic equilibrium in which the particles velocities of advection toward the membrane (proportional to the permeate flux) and back toward the bulk liquid (proportional to shear forces "lifting" the particle away from the surface) balance each other. Although the back-transport mechanism depends on particle size, shear-induced diffusion is considered to be dominant in the 1–40 μm size-range typical of MBRs (8). Shear-induced diffusion is proportional to the concentration gradient between the polarization layer and the bulk mixed liquor. If the particle velocity toward the membrane surface exceeds the maximum back-diffusion velocity, a cake layer continually grows, making a steady state based on concentration polarization impossible.

According to the shear-induced diffusion model (7), the critical permeate flux (J_c) is equivalent to the maximum back-transport velocity (v_b). The value of J_c or v_b depends on the limiting surface MLSS concentration (C_w in g/L), the bulk MLSS concentration (C_b in g/L), membrane length (in m), the wall shear rate (γ_0 in s^{-1}), and the particle radius (a in m) as shown in the following equations.

$$J_c = v_b = 0.126\gamma_0\left(\frac{C_w a^4}{C_b l}\right)^{1/3} \tag{1}$$

$$J_c = v_b = 0.078\gamma_0\left(\frac{a^4}{l}\right)^{1/3} ln\left(\frac{C_w}{C_b}\right) \tag{2}$$

Eqs. (1) and (2) represent limits for low and high MLSS concentrations, respectively. According to these relationships, the critical flux can be increased by making the particle size (a) or shear rate (γ_0) larger, but increasing the bulk MLSS concentration (C_b) causes the critical flux to decline. The latter trend is consistent with the hypothesis being evaluated. Because of the 1/3rd exponent in Eq. (1), the effect of MLSS concentration on flux is strong at low C_b, but declines as C_b increases. However, as C_b approaches C_w, the effect of MLSS concentration on flux becomes important again [Eq. (2)]. On the other hand, the effect of the shear rate is the same no matter the C_b value.

Compared to conventional activated sludge, the average diameter (a) of a particle in an MBR is considerably smaller, because bacteria are not selected for their ability to aggregate to large, settleable flocs. Moreover, the high shear forces introduced, particularly by pumping during cross-flow filtration, break up flocs. Thus, the average particle size is 1–3.5 μm in EMBRs, while IMBR particles vary between 20 and 40 μm (5). By comparison, activated-sludge flocs are usually larger, up to 200 μm (9). Smaller aggregates are less likely to be removed from the surface by inertial lift or shear-facilitated diffusion, and this is reflected in Eqs. (1) and (2) by a in the numerator.

A mixed liquor property that has been implicated with flux decline is viscosity, which affects the capacity of shear to lift particles from the surface. Trussell et al. (10) described an upper MLSS limit, ranging from 24 to 34 g/L, for which a sharp viscosity increase led to severe fouling and system failure.

The effect of viscosity on J_c is reflected mainly by the wall shear rate, which is defined as

$$\gamma_o = \tau_o/\eta \tag{3}$$

in which γ_o is the wall shear rate (s^{-1}), τ_o is the wall shear stress (Pa), and η is the dynamic viscosity (Pa-s). The wall shear stress depends on the friction factor (f), fluid density (ρ in g/L), and the fluid velocity past the membrane (u in m-s^{-1}) by

$$\tau_o = f\rho u^2/8 \tag{4}$$

If the flow is in the laminar region near the surface, then f can be estimated as

$$f = 64/Re \tag{5}$$

where $Re = \rho u d_h/\eta$ and d_h = the average channel diameter (m) (e.g., interior diameter of hollow fibers). Substituting Eqs. (5) and (4) into Eq. (3) gives

$$\gamma_o = 8u/d_h \tag{6}$$

which is independent of η, but first order in u. On the other hand, if the flow is in the turbulent region near the surface, then

$$f = 0.316/Re^{0.25} \quad (7)$$

and

$$\gamma_o = 0.0395\rho^{0.75}u^{1.75}/d_{h^{0.25}}\eta^{0.75} \quad (8)$$

Then, increasing η makes γ_o and J_c smaller, while u makes γ_o larger to the 1.75 power. Transition fluid dynamics near the wall should give an effect intermediate between Eqs. (6) and (8).

According to Xing et al. (11), η and ρ are related to C_b:

$$\eta = 0.2125C_b + 1.4793 \quad \text{(in mPa-s)} \quad (9)$$

and

$$\rho = 1000 + C_b \quad \text{(in g/L)} \quad (10)$$

where the expression for η was adjusted for use with mixed liquor at 15°C.

The C_b effect is considerably stronger on η than on ρ. Thus, an increase in C_b will decrease J_c directly in all cases [Eqs. (1) and (2)], but should indirectly decrease J_c by its effect on γ_o when flow conditions are turbulent near the membrane surface [Eqs. (9) and (8)].

Results and Discussion

Several researchers have determined how critical flux is affected by hydrodynamics and MLSS concentration. Table 1 summarizes this information for both MBR types. Some researchers report stabilized or steady-state flux instead of critical flux for EMBRs. The IMBR cross-flow velocities (CFV) were measured with a velocity meter. In one case, the bubbling airflow (AF) is reported instead of CFV.

Because EMBRs were introduced first, comparatively more studies have addressed the effect of operating parameters on EMBR membrane performance. Figure 4 summarizes the available flux-MLSS data for CFVs of 1 m/s and 3 m/s. First, Fig. 4 clearly shows that each CFV yields an overall decreasing trend of flux with MLSS concentration, which supports the hypothesis. This empirical observation agrees with the shear-induced diffusion modeling: the rate of J_c declines slows greatly as C_b becomes larger. In both cases, the critical flux almost plateaus for C_b greater than about 5 g/L. Second, a higher u increases J_c significantly, especially in the plateau region. Again, this agrees with the modeling concept that u and γ_o act on J_c for all C_b values, which means that increased shear is effective for increasing J_c when MLSS is greater than 5 g/L.

We used a simple potential function, similar to the shear-induced diffusion model summarized above [Eq. (1)], to quantify the flux-MLSS

Table 1. Review of the effect of MLSS concentration on critical flux for EMBR and IMBR systems

Membrane configuration and operating conditions	MLSS range tested (g/L)	CFV range tested (m/s)	Determination method	Reference
EMBR Kerasep, ceramic, 300 kDa T = 18°C, HRT = 6 h, SRT = 30 d	2.1–15.4	1–4	TMP-step	Cicek et al. (12)
EMBR Ceramic, 0.2 μm T = 35°C, HRT = 24 h, SRT = 30d	0.4–22	1–4	TMP-step (30 min)	Beaubien et al. (6)
EMBR Kerasep, ceramic, 0.1 μm T = 20°C, HRT = 24 h, SRT = 60d	0.9–9	3	Stabilized flux (4 h, 100 kPa)	Defrance et al. (13)
EMBR HVLP, hydrophilic, 0.45 μm Activated sludge filtration	1–10	1	Flux-step (30 min, 1 L/m^2-h)	Madaeni et al. (14)
EMBR Kerasep, ceramic, 0.1 μm T = 20°C, HRT = 24 h, SRT = 60 d	10	1–5	TMP-step (15 min, 0.2 bar) Flux-step (60 min, 10 L/m^2-h)	Defrance and Jaffrin (15)
IMBR Tubular, ceramic, 0.5 μm Hollow fiber, polyethylene, 0.1 μm T = 20°C, HRT = 12 h	3–20	0.3–0.8	Steady-state flux (4 h, 4–50 kPa)	Shimizu et al. (16)
IMBR Hollow fiber, polysulfone, 0.2–0.4 μm Activated sludge filtration	4–15.1	AF = 400 h	Flux-step (90 min)	Bouhabila et al. (17)

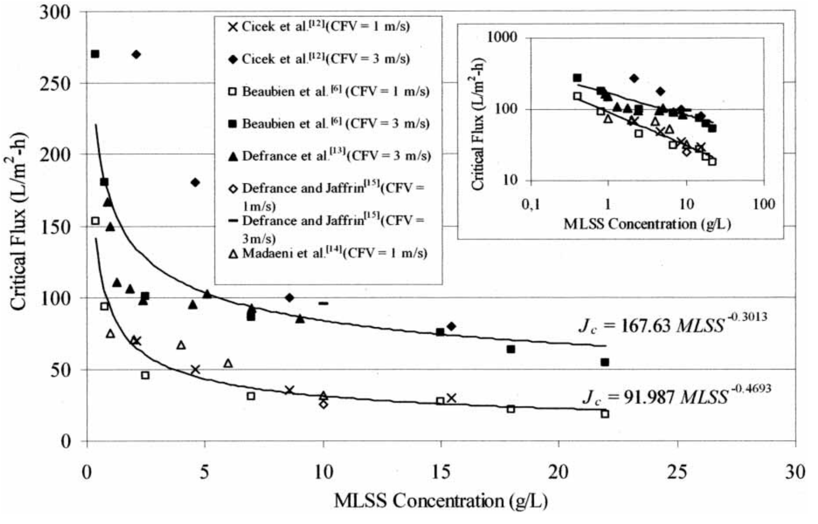

Figure 4. Effect of suspended solids concentration on critical flux for EMBRs, at cross flow velocities (CFV) of 1 m/s and 3 m/s. Potential curves give a good overall fit to the data. As cross-flow velocity increases, the MLSS exponents increase (see inset showing the data in the logarithmic domain).

relationship. Clearly, the data cluster around the two constant-CFV curves. Both curves flatten out at around 5 g/L, and the 3-m/s curve is higher than the 1-m/s curve by the same amount as the experimental data. In the low-MLSS zone (<5 g/L), high fluxes are explained by the large concentration gradient between C_w and C_b. The flux nearly stabilizes as the bulk MLSS concentration increases above 5 g/L. In this high-MLSS zone, shear rate more than MLSS concentration controls the flux. Interestingly, the MLSS exponent of the 3-m/s curve (−0.30) approaches the theoretical value of −0.33, suggesting that Eq. (1) alone could be used to represent the flux-MLSS relationship. The MLSS exponent of the 1-m/s curve (−0.47), however, is much lower than the theoretical value, suggesting that a combination of Eqs. (1) and (2) ought to be used in this case for the MLSS range tested (see inset in the logarithmic domain). Hence, the effect of MLSS on flux at higher MLSS becomes stronger at lower cross flow velocities.

Much less information on the flux-MLSS relationship is available for IMBRs. For immersed hollow-fiber and tubular membranes, Shimizu et al. (18) determined that the steady-state or stabilized filtration flux depended on MLSS concentration by

$$J_{ss} = K \cdot u^{*} \phi \cdot C_b^{-0.5} \tag{11}$$

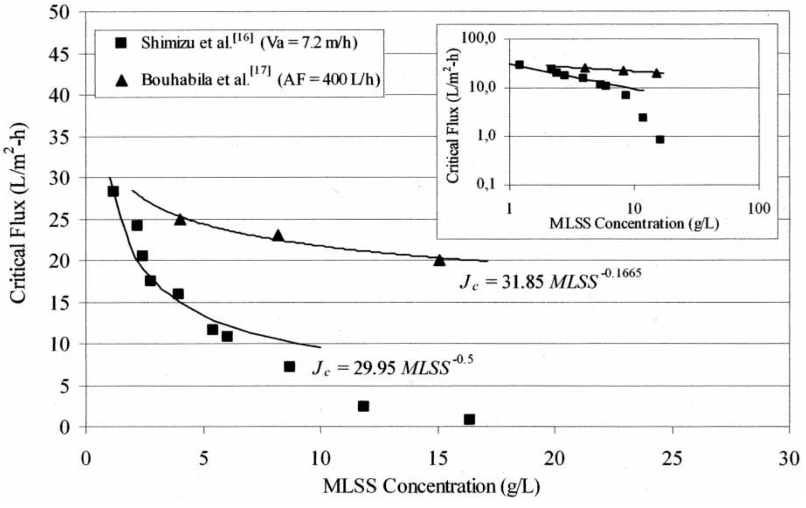

Figure 5. Effect of suspended solids concentration on critical flux for IMBRs. Solid line for Shimizu et al. (16), using $K = 2.6\,10^{-5}\,kg^{0.5}\,m^{-1.5}$, $u^* = 0.32\,m/s$, and $\phi = 1$ for Eq. (11). Solid line for Bouhabila et al. (17), is the best-fit potential curve. As for EMBRs, as aeration intensity increases, MLSS exponents in model curves increase. The steep decrease in flux for MLSS $> 10\,g/L$ in Shimizu et al. (16), occurs when insufficient vibration of the fibers with increasing viscosity leads to their crowding (see inset showing the data in the logarithmic domain). V_a is bubbling strength ($m^3\ m^{-2}\ h^{-1}$), the bubbling air-flow rate per unit area basal projection of membranes, and AF is bubbling air flow (h).

where J_{ss} is the steady-state flux, K is the filtration constant ($kg^{0.5}m^{-1.5}$), u^* is the air-liquid two-phase velocity (m/s), ϕ is the membrane geometric hindrance factor, and C_b is the bulk MLSS concentration (kg/m^3). Eq. (11), which is plotted in Fig. 5 for u* equal to 0.32 m/s, has a first-order relationship between flux and CFV. The shear-induced diffusion model reproduces the first-order relationship if the friction factor expression for laminar flow is used [Eqs. (1) and (6)].

It is interesting to compare the effect of MLSS between EMBRs and IMBRs. C_b exponent ranges are, respectively, -0.47 to -0.30 and -0.5 to -0.17; thus, both are similar, showing that increasing MLSS reduces the permeate flux. The AF = 400 h-data and Eq. (11) cannot be compared quantitatively, because it is not clear what is the correspondence between AF and u^*. Furthermore, IMBRs and EMBRs may have distinct hydrodynamics, while critical fluxes [Eq. (1)] are not exactly the same as steady-state fluxes [Eq. (11)].

The steep decrease in flux for MLSS $> 10\,g/L$ in Shimizu et al. (16) occurs when insufficient vibration of the fibers with increasing viscosity leads to their crowding (see inset showing the data in the logarithmic domain). Importantly and similar to EMBRs, higher aeration intensities and cross flow velocities not only enhance fluxes, but also extend the range of stable operation, or where fluxes are not significantly affected by MLSS changes.

The data presented in Figs. 4 and 5 support the hypothesis and are consistent with practical experience. On the one hand, the figures indicate that the critical flux is relatively insensitive to the MLSS concentrations above about 5 g/L—a result that is consistent with practical experience on the lower end of the practical MLSS operating range (4). Additionally, current practice for IMBRs is to limit the MLSS to about 10 to 15 g/L, as practical experience indicates that the allowable operating flux declines significantly as the MLSS increases beyond that range (4).

The critical flux and its associated critical TMP delimit the range of stable MBR operation when operating at steady state (point 1 in Fig. 3). Unfortunately, no published studies have addressed the flux-MLSS relationship during non-steady-state or supra-critical operation (points 2, 3, and 4 in Fig. 3). Perhaps the critical flux also is relevant for supra-critical operation, an issue that should be elucidated in future studies.

In summary, the results of this critical evaluation of hypothesis 1 indicate that this hypothesis is true. Increasing MLSS up to about 5 g/L causes the critical flux to decline, and Eqs. similar to (1), (2), and (11) allow us to express the relationship of flux to MLSS quantitatively. Additional research is needed to further understand and characterize the relationships, particularly for IMBRs.

HYPOTHESIS 2: AERATION ALPHA DECREASES WITH INCREASING MLSS

Background

The relatively high MLSS and small reactors often associated with MBRs require that more oxygen be transferred per unit reactor volume, but the oxygen-transfer kinetics may decrease with increasing MLSS concentration. In fact, several MBR studies report that oxygen demand exceeded the volumetric capacity of the aeration system at high MLSS concentration ($>$13 g) (19, 20). Additionally, Bratby et al. (21), using a model that explicitly included how oxygen transfer depends on MLSS concentration, determined that oxygen transfer was a key factor when selecting between MBR configurations.

MBRs most often employ diffused aeration, in which compressed air is discharged through submerged diffusers and rises through the liquid as bubbles. Process oxygen normally is supplied using high-efficiency, fine-bubble diffusers, while scouring air for membrane-fouling control is generated using coarse-bubble diffusers, which have lower oxygen-transfer efficiency.

Gander et al. (22) reviewed energy costs for the two MBR configurations. Energy costs associated with aeration in IMBRs represented greater than 90% of the total energy cost. The total energy cost of EMBRs can be higher by up to two orders of magnitude due to cross-flow pumping for fouling control. The aeration energy cost is approximately 20% of the total energy cost in EMBR systems. Therefore, potential oxygen-transfer limitations appear to have a greater relative cost impact for IMBRs.

The influence of mixed-liquor constituents on aeration capacity can be quantified by the alpha value (α), which is multiplied by the clean-water K_La to give a lumped first-order rate coefficient that is corrected for field conditions, αK_La. Because α varies with the physical features and operating conditions of the aeration equipment, α-MLSS relationships are system-specific (23). Operating factors, such as SRT, affect oxygen transfer (23, 24), probably due to changes in biopolymers and surfactants that interfere with oxygen transfer. For example, Rosso et al. (24) reported that α was twice as high for an SRT of 17 d than for 3.2 d. In addition, their results from off-gas measurements at 24 different conventional activated sludge plants also indicated that α increased sharply around an SRT of 5 d, but was SRT-independent above 10 d, the typical operating range of MBRs. It is not clear the degree to which these data apply to MBRs, particularly since the study did not detect an effect of MLSS.

Table 2. Review of the effect of MLSS concentration on oxygen transfer for MBR systems

Reactor configuration and scale	MLSS range tested (g/L)	Aeration system(s)	Determination method	Reference
Several activated sludge types	8–28	Fine-bubble, injector	Clean water (absorption), mixed liquor (absorption)	Krampe and Krauth (25)
IMBR (pilot scale), EMBR (pilot scale)	8–25	Fine-bubble, coarse-bubble, surface	Not specified	Gunder and Krauth (26)
Single-tank IMBR (full scale), dual-tank IMBR (full scale)	7–17	Fine-bubble	Clean water (absorption), mixed liquor (off-gas, absorption)	Cornel et al. (27) Wagner et al. (28)

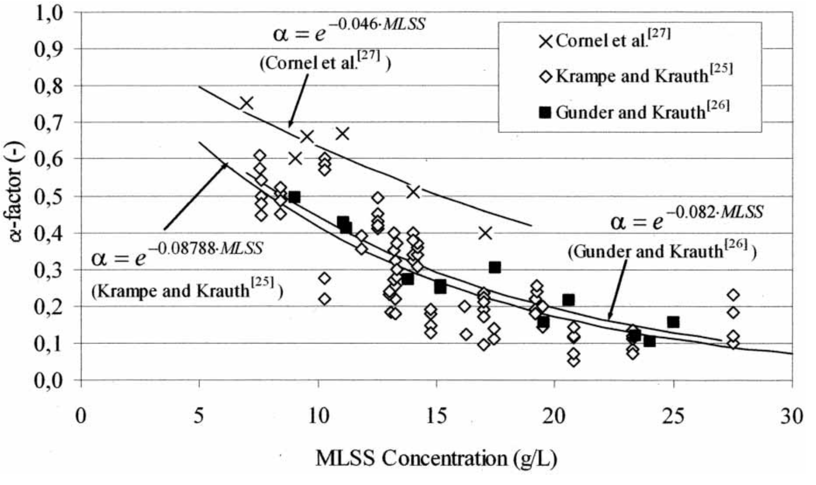

Figure 6. α-MLSS relationships for fine-bubble systems cited in Table 2. The regression line of Krampe and Krauth (25) also represents injector systems, but it was not clearly specified whether the data of Gunder and Krauth (26) is also for coarse-bubble and surface aeration. We determined the equation for the exponential regression of Cornel et al. (27).

Results and Discussion

The effect of MLSS concentration on oxygen transfer rates and, particularly, on α values was addressed in the three studies listed in Table 2. The α results of these studies are summarized in Fig. 6 in the form of exponential regression lines obtained by fitting their experimental data. In all cases, α decreased exponentially with MLSS concentration. The rate of decrease, however, varied, since factors other than MLSS can affect α. The only data on full-scale MBR systems (27) indicated that α decreased from 0.6 to 0.4 as MLSS went from $10\,g/L$ to $20\,g/L$. The smaller-scale results suggest a more dramatic decrease in α, down to as low as 0.2 at $20\,g/L$.

Cornel et al. (27) determined α-values for fine-bubble aeration systems of single-tank and dual-tank IMBRs. The α values for both IMBRs were similar. Cornel et al. (27) determined that coarse-bubble aeration provided some oxygenation, but at low efficiency. Additionally, α for coarse-bubble aeration was independent of MLSS, probably because of the higher turbulence caused by comparatively higher airflows.

Wagner et al. (28) determined that fine-bubble diffusers had standard aeration efficiencies (SOTEs in kg O_2/kWh) three times greater than coarse-bubble diffusers. Hence, they recommended minimizing coarse-bubble aeration, constraining its use to fouling control. Indeed, cycling coarse-bubble aerators on and off has been suggested as a means of optimizing energy use. Additional options to enhance oxygen transfer include delivering pure oxygen instead of air and pressurizing the aeration basin (29).

Wagner et al. (28) and Krampe and Krauth (25) evaluated the effect of mixed liquor viscosity on α. The Wagner et al. (28) data were for MBRs, while the Krampe and Krauth (25) data were for high-MLSS activated sludge. Both groups found that α correlated better with viscosity than with MLSS concentration, which suggests that the effect of MLSS on α might be best explained in terms of the influence of MLSS on viscosity [recall Eq. (9)]. High viscosity may lower α by increasing the rate of bubble coalescence and, thus, reducing the interfacial area for oxygen transfer.

In summary, the results indicate that the second hypothesis is true: higher MLSS systematically decreases the α value for aeration. However, the rate of decrease is system specific, and the effect of MLSS on α may be related more to the viscosity of the mixed liquor than to the MLSS concentration itself, a subject warranting more investigation.

HYPOTHESIS 3: SLUDGE THICKENING CHARACTERISTICS OF MBR SLUDGE ARE POORER THAN THOSE OF TRADITIONAL ACTIVATED SLUDGE

Background

As a general rule, sludge thickening refers to processes that increase the concentration of wastewater solids up to about 5% by removing a fraction of the water (30). The most common thickening technologies include gravity settling, flotation, gravity belts, and centrifugation. Chemicals often are added to improve the separation characteristics of wasted solids. Good thickening can bring about large cost savings for downstream sludge handling and disposal. Adham and Trussell (31) estimated that sludge handling and disposal costs were 24% of total operation and maintenance costs for a 1-MGD ($\sim$3,800 m^3/d) MBR installation and 34% for a 5-MGD ($\sim$19,000 m^3/d) MBR installation. As designers reduce SRT and MLSS in order to increase permeate flux and reduce the cost of membrane equipment, the volumetric flow of sludge wasted from an MBR becomes larger. Because of this tension between membrane capacity and sludge-handling capacity, the thickening characteristics of MBR sludge must be well understood.

Gravity thickening requires that sludge flocs settle and compact well. A filamentous backbone and EPS are central to the formation of compact and good-settling flocs (9, 32). Additionally, multivalent cations act as bridges between negatively charged EPS molecules, stabilizing the floc structure. Thickening by gravity belts is influenced by the particle-size distribution of activated sludge floc. Free water drains better from suspensions consisting of larger flocs and having a lower degree of dispersion (33).

Excessive growth of filamentous bacteria can negatively affect settling and thickening characteristics of activated sludge. Poor settling or sludge bulking occurs when filaments extend outside flocs, preventing them from coming close together and compacting or expand floc volume (32). Causes of sludge bulking include low DO, long SRT, and input reduced sulfur (9, 34).

EPS is important for sludge flocculation and, hence, thickening. Settling problems may occur at low SRT because the amount of EPS synthesized by bacteria is too small to allow good flocculation (32). However, EPS is associated with small cake dry matter during dewatering (35), because EPS is highly hydrated. So-called viscous bulking occurs when bacteria produce an excessive amount of EPS.

The capillary suction time (CST) test is commonly used to characterize the performance of mechanical thickening and dewatering processes. It is a fast and relatively simple test compared to other dewatering diagnostic tests, such as specific resistance (SR) and time-to-filter (TTF) tests (36). In the CST test, a sludge sample is placed in a small cylinder on top of a Whatman No. 17 chromatography paper. The CST is the time, in seconds, required for the free liquid to travel through the paper a certain distance due to the paper's capillary action. Variations in temperature, paper type, CST apparatus, and suspended solids concentration can affect CST results (37).

Basis for Expected Poorer Thickening and Dewatering Properties of MBR Solids

Excess sludge wasted from MBRs might be expected to thicken poorly compared to activated sludge. Activated sludge selects for microorganisms that are well flocculated, which should correlate to good thickening. MBRs, on the other hand, retain all microorganisms regardless of their settling properties. Hence, MBRs may generate smaller and weaker flocs. Additionally, MBR flocs may be subject to erosion because of a higher MLSS concentration and increased shear, particularly in EMBRs. As a consequence, MBR sludge may thicken poorly or require high doses of conditioning polymer.

Cicek et al. (38) and Manem and Sanderson (39) found that MBR sludge had smaller flocs and less EPS, a finding consistent with the expectation that MBR sludge might be more difficult to thicken. On the other hand, less EPS could lead to retention of less water, which could lead to a higher dry-matter content during thickening and dewatering.

Results and Discussion

Table 3 lists the several publications that reported thickening and dewatering characteristics of MBR sludge, often comparing them with those of activated sludge run in parallel. These publications generally provide the capillary

Table 3. Review of thickening characteristics of excess sludge wasted from MBRs and TAS reactors

Reactor configuration and scale of work	MLSS range tested (g/L)	Test	Reference
IMBR (pilot scale, municipal)	5–13	CST	Adham et al. (40)
IMBR (pilot scale, municipal) TAS (full scale, municipal)	1–23	CST	Adham and Trussell (31)
IMBR (pilot scale, municipal) TAS (full scale, municipal)	Not specified	CST	Murakami et al. (41)
IMBR (pilot scale, municipal) TAS (full scale, municipal)	6–10	CST	Fernandez et al. (19)
EMBR (pilot scale, industrial laundry)	<10	CST, SVI	Andersen et al. (42)

suction time (CST). Good dewaterability is associated with a small CST (37, 43). Unfortunately, we found no MBR-specific data on the thickened sludge concentration resulting from gravity or belt filter thickening technologies. Thus, our analysis mainly relies on the available CST data.

CST results presented in Table 3 cannot be compared across studies, because CST values depend on the particular instrument used. Specific resistance (SR) results could be compared, but none were reported, and information provided is insufficient to estimated SR from CST values. Since all CST measurements within each study probably were performed with the same CST apparatus, intra-study CST data can be compared. Three studies offer this possibility: Adham and Trussell (31), Murakami et al. (41), and Fernandez et al. (19).

The results of Adham and Trussell (31) show that the CST ranges of IMBR sludge (5.5 s–17.5 s) and activated sludge (5.5 s–9.9 s) overlap. Thus, the dewatering characteristics of IMBR and activated sludges were not significantly different. However, interpretation of their data is tenuous, because a significant portion of their data clustered around the capillary suction time of clean water (CST_w). Also, CST and MLSS did not correlate, again suggesting that CST_{w} dominated CST. Thus, it appears that their sludges dewatered too fast for their CST equipment to give adequate resolution.

Murakami et al. (41) determined that the CST was slightly better for IMBR sludge (9–19 s) than for activated sludge (12–24 s) after polymer conditioning. Without polymer addition, however, the CST value of IMBR sludge was considerably lower. Unfortunately, the MLSS concentrations associated with the CST measurements were not reported, and the relatively low CSTs for the IMBR sludge could have been due to a lower MLSS.

Fernandez et al. (19) determined that IMBR sludge had an average CST of 112 s at 10 g/L, but 6 g/L gave an average CST of only 35 s. The mean CST for activated sludge at a MLSS of 3 g/L was 18 s. The IMBR CST values of this study are considerably higher than the CST values of other studies for similar MLSS concentration, perhaps reflecting the reported sludge-bulking problems, particularly at the high MLSS concentration. Normalizing the IMBR CST values by MLSS concentration gives 11.2 s L/g and 5.8 s L/g at 10 g/L and 6 g/L, respectively. The normalized activated sludge CST is 6 s L/g, which is similar to the normalized low-MLSS IMBR CST, indicating that dewatering properties of CAS and IMBR sludges are not significantly different.

The sludge volume index (SVI) results from Andersen et al. (42) for EMBR sludge indicate good thickening properties. Their data show that the SVI did not depend on MLSS; however large variations occurred. The good SVI values (50–70 mL/g) were attributed to the high concentration of Al and Fe in the wastewater, which might have served as coagulants. Additionally, the CST after 10 s of stirring varied in the range of 20 to 30 s with addition of polymer. The optimum dose of the cationic polymer was 3–5 mg/g SS. Addition of polymer was necessary because, otherwise, the CST value was 340 s. The MLSS concentration associated with the CST determination was not reported.

Several other studies also reported information relevant to thickening of MBR sludge, but did not provide data and, thus, are not listed in Table 3. However, for completeness we summarize their conclusions. Cicek et al. (38) reported that EMBR sludge contained small flocs (3–5 μm), dispersed bacteria, and few filamentous organisms. On the other hand, activated sludge contained comparatively large flocs (80–120 μm) and more filamentous organisms. As a result, activated sludge "settled well," while EMBR sludge "settled poorly." Fleisher et al. (44) reported that IMBR biosolids exhibited good flocculation and dewatering characteristics, similar to those of an activated sludge plant operated with the same wastewater feed. In this case, addition of alum (73 mg/L) for phosphorus removal might have enhanced dewatering characteristics. Thickening and dewatering results of several large, normally loaded, MBR plants in Germany were comparable to activated sludge results (45). Additionally, STOWA (45) determined that, for raw/screened influent, thickening using a belt thickener was similar for IMBR and TAS activated sludges. However, for influent after primary sedimentation and pre-precipitation, polymer doses became excessive for IMBR sludge. Thickening with a centrifuge was comparable to TAS sludge. Furthermore, dewatering MBR sludge with a lab-scale filter press was not possible, because MBR flocs were small and unstable. Centrifuge dewatering results were comparable to TAS sludge. Notably, new designs are considering membranes for thickening MBR sludge (46, 47). It remains to be determined how effective and economical this option will be compared to more traditional alternatives. Finally, the largest membrane bioreactor facility in North America, involving the upgrade of conventional activated sludge, will use the combination of a new gravity-belt thickener and an existing sieve-drum thickener to thicken excess activated sludge from a concentration of 1% to 5.5% solids (48).

In summary, the results indicate that hypothesis 3 is not necessarily true. SVI and CST values for the sludges produced in IMBRs vary widely, but generally are similar to values obtained with activated sludge when the same testing method is used. Research focusing on obtaining generalized measures, such as specific resistance, would be especially valuable. Also especially valuable would be data for EMBR sludge. Because of the higher shear associated with EMBRs, flocs may break apart, leading to poor thickening and dewatering. However, the studies with EMBRs (38, 42) are not consistent with each other on these issues.

SUMMARY

Hypothesis 1

It is true that increasing MLSS decreases the critical permeate flux, but the effect is strong only for MLSS $< \sim 5\,g/L$ and for high MLSS with low cross-flow velocity or low aeration intensity. MLSS has minimal impact on the critical flux for operation in the typical MLSS zone for MBRs ($>5\,g/L$). For the typical MLSS zone, flux-management techniques to prevent serious cake formation are more important than MLSS. Eqs. similar to (1), (2), and (11) provide bases for establishing empirical critical flux-MLSS relationships that also include the effect of cross-flow velocity to induce wall shear and prevent serious cake formation. These relationships are system specific.

Our finding that the effect of MLSS increases significantly for high MLSS appears to be consistent with practical experience, which indicates that the permeate flux continues to decline for MLSS as high as 10 to $15\,g/L$. In addition, the relevance of the critical flux is not obvious for non-steady state operation with cyclic filtration and back pulsing. This question seems especially relevant for IMBRs, which rely more heavily on back pulsing. Thus, a theory for supra-critical, cyclic operation should be developed and tested.

Hypothesis 2

It is true that the aeration α decreases with increasing MLSS concentration, although the strength of the correlation depends on system-specific factors that are poorly understood. Some results suggest that high MLSS may affect α indirectly by increasing the viscosity of the mixed liquor, which subsequently reduces the interfacial surface area for oxygen transfer. The viscosity effect warrants study.

Hypothesis 3

It is not true that thickening properties of IMBR sludges are significantly poorer than those of traditional activated sludge, based on available CST tests. Moreover, IMBRs can produce solids with good thickening characteristics. Information on thickening properties of EMBR sludge is minimal. To improve the situation, research should obtain SR information, which can be compared across studies; more SVI measurements, which are more relevant for gravity thickening; and more information on EMBR sludge, which has not been well studied.

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