EFFECTS OF MIXED LIQUOR SUSPENDED SOLIDS ON MEMBRANE BIOREACTOR OPERATION: A CRITICAL REVIEW BASED ON THE WERF MBR DATABASE

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WERF MBR Website

- WERF = Water Environment Research Foundation
- The MBR website was compiled by the team of CH2M-Hill, Northwestern U., Howard U., and U. Cincinnati.
- It went on-line for WERF subscribers in December, 2002.
- CH2M-Hill and Northwestern University are now updating and expanding the website, as well as doing critical reviews based on its contents.

MBR Website Contents

- Database of all published research, now up-to-date with 460 entries as of May 2004
- Database of "grey literature," including mainly conference abstracts and manufacturers literature (68 entries)
- Database of full-scale installations, now being significantly updated and improved
- Tutorials on activated sludge, MBR basics, and MBR applications and sites
- Preliminary design tool
- Three technical memos providing critical evaluations based on information in the first two databases

Critical Reviews

- The goal was to exploit the information gathered in the website's databases -- information mining.
- The critical evaluations were mainly carried out at Northwestern U. (Alex Schwarz and me), but with important feedback from CH2M-Hill.
- They were based on searches of the published and grey literature databases, with detailed analysis of the relevant sources.
- We augmented the databases with other sources of key fundamental information and principals.
- We just completed a manuscript for submission to *Water Environment Research.*

Theme -- Effects of High MLSS

- MBRs and traditional activated sludge (TAS) have many similarities, particularly in terms of microbial metabolism and kinetics.
- However, substituting membrane separation for gravity sedimentation allows much higher mixed liquor suspended solids (MLSS) concentrations.
- Elevated MLSS may produce adverse effects: e.g.,
  - Lower hydraulic capacity (i.e., permeate flux for membrane systems)
  - Lower oxygen-transfer rate
  - Waste sludge with poorer thickening characteristics that impede the performance of subsequent sludge-processing steps

Three Hypotheses

1. Increased MLSS concentration reduces the membrane flux, and an empirical relationship can be found for the same membrane system.
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).

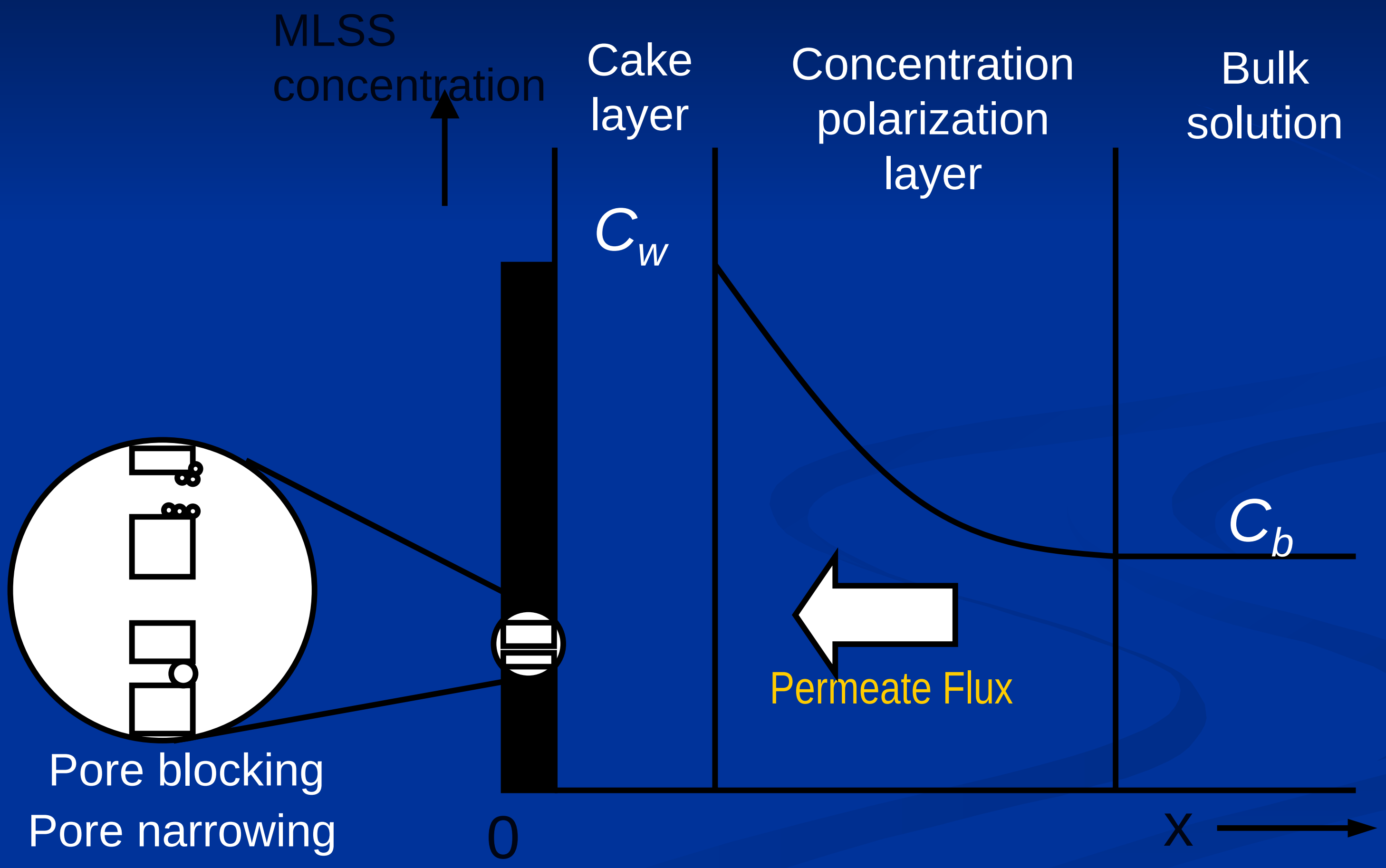
Hypothesis 1 -- Membrane Flux

Increased MLSS concentration reduces the membrane flux, and an empirical relationship can be found for the same membrane system.

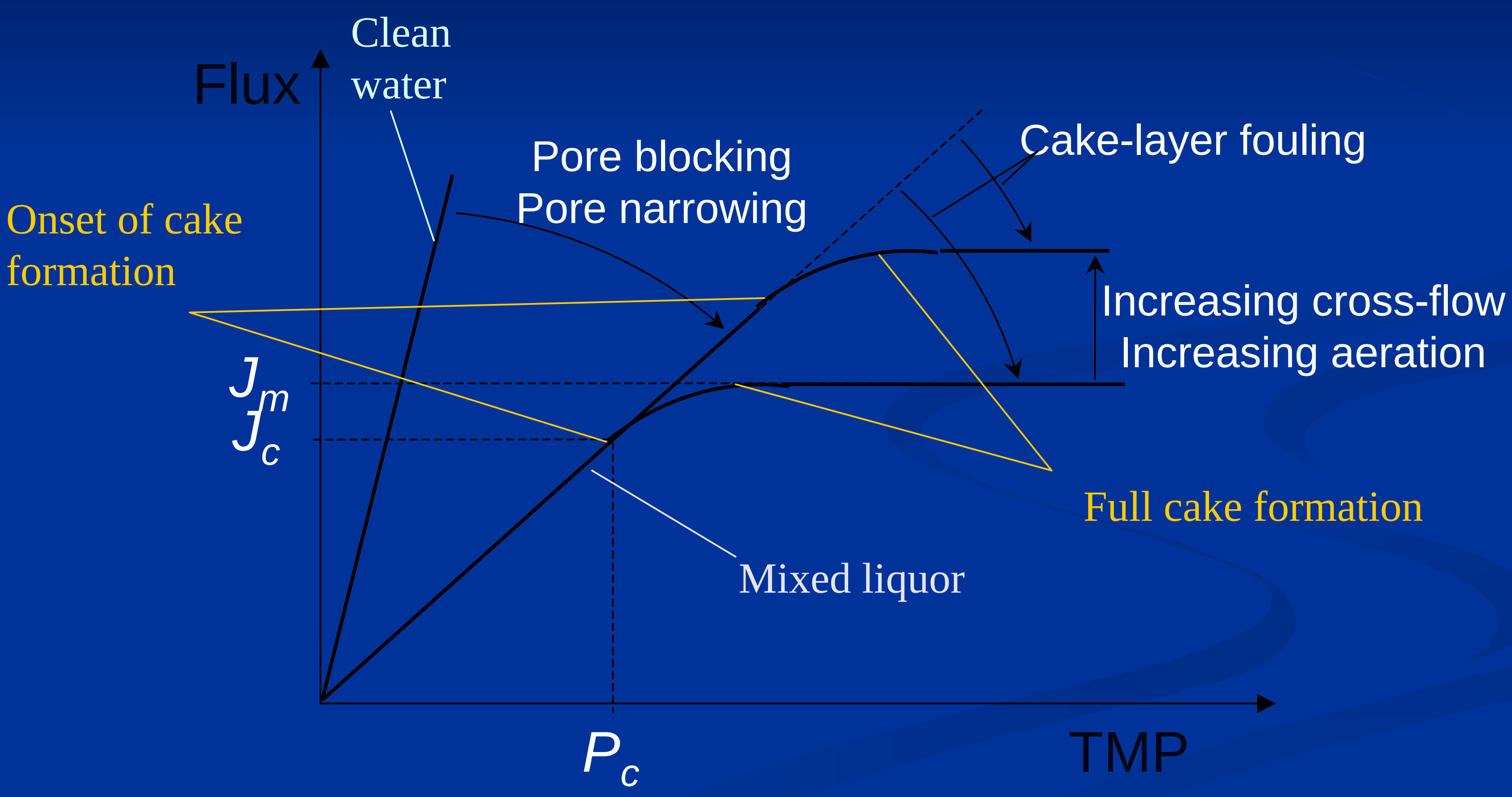
Background -- MBR Phases

- Originally, MBR package plants were operated at long SRT (>50 days), high MLSS (15,000-25,000 mg/l), and low permeate flux (<20 l/m^2-h, or <0.02 m/h). They achieved good effluent quality, complete nitrification with infrequent sludge wasting, and minimal membrane fouling and cleaning.
- Later, designers reduced the SRT and MLSS in an attempt to increase permeate flux and reduce membrane surface area. 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 <u>assumption</u> underlying this MBR development is that membrane flux improves at lower MLSS.

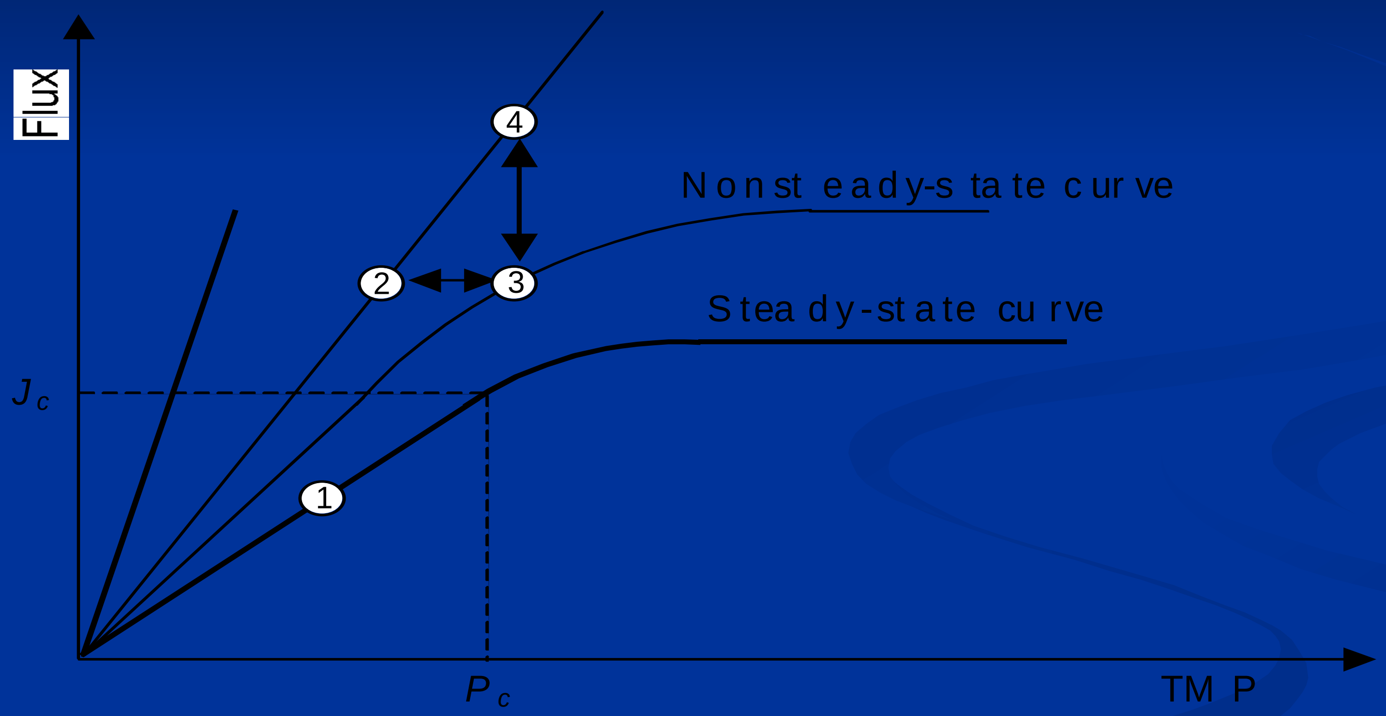
Fouling Mechanisms



Flux-TMP curves show effects of fouling mechanisms



Sub-critical (point 1) and supra-critical (points 2, 3, and 4) operating strategies



Sub-critical operation (point 1) 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 backpulsing to remove cake resistance for constant-flux operation (between points 2 and 3) or constant-TMP operation (between points 4 and 3).

Flux Modeling Framework

According to the shear-induced diffusion model, 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 (L in m), the wall shear rate (γ_0 in s^{-1}), and the particle radius (a in m). When $C_b << C_w$, J_c can be related to the controlling parameters by

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

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, the effect of MLSS concentration on flux is strong at low C_b, but declines as C_b approaches C_w. On the other hand, the effect of the shear rate is the same no matter the C_b value.

Floc Size

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. By comparison, activated-sludge flocs are usually larger, up to 200 μm. Smaller aggregates are less likely to be removed from the surface by inertial lift or shear-facilitated diffusion, and this is reflected in Eqn. 1 by *a* in the numerator.

Viscosity and Critical Flux

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

$$\gamma_o = \tau_o / \eta$$

where τ_o is the wall shear stress. For laminar flow conditions, we can derive an expression that is in more easily understood parameters: u = the fluid velocity past the membrane and d_h = the channel diameter (hollow-fiber diameter).

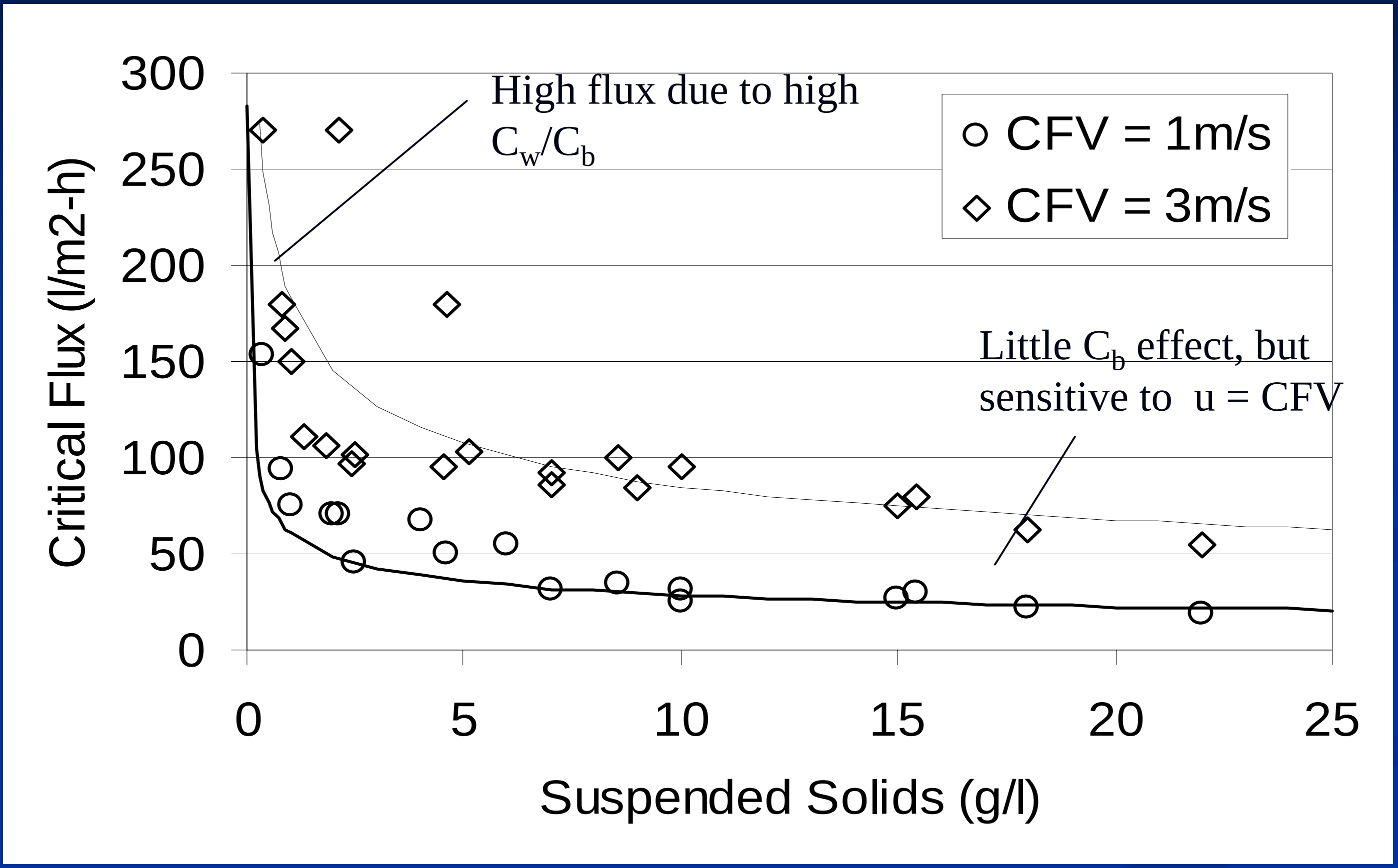
$$\gamma_o = 8u / d_h$$

Note that γ_o is independent of η, but proportional to u!

Parameter Values and Expressions Used with Equation 1 to Simulate EMBR Data			
Parameter	Symbol (+ Equation)	CFV = 1 m / s	CFV = 3 m/s
Membrane length	L	1 m	
Channel diameter	d_h	4 mm	
Bulk MLSS concentration	C_b	0–20 g/L	
Surface MLSS concentration	C_w	60 g/L	
Bulk density[1]	$\rho = 1000 + C_b$	1000–1020 g/L	
Dynamic viscosity[1]	$\eta = 0.2126 C_b + 1.4793$	1.48–5.73 mPa s	
Particle radius	a	1.5 µm	
Reynolds number	$Re = \rho u d_h / \eta$	712–2703	2136–8108
Friction factor[2]	$f = 64/Re$	0.09–0.024	0.008–0.030
Wall shear stress	$\tau_0 = f \rho u^2 / 8$	3.0–11.5 Pa	8.9–34.4 Pa
Wall shear rate	$\gamma_0 = \tau_0 / \eta = u / d_h$	2000 s^{-1}	6000 s^{-1}

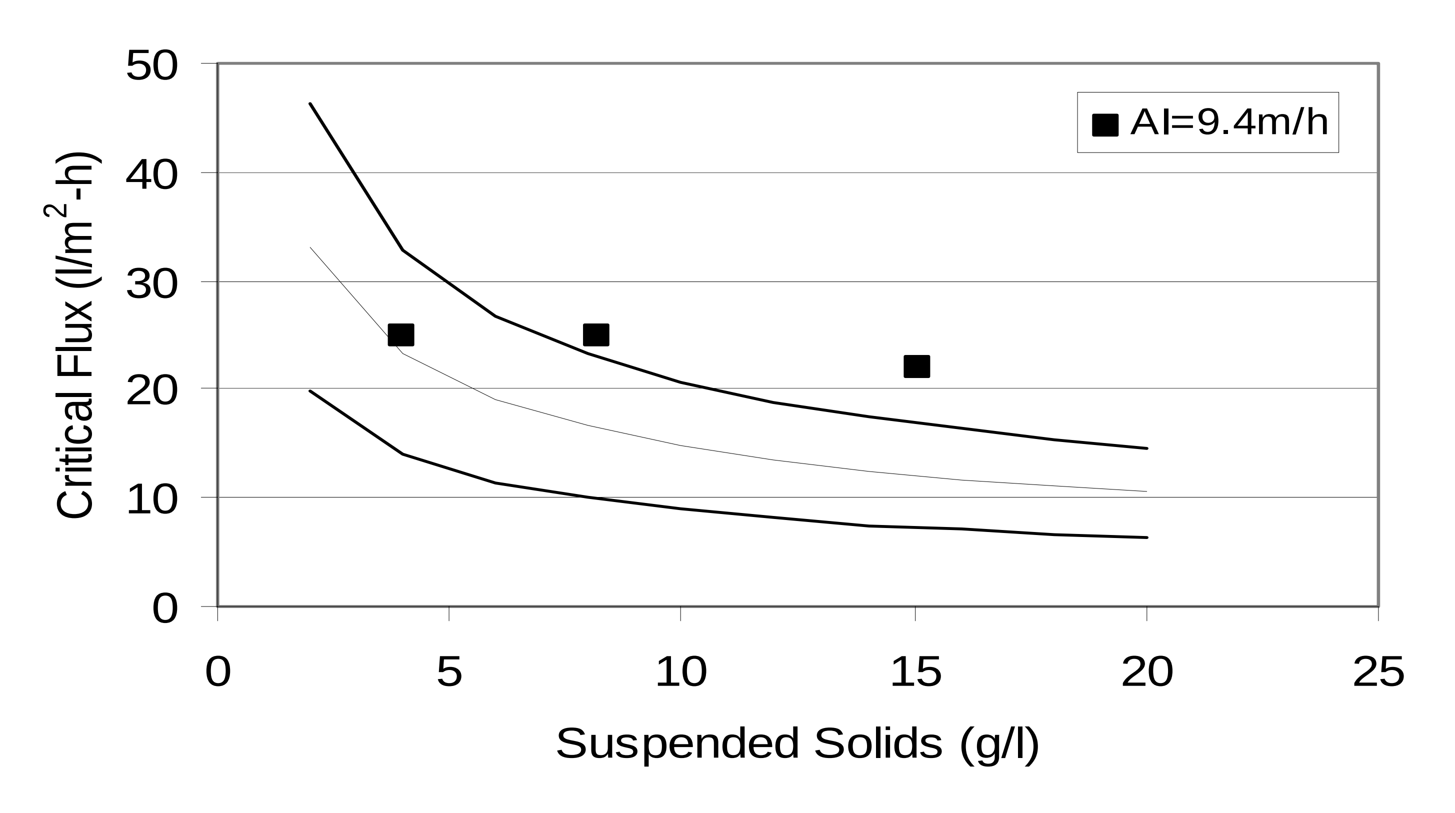
[1] Xing et al. 2001 (the expression for η was adjusted for use with mixed liquor at 15 °C).
[2] Streeter and Wylie 1985, assuming laminar flow conditions

EMBR Data for Critical Flux



The shear-induced diffusion model (Eqn. 1) using the friction factor expression for laminar flow gives a good fit to all the data when a = 1.5 µm.

IMBR Data for Critical Flux



Effect of suspended solids concentration on critical flux at IMBR crossflow velocities between 0.3, 0.5, and 0.7 m/s (solid lines from Shimizu et al. (1996b) using K = 2.6 10^{-5} $kg^{0.5}$ $m^{-1.5}$, and ϕ=1 for $J_{ss} = K \cdot u * \phi \cdot C_b^{-0.5}$), and AI=9.4 m / h (symbols for Bouhabila et al., 1998). Similarly to the EMBR results, the IMBR result of Shimizu et al. (1996b) shows a zone of rapid flux decline, followed by a zone of stabilized flux.

Conclusion for Hypothesis 1

Hypothesis 1 is true: Increasing MLSS up to about 5 g/L causes the critical flux to decline, and two the mechanistically based equations allow us to express the relationship of flux to MLSS quantitatively. But,………

The flux decline nearly stops for C_b greater than about 5 g/L.

Cross-flow velocity, but not viscosity, has a major impact on the critical flux, particularly for the high-MLSS regions often used with MBRs.

Additional research is needed to further understand and characterize the relationships, particularly for IMBRs.

Hypothesis 2 -- Aeration Alpha

The aeration alpha value decrease with increasing MLSS concentration.

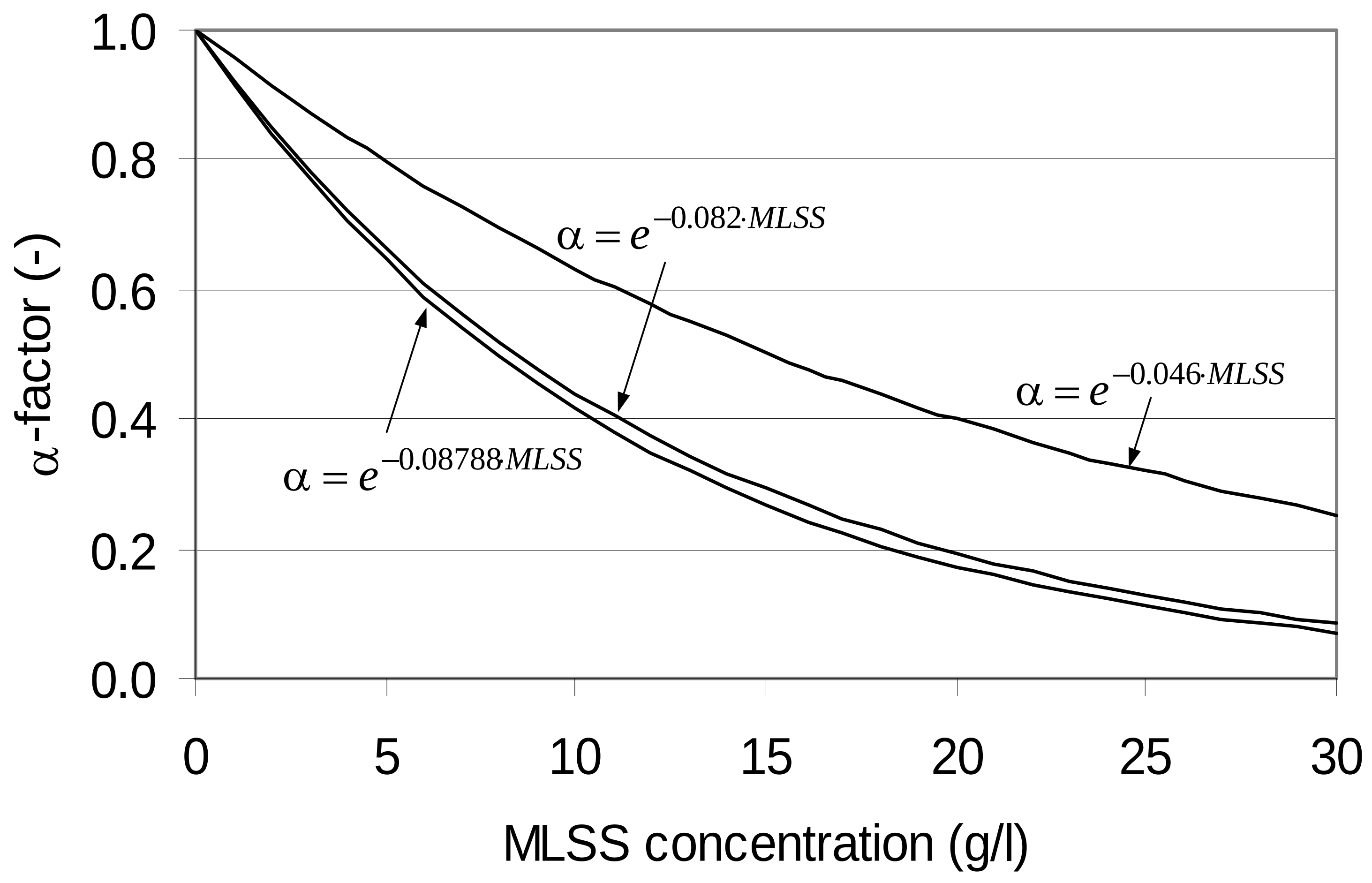
The relatively high MLSS and small reactors often associated with MBRs require that more oxygen be transferred per unit reactor volume, but the oxygen-transfer kinetics may decrease with increasing MLSS concentration. In fact, several MBR studies report that oxygen demand exceeded the volumetric capacity of the aeration system at high MLSS concentration.

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. Operating factors, such as SRT, affect oxygen transfer, probably due to changes in biopolymers and surfactants that interfere with oxygen transfer.

High MLSS should concentrate these materials.

α-MLSS relationships for fine-bubble systems



Viscosity and Alpha

Wagner et al. (2002) and Krampe and Krauth (2003) evaluated the effect of mixed liquor viscosity (η) on α. The Wagner et al. (2002) data were for MBRs, while the Krampe and Krauth (2003) 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 that $\eta = 0.2125\ C_b + 1.4793$ (in mPa-s)).

High viscosity may lower α by increasing the rate of bubble coalescence and, thus, reducing the interfacial area for oxygen transfer.

Conclusions for Hypothesis 2

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 -- Poor Dewaterability

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).

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.

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.

Capillary Suction Time (CST)

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).

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.

Basis for the Hypothesis

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.

Additionally, MBR flocs may be subject to erosion because of a higher MLSS concentration and increased shear, particularly in EMBRs.

Manem and Sanderson (1996) 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.

Review of Thickening Characteristics of Excess Sludge Wasted From MBRs and TAS Reactors				
Reference number	**Reactor configuration and scale of work**	**MLSS range tested (g/l)**	**Test**	**Reference**
1	IMBR (pilot scale, municipal)	5 - 13	CST	Adham et al., 2000
2	IMBR (pilot scale, municipal) TAS (full scale, municipal)	1 - 23	CST	Adham and Trussell 2001
3	IMBR (pilot scale, municipal) TAS (full scale, municipal)	Not specified	CST	Murakami et al., 2000
4	IMBR (pilot scale, municipal) TAS (full scale, municipal)	6 - 10	CST	Fernandez et al., 2000
5	EMBR (pilot scale, industrial laundry)	<10	CST, SVI	Andersen et al., 2002

CST results presented in the table 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 (2001), Murakami et al. (2000), and Fernandez et al. (2000).

Adham and Trussell (2001)

The results of Adham and Trussell 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.

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Murakami et al. (2000)

Murakami et al. 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. (2000)

Fernandez et al. 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.

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Sludge Volume Index

The sludge volume index (SVI) results from Andersen et al. (2002) 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.

Conclusions for Hypothesis 3

Hypothesis 3 probably is not 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.

Overall Summary

- Hypothesis 1. It is true that increasing MLSS decreases the critical permeate flux, but the effect is strong only for MLSS < ~ 5 g/L.
- For the typical MLSS zone (> ~ 5 g/L), flux-management techniques to prevent serious cake formation are more important than MLSS.
- Two mechanistically based equations 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.
- Viscosity does not appear to affect the critical flux.

Overall Summary

- Hypothesis 2. It is true that the aeration α decreases with increasing MLSS concentration. High MLSS may affect α indirectly by increasing the viscosity of the mixed liquor, which subsequently reduces the interfacial surface area for oxygen transfer.

- 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.