Influence of Mixed Liquor Properties and Aeration Intensity on Membrane Fouling in a Submerged Membrane Bioreactor at High Mixed Liquor Suspended Solids Concentrations

by

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ABSTRACT

This paper presents the results of 195 days of pilot-scale submerged membrane bioreactor (SMBR) experiments on settled municipal wastewater. Short-term and long-term thickening experiments were performed at a constant membrane flux of 30 LMH to determine the impact of the following mixed liquor properties: colloidal material, soluble COD, soluble microbial products, extracellular polymeric substances, and viscosity along with aeration intensity on membrane fouling at high mixed liquor suspended solids (MLSS) concentrations. The normalized specific flux declined with increasing MLSS concentrations in all experiments and increasing the coarse bubble aeration intensity increased the specific flux at a given MLSS concentration. Using a dynamic approach, this work demonstrates the importance of mixed liquor viscosity, which impacts the efficacy of the coarse bubble aeration, in sustaining membrane permeability. Over an extended thickening time period, a small increase in MLSS concentration and mixed liquor viscosity becomes more prevalent and leads to greater specific flux decline at a given MLSS concentration.

KEYWORDS

Submerged membrane bioreactor (SMBR), aeration intensity, membrane fouling, viscosity, soluble microbial products (SMP), extracellular polymeric substances (EPS)
INTRODUCTION

The membrane bioreactor (MBR) process can operate at high MLSS concentrations because a membrane, rather than a gravity sedimentation basin, is used for solid-liquid separation (Chiemchaisri and Yamamoto 1994; Trussell et al. 2005; Yamamoto et al. 1989). Increased MLSS concentrations allow reduced hydraulic residence times (HRTs) at a given mean cell residence time (MCRT) resulting in a more compact treatment process (Trussell et al. In Press). For a given HRT, higher MLSS concentrations allow operation at increased MCRTs resulting in reduced sludge production and other advantages (Adham et al. 2001; Innocenti et al. 2002; Metcalf&Eddy 2003; Muller et al. 1995; Scholzy and Fuchs 2000; Wei et al. 2003; Yoon 2003; Yoon and Lee 2005). High MLSS concentrations can have detrimental effects on membrane performance (Le Clech et al. 2003; Yamamoto et al. 1989), but the available literature data does not adequately describe the complex factors influencing membrane permeability at high MLSS concentrations. Previous research has developed empirical relationships between the aeration intensity, membrane flux, and MLSS concentrations (Liu et al. 2003; Shimizu et al. 1996), but the influence of mixed liquor properties, such as bulk mixed liquor viscosity and colloidal content, have not been incorporated. Research has shown that increasing bulk viscosity will decrease the mass transfer coefficient of material from the membrane surface to the bulk solution (Pritchard et al. 1995) and bulk viscosity has been shown to increase with increasing MLSS concentration (Dick and Ewing 1967; Krampe and Krauth 2003). Recent work has also demonstrated the importance of the organic colloidal mixed liquor fraction on long-term membrane fouling rates and the membrane critical flux (Fan et al. 2006; Rosenberger et al. 2006; Trussell et al. In Press). The goal
of this research was to examine the effects of aeration intensity and mixed liquor properties on membrane permeability at high and changing MLSS concentrations.

**MATERIALS AND METHODS**

**Pilot-Scale Submerged Membrane Bioreactor (SMBR):** A pilot-scale SMBR, designed to operate at a range of variable hydraulic retention times (HRTs) while maintaining a constant membrane flux of 30 L/m²-h (LMH) and a working volume of 1,514 L was custom built by ZENON Environmental Services Inc., Ontario, Canada. A complete description of this pilot unit is provided in (Trussell et al. In Press). ZW500C ultrafiltration modules provided a total membrane surface area of 61.3 m² (660 ft²) with a vertical hollow fiber configuration.

**Feedwater Characteristics:** The SMBR was fed with primary effluent from the Southeast Water Pollution Control Plant (SEP), San Francisco, CA and the median COD, TSS, and TKN concentrations were 345, 99, and 30 mg/L respectively. A centrifugal pump was immersed in the SEP primary effluent channel and operated continuously.

**Reactor Operation:** The reactor was operated for at least 2 MCRTs prior to steady-state data collection at each MCRT. The mixed liquor dissolved oxygen (DO) concentration was always more than 2 mg/L and sodium bicarbonate was added to the feed wastewater to elevate its alkalinity and maintain pH in the SMBR above 6.5.
Membrane Performance: Membrane fouling at high MLSS concentrations was investigated with short-term and long-term experiments at 10-d, 20-d and 30-d MCRTs. The short-term experiments (each lasting less than 1 hour) were performed after achieving steady state MCRTs of 10, 20 and 30 d at an MLSS concentration of approximately 15 g/L. Long-term (no-wasting) experiments were performed over several days using the previously obtained, steady-state conditions as starting points (10, 20 and 30-d MCRTs).

In the short-term experiments, the wastewater feed to the SMBR was stopped. While the permeate flow was maintained, mixed liquor was pumped from the aeration basin to the membrane tank and the membrane was used as a dewatering device, increasing the MLSS concentration in the membrane tank linearly with time. Membrane performance was observed at a constant flux of 30 LMH (18 gfd) while monitoring MLSS concentration increase. In addition to MLSS concentration, viscosity and soluble COD (sCOD) concentrations were determined on all collected samples. Soluble microbial products (SMP) and colloidal material content were determined on the initial and final mixed liquor samples and extracellular polymeric substance (EPS) content on the initial mixed liquor sample. The experiment was repeated at each MCRT with coarse bubble aeration intensities of $1.5 \times 10^{-4}$, $2.3 \times 10^{-4}$, and $3.0 \times 10^{-4}$ m$^{3}$/m$^2$ s (m/s). The aeration intensity was the calculated by dividing the coarse bubble aeration rate (9.4, 14.2, and 18.9 L/s) by the total membrane area (61.3 m$^2$). At the end of each experiment, the mixed liquor was diluted to the initial MLSS concentration with membrane permeate and membrane permeability was restored without chemical cleaning.
Extended short-term experiments were performed at the 20-d and 30-d MCRT conditions by recycling 50% of the membrane permeate back to the system. With the permeate recycle, the rate of MLSS concentration increase was half of that in the previously described short-term experiments. The same analytical measurements were performed while observations of membrane performance were made. The membrane flux and coarse bubble aeration intensity were constant at 30 LMH and 2.3x10^{-4} m/s, respectively.

The long-term experiments were performed at the conclusion of the short-term experiments at each MCRT. The established steady-state condition was used as a starting point. The SMBR was treating wastewater but sludge wasting was stopped to allow the MLSS concentration to increase; the mixed liquor was characterized daily (i.e. MLSS, viscosity, colloidal material, soluble COD, SMP, EPS) until the maximum vacuum pressure (18 in. Hg) was reached. The membrane flux and coarse bubble aeration rate were constant at 30 LMH and 2.3x10^{-4} m/s, respectively.

Membrane performance was measured by a temperature corrected specific flux to 20°C using the following equation:

\[ L_{p}^{20\degree C} = \frac{1}{\mu_{w}^{20\degree C}R} \cdot \frac{J \cdot e^{(0.0239(T-20))}}{\Delta P} \]  \hspace{1cm} \text{Equation 1} 

where,

\[ L_{p}^{20\degree C} \]  = specific flux at 20°C, L/m² h bar (LMH/bar) 

\[ T \]  = temperature of water, °C
\[ \mu_{w}^{20^\circ C} = \text{absolute viscosity of water at } 20^\circ C, \text{ kg/m}^s \]

R = total resistance, m\(^{-1}\)

J = membrane flux, L/m\(^2\cdot h\) (LMH)

\(\Delta P\) = transmembrane pressure, Pa

It is important to note that the filtration resistance, R, can be obtained by multiplying the specific flux by the absolute viscosity of water at 20°C. For ease of comparison, the specific flux data for each experiment was divided by the initial specific flux to determine a normalized specific flux.

**Analytical Methods:** MLSS and mixed liquor volatile suspended solids (MLVSS) were measured according to Standard Methods 2540 D/E (APHA 1998). Mixed liquor viscosity measurements were made using a rotational disk viscometer (Viscometers UK Ltd, London – LV spindle #2) for all samples collected during high MLSS experiments. The rheological properties of the sludge were that of a power-law fluid, or “shear-thinning”. Mixed liquor sCOD was determined by analyzing the mixed liquor filtrate from a 0.45 μm nitrocellulose membrane (Fisherbrand Water-Testing Membrane Filters, Fisher Scientific L.L.C., Hampton, NH) using Standard Method 5220 D (APHA 1998).

Extracellular polymeric substances (EPS) concentrations were measured as carbohydrate and protein using a cation exchange resin (CER) (Dowex\textsuperscript{®} Marathon\textsuperscript{®} C, Na\textsuperscript{+} form, Sigma-Aldrich, Bellefonte, PA) extraction method (Frolund et al. 1996). A mixed liquor sample was immediately cooled to 4°C to minimize microbial activity. The exchange resin (70 g of CER/g VSS) was added to a 50-mL sample and mixed at 600 rpm using a
single blade paddle for 2 h at 4°C. The mixture (50 mL) was centrifuged for 15 min at 12,000 g to remove MLSS. Supernatant carbohydrate and protein concentrations were measured colorimetrically by the methods of Dubois et al. (1956) and Lowry et al. (1951), respectively. At the same time, 50 mL of untreated mixed liquor was centrifuged for 15 min at 12,000 g, and the protein and carbohydrate concentrations were determined on the supernatant to represent the soluble fraction (Soluble Microbial Products, SMP). The centrifuge supernatant of the mixed liquor sample represented the SMP concentration, and the centrifuged supernatant of the sample after CER addition represented the sum of SMP and EPS concentrations. The difference between these measurements is the EPS concentration. Bovine serum albumin (BSA) was used as a protein standard, and dextrose was used as a carbohydrate standard.

Mixed liquor colloidal material was measured by a method modified from Wilen et al. (2000). Mixed liquor from each reactor was centrifuged for 2 min. at 1000g and then the supernatant turbidity was measured using a Hach 2100N nephelometer (Hach Company, Loveland, Co).
RESULTS

The SMBR pilot plant was operated for 415 d to study the effects of organic loading on membrane fouling (Trussell et al. In Press). Following completion of these experiments, the SMBR pilot was operated for an additional 195 d to perform the experiments presented here.

**Mixed Liquor Suspended Solids:** The MLSS concentration was initially maintained at approximately 14 g/L (Figure 1). After completing the 10-d MCRT experiments, the MLSS concentration was reduced during the 20-d MCRT to approximately 12 g/L by decreasing the reactor HRT. The MLSS was reduced to ensure that SMBR operation prior to the high-solids experiments did not result in significant membrane fouling. The MLSS concentrations for the long-term high solids experiments are shown in Figure 1. In all experiments, the MLSS concentration approached 18 g/L at the end of the experiment.

**Membrane Performance:** Membrane performance data for the entire 195 d of operation are presented in Figure 1. The system was operated at the target flux of 30 LMH a majority of the time. However, during the 10-d MCRT phase and for part of the 20-d MCRT phase, the mixed liquor filterability was poor and continuous operation at the target membrane flux of 30 LMH was not possible. When we attempted to maintain the membrane flux near the target flux of 30 LMH for a 2-week period (Days 9 to 24) and the specific flux declined rapidly (due to TMP increase). Because the goal of our high-solids experiments was to start them after reaching high-solids steady-state conditions, the
membrane flux was reduced to 13 LMH to prevent further membrane fouling. The actual experiments described in this work were conducted at 30 LMH as described in the previous section. Although SMBRs operated at higher MCRTs have been shown to reduce membrane fouling (Lee et al. 2003; Ng et al. 2006; Trussell et al. 2005), the authors believe that the reduced sludge filterability was a result of large rainwater inflows to the San Francisco combined sewer system serving the treatment plant (Trussell et al. 2006) and did not result from the differences in MCRT. Trussell et al. (In Press) presents steady state 10-d MCRT conditions where the same SMBR system was capable of sustaining a membrane flux of 30 LMH for 87 d without requiring a chemical clean treating the same wastewater.

The mixed liquor filterability improved during the 20-d MCRT and the membrane flux remained at 30 LMH for the remaining test periods with no significant decline in specific flux. The long-term (no wasting) experiments are also presented on Figure 1; rapid membrane fouling was observed at the conclusion of each experiment. The membrane was chemically cleaned between each operating condition.

**Short-term experiments:** Figures 2 and 3 show the results of the short-term, high-solids experiments at coarse bubble aeration intensities of $1.5 \times 10^{-4}$, $2.3 \times 10^{-4}$ and $3.0 \times 10^{-4}$ m/s for all MCRT conditions tested. In all experiments, the normalized specific flux declined as the membrane tank MLSS concentration increased. At an MCRT of 10-d and an aeration intensity of $1.5 \times 10^{-4}$ m/s, the specific flux declined notably with increasing MLSS concentrations with a 10% specific flux decline occurring at 18.2 g/L (Figure 2).
The specific flux declined to a lesser extent with increasing MLSS concentrations at the 20-d and 30-d MCRTs with a 10% specific flux decline occurring at an MLSS concentration of 21.5 g/L (Figure 2).

Higher aeration rates have been previously demonstrated to allow operation at increased membrane flux values and higher MLSS concentrations before significant specific flux decline occurred (Bouhabila et al. 2001; Hwang et al. 2003; Le Clech et al. 2003; Liu et al. 2003; Liu et al. 2000; Tardieu et al. 1998; Tardieu et al. 1999; Ueda et al. 1997). However, these experiments were all performed at constant MLSS concentrations while, varying the membrane flux and aeration intensity. Our approach was to hold to the membrane flux and aeration intensity constant while the MLSS concentration is increased, either by mechanical dewatering or microbial growth. This approach emphasizes that the aeration intensity, while an important parameter, cannot be interpreted in isolation without considering the operational changes of MLSS and its properties ultimately affecting sludge viscosity. To assess these interactions, we considered the changes of MLSS from the steady state (i.e. at start of each experiment) yielding 10% decrease from the initial specific flux. Comparing the MLSS concentrations at 10% specific flux decline, the increase in aeration intensity from the lowest value of 1.5x10^{-4} to 2.3x10^{-4} m/s resulted in a more significant increase in the allowed MLSS concentration at the 20-d and 30-d MCRT compared to conditions of poor filterability sludge at the 10-d MCRT. The 20-d and 30-d MCRT MLSS concentrations increased by 3.1 g/L from 21.5 to 24.6 g/L at 10% specific flux decline, while the 10-d MCRT MLSS concentration increased by 1.6 g/L from 18.2 to 19.8 g/L at 10% specific flux decline.
(Figure 2). However, further increasing the aeration intensity from 2.3x10^{-4} to 3.0x10^{-4} m/s resulted in similar increases in the MLSS concentration at the 10% specific flux decline for all sludge conditions. The 20-d and 30-d MCRT MLSS concentrations increased by 2.3 g/L from 24.6 to 26.9 g/L at 10% specific flux decline, while the 10-d MCRT MLSS concentration increased by 2.2 g/L from 19.8 to 22.0 g/L at 10% specific flux decline (Figures 2 and 3).

At the conclusion of all short-term experiments, the mixed liquor was returned to the initial MLSS concentration by returning membrane permeate collected during the short-term experiments to the biological reactor. For all experiments, the membrane permeability was recovered within 3 h by agitating the membranes with 14.2 L/s of coarse bubble aeration and with no permeate flow (Table 1). This indicates that the flux decline was caused by the reversible accumulation of filtration cake at the membrane surface. Chemical cleaning was not required, demonstrating that membrane fouling was not caused by adsorption of fouling components or by pore plugging. At the 10-d MCRT, the mixed liquor produced a “stickier” cake that required the full recovery period (3 h) to restore the specific flux to its initial value (Table 1). Table 1 shows that the specific flux was often restored to within 1-2% of its initial value immediately following the dilution of the mixed liquor to its initial MLSS concentration at the 20-d and 30-d MCRT conditions.

**Long-Term Experiments:** The long-term experiments (with no sludge wasting) at initial MCRT conditions of 10-d, 20-d and 30-d (Figure 3) showed that regardless of differences
in sludge filterability, the specific flux declined by 10% at approximately 16 g/L MLSS — a value that is significantly lower than that for the short-term experiments.

**Mixed Liquor Properties:** Table 2 summarizes the mixed liquor properties for the short-term experiments where the initial \( t_0 \) and final \( t_f \) mixed liquor samples were analyzed. The mixed liquor properties are significantly different between the sludge with poor filterability (e.g. 10-d MCRT) and sludges with normal filterability (e.g. 20-d and 30-d MCRTs).

While mixed liquor colloidal material can affect the filterability of a sludge cake and colloids have been implicated in MBR fouling, these effects were not observed in these experiments (Itonaga et al. 2004; Ma et al. 2005; Ng and Hermanowicz 2005). The initial colloidal material concentration was significantly higher at the 10-d MCRT than at the 20-d and 30-d MCRTs. During the short-term experiments, the colloidal material concentration varied significantly. In general, the colloidal material concentration increased through the short-term experiments, but on two occasions it decreased. Thus, the observed membrane fouling could not be attributed unambiguously to colloids.

Recent work has found that soluble carbohydrate (e.g. SMP\(_c\)) is the primary cause of increased membrane fouling rates (Rosenberger et al. 2005; Rosenberger et al. 2006). However, as Table 2 shows, the SMP\(_c\) concentration remained relatively constant around 20 mg/L for the conditions tested, ranging from 12 mg/L to 27 mg/L (Table 2). The short-term experiments did not increase the SMP\(_c\) concentration significantly regardless of the
sludge properties or aeration intensity. In fact, one of the poor filterability sludge samples exhibited the lowest SMPc concentration in any mixed liquor tested. However, the SMPp concentration varied more significantly and ranged from 10 to 140 mg/L. The poor filterability sludge (10-d MCRT) was influenced by the aeration intensity and the highest SMPp concentration was observed at the highest aeration intensity, indicating that this sludge was more sensitive to the additional shear force provided by the increased aeration intensity, resulting in released SMPp from the biological floc. The average total SMP concentration was higher for the poor filterability sludge and was lowest for the 30 d MCRT. The average ratio of SMPp to SMPc was higher for the poor filterability sludge, not lower, which supports the importance of the total soluble organic concentration as the best measure of membrane fouling. This is in agreement with recent work that demonstrated the importance of the colloidal organic content on the membrane critical flux (Fan et al. 2006). It is important that the soluble organic content be determined by a centrifugation method or possibly paper filtration and not by bench membrane filtration (≤0.5μm) because this method does not correlate with membrane fouling rates (Itonaga et al. 2004; Rosenberger et al. 2005; Trussell et al. In Press).

The total EPS concentration was lowest for the poor filterability sludge (e.g. 10-d MCRT) and this may have contributed to the poor flocculation indicated by high colloidal material content at this condition. Similar to the SMP, the carbohydrate fraction (EPSc) was relatively constant for all conditions tested, ranging from 24 to 29 mg/gVSS. The EPSp varied significantly from 57 to 88 mg/gVSS and primarily influenced changes
in the total EPS concentration and the ratio of EPS P/C. These data show that measuring EPS P/C does not provide significant information about sludge filterability.

Table 2 shows that the sCOD concentrations were higher for the poor filterability sludge and increased during the short-term experiment. However, the sCOD concentration did not increase for all the short-term experiments as shown in Figure 4. The sCOD at the 10-d MCRT condition increased with increasing MLSS concentration while the sCOD at the 20-d and 30-d MCRTs did not consistently increase during the short-term experiments. The increase in sCOD for the 10-d MCRT and not the 20-d and 30-d MCRTs indicates that organics, smaller than 0.45μm, are being retained as the poor filterability sludge was being thickened. In contrast, these organics were readily passing through the membrane while the 20-d and 30-d MCRT sludges were thickened.

The mixed liquor properties were measured daily in the long-term experiments (Figure 5). The mixed liquor properties did not increase in the long-term experiments with the exception of the mixed liquor viscosity and 20-d MCRT colloidal content. However, the 30-d MCRT colloidal content did not increase in the long-term experiment and the only mixed liquor property that consistently increased for all three experiments was the mixed liquor viscosity. Figure 5 presents the mixed liquor viscosity for all the samples, from both the short-term and long-term experiments, as a function of MLSS concentration, and clearly shows that the 10-d MCRT sludge was more viscous than the measured 20-d and 30-d MCRT sludges. It is important to note that activated sludge is a non-Newtonian fluid whose viscosity depends on the applied shear rate and the same device, speed, and
spindle are required to compare viscosity data with those presented here (Defrance et al. 2000; Dick and Ewing 1967).

DISCUSSION

Membrane Filtration in the SBR: The SBR process uses direct membrane filtration of mixed liquor to provide solid-liquid separation and the membrane permeability declines with increases in filtrate volume or operational time. Agitation and cross-flow velocity provided by coarse bubble aeration produce shear forces that re-suspend the rejected materials into the bulk solution and maintain membrane permeability. A balance must be maintained between the flux of materials toward the membrane surface and the re-suspending flux provided by the coarse bubble aeration intensity.

For the experiments presented in this paper, the membrane hydraulic flux was held constant while the concentration of MLSS increased, thus increasing the solids flux towards the membrane. The coarse bubble aeration intensity was also constant, but as the MLSS concentration increased, the mixed liquor viscosity increased exponentially and changed the flow regime of the coarse bubble aeration and therefore its efficacy (Cui et al. 2003). Figure 6 illustrates the effect of mixed liquor viscosity on the specific flux for all of the short-term experiments where the specific flux began to decline above a viscosity of 190 cP. For each coarse-bubble aeration intensity, the flux decline curves collapse to a single line when plotted as a function of viscosity (Figure 6) regardless of
sludge properties and operating conditions. Thus, the membrane performance was primarily affected by changes in viscosity for the high MLSS concentrations in the short-term experiments. Based upon the data and samples collected, no other mixed liquor property could have impacted membrane performance so dramatically (Table 2). This finding underscores the importance of the external mass transfer in the SMBR operating at high MLSS concentrations. For a particular reactor design, the resuspending solids flux is an increasing function of the aeration intensity and the counteracting effects of mixed liquor viscosity. The viscosity is in turn affected by the MLSS concentration and the biomass composition and structure.

**Effect of Time Exposure on Specific Flux Decline:** The length of time that the SMBR process was exposed to the increasing MLSS concentrations affected the degree of membrane permeability decline. Figure 7 shows the effect of filtration time on membrane permeability with MLSS concentrations for the 20-d and 30-d MCRTs. In the short-term experiments, the MLSS concentration increased more rapidly (reaching 25 g/L and a 10% specific flux decline in 30 min) than in the extended short-term experiment (reaching 22 g/L and a 10% specific flux decline in 1 h). In the long-term experiment, the MLSS concentration increased gradually over a one-week period and reached a concentration of 16 g/L at 10% specific flux decline. The effect of filtration time on the specific flux decline at increasing MLSS concentrations is expected since small differences in equilibrium between MLSS transport to and from the membrane will be exaggerated over extended periods of time.
CONCLUSIONS

- All experiments showed that membrane permeability decreased as MLSS concentrations increased.
- Increasing the coarse bubble aeration intensity increased the MLSS concentration that could be obtained before a 10% decline in specific flux occurred.
- Highest colloidal material, total SMP and soluble COD concentrations were obtained at the 10-d MCRT when the mixed liquor filterability was the poorest. The lowest total EPS concentration was obtained at these conditions.
- Poor mixed liquor filterability (10-d MCRT) affected the influence of MLSS concentration on specific flux.
- Increasing the MLSS concentration in the long-term experiments resulted in similar specific flux declines regardless of mixed liquor properties.
- Virtually complete specific flux recovery could be obtained by diluting to the initial MLSS concentration and aerating the membrane without permeate production.
- Poor mixed liquor filterability (10-d MCRT) required a longer aeration period to restore the original specific flux, indicating the formation of a “stickier” cake layer.
- Mixed liquor viscosity, not other mixed liquor properties, controlled the specific flux decline for these experiments.
- A longer exposure time to increasing MLSS conditions resulted in a greater specific flux decline with MLSS.
ACKNOWLEDGEMENTS

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REFERENCES


### TABLES

Table 1. Summary of Membrane Permeability Recovery for High Solids Experiments

<table>
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<tr>
<th>MCRT, d</th>
<th>Coarse Aeration Rate, L/s</th>
<th>Specific Flux@20°C, LMH/bar Initial</th>
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Table 2. Summary of Mixed Liquor Properties For Short-Term Experiments

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<td>Total SMP</td>
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<td>26</td>
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<td>SMP_p</td>
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<td>t₀</td>
<td>Total EPS</td>
<td>mg/g VSS</td>
<td>81</td>
<td>87</td>
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<td>mg/g VSS</td>
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<td>mg/g VSS</td>
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<tr>
<td>t₀</td>
<td>sCOD</td>
<td>mg/L</td>
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<td>82</td>
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<td>101</td>
<td>115</td>
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</table>

* t₀ – mixed liquor sample collected at start of short-term thickening experiment and t_F – final mixed liquor sample collected.
Figure 1. Daily MLSS concentrations and membrane performance for 10-d, 20-d and 30-d MCRT high solids experiments
Figure 2. Effect of MLSS on specific flux in short-term experiments at aeration intensities of 1.5x10^{-4} and 2.3x10^{-4} m/s
Figure 3. Effect of MLSS on specific flux in short-term experiments at an aeration intensity of 3.0x10^{-4} m/s and long-term experiments at an aeration intensity of 2.3x10^{-4} m/s

*Sludge wasting was stopped after achieving steady state at the specified condition
Figure 4. Changes in mixed liquor sCOD with MLSS for short-term experiments
Figure 5. Changes in all mixed liquor properties for the duration of the long-term experiments
Figure 6. Effects of MLSS on sludge viscosity for LV spindle #2 at 100 rpm
Figure 7. Effect of sludge viscosity and aeration intensity on specific flux
Figure 8. Effect of exposure time to high MLSS on specific flux