Optimising the operation of a MBR pilot plant by quantitative analysis of the membrane fouling mechanism

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Abstract In order to optimize some operational conditions of MBR systems, a MBR pilot plant equipped with a submerged hollow fibre membrane module was employed in this study. The pilot MBR was fed with real municipal wastewater and the filtration flux, backwashing interval, aeration frequency and temperature were varied. A filtration flux below 25 l/m^{2}h is generally recommended, at below this flux, the MBR operated at sub-critical flux conditions, the filter cake was minimized and membrane fouling was mainly attributed to the membrane pore blocking. Moreover, the membrane fouling, at below 25 l/m^{2}h, was more reversible to backwashing; above this value, backwashing became less efficient to clean the membrane. Less frequent backwashing (e.g. 600 s filtration/45 s backwashing) decreased the amount of fouling irreversible to backwashing and its performance was superior to that of frequent backwashing (e.g. 200 s filtration/15 s backwashing). The MBR suffered more fouling at low temperature conditions (e.g. at 13–14 °C) than at high temperature conditions (e.g. at 17–18 °C). A conceptual model was built up and successfully interpreted this temperature effect.

Keywords Membrane bioreactor; fouling; critical flux; temperature

Introduction

A submerged membrane bioreactor normally applies coarse bubble aeration to slough the membrane surface and control the membrane fouling, and no energy intensive sludge recirculation is required. Consequently, a submerged MBR is characterized by lower operational costs and more stable operation compared with side-stream MBRs. However, membrane fouling remains an essential issue.

Most studies on MBR fouling mechanisms are carried out at laboratory scale, which guarantees stable and flexible operation. However in laboratory MBRs, the influent characteristics are often different from field conditions and the hydrodynamic conditions in membrane tanks are essentially different from those in full scale MBRs (e.g. scale, geometry and aerator, etc.). On the other hand, purely mathematical modeling of the hydrodynamic conditions in the membrane tank and membrane fouling encounters many difficulties, due to the complicated membrane module layout arid the occurrence of sludge/air two-phase flows. Hence, the results obtained from laboratory scale MBRs might be difficult to scale up to full-scale installations. Consequently, pilot MBR studies are often carried out.

The goal of this study is to optimize some operational conditions of a MBR pilot plant from the point of view of the membrane fouling mechanisms, especially study the temperature effects on MBR fouling. Real municipal wastewater and a ZeeWeed® 500 C module (ZENON), which is identical to the ones used in full-scale MBR installations, were employed in this study.

Methods

A ZENON MBR pilot plant, located in Beverwijk, The Netherlands, was fed with municipal wastewater from the Beverwijk Zaanstreek wastewater treatment plant (40 m^3/d) (Figure 1). The raw wastewater was passed through a 0.5 mm micro-screen to remove hair, debris, rags and sand etc. Thereafter, the prescreened wastewater entered the aeration tank where organic matter, nitrogen and phosphorus were removed. The effluent sludge from the aeration tank was pumped to a membrane tank for biomass separation. The permeate was sucked from the membrane module and passed though in a CIP (Cleaning In Place) tank and the concentrated sludge was returned to the aeration tank. The sludge age of the pilot MBR was controlled around 22–25 days and the Mixed Liquor Suspended Solid (MLSS) concentration in the aeration tank was controlled around 10–12 g/l.

A ZENON membrane module (ZeeWeed® 500 C) with a total surface area of 60 m^2 and normalized pore size of 0.04 μm was installed in the membrane tank for biomass separation. This membrane module is also widely used for full-scale MBR installations. Consequently, the results obtained from this MBR system are easy to scale up. Air was continuously introduced to the bottom of the membrane module at 50 Nm^3/h to move and slough membrane fibers. The default values and the range of operational conditions are summarized in Table 1.

The sampling frequency of the transmembrane pressure (TMP) was once per second. The TMP data at various temperature conditions were normalized into the corresponding values at 15 °C, by normalizing the permeate viscosity to the values at 15 °C (Eq. (1); White, 1986), where T_0 and T are absolute temperature at 273.16 K and field conditions; μ_0 and μ are the corresponding permeate viscosity ($\mu_0 = 1.788 \times 10^{-3}$ Pa s); $a = -1.94$; $b = -4.80$ and $c = 6.74$. The amount of blocking/cake resistance and the reversible/
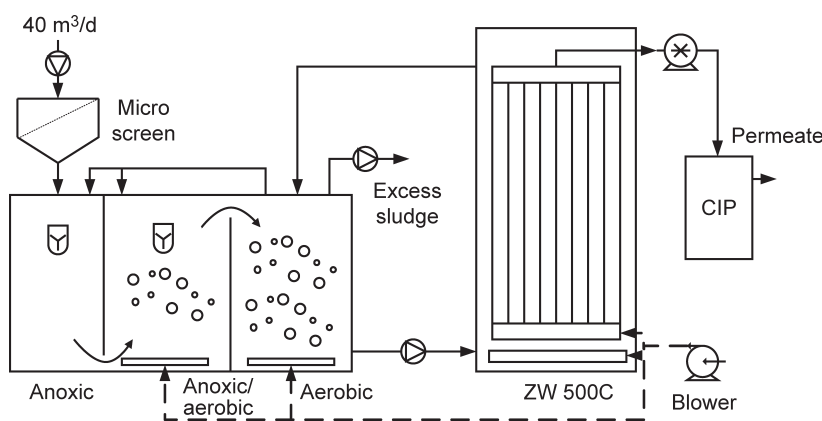

Figure 1 Schematic of ZENON MBR pilot plant

Table 1 Default values and range of operational conditions

Parameter	Unit	Default value	Tested range
Filtration flux	l/(m^{2}h)	30	10–50 (intervals of 5)
Backwashing/filtration flux ratio	–	1.25	1.25
Backwashing duration	s	15	15, 30 and 45
Backwashing interval	s	200	200, 400 and 600
Aeration frequency (On/Off)	s	10/10	10/10, 10/30 and 10/60
Temperature	°C	17–18	17–18 and 13–14

irreversible resistance were quantified according to the method of Jiang *et al.* (2003).

$$\ln\frac{\mu}{\mu_0} \approx a + b\left(\frac{T_0}{T}\right) + c\left(\frac{T_0}{T}\right)^2 \tag{1}$$

Results and discussion

Critical flux

To obtain the value of the critical flux, the filtration flux was increased from 10 to $50\,l/m^2\,h$, with steps of $5\,l/m^2\,h$. At each flux, 30 minutes filtration was carried out continuously without backwashing, but intensive backwashing was performed after each flux test. The results are plotted in Figure 2. Up to $30\,l/m^2\,h$, no significant increase in TMP occurred (no strong form of critical flux defined by Field *et al.* (1995) was observed either); however, fluxes higher than $30\,l/m^2\,h$ resulted in a rapid increase in TMP, which suggested that the membrane fouling remained limited below the flux of $30\,l/m^2\,h$ but intensified above. As a result, a "weak" form of critical flux (or sustainable flux defined by Defrance and Jaffrin (1999) in MBRs) was obtained and it was around $30\,l/m^2\,h$ at the specific operational conditions under study (17–18 °C, feed MLSS concentration 12–15 g/l, and air flow rate $50\,Nm^3/h$). It is advised to run the MBR at sub-critical flux conditions in order to minimize the membrane fouling (Field *et al.* (1995); Defrance and Jaffrin 1999); while operating above critical flux is also possible but membrane cleaning should be intensified. However, it should be noted that the critical flux value is subject to change when environmental and operational conditions vary and the value obtained here should not be generalized.

Fouling mechanism

By quantifying and comparing the blocking and cake resistance as a function of filtration flux (Figure 3), it appeared that below $35\,l/m^2h$, the blocking resistance ($R_{b,cycle}$) was higher than the cake resistance ($R_{c,cycle}$) during one filtration cycle and blocking was identified as the main fouling mechanism. However, above a flux of $35\,l/m^2h$ (more pronounced at fluxes of 45 and $50\,l/m^2h$), the cake resistance ($R_{c,cycle}$) increased significantly and it became higher than the blocking resistance ($R_{b,cycle}$). The blocking resistance appeared stabilized throughout the flux range, which can be attributed to the role of dynamic cakes, formed intensively on the membrane surface above $30\,l/m^2h$. The dynamic cake functioned as a "secondary membrane" and reduced the direct contact of small colloidal particles to the membrane surface (Lee *et al.*, 2001). As a result, the true membrane pores were protected from direct blocking/adsorption by small colloidal particles.
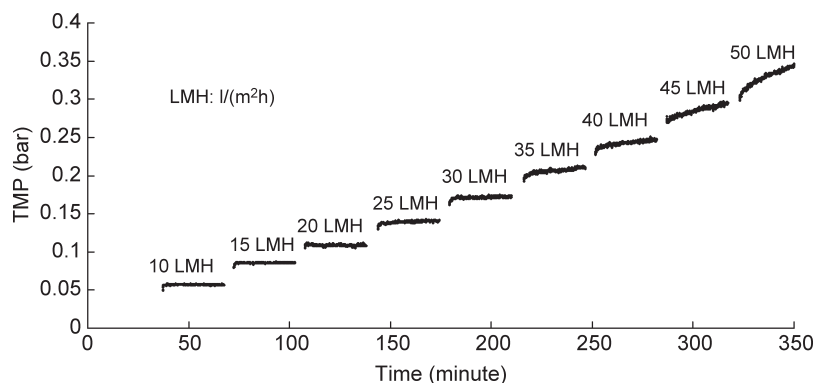

Figure 2 The increase in TMP during 30 minutes continuously filtration ($10-50\,l/m^2h$)
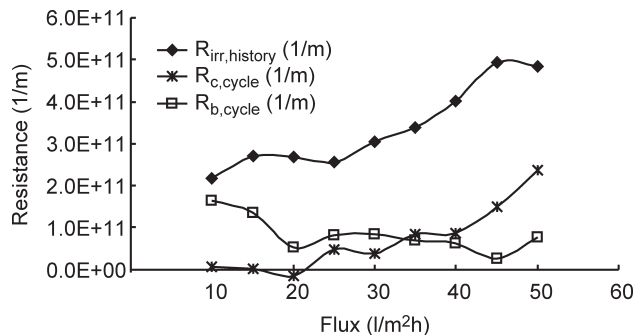
Figure 3 The influence of filtration flux on membrane fouling mechanism and reversibility

According to this shift of fouling mechanism, the "weak" form of critical flux in this MBR can be interpreted as the point that below which, cake formation is minimized and membrane fouling is mainly due to the membrane pore blocking by small colloids or solutes; above the critical flux, filter cake formation is initiated. In addition to the colloidal and solute blocking/adsorption, even large flocs are able to deposit, driven by the intensified permeation flow above the critical flux.

To evaluate the membrane fouling reversibility to backwashing (backwashing flux remained 1.25 times the filtration flux and frequency was once per 200 s), the irreversible fouling due to the membrane history ($R_{irr,history}$, the difference in resistance between at the beginning of a filtration cycle and the clean membrane resistance) was calculated (Figure 3). $R_{irr,history}$ appeared stable below a flux of 25 l/m^{2}h, but increased above this value. This observation suggests that the amount of membrane fouling irreversible to backwashing was intensified above a flux of 25 l/m^{2}h, and operating above this value need to intensify membrane cleaning. The increased irreversible fouling could probably be attributed to the cake compression above 25 l/m^{2}h.

Backwashing frequency

To optimize the backwashing frequency, three scenarios of filtration/backwashing conditions were evaluated for approximately 24 hours each. Scenario 1 (200 s filtration/15 s BW) was the default operation condition; afterwards, 400 s filtration/30 s BW and 600 s filtration/45 s BW were tested respectively. The three scenarios had a fixed gross flux of 30 l/m^{2}h, which means that the backwashing/permeate water ratios remained the same. The results are summarized in Table 2. Scenario 1 had the maximum increase rate of irreversible resistance (1.66×10^{10} l/(m·h)) and scenario 3 had the minimum increase rate of irreversible resistance (1.24×10^{10} l/(m·h)). It appeared that at the same net filtration flux conditions, less frequent backwashing reduced the total amount of membrane fouling. This observation was again interpreted as the role of filter cake as stated above. The filter cake reduced the direct contact of small colloidal particles with the membrane and consequently reduced the membrane pore blocking (e.g. the adsorption of small colloidal organic particles). Membrane pore blocking is often reported to be more difficult to clean than filter cake using backwashing (Lee *et al.*, 2001).

Table 2 Increase rate of irreversible resistance for three filtration/backwashing conditions

Scenario No.	Filtration/backwashing duration	Increase rate of irreversible resistance (m^{-1}/h)
1	200 s filtration & 15 s BW	1.66×10^{10}
2	400 s filtration & 30 s BW	1.37×10^{10}
3	600 s filtration & 45 s BW	1.24×10^{10}

Temperature

To evaluate the filtration performance at low temperature conditions, the operational temperature of the MBR system was artificially decreased from 17–18 °C to 13–14 °C during 5 weeks. The results are summarized in Table 3. The blocking and cake resistance of a filtration cycle ($R_{b,cycle}$ and $R_{c,cycle}$) increased significantly by 202% and 47% at the aeration frequency of 10 s On/10 s Off, and 169% and 278% at the aeration frequency of 10 s On/60 s Off respectively. This observation at pilot scale agrees with the results of a lab MBR, where the total filtration resistance increased from 1.2×10^{13} to $3.0 \times 10^{13} \, m^{-1}$ as the temperature decreased from 25 to 5 °C, and the authors attributed the increased resistance to the change of cake properties (thickness and porosity) (Chiemchaisri and Yamamoto, 1994).

The resistances presented in Table 3 have been corrected the temperature effect on permeate viscosity. Therefore, the increasing resistance at low temperature could not be simply interpreted by Darcy's law, and some other factors must contribute, including:

(1) The sludge was more viscous at low temperature (Sozanski *et al.*, 1997; Lin and Shien, 2001) and therefore, the shear stress generated by the coarse bubble aeration was reduced and particle deposition on the membrane could be intensified. Sozanski *et al.* (1997) used a temperature factor to quantify the influence of temperature on sludge viscosity. According to this model, decreasing the temperature from 17–18 °C to 13–14 °C would increase the sludge viscosity by approximately 10% (5% dry solid).

(2) The characteristics of the MLSS (e.g. the particle size distribution, particle shape and floc porosity etc.) were changed or in other words, the MBR sludge was deflocculated as temperature decreased. Wilen *et al.* (2000) reported that the effluent turbidity of a full-scale WWTP increased during the autumn and winter when the temperature in the aeration tank was lower, which was attributed to the intensified deflocculation of activated sludge at low temperature conditions. The same group also measured the compounds released during the deflocculation, such as proteins, humic substances and carbohydrates (the major part of them are Extracellular Polymetric Substances (EPS). It can be hypothesized that decreasing the temperature resulted in MBR sludge deflocculation and the release of EPS, which was originally bound to the flocs functioning as some kind of "glue". Hence, the smaller particle size and the released soluble EPS consequently facilitated membrane fouling.

(3) The decreasing temperature reduced the mass transfer rate, i.e. the Brownian diffusion coefficient is linear to the absolute temperature (Davis, 1992). Consequently, the particle backtransport velocity was reduced.

(4) The decreasing temperature slowed down the biodegradation of COD and probably resulted in a higher concentration of soluble and particulate COD in the membrane tank.

The influence of temperature on membrane fouling is conceptually illustrated in Figure 4. It should be noted that the release of EPS not only directly intensifies membrane fouling, but also increases the viscosity of the MBR sludge and further weakens the structure of the MBR flocs, which indirectly intensifies membrane fouling too.

Table 3 Influence of temperature on blocking and cake resistance of one filtration cycle

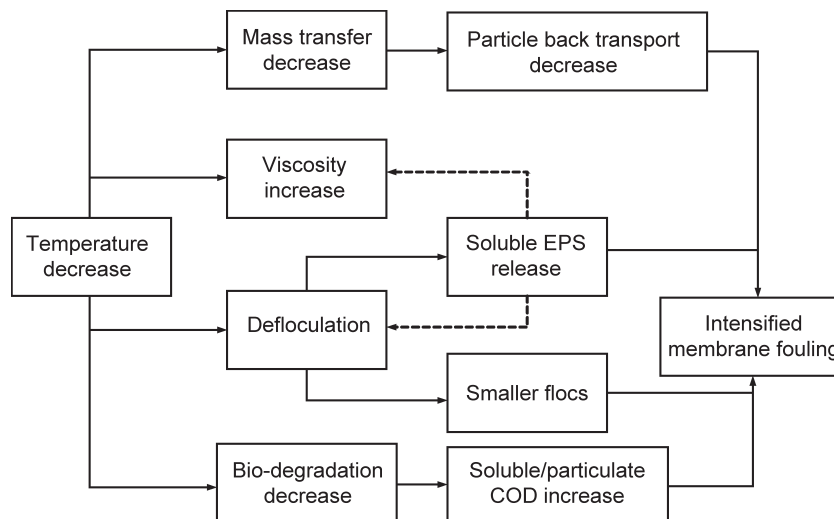| Aeration Frequency	17–18 °C		13–14 °C		Increase	
	$R_{b,cycle}$ (m^{-1})	$R_{c,cycle}$ (m^{-1})	$R_{b,cycle}$ (m^{-1})	$R_{c,cycle}$ (m^{-1})	$R_{b,cycle}$ (%)	$R_{c,cycle}$ (%)
10 s On/10 s Off	4.32×10^{10}	7.17×10^{10}	1.31×10^{11}	1.05×10^{11}	202	47
10 s On/30 s Off	5.38×10^{10}	1.10×10^{11}	1.41×10^{11}	1.76×10^{11}	163	61
10 s On/60 s Off	6.54×10^{10}	1.14×10^{11}	1.76×10^{11}	4.30×10^{11}	169	278

Figure 4 A conceptual model of temperature effects on membrane fouling

The significant impact of temperature on MBR fouling suggests that winter is the critical time for membrane operation. To control the possible intensification of membrane fouling under winter conditions, it is suggested to run the MBR at a lower filtration flux, if possible, and to intensify the coarse bubble aeration.

Conclusions

- The "weak" form of critical flux in this MBR pilot plant was around $30\,l/m^2h$, below this value, filter cake was minimised and membrane fouling could mainly attributed to pore blocking. However, above this value, filter cake build up was intensified. Furthermore, membrane fouling was more reversible to backwashing (1.25 times the filtration flux) at fluxes below $25\,l/m^2h$; above this value, backwashing became less efficient to clean the membrane.
- Generally a filtration flux below $25\,l/m^2h$ is recommended in this MBR pilot plant under the specific test conditions. However, this value is subject to change as environmental and other operational conditions may vary, e.g. at low temperature conditions (e.g. winter), further decreasing the filtration flux is suggested, if possible.
- Less frequent backwashing (e.g. $600\,s$ filtration/$45\,s$ backwashing) decreased the amount of fouling irreversible to backwashing and thus its performance was superior to that of frequent backwashing conditions (e.g. $200\,s$ filtration/$15\,s$ backwashing).
- The MBR suffered more fouling at low temperature conditions (e.g. at 13–14 °C) than at high temperature conditions (e.g. at 17–18 °C). A conceptual model was built up and successfully interpreted this temperature effect.

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