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Compressibility of fouling layers in membrane bioreactors

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ABSTRACT

In membrane bioreactor (MBR) systems, several fouling mechanisms occur; e.g. pore blocking, gel formation, biofilm growth and cake formation. This study focuses on the cake layer which is easily removed e.g. by relaxation and the inner gel layer that is not removed by relaxation. The cake layers are compressible and significantly influence MBR operation, especially for short term filtrations. Over longer filtrations, an inner gel layer is formed. The gel layer consists of soluble microbial products (SMP). To investigate whether this structure exhibits a pressure dependent filtration resistance, the compressibility of the fouling layers was studied by a TMP step procedure. The data from the experiments show that the gel layers are compressible. Further, there is a pressure in the range of 4.9–7.9 kPa, where a compressive yield stress was observed, below which the gel is incompressible and above which the gel is compressible. The compression was reversible, both for the cake layer and for the gel layer. This shows that the fouling layers formed in MBRs are highly compressible which should be accounted for during both short and long term operation.

1. Introduction

Membrane bioreactor (MBR) is a useful technology for wastewater treatment as the introduction of a membrane to a bioreactor provides a clear effluent and allows handling of higher sludge concentrations and thereby lower footprint or lower sludge production [1]. However, MBR systems suffer from the problem of fouling which has limited their broad application [2]. Fouling is the deposition of sludge compounds on the membrane surface and/or within the membrane pores, which gives an extra resistance to filtration. This will either result in a higher transmembrane pressure (TMP) for constant flux operation or lower flux over time in constant TMP filtration. This lowers the performance of the MBR system and by implementation of air scouring for removal of fouling, the specific energy consumption increases.

Sludge can be divided into two phases: solid and liquid. The solid phase consists of sludge flocs and other particles larger than 1 μm and suspended colloids, e.g. single cell bacteria [3]. The liquid phase contains bio-macromolecules including proteins, humic-like substances and carbohydrates generally known as soluble microbial products (SMP) [1,2,4]. Deposition of the components of the solid phase forms a cake layer during filtration, which to a high degree can be removed by relaxation [5], but the smaller components, the colloids, can also lead to pore blocking. Accumulation of SMP results in gel formation, adsorption and pore blocking during filtration, which is not removed by relaxation [6].

MBR membranes are fouled by cake formation, pore blocking, adsorption, and gel formation [1,2]. While growth of the cake layer and its effect on permeate flux takes place within 10 min, growth of the gel layer and its effect on permeate flux takes place within several months [7]. SMP have been shown to adsorb to polymeric PVDF membranes but not with a significant influence on flux [8]. Further, it has been shown that pore blocking mainly occurs during the start of filtration until a cake layer has formed, which protects the pores of the membrane [9]. Therefore, cake formation and gel formation are often considered to be the most significant fouling mechanisms in MBRs [9,10,11]. If it is assumed that pore blocking and adsorption is negligible, and cake and gel layer formation are the dominating fouling mechanisms, the flux influence of additional hydraulic resistance can be described by Eqs. (1) and (2).

$$J = \frac{\text{TMP}}{\mu(R_m + R_f)} \tag{1}$$

$$R_f = R_c + R_g \tag{2}$$

J is the permeate flux (m s^{-1} or lmh), tmp is the transmembrane pressure (pa), μ is the dynamic viscosity of water (pa s) and R_m, R_f, R_c and R_g are the hydraulic resistances (m^{-1}) of the membrane, fouling layer, cake and gel layer, respectively. the fouling resistance can be described as the product of the area-specific amount of fouling, ω (kg m^{-2}), and the specific resistance of the fouling layer,

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α ($\mathrm{m\,kg^{-1}}$) as described in Eq. (2).

$$R_f = \alpha\omega \tag{3}$$

In the MBR systems operated in constant flux mode, operating TMP is usually elevated to compensate for permeability loss and keep the permeate flux constant. The gradual elevation of TMP leads to compaction of the fouling layer, which further lowers the permeability. This can in the end result in the TMP jump; the sudden increase in pressure, after which the membrane has to be chemical cleaned [12,13]. The cake layer is described to be highly compressible in recent studies, i.e. the specific resistance is pressure dependent, and can be described by Eq. (4) [5,14].

$$\alpha = \alpha_0\left(1+\frac{\Delta P}{P_a}\right) \tag{4}$$

α_0 is the specific resistance at zero pressure ($\mathrm{m\,kg^{-1}}$), ΔP is the pressure drop across the cake (Pa), P_a is a compressibility parameter (Pa). It follows that the slope of this relationship, α_0/P_a, represents the compressibility of the fouling layer. The specific resistance of the gel layer will normally differ from the cake layer specific resistance. It is unknown to which extent the gel layer formed by soluble microbial products (SMP) is compressible and whether the compression of a gel layer can explain the high fouling intensity at long term filtration.

In this paper, the compressibility of both cake and gel layers is investigated in two sets of immersed membrane filtrations of MBR sludge samples and SMP solutions. It is assumed that the short term filtrations (2–3 h) of sludge samples result in formation of a cake layer by the wide range of foulants in the sludge and that this is the dominating fouling mechanism with respect to hydraulic resistance. The compressibility of the fouling layers is studied by measuring the filtration resistance response to TMP elevations. Furthermore, the reversibility of compression is found by releasing the TMP after compression. Dead-end filtrations of SMP suspensions are performed to verify the gel compressibility observations of the SMP filtrations with a submerged membrane.

2. Experimental

2.1. Sludge sampling

Sludge was sampled from a pilot plant MBR unit of an enhanced biological phosphorous removal process. The feed of the MBR unit was municipal wastewater passed through a side-stream anaerobic hydrolysis and an anoxic tank. The MBR unit was 1.6 $\mathrm{m^3}$ in volume and the trans-membrane pressure (TMP) approximately 3 kPa being run in constant TMP mode, with 10 min filtration and 2 min relaxation periods.

SMP solutions without presence of colloids were prepared to study the compressibility of gel layers formed by SMP. SMP was extracted by centrifugation of MBR sludge and two subsequent filtrations of the supernatant through glass fiber and mixed cellulose ester membranes of 1.6 and 0.45 μm pore diameter, respectively. The filtrate of the second filtration was regarded as the SMP suspension. Similar procedures have been used for SMP extraction, reportedly [15].

2.2. EPS measurement

The concentration of protein, humic-like substances and carbohydrate was measured in the sludge and the extracted SMP suspension. Concentration of protein and humic-like substances was measured by the modified Lowry method using bovine serum albumin and Aldrich humic acid as standard for protein and humic-like substances, respectively [16]. One limitation with this method is that at high calcium concentrations, the proteins precipitates and will not be detected [10]. However, no precipitation was observed in these experiments. The concentration of carbohydrates was measured by the Anthrone method using glucose as standard [16]. The EPS concentration and other characteristics of the MBR sludge and SMP are summarized in Table 1.

2.3. Filtration of MBR sludge

Filtration of MBR sludge was done in a submerged system of 120 L volume similar to the system applied in a previous paper [5]. Sludge was taken from the pilot plant and permeate was collected in a closed, vertical tube with valves mounted in different heights of the tube. The difference in level between the open permeate valve of the closed tube and the suspension level determines the transmembrane pressure (TMP), enabling filtration in the range 2–13 kPa. The permeate was collected in a beaker on a balance (PB 3002-S, Mettler-Toledo, Switzerland) connected to a computer to monitor the increment of permeate volume and from this the permeate flux. The membrane was scoured by air with a flow rate of 2.5 $\mathrm{L\,min^{-1}}$. A 15 cm × 30 cm microfiltration membrane sheet with a nominal pore diameter of 0.2 μm (Alfa Laval A/S, Copenhagen, Denmark) was used. The active surface of the membrane was made of poly vinylidene di-fluoride (PVDF), and membrane preparation was done according to the manufacturer instructions. Chemical cleaning of the membrane was done after each filtration experiments by immersing the membrane in 3% sodium hypochlorite solution and subsequently DI water for several hours. Then, Milli-Q water was filtered through the clean membrane and flux was measured. From the measured flux, R_m was determined using Eq. (1) and considering $R_f=0$. Having R_m calculated, R_f was calculated during filtration of fouling suspension i.e. MBR sludge.

To observe the effect of changing TMP, TMP-step filtrations on MBR sludge were performed by stepping pressure in two steps between a reference TMP and a compressive TMP. The reference TMP was 7.8 kPa whereas the compressive TMPs applied were 9.8, 11.4 and 12.8 kPa for three different filtration experiments, respectively. Filtrations started with the reference TMPs for 90 min. Then, filtration was continued with a jump from the reference to the compressive TMP (pressure elevation step) for 30 min. Finally, pressure was reduced to the reference TMP (pressure release step) for 30 min. The sludge filtration experiments were triplicated.

Table 1
MBR sludge and supernatant physical–chemical characteristics.

Sample	pH	Conductivity (μS $\mathrm{cm^{-1}}$) at 20 °C	Concentration of SS	Concentration of humic-like substances	Concentration of proteins	Concentration of carbohydrates
MBR sludge	7.8	1000	10.5 $\mathrm{g\,L^{-1}}$	200 $\mathrm{mg\,g^{-1}}$ SS	200 $\mathrm{mg\,g^{-1}}$ SS	84 $\mathrm{mg\,g^{-1}}$ SS
SMP suspension	8.1	1000	N.A.	22 $\mathrm{mg\,L^{-1}}$	0 $\mathrm{mg\,L^{-1}}$	3 $\mathrm{mg\,L^{-1}}$