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On the reversibility of cake buildup and compression in a membrane bioreactor

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ABSTRACT

Fouling in a membrane bioreactor was studied by describing the reversibility of fouling developing during short-term experiments. Data were fitted to a recently proposed model of the buildup and compression of fouling layers. Shear stepping experiments performed to characterize the efficiency of increased shear rates at removing cake layers indicated that cake layer removal follows the same kinetics as does cake layer development, so the fouling layers can be characterized as removable fouling. Furthermore, transmembrane pressure stepping indicates compression reversibility, so when the pressure on compressed cake layers is released, the cake swells back to a looser structure. Based on these observations, we discuss the validity of using the critical flux concept to study fouling irreversibility. Modeling data of short-term filtration tests shows that the presence of a critical flux for irreversible fouling depends on the relaxation time relative to the filtration time and pressure. Therefore, to observe a critical flux for irreversible fouling, the relaxation times applied in the stepping approach should be customized to be sufficient to remove all removable fouling. The model suggests that the critical flux occurs when the critical amount of deposit forming a stagnant cake on the membrane has been reached.

1. Introduction

Limiting and controlling the fouling of membranes in membrane bioreactors (MBRs) is the key to the widespread application of MBR technology. Such membranes yield clear effluent, compared to conventional activated sludge treatment processes, but the energy consumption associated with fouling and the cost of membrane replacement make the technology more expensive and less competitive [1,2]. Therefore, several studies have attempted to characterize the fouling layer, constructing models to simulate, monitor, and thereby reduce fouling [2]. Fouling can be reduced by enhancing shear at the membrane, for example, by means of crossflow of the feed suspension or air scouring, which is associated with higher energy consumption [1]. Therefore, there should be a balance between the extra production of permeate and the extra energy required to generate the enhanced shear. Furthermore, frequent physical cleaning such as relaxation or backwashing is used to remove reversible fouling and restore membrane permeability. However, physical cleaning requires short periods with no filtration and has been reported to induce irreversible fouling as the membrane becomes more vulnerable to, for example, pore blocking [3].

Reversible fouling is typically described as occurring in cake layers developing on the membranes. The development of these has in some cases been shown to be reversible [4,5], but in others to be somewhat irreversible [6–9].

Irreversible fouling, i.e. fouling that cannot be removed by physical or chemical cleaning, is a consequence of various fouling mechanisms. It can be due to pore blocking, foulant adsorption and gel layer formation [10–14], where the adsorbed foulants will develop into an irreversible gel layer when the gel concentration is reached [12]. Furthermore, compressing sludge cakes can result in more cohesive cakes that are more difficult to remove [15].

Recent studies have proposed a model for simulating fouling in lab- and pilot-scale MBRs by considering short-term fouling as a consequence of cake layer formation, describing it using a mass balance of foulant transport between membrane surface and bulk feed, and cake compression [4,5]. The ability of the model, assuming reversible buildup and compression, to describe the short-term development of flux at different transmembrane pressures (TMPs) and after relaxation phases suggests that the buildup and compression of fouling layers is reversible. However, the same data from Jørgensen et al. [4] analyzed in light of the critical flux concept suggest that there is a critical flux for irreversible fouling. The cake buildup and compression model fits data from short-term experiments well, but assumes that fouling is reversible, i.e.

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that cake removal has the same kinetics as does cake buildup. It would be useful to determine whether this assumption is fair, as other studies have found that MBR fouling is irreversible over time [6–8]. In addition, as other studies have demonstrated the irreversibility of cake buildup and compression, it would also be useful to study the reversibility of these processes. Pore blocking and foulant adsorption may play important roles in the short-term TMP step experiments performed in these studies, as there may be some irreversibility of cake buildup and compression.

Due to uncertainties of the reversibility of cake buildup observed with the critical flux concept in Jørgensen et al. [4], the present study investigates whether cake buildup and compression can be considered reversible in short term TMP step filtrations of MBR sludge. Furthermore it is investigated, if the already proposed model can simulate the removal of cake at enhanced shear and swelling of cake when lowering pressure. This is done by characterizing the removal of cake layers relative to their buildup using a shear stepping approach inspired by Defrance and Jaffrin [6]. The reversibility of compression is studied using TMP step experiments in which the mass balance determining cake buildup is kept constant by lowering shear when stepping down pressure. All data are fitted to the model describing fouling as reversible cake buildup and compression [4,5]. Furthermore, observations from the model are compared with results obtained using the critical flux concept to determine how critical fluxes are linked to model observations.

2. Theory

2.1. Model

The model proposed by Jørgensen et al. [4] and Bugge et al. [5] simulates the flux using the following equation derived from Darcy's law:

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

where μ is the dynamic viscosity of water (Pa s), R_m is the membrane resistance (m^{-1}), and R_f is the resistance from fouling (m^{-1}). The fouling resistance is a sum of resistances from a cake layer (R_c) pore blocking (R_p), adsorption (R_a), and others. In literature, it has been shown that during short term filtration the dominant fouling mechanism is cake formation [16–18]. Therefore, it is assumed that $R_f=R_c$. The cake resistance is described as the product of the specific cake resistance, α (m kg^{-1}), and the specific mass of cake per area of membrane, ω_c (kg m^{-2}):

$$R_c=\alpha\omega_c \tag{2}$$

It is via this term that either the flux or the TMP is affected by fouling in Eq. (1), depending on whether filtration is performed at constant pressure or constant flux, respectively. The development of a cake layer is described using the following mass balance:

$$\frac{d\omega_c}{dt}=JC-J_{SS}C \tag{3}$$

J_{SS} (m s^{-1}) is the steady state flux where there is no development in amount of cake and flux is constant. The steady state flux is a function of shear, sludge concentration, Brownian diffusion, etc. [4], while C is the concentration of foulants (kg m^{-3}). If $J>J_{SS}$, the permeation drag exceeds the back transport and the cake will grow, whereas if $J<J_{SS}$, part of the cake will be removed if the cake is reversibly attached to the membrane. As cake develops the flux will decline until $J=J_{SS}$. At this point there is no further development in amount of cake; hence the steady state flux is reached when the permeation drag equals the back transport. If the cake buildup is reversible, cake removal should follow the same kinetics as does cake buildup, as suggested by Eq. (3). When the flux equals the back transport flux the development in amount of cake has reached zero and the back transport flux equals the steady state flux. Obviously, the back transport on a membrane surface will vary over the membrane surface leading to a distribution of flux [19]. However, in a study by Jørgensen et al. [4] it is shown that an average back transport over a rotating membrane disc can be used to simulate the average development in amount of cake over the membrane surface and thereby the permeate flow.

As back transport is a shear-induced diffusion phenomenon, it depends on the concentration gradient of foulants over the membrane. Therefore, back transport and steady state flux will increase with the amount of material deposited on the membrane until a maximum concentration is reached, at which point a cake forms. To describe the dependence of the amount of material deposited on the membrane on the steady state flux, the mass balance in Eq. (3) has been modified to give the following cake-buildup model:

$$\frac{d\omega_c}{dt}=JC-J_{LIM}C(1-e^{-(\omega/\omega_{crit})}) \tag{4}$$

where ω_{crit} is the critical amount of deposited material required to form a stagnant cake (kg m^{-2}). At $\omega_c>\omega_{crit}$, the steady state flux is constant and $J_{SS}=J_{LIM}$.

The compressibility of the cake is described by Eq. (5)

$$\alpha=\alpha_0\left(1+\frac{\Delta P_c}{P_a}\right) \tag{5}$$

where ΔP_c is the pressure drop over the cake (Pa), α_0 the specific cake resistance at zero pressure (m kg^{-1}), and P_a (Pa) is the pressure required to obtain a specific cake resistance twice as high as α_0. The specific cake resistance is assumed to respond instantly to pressure changes. ΔP_c is calculated from Eq. (6)

$$\Delta P_c=TMP-R_m\mu J \tag{6}$$

where $R_m\mu J$ is the pressure drop over the membrane.

2.2. Critical and limiting flux

The critical flux concept is widely used to characterize the criticality of fouling under different operating conditions. The strength of the concept is that it can be used to characterize fouling in various systems with complex fouling mechanisms and to link the critical flux or limiting flux to the operating conditions. As the critical flux and the limiting flux are results of transport phenomena near the membrane surface, it is useful to understand how these can be related to the cake formation model.

Field et al. [20] has defined the critical flux, J_{crit} (m s^{-1}), as "the flux below which a decline in flux does not occur; above it fouling is observed." The critical flux is present in two forms, strong and weak. The strong form occurs when the *J*–*TMP* relationship starts to deviate from that of water (straight line) [21]. Analyzing the weak form of critical flux, it is assumed that the *J*–*TMP* relationship is lower than that of water, due to the almost instantaneous loss of permeability caused by adsorption. The weak form of critical flux is the flux level above which the flux no longer increases linearly with TMP (Fig. 1) [21]. However, the linearity in the lower range does not follow the linearity of the pure water *J*–*TMP*, as adsorption occurs even at low fluxes. Instead, the weak form of critical flux is the flux level at which deposition on the membrane, induced by permeation, starts. In the case of MBR fouling, the critical flux will be the weak form, as adsorption will occur even without permeation. The critical flux for irreversible fouling, $J_{c,i}$ (m s^{-1}) [21,22], defined as the flux above which irreversible fouling occurs, has also been introduced. It can be determined from stepping experiments, with physical cleaning phases between each