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A novel approach to evaluate the permeability of cake layer during cross-flow filtration in the flocculants added membrane bioreactors

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ABSTRACT

In order to obtain a better understanding of the cake layer formation mechanism in the flocculants added MBRs, a model was developed on the basis of particle packing model considering cake collapse effect and a frictional force balance equation to predict the porosity and permeability of the cake layers. The important characteristic parameters of the flocs (e.g., floc size, fractal dimensions) and operating parameters of MBRs (e.g., transmembrane pressure, cross-flow velocity) are considered in this model. With this new model, the calculated results of porosities and specific cake resistances under different MBR operational conditions agree fairly well with the experimental data.

1. Introduction

It is widely known that membrane bioreactors have gained significant popularity for municipal and industrial wastewater treatment in recent years. The advantages offered by MBRs are numerous such as a higher biomass concentration, reduced footprint, less sludge production, and superior water quality outputs (Malamis and Andreadakis, 2009; Miura et al., 2007). However, membrane fouling results in severe decline of the permeation flux or rapid transmembrane pressure (TMP) increase, high energy consumption, and frequent membrane cleaning or replacement, which directly leads to the increase in operating cost (Khan et al., 2009; Wang et al., 2009).

In MBRs, the factors affecting membrane fouling mainly originate from membrane properties, sludge characteristics and operating parameters. In terms of sludge characteristics, their effects on membrane fouling are very complicated. Lately, many researchers tried to add adsorbent or coagulant into MBRs artificially for the modification of activated sludge, and effective results on the alleviation of membrane fouling were obtained (Ji et al., 2010, 2008; Hwang et al., 2007; Koseoglu et al., 2008; Teychene et al., 2011). Compared to the control MBR (without adding filter aids), the floc size increased and the fractal dimension decreased in the flocculants added MBR, leading to low specific cake resistance. Adoption of flocculants as filter aids seems quite favorable because of several advantages such as low expenditures and toxicity and has been applied in water and wastewater treatment for many years. However, the cake layer formation mechanism in MBR with addition of filter aids has not been fully explored.

Recently, several researchers have reported that the total resistance of a MBR is mainly attributed to cake resistance on the membrane surface (Lee et al., 2001; Chu and Li, 2006; Meng and Yang, 2007; Wang et al., 2007). Therefore, the study of the cake layer formation mechanism in a MBR is helpful for understanding membrane fouling. In fact, the cake resistance is mainly determined by the porosity of the cake layer formed by deposited flocs on the membrane surface. Consequently, characteristics of the flocs as a whole, which are closely related to the cake resistance, should be the key factors contributing to cake layer fouling (Ji et al., 2010).

During the process of membrane filtration, either the porosity between aggregates, which are formed by flocculation of sludge flocs, or the inner porosity of aggregates may decrease because of interpenetration and/or partial compression (Park et al., 2006). Therefore, in order to investigate the permeability of cake layer during the operation of MBRs, it is necessary to consider the reduction of both the intra-aggregate and inter-aggregate porosities. Based on the above analysis, Park et al. (2006) creatively employed fractal theory and cake collapse effect to study the permeability of cake layer that is formed by inorganic flocs on membrane surface in dead-end filtration.

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Nomenclature

A_m	the area of the membrane (m^2)
c	the packing coefficient
d_a	the average particle size of the aggregates (m)
d_{rel}	the distance between two centers of aggregates in contact
d_p	the primary particle size (m)
D_f	fractal dimensions of aggregates
F_B	concentration polarization (Brownian diffusion)
F_d	permeation drag
F_F	the net friction force
F_l	lateral inertial lift
F_s	shear-induced diffusion
J	the membrane permeate flux (m/h or m^3/m^2h)
k	the frictional coefficient
k'	the pressure coefficient
k_B	Boltzmann's constant
L	the membrane module channel length (m)
M	the mass of cake deposited on the membrane surface (kg)
ΔP	the transmembrane pressure (Pa)
R_c	the cake resistance caused by the cake layer deposited on the membrane surface (m^{-1})
R_f	the fouling resistance due to irreversible adsorption and pore blocking (m^{-1})
R_m	the membrane resistance (m^{-1})
R_t	the total membrane filtration resistance (m^{-1})
t	the time (s)
T	the absolute temperature (K)
u	the cross-flow velocity (m/s)
v_a	the transport velocity of the aggregates (m/s)
V_a	the packing volume in the unit cell
V_u	the volume of the unit cell
α	the specific cake resistance (m/kg)
γ_w	the shear rate at the membrane surface (s^{-1})
ϵ_{cake}	the porosity of cake
ϵ_{inter}	the inter-aggregate porosity
ϵ_{intra}	an aggregate porosity (intra-aggregate porosity)
ϵ^c_{intra}	the decreased intra-aggregate porosity due to cake collapse
μ	the fluid viscosity (Pa s)
ρ_a	the density of the aggregates (kg/m^3)
ρ_p	the density of particles (kg/m^3)
ρ_0	the fluid density (kg/m^3)
ϕ_b	the aggregate volume fraction in the bulk solution
ϕ_w	the aggregate volume fraction at the edge of the cake layer

In this study, a new particle packing model (body-centered cubic packing model) and a force balance equation for particles are utilized to explore the permeability of cake layer in the Chitosan added MBR comprising of aggregates under cross-flow filtration, which will help us better understand membrane filtration performance and membrane-fouling characteristics in the flocculants added MBRs. Concretely, the application of the model in the Chitosan added MBR was studied to investigate the effect of characteristic parameters of the flocs (e.g., floc size, fractal dimensions) and operating parameters of MBRs (e.g., transmembrane pressure, cross-flow velocity) on the permeability of cake layer. This will be helpful for determining "Critical Flux" (Tiranuntakul et al., 2011; Buetehorn et al., 2011) through the optimization of operational parameters in MBRs. Furthermore, the reason why Chitosan was selected rather than other common coagulants is that Chitin, the raw material of Chitosan, is the natural organic matter that has the second most amount in the world, and it has not been widely investigated as flocculants; therefore, studying Chitosan as flocculants has important practical significance.

2. Theoretical calculations

2.1. Resistance-in-series model

In cross-flow filtration, the permeate flux (J) of fluid across a membrane can be expressed by Darcy's law:

$$J = \frac{\Delta P}{\mu R_t} = \frac{\Delta P}{\mu (R_m + R_c + R_f)} \tag{1}$$

where J is the membrane permeate flux; ΔP is the transmembrane pressure; μ is the fluid viscosity; R_t is the total membrane filtration resistance; R_m is the membrane resistance; R_c is the cake resistance caused by the cake layer deposited on the membrane surface and R_f is the fouling resistance due to irreversible adsorption and pore blocking.

The cake resistance, R_c (related to the specific cake resistance, α, and the mass of cake deposited on the membrane surface, M), can be given by the following equation (Lee et al., 2000):

$$R_c = \frac{\alpha M}{A_m} \tag{2}$$

where A_m is the membrane area.

The specific cake resistance (α) can be approximately related to the density of particles (ρ_p), the primary particle size (d_p) and cake porosity (ϵ) by Carman–Kozeny equation:

$$\alpha = \frac{180}{\rho_p d_p^2} \left(\frac{1-\epsilon}{\epsilon^3} \right) \tag{3}$$

2.2. Fractal dimensions of aggregates, D_f

The fractal can be characterized by a single fractal dimension, D_f, which is of ultimate importance in the description of the behaviors and properties of microbial flocs in wastewater treatment systems. The sludge suspension collected from bioreactors has been reported to have a value of $D_f > 2$ for flocs in most studies (Li and Leung, 2005).

2.3. Cake layer permeation model

Intra-aggregate porosity means porosity inside aggregates, which is related to the primary particle size (d_p), the aggregate size (d_a), and the fractal dimension by Lee et al. (2005)

$$\epsilon_{intra} = 1 - c \left(\frac{d_a}{d_p} \right)^{D_f - 3} \tag{4}$$

where c is the packing coefficient. In this paper, c was assumed to be 0.25 (Li and Logan, 2001). Meanwhile, the value of d_p was estimated to be ca. 0.5 μm because the sludge floc is mainly made up of prokaryotic microbes. Based on Eq. (4) with c = 0.25 and $d_p = 0.5$ μm, the porosity of sludge floc (ϵ_{intra}) could be estimated to be ca.