Structure and flow calculation of cake layer on microfiltration membranes

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ABSTRACT

Submerged membrane bioreactors (SMBR) are widely used in wastewater treatment. The permeability of a membrane declines rapidly because of the formation of a cake layer on the membrane surface. In this paper, a multiple staining protocol was conducted to probe the four major foulants in the cake layer formed on a filtration membrane. Fluorescent images of the foulants were obtained using a confocal laser scanning microscope (CLSM). The three dimensional structure of the cake layer was reconstructed, and the internal flow was calculated using computational fluid dynamics (CFD). Simulation results agreed well with the experimental data on the permeability of the cake layer during filtration and showed better accuracy than the calculation by Kozeny–Carman method. β-D-Glucopyranose polysaccharides and proteins are the two main foulants with relatively large volume fractions, while α-D-glucopyranose polysaccharides and nucleic acids have relatively large specific surface areas. The fast growth of β-D-glucopyranose polysaccharides in the volume fraction is mainly responsible for the increase in cake volume fraction and the decrease in permeability. The specific area, or the aggregation/dispersion of foulants, is less important to its permeability compared to its volume fraction.

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Introduction

Submerged membrane bioreactors (SMBRs) are widely used in wastewater treatment. The SMBR system has many advantages over conventional activated sludge methods, including smaller space requirement, higher effluent quality, and lesser sludge production (Judd, 2010). However, membrane fouling inevitably happens, which causes an increased flow resistance and that severely declines the permeation flux (Zhao et al., 2000). The fouling problem causes high energy consumption and frequent cleaning/replacement of the membrane, directly increasing the operational costs (Miura et al., 2007; Yang et al., 2006). For a fouled membrane, the total filtration resistance consists of three parts: the initial resistance of a clean membrane (membrane resistance), the pore blocking resistance (fouling resistance), and the cake layer resistance caused by a cake formed by pollutant particles on the membrane surface (Chang and Lee, 1998; Cheryan, 1998; Guo et al., 2008). Among the three resistances, cake layer resistance is considered the dominant one (Lee et al., 2001; Chu and Li, 2006; Wang et al., 2007).

The cake layer consists of multiple foulants, such as proteins and polysaccharides. The structure, composition, and permeability of the cake layer change during the filtration process (Yu et al., 2006). Chen et al. (2016) investigated the mechanisms of membrane fouling caused by a gel layer and found that filtration resistance linearly increased with gel thickness. Studies have been conducted on the influences

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that cause the formation of cake layers, including sludge characteristics, operation conditions, and membrane materials (Le-Clech et al., 2006; Meng et al., 2009). However, understanding the fouling process without considering the complex structure of the cake layer remains difficult. Understanding the flow within the cake layer is helpful in revealing the fouling mechanism of SMBR.

Several approaches are used to observe the cake layer structure, such as scanning electron microscopy (Lee et al., 2001; Fan and Huang, 2002) and atomic force microscopy (Bowen et al., 1999; Yamamura et al., 2008). Gao et al. (2011) characterized the cake layer structure by using various analytical techniques and observed that the areal porosity decreased from the top layer to the bottom layer. Recently, fluorescent staining and confocal laser scanning microscopes (CLSMs) have been frequently used to morphologically visualize cake layers (Neu and Lawrence, 1999; Strathmann et al., 2002; Yun et al., 2006). The main advantage of fluorescent staining is that the different membrane foulants are shown when corresponding fluorescence probes are used. Yoon Kim et al. (2006) probed the cells, polysaccharides, and proteins in a cake layer by using three stains: SYBR Green I, fluorescent-labeled lectins and Hoechst 2495. Chen et al. (2006a, 2006b) probed nucleic acids, α-D-glucopyranose polysaccharides, β-D-glucopyranose polysaccharides, and proteins using four stains: SYTO 63, Concanavalin A (Con A), Calcofluor White, and Fluorescein Isothiocyanate (FITC). These components constitute the major biopolymers in a cake layer. In this study, a multiple staining protocol was conducted to probe the four major foulants in the cake layer.

With the detailed component images acquired, the structural parameters of the cake layer, such as porosity, can then be calculated (Chen et al., 2006a, 2006b; Hwang et al., 2007). Computational fluid dynamics (CFD) can then be used to calculate 3D flow in the cake layer (Yang et al., 2012), and important flow parameters, such as permeability, can be obtained. However, the CFD calculations are only accurate when experimental validation is used. Thus far, very few studies have been performed on this subject.

In this study, both experiment and CFD simulation were performed on a submerged membrane filtration process. A multiple staining protocol was conducted to probe the four major foulants in the cake layer formed on the membrane, and fluorescent images for each foulant were obtained. The 3D structure of the cake layer was reconstructed from the fluorescent images. Then, the flow in the cake layer was calculated using the CFD. The CFD method was compared with the Kozeny–Carman model on permeability calculation. The influence of volume fraction and specific surface area of each foulant on its flow at different filtration times was analyzed.

1. Materials and methods

1.1. Experimental system

A schematic of the submerged membrane filtration system is shown in Fig. 1. The system consisted of a feed tank, a stirrer, a membrane chamber, a filtrate collection vessel, an electronic
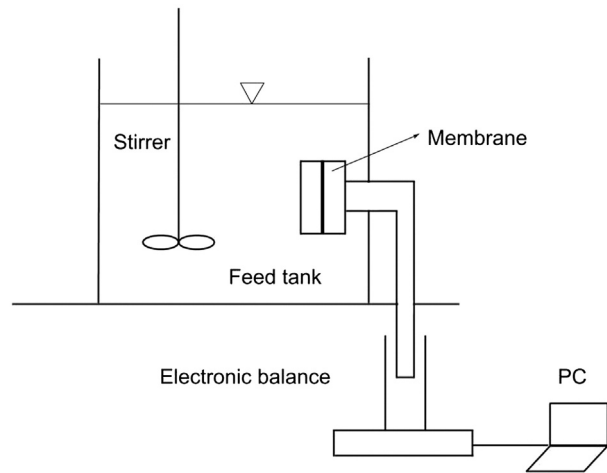

Fig. 1 – Schematic diagram of the submerged membrane filtration system.

balance and a PC. The filter membrane was fixed on the membrane chamber module with a filtration area of 1.77 cm^2. A water head of about 7.5 kPa (a 77 cm-high water column below the membrane) supplied the filtration pressure. The stirring rate is 200 r/min. The operating temperature was kept at 20°C. The filtrate weight was measured using the electronic balance and recorded by the PC.

1.2. Permeability from experiment

A mixed cellulose esters membrane (HAWG04700, Millipore) is employed as the filtration membrane. It has a 0.45-μm pore size, 150-μm thickness and 79% porosity. The membrane is hydrophilic and made from biologically inert materials of cellulose acetate and cellulose nitrate. Prior to use, the membrane was immersed in deionized water for 24 hr to remove the soluble impurities and additives from the fabrication process. Active waste sludge was acquired from a wastewater treatment plant in Beijing. After 4-h gravitational sedimentation, most suspended solids were removed from the active sludge to show the contribution of colloidal fractions in supernatant. The chemical oxygen demand for the sludge and filtrate was 16,000 and 86.7 mg/L respectively. The elemental composition of the dried samples was as follows: C, 41.4%; H, 6.3%; and N, 5.6%. The sludge pH was approximately 6.9. Membrane filtration experiments were conducted under the same conditions, with different filtration times of 300, 600, 900, 1200, 1500, and 1800 sec. The permeability of the cake layer at different times was calculated using the experiment method illustrated below.

In the filtration experiments, the permeate flux of fluid across the membrane was expressed by Darcy's law with the resistance-in-series model:

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

where J_t (m/s) is the membrane permeate flux, ΔP_t (Pa) is the transmembrane pressure, μ (Pa·sec) is the fluid viscosity, R_t (m^{-1}) is the total membrane filtration resistance, R_m (m^{-1}) is