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Membrane fouling in a submerged membrane bioreactor: Impacts of floc size

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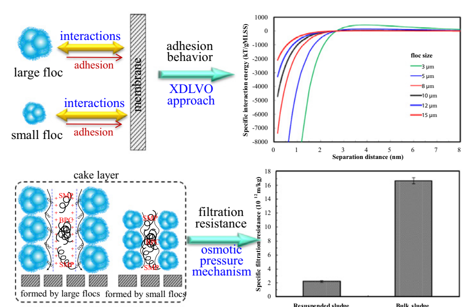
HIGHLIGHTS

- Small floc had high specific contact interaction energy, and easily adheres to membrane.
- Presence of SMP and colloids in cake layer highly increased cake resistance.
- Floc size highly affected cake resistance due to the osmotic pressure mechanism.

GRAPHICAL ABSTRACT



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ABSTRACT

A submerged membrane bioreactor (MBR) treating synthetic wastewater was continuously operated to investigate the impacts of floc size on membrane fouling. Particle size distribution (PSD) analysis showed that almost all the sludge flocs in sludge suspension had size larger than 1 μm, which corresponded to low pore clogging fouling. Thermodynamic analyses showed that adhesion of sludge flocs on membrane surface needed to overcome a repulsive energy barrier. Decrease in floc size slightly increased the specific energy barrier, but highly increased the attractive specific interaction energy in contact, and as whole, facilitated adhesion of small flocs to the membrane surface. Presence of biopolymer matters in sludge suspension remarkably gave rise to the cake resistance. This result could be explained by the osmotic pressure mechanism. Decrease in floc size would greatly increase both of hydraulic cake resistance and osmotic pressure-induced resistance. The findings shed significant light on membrane fouling control.

1. Introduction

Membrane bioreactors (MBRs) technology has emerged as an important innovation for wastewater treatment and reuse [1,2]. However, membrane fouling, which will increase filtration resistance and energy consumption, has highly hampered the widespread use of this technology [1,3–5]. Therefore, it is of essential importance to investigate causes, characteristics and mechanisms of fouling for membrane fouling mitigation in MBRs [1,6,7].

Membrane fouling in MBRs is caused by the interactions between sludge suspension and membrane. Membranes used in MBRs definitely play key roles in membrane fouling. Some novel membranes or membrane devices have been reported [8,9]. Sludge suspension is a collection of various matters where sludge flocs account for the largest proportion of biomass [6,10]. For a given membrane, membrane fouling in MBRs is largely determined by the properties of sludge flocs [11,12]. The size of sludge floc is a

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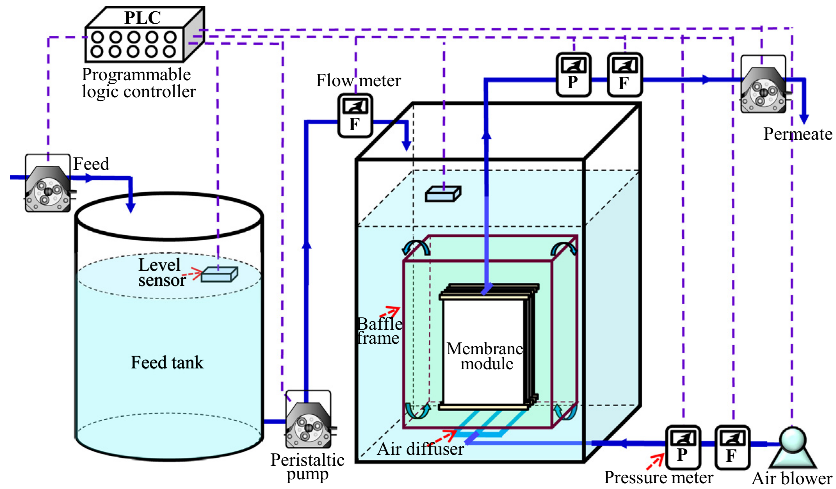

Fig. 1. Schematic of the lab-scale SMBR system.

primary property which generally exerts important roles in membrane fouling in MBRs. Some studies observed that the formed cake layer possessed a higher fraction of small sludge flocs as compared with bulk sludge [12–16]. These studies suggested that small flocs could more easily adhere to the membrane surface. Moreover, cake layer formed by small flocs was much denser than that formed by large ones, which corresponded to a higher specific cake resistance [14,17,18]. Significant efforts have been devoted to exploring the mechanisms underlying these phenomena. For example, the stronger adhesion tendency of small floc has been explained by the hydrodynamic fact that back transport velocity increases with floc size [4,19]. The higher resistance of cake layer formed by small flocs has been explained by the Carman–Kozeny equation [20,21].

However, studies demonstrated that these phenomena have not yet been exactly explained. In MBR system, motion of sludge flocs towards the membrane surface is mainly controlled by two opposite forces: permeation drag force and back transport force [19]. The former stems from permeate flux, and the latter consists of Brownian diffusion, inertial lift and shear induced diffusion [22]. From the hydrodynamic viewpoint, hydrodynamic forces just take the roles of bringing the flocs close to the membrane surface, but are not responsible for the actual binding (adhesion) of flocs on the membrane surface [23,24]. Both small and large flocs can be forwarded to the vicinity of membrane surface by hydrodynamic forces. Considering that small flocs only account for a small fraction (<3%) of total biomass in the sludge suspension in MBRs [13,14], it appears that large flocs have more opportunities to adhere to the membrane surface, corresponding to a stronger adhesion tendency of large flocs, which is contrary to experimental observations. Therefore, hydrodynamic viewpoint cannot explain the stronger adhesion tendency of small flocs. Meanwhile, it was reported that biopolymer matters (mainly including extracellular polymeric substances (EPSs), soluble microbial products (SMPs) and biopolymer clusters (BPCs)) highly affected cake resistance [3,10]. In these studies, BPCs only accounted for about 1% of the total dry mass of cake layer. Apparently, presence of a small amount of BPCs in cake layer did not significantly change the size of flocs. However, when BPCs were removed from the cake layer, the specific cake resistance was reduced remarkably from 4.9×10^{13} to 8.4×10^{12} m^{-1} kg^{-1} [10]. This phenomenon cannot be explained by the Carman–Kozeny equation. The situation calls for further research regarding the effects of floc size on membrane fouling.

Membrane fouling in MBRs can occur in forms of pore clogging, sludge adhesion (cake formation) and changes of cake layer. Pore clogging fouling highly depends on the match of particle size and membrane pore size [6]. Recent studies suggested that adhesion of flocs to membrane surface in MBRs is a thermodynamic process [23–25]. While hydrodynamic forces forward the flocs close to the membrane surface, it is the thermodynamic forces (thermodynamic interactions) that cause binding (adhesion) of the flocs to the membrane. The particle–substrate thermodynamic interactions in aqueous media can be profiled via the extended Derjaguin–Landau–Verwey–Overbeek (XDLVO) theory [26,27]. Different size flocs may possess different thermodynamic interactions, and then show different adhesion behaviors. Therefore, the roles of floc size in membrane fouling may be explored through XDLVO approach. Meanwhile, a new membrane fouling mechanism, osmotic pressure effect during cake layer filtration, has been recently revealed [24,28,29]. The existence of osmotic pressure effect was reported to remarkably give rise to the cake resistance [24,28]. The significance of osmotic pressure highly depended on the cake layer structure. Floc size apparently affects cake layer structure, and therefore, may take roles in the osmotic pressure mechanism and cake resistance. Although floc size may have important influences on membrane fouling, to the best of our knowledge, there has been no specific study conducted to investigate its roles in MBR fouling.

The aim of this study was to investigate the effects of floc size on membrane fouling with respect to adhesion of sludge flocs and cake resistance in a MBR. A laboratory scale MBR was continuously operated. The surface properties of the membrane and sludge samples were characterized. Thereafter, the effects of floc size on the thermodynamic interactions between membrane and sludge flocs were investigated. Meanwhile, series filtration tests were performed to study the effects of floc size on the cake resistance.

2. Material and methods

2.1. Experimental setup and operation

A lab-scale submerged MBR (SMBR) as shown in Fig. 1 was utilized in this study. The reactor had a working volume of 65 L ($0.54 \times 0.30 \times 0.40$ m height × length × width), where a polyvinylidene fluoride (PVDF) membrane module consisting of five flat-sheet membrane elements was mounted vertically. Each membrane element had 0.1 m^2 effective filtration area with 0.3 μm normalized membrane pore size. An air diffuser was located underneath the membrane module to provide aeration with specific aeration demand per permeate product (SADp) of about