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Regular Article

Thermodynamic insights into membrane fouling in a membrane bioreactor: Evaluating thermodynamic interactions with Gaussian membrane surface

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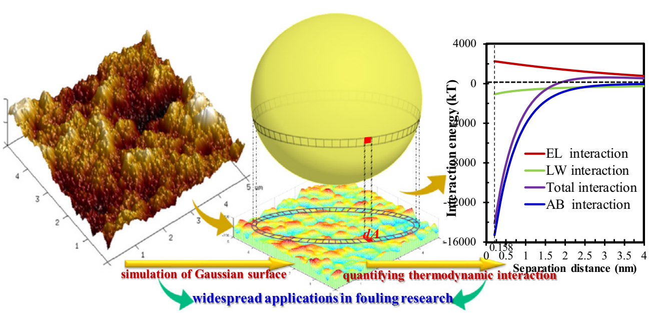
GRAPHICAL ABSTRACT



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ABSTRACT

While membrane bioreactor (MBR) technology is generally considered as one of the most promising technologies for wastewater treatment and recovery, membrane fouling remains the major obstacle limiting its applications. Interfacial interactions, which critically determine adhesion process and membrane fouling, were investigated in this study. It was found that, natural membrane surface was of a Gaussian surface obeying Gaussian distribution. A Gaussian approach integrating Fourier transform technique, Gaussian distribution and spectrum method was deduced to simulate rough surface topography of membrane. Thereafter, surface element integral (SEI) method, together with composite Simpson rule and triangulation of Gaussian surface was proposed to calculate interfacial interactions. By using the unified method, quantification of interfacial interactions with a Gaussian membrane surface was realized for the first time to date. It was further found that, membrane surface topography had profound impacts on interfacial interactions and adhesive fouling in the MBR. The deduced method can be used to address impacts of various factors on interfacial interactions and adhesive fouling, posing in-depth thermodynamic insights into membrane fouling and pointing towards its widespread potential in fouling research in MBRs.

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1. Introduction

Owing to the overriding advantages of compact footprint, high-quality effluent production, high organic loading, and reduced surplus sludge production, membrane bioreactor (MBR) technology has been more and more popularly deployed for treatment and reclamation of both municipal and industrial wastewaters in the past decade [1–3]. However, the relatively high energy consumption and membrane investment associated with membrane fouling are still serious challenges in its further development [4–6].

Membrane fouling mainly results from unwanted deposition/adhesion of various foulants (including suspended particulates, colloids, and solutes) in the sludge suspension inside membrane pores and/or on membrane surface [7–10]. It is generally accepted that, such a deposition/adhesion process is controlled by the interfacial interactions between two surfaces [11–14]. In other words, the thermodynamic mechanisms of adhesion process are straightforward, namely, the more strengthen the attractive interactions are, the higher adhesion ability/fouling propensity of foulants and membrane is. Interfacial interactions can be traditionally depicted in the frame of the theory of extended Derjaguin-Landau-Verwey-Overbeek (XDLVO) [15–18]. So far, the approaches provided in the XDLVO theory are solely viable for the interaction scenario regarding 2 smooth flat surfaces [19–21]. However, an indisputable fact is that, all of commercial membranes used for MBRs possess randomly rough surfaces in nature [16,17,20–22]. Studies also frequently reported the significant discrepancies of the deposition/adhesion process between experimental observation and theoretical prediction by the XDLVO approaches [20,23]. Therefore, it is desirable to evaluate interfacial interactions between rough surfaces.

While unfeasible to directly calculate interfacial interactions with rough surface, the XDLVO approaches do give significant hints to develop suitable methods satisfying this need. If a rough surface is regarded as combination of numerous differential smooth flat surfaces, the total interfacial interaction with a rough surface could be derived by summation of differential interfacial interaction with a differential smooth flat surface, since the later can be calculated by the XDLVO approaches. This idea should be reasonable, which led to establishment of the surface element integration (SEI) method [19]. However, real applications of this method should meet at least 2 requirements: simulation of rough surface topography by continuous function, and calculation of the complex double integrals involved in the SEI method [19,24]. These requirements bring difficulties to evaluate the interfacial interactions with a rough surface. Fortunately, recent studies have successfully simulated randomly rough topography of membrane by a continuous modified two-variable Weierstrass-Mandelbrot (WM) function based on fractal theory [25,26], and also successfully approximated the complex double integrals involved in the SEI method [22]. However, a concern raised was that, the surface simulated by the fractal theory cannot well represent the distinct characteristics of a real rough membrane surface, namely, Gaussian distribution of heights and even distribution of surface asperities [27]. Accordingly, a new method based on Gaussian distribution was developed to overcome this problem [27]. The Gaussian approach could well reflect the real surface topography since most of real surfaces in nature are of essentially Gaussian surfaces [27,28]. Whereas, the simulated topography by the novel simulation method is not a continuous surface because only a matrix of limited position data is generated [27]. This characteristic makes difficulties to evaluate interfacial interactions with a rough surface. Although the new method is more suitable for simulating rough membrane surface topography, there is a lack of methods to calculate interfacial interactions with the simulated rough membrane surface. Considering the importance of interfacial interactions in deposition/adhesion process and membrane fouling [15–17,29], it is desirable to realize quantification of interfacial interactions with a real rough surface with Gaussian distribution.

Therefore, this study was conducted to develop a method enable to quantitatively evaluate interfacial interactions between a Gaussian surface and a granular foulant. Accordingly, rough surface topography of a polyvinylidene fluoride (PVDF) membrane used for a MBR was simulated by a Gaussian distribution approach. Gaussian distribution approach generated a non-continuous membrane surface, which was further converted to a continuous membrane surface. Thereafter, this simulated continuous surface was involved into SEI method, leading to deducing complex double integrals for evaluation of interfacial interactions with the rough membrane surface. The complex double integrals were then approximated according to composite Simpson's rule by supercomputer programming technique. The unified method proposed in current paper was finally used to evaluate interfacial interactions in the MBR, and impacts of membrane topography on interfacial interactions were also assessed.

2. Materials and methods

2.1. MBR apparatus and sample preparation

A lab-scale MBR apparatus as shown in Fig. 1 possessing 26 L working volume was continuously operated in this study. The apparatus was equipped with a membrane module which consisted of 4 flat-sheet membrane elements laminated by polyvinylidene fluoride (PVDF) membrane (normalized pore size: 0.10 μm). An intermittent suction mode was adopted to obtain permeate from the MBR, corresponding to a membrane flux of about 20 L m^{-2} h^{-1}. Hydraulic retention time (HRT) of the MBR was controlled to be about 5.5 h. All the pumps, air blower and level sensors were controlled automatically through a programmable logic controller (PLC) system. The MBR went through a continuous-running of over 150 days.

The sludge suspension samples were derived from the stable-running MBR apparatus. The membrane samples used for contact angle measurements were pretreated as follows: the pristine PVDF membrane was cut into size of 4 cm × 4 cm and immersed in ultrapure water to get rid of impurities for 24 h, followed by compression tightly by 2 glass slides, and dehydration in a bake oven at 37 °C for 1.5 h to eliminate redundant water. Following procedure was

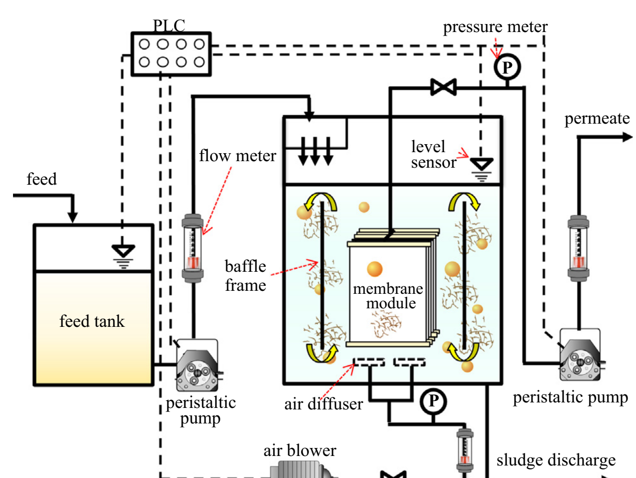

Fig. 1. Schematic of the MBR apparatus used in this study.