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Effects of fractal roughness of membrane surfaces on interfacial interactions associated with membrane fouling in a membrane bioreactor

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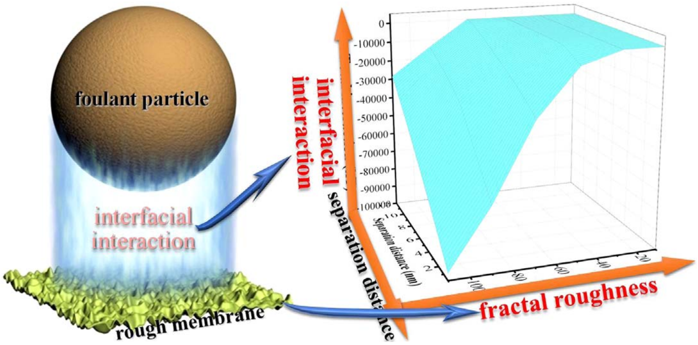
GRAPHICAL ABSTRACT



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ABSTRACT

Fractal roughness is one of the most important properties of a fractal surface. In this study, it was found that, randomly rough membrane surface was a fractal surface, which could be digitally modeled by a modified two-variable Weierstrass-Mandelbrot (WM) function. Fractal roughness of membrane surfaces has a typical power function relation with the statistical roughness of the modeled surface. Assessment of interfacial interactions showed that an increase in fractal roughness of membrane surfaces will strengthen and prolong the interfacial interactions between membranes and foulants, and under conditions in this study, will significantly increase the adhesion propensity of a foulant particle on membrane surface. This interesting result can be attributed to that increase in fractal roughness simultaneously improves separation distance and interaction surface area for adhesion of a foulant particle. This study gives deep insights into interfacial interactions and membrane fouling in MBRs.

1. Introduction

As a high-efficiency fluid separation technology, membrane technology has attracted remarkable attention due to its decisive roles in energy conservation and emission reduction, cleaner production and recycling economy (Guo et al., 2012; Shen et al., 2017a; Zhang et al., 2017). A case in point is membrane bioreactor (MBR) technology, which has been regarded as a well-established, mature technology with more than 5 million m^3 of wastewater per day treated by MBR plants worldwide (Krzeminski et al., 2017; Lin et al., 2013; Zuthi et al., 2017).

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Nomenclature

A_H	Hamaker constant, equal to $-12\pi h_0^2 \Delta G_{h0}^{LW}$
D	distance between a spherical particle and a planar smooth surface (nm)
D_f	fractal dimension of a solid
dA	differential projected area of differential element on membrane surface (m^2)
dr	differential ring radius (m)
$d\theta$	differential angle of the differential circular arc (°)
$f(r,\theta)$	local amplitude directly below the circular arc as a function of the position of the differential circular arc defined by r an $d\theta$
e	electron charge (1.6×10^{-19} C)
h	separation distance between two planar surfaces (nm)
k	Boltzmann's constant (1.38×10^{-23} $J{\cdot}K^{-1}$)
L	sample length (m)
L	cutoff frequency (m)
M	number of superposed ridges
n	frequency number
G	fractal roughness (m)
ΔG	interaction energy per unit area ($mJ{\cdot}m^{-2}$)
R	radius of foulant particle (μm)
R_a	average roughness (nm)
R	root-mean-square roughness (nm)
r	radius of differential circular ring on particle surface (μm)
S	closest distance between a particle and a planar surface (nm)
U	interaction energy between membrane surface and particle (kT)
z	height of membrane surface (nm)
z_0	minimum height of membrane surface in contact (nm)

Greek letters

γ	surface tension parameter ($mJ{\cdot}m^{-2}$)
$\varepsilon_r \varepsilon_0$	permittivity of the suspending liquid ($C{\cdot}V^{-1}{\cdot}m^{-1}$)
η	parameter of frequency density
θ	angle of the circular arc in the circular ring
κ	reciprocal Debye screening length (nm^{-1})
τ	decay length of AB interactions in water (0.6 nm)
	surface roughness frequency
ξ	zeta potential (mV)
$\phi_{m,n}$	random phase
φ	contact angle (°)

Superscripts

AB	Lewis acid-base
EL	electrostatic double layer
LW	Lifshitz-van der Waals
tol	total
+	electron acceptor
-	electron donor

Subscripts

f	foulant particle
h	minimum equilibrium cut-off distance (0.158 nm)
l	liquid
m	membrane
max	maximum value
s	solid
w	water

Moreover, it was estimated that, MBR market would grow at an annual growth rate of about 15% (Judd, 2016). Despite that, membrane fouling is the largest bottleneck limiting wider spread applications of membrane and MBR technology, and remains the major research interest in this field (Chen et al., 2016b; Guo et al., 2012; Lin et al., 2012; Zhang et al., 2013). It is generally accepted that, adhesion of various foulants (colloids, soluble microbial products (SMPs), extracellular polymeric substances (EPSs), sludge flocs, cell debris, et al.) in sludge suspension on membrane surface is the main cause of membrane fouling in MBRs (Lin et al., 2009; Wang et al., 2014; Zhao et al., 2016b). Exploring adhesion mechanisms would facilitate to develop measures for control of adhesion process and membrane fouling.

In MBRs, susceptibility of a membrane to adhesion of foulants can be predicted by assessing the interfacial interactions between foulants and membrane surfaces (Cai et al., 2017b; Chen et al., 2012; Tian et al., 2013). Although membranes in MBRs are submerged in sludge suspension, and surrounded by a large number of foulant particles, final adhesion of these foulants on membrane surface rests with the interfacial interactions between foulants and membrane surfaces (Hong et al., 2013; Zhang et al., 2015; Zhao et al., 2017). Basically, the interfacial interactions between two smooth planar surfaces can be described by the extended Derjaguin-landau-verwey-overbeek (XDLVO) theory (Hoek and Agarwal, 2006; Lin et al., 2014a). However, real surfaces of any membranes and foulants in MBRs are far from smooth and planar, which poses considerable challenge to assessing the interfacial interactions between foulants and membrane surfaces in MBRs (Bhattacharjee et al., 1998; Chen et al., 2012; Hoek and Agarwal, 2006; Zhao et al., 2015). In order to rise to this challenge, surface element integration (SEI) method, which integrates the interaction energy per unit area between two opposing differential planar elements over the entire surfaces, has been proposed (Bhattacharjee and Elimelech, 1997; Dantchev and Valchev, 2012).

In theory, SEI method enables to evaluate the interfacial interactions between two randomly rough surfaces, provided that digital surface morphology data are obtained (Bhattacharjee and Elimelech, 1997; Chen et al., 2017; Dantchev and Valchev, 2012). In other words, evaluation of the interfacial interactions for a randomly rough membrane surface primarily requires modeling randomly rough surfaces, especially, membrane surfaces, with proper continuous functions. This requirement has been recently satisfied by introducing a modified two-variable Weierstrass-Mandelbrot (WM) function involved in fractal geometry theory into rough surface construction (Cai et al., 2017a; Zhang et al., 2016). The fractal geometry theory includes two important parameters: fractal dimension and fractal roughness (Thielen et al., 2016). Fractal dimension (D_f) is the parameter that represents the complexity of the membrane contour structure. The larger the D_f value is, the more the contour detail is. The fractal roughness (G) is amplitude coefficient, which affects the magnitude of membrane contour (Gagnepain and Roques-Carmes, 1986; Yan and Komvopoulos, 1998). These two parameters represent two most important factors defining the morphology of a rough surface. Considering the decisive roles of surface morphology in interfacial interactions, and the dependence of adhesion process on interfacial interactions, it is hypothesized that fractal parameters would significantly affect adhesive forces and membrane fouling in MBRs. This hypothesis has been partly tested by a recent study which found that D_f directly affected the strength and distribution of interfacial interactions with a randomly rough membrane surface (Cai et al., 2017a). Such a study gave significant insights into membrane fouling mechanisms and control. However, to our knowledge, none specific study has explored effects of fractal roughness on interfacial interactions and membrane fouling.

This article aims to study impacts of fractal roughness on interfacial