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Quantification of interfacial interactions between a rough sludge floc and membrane surface in a membrane bioreactor

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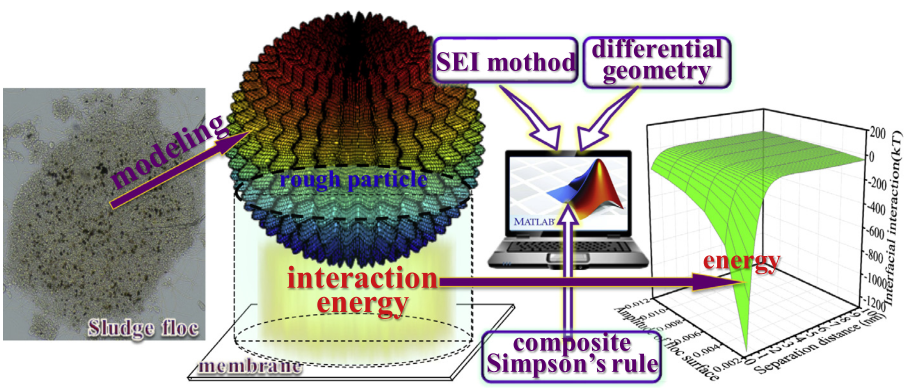
GRAPHICAL ABSTRACT



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ABSTRACT

Interfacial interactions between foulants and membrane directly determine foulant adhesion and membrane fouling. In this study, surface of sludge foulant particles (flocs) was found to be rough, and could be modeled by a sinusoidal sphere function. A novel method, which combined surface element integration (SEI) method, differential geometry and composite Simpson's rule, was developed to quantify the interfacial interactions between the modeled rough floc surface and membrane surface. Application of the novel method in a membrane bioreactor (MBR) provides broad profiles of quantitative interactions with rough floc surface with separation distance. It is also found that increase in the scaled amplitude of floc surface significantly reduced the interaction strength. Derjaguin's approximation (DA) can be regarded as a special case of the novel method, indicating the extensive application prospect of the novel method. The novel method for interaction calculation was verified to be correct and feasible. Finally, roles of the novel method in membrane fouling research were discussed.

1. Introduction

While regarded as a promising and proven technology for wastewater treatment, membrane bioreactor (MBR) encounters problem of membrane fouling, which highly limits its popularity in treatment of a wide variety of wastewaters [1–4]. Therefore,

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Nomenclature

A_H	Hamaker constant, equal to $-12\pi h_0^2\Delta G_{h_0}^{LW}$
D	closest distance between a floc and a planar surface (nm)
dA	differential projected area of differential element on membrane surface (m^2)
dr	differential ring radius (m)
dS	differential projected area of differential circular arc on floc surface (m^2)
$d\theta$	differential angle along θ coordinates (°)
$d\varphi$	differential angle along φ coordinates (°)
$\underset{\sim}{h}$	separation distance between two planar surfaces (nm)
$\underset{\sim}{i}$	unit vector along positive x-direction
$\underset{\sim}{j}$	unit vector along positive y-direction
k	unit vector along positive z-direction
$\underset{\sim}{n}$	frequency of the ripples
$\vec{n}$	the unit outward normal to the surface
ΔG	interaction energy per unit area (mJ m^{-2})
r	radius of sludge floc (nm)
U	interaction energy between membrane surface and particle (kT)

Greek letters

α	floc radius when λ is zero (nm)
γ	surface tension parameter (mJ m^{-2})
$\varepsilon_r\varepsilon_0$	permittivity of the suspending liquid (C V^{-1} m^{-1})
θ	angle coordinate in spherical coordinate system
κ	reciprocal Debye screening length (nm^{-1})
λ	scaled amplitude of ripples
ξ	zeta potential (mV)
ϕ	contact angle (°)
φ	angle coordinate in spherical coordinate system
τ	decay length of AB interactions in water (0.6 nm)

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_0	minimum equilibrium cut-off distance (0.158 nm)
l	liquid
m	membrane
s	solid
w	water

membrane fouling mitigation is the largest research interest for this technology as well as other membrane separation processes.

Better understanding of membrane fouling mechanisms is the base of fouling mitigation. It is well accepted that, foulant adhesion, a main form of membrane fouling, is directly resulted from the interfacial interactions between foulants and membrane surface [5–7]. Understanding these interactions is of primary importance for understanding of membrane fouling mechanisms and membrane fouling mitigation. The interfacial interactions are generally described by the extended Derjaguin-Landau-Verwey-Overbeek (XDLVO) theory, where three types of interactions including acid-base (AB), Vander Waals (LW) and electrostatic double layer (EL) energies are included [8,9]. A basic assumption in XDLVO theory is that both of membrane and foulant surfaces are perfectly smooth [8,9]. However, at a small enough scales, all real surfaces are certainly rough [10]. Especially in MBR systems, foulants including sludge flocs [11] and colloids [12] possessed significantly rough surfaces. The effects of surface morphology on the XDLVO interactions have been considered as a major contributor to the discrepancies between theoretical predictions and experimental observations of particle adhesion and membrane fouling phenomena [13–15]. In order to make these phenomena more predictable, a method to quantitatively assess the interfacial interactions between rough particles (foulants) and membrane is rather desirable.

The desirable method should consist of two major parts: modeling surface roughness and subsequent calculation of the interaction energy with rough particle. Many efforts have been devoted to model rough surface. In the literature, rough surface was generally modeled by random placement of geometrically regular asperities (like hemispheres, cones) on a smooth surface [16–19], or using periodic functions (like sine function) to define the distribution and morphology of asperities on a surface [13,20]. Pursuing literature shows that almost all of these efforts focused on modeling planar rough surface. In contrast, most biomass in sludge suspension in MBR systems is in form of flocs, which are generally assumed to be spherical [21,22]. Therefore, effective model methods for rough particle/floc surface are yet to be developed.

A more involved theoretical problem, however, lies not in the characterization of the roughness but in the quantitative evaluation of the interaction energy between such geometrically random surfaces. Conventional methods for calculation of interfacial interactions with rough flocs encounter lots of problems. For example, Hamaker's technique for LW interaction with rough surface involves evaluation of six nested integrals defined over the volumes of two macroscopic bodies [23]. Meanwhile, solution of the nonlinear Poisson-Boltzmann equation to determine EL interaction with curved surface is a formidable task [24,25]. It is, therefore, basically impossible in practice to quantitatively assess all the three types of interfacial interactions with rough particles by using the conventional methods. An alternative approach, Derjaguin's approximation (DA), allows to determination of the interactions between two gently curved surfaces or a curved surface and a flat plate [26]. This method, however, is not valid when the separation distance is comparable to or larger than the principal radii of curvature of the surfaces, and when the particles are small or with highly curved surfaces [27]. Apparently, this method cannot be applied to quantitative calculation of interfacial interactions with rough sludge foulant particles in MBRs. As a development of DA approach, surface element integration (SEI) method, which integrates the interaction energy per unit area between opposing differential planar elements over the entire surfaces, can circumvent the limitations of DA method [7,24,28]. However, application of this method to rough particles still involves calculation of two nested integrations of complicated expressions, posing a substantial computational burden. Therefore, application of SEI method is cumbersome for rough particles.

By literature review, it can be found that there is a lack of effective method for quantitative evaluation of interfacial interactions with rough particles/flocs. Since interfacial interactions directly determine the adhesion process of foulants and membrane fouling, it is of primary importance to develop methods for modeling rough