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Effects of surface charge on interfacial interactions related to membrane fouling in a submerged membrane bioreactor based on thermodynamic analysis

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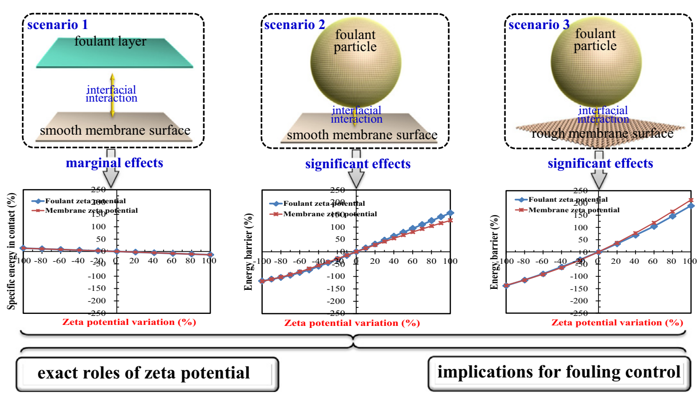
HIGHLIGHTS

- Zeta potential had minor effects on interactions between two planar surfaces.
- Zeta potential greatly affected interactions between membrane and foulant particles.
- There are an energy barrier and a critical zeta potential regarding its effects.
- Rough surface membrane corresponded to a significantly low interaction strength.

GRAPHICAL ABSTRACT



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ABSTRACT

Effects of both membrane and sludge foulant surface zeta potentials on interfacial interactions between membrane and sludge foulant in different interaction scenarios were systematically investigated based on thermodynamic methods. Under conditions in this study, it was found that zeta potential had marginal effects on total interfacial interaction between two infinite planar surfaces, and the total interfacial interaction between foulant particles and membrane would be more repulsive with increase of absolute value of zeta potential. Adhesion of foulant particles on membrane surface should overcome an energy barrier. There exists a critical zeta potential below which energy barrier would disappear. Results also showed that rough surface membrane corresponded to significantly low strength of interfacial interactions. This study not only provided a series of methods to quantitatively assess the interfacial interactions between membrane and sludge foulants, but also reconciled the contradictory conclusions regarding effects of zeta potential in literature, giving important implications for membrane fouling mitigation.

1. Introduction

Membrane fouling is one of the major concerns in the applications and development of membrane bioreactor (MBR) technology [1–4], which is considered as a promising technology

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Nomenclature

D	closest distance between a particle and a planar surface (nm)
$f(r,\theta)$	local amplitude directly below the circular arc as a function of the position of the differential circular arc defined by r and θ
h	separation distance between two planar surfaces (nm)
e	electron charge (1.6×10^{-19} C)
k	Boltzmann's constant (1.38×10^{-23} J K^{-1})
ΔG	interaction energy per unit area (mJ m^{-2})
R	radius of foulant particle (μm)
r	radius of differential circular ring on particle surface (μm)
U	interaction energy between membrane surface and particle (kT)
z	roughness of membrane surface (nm)

Greek letters

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

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

for wastewater treatment and reclaim. Therefore, investigating factors, mechanisms and control strategies of membrane fouling has drawn significant interests for research community regarding MBR technology [3,5–7].

Membrane fouling in MBRs can be generally classified into two categories: pore clogging and foulant adhesion [1,2]. A lot of studies and practical operations have demonstrated that foulant adhesion to surface of membrane (cake layer formation) is the major cause of membrane fouling in submerged MBRs [8–10]. Foulant adhesion in MBRs is a complicated process which depends on both of bioreactor hydrodynamic and thermodynamic conditions regarding foulants and membrane [3]. It is generally believed that hydrodynamic conditions take roles of bringing foulants to the vicinity of membrane surface, whereas, thermodynamic conditions indicated by interfacial interactions between foulants and membrane directly determined the eventually binding the foulants to membrane surface [11,12]. Surface charge is one of the primary surface parameters of a substance, and no doubt plays important roles in the interfacial interactions and membrane fouling in MBRs. Understanding the exact roles of surface charge in membrane fouling is therefore an essential interest for MBR research.

In MBR systems, both of foulants and membrane surface are generally negatively charged [3]. Some efforts have made to investigate the effects of surface charge on membrane fouling. It was reported that surface charge of flocs had a strong positive correlation with the microbial floc-caused fouling propensity in a MBR [13]. Zhan et al. [14] grafted acrylic acid as a monomer on the membrane surface, and found that the modified membrane had an intensified negative surface charge, and adsorption of bovine serum albumin (BSA) on membrane surface was significantly reduced. The essential reason of these results was considered to be the increased repulsive interactions between foulants and membrane surface with the increased negative charge. However, contradictory conclusions were also drawn based on experimental results. For instance, Xiao et al. [15] suggested that surface charge in term of zeta potential exhibited marginal impact on adsorptive fouling. Wu and Huang [16] concluded that zeta potential of foulants had no significant effect on membrane filterability. The conflicted conclusions in literature suggest that the effect of surface charge on membrane fouling is much more complicated, and deserves a comprehensive and anatomized investigation.

It is well accepted that the extended Derjaguin–Landau–Verwey–Overbeek (XDLVO) theory is the most commonly used theory describing the interfacial (thermodynamic) interactions between two infinite planar surfaces [17,18]. The interfacial interactions consist of three types of interactions: Lifshitz-van der Waals (LW), acid-base (AB), and electrostatic double layer (EL) interaction which surface charge is pertained to. A lot of studies have evidenced the feasibility of XDLVO in predicting and interpreting some membrane fouling phenomena in MBRs [11,12,19]. Therefore, XDLVO theory may provide a useful tool to explore the exact roles of surface charge in membrane fouling, and explain the conflicting conclusions in literature as well. The adhesion behavior is controlled by the overall of the three types of interactions. Most of previous studies, however, focused on the effects of surface charge on EL interaction rather than total interaction [13–16]. Moreover, as a fact, most of real membrane surfaces are significantly rough [19–21], and foulants are generally treated as particles [11,20,22]. Surface roughness can significantly affect interfacial interactions [23] and ion transport [24,25]. However, conventional XDLVO theory is only feasible for describing the interfacial interactions between two infinite planar surfaces [17,18]. In the previous study [26], the authors of this study extended XDLVO theory and developed a novel method which allows to quantitative calculation of the interfacial interactions between foulants and rough membrane surface. To the best of our knowledge, so far, there is no study investigating effects of surface charge on interfacial interactions under conditions of rough surface. A comprehensive assessment of effects of surface charge on membrane fouling under various conditions would provide significant insights into membrane fouling, and also facilitate development of novel fouling control strategies.

The aim of this study, therefore, was to investigate effects of surface charge of membrane and sludge foulants on membrane fouling in a submerged MBR (SMBR). Membrane and sludge foulants were sampled from a stable operated SMBR setup. Surface properties including surface charge in terms of zeta potential were characterized. The interfacial interactions between sludge foulants