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A novel integrated method for quantification of interfacial interactions between two rough bioparticles

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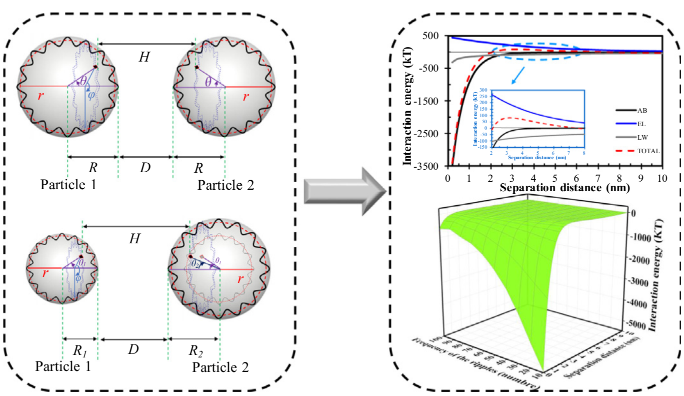
GRAPHICAL ABSTRACT



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ABSTRACT

Quantification of interfacial interactions between particles provides a way to regulate the interface behaviors of particles related with adhesion, aggregation, flotation, flocculation, membrane fouling, etc. Existing methods are based on assumptions of smooth particles although real particle surfaces are rather rough. This study proposed a new method to quantify interfacial interactions between two rough particles. In this study, a rigorous mathematical equation was firstly introduced to construct surface topography. In the framework of surface element integration (SEI) method, the spatial relationship between two rough particles was significantly explored, resulting in establishment of a formula of double integrals for interaction quantification. Thereafter, surface properties of the microbial aggregations obtained from a membrane bioreactor (MBR) were experimentally measured. With these data, the interfacial interactions between two rough microbial aggregations were numerically quantified according to composite Simpson's rule. The new method was compared with Derjaguin approximation (DA) method. It was found that ripple frequency and particle radius had profound effects on the total interfacial interaction. This method has extensive application foreground in interfacial behavior research.

1. Introduction

Interfacial interaction has drawn extensive attention when considering problems related with adhesion, aggregation, flotation, flocculation, membrane fouling, etc. [1–4]. These problems are

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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 (°)
$\underline{h}$	separation distance between two planar surfaces (nm)
k	unit vector along positive z-direction
$\underline{n}$	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 microbial aggregation (nm)
U	interaction energy between membrane surface and particle (kT)
Greek letters	
r	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
λ_0	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
s	solid
w	water

classic interface behaviors in bacterial or sludge aqueous media which have a broad range of potential applications in industry, such as drinking water production, membrane separation process, oil recovery, and so on [2,5,6]. For example, microbial adhesion on membrane surface could significantly reduce the separation efficiency of membrane and increase operational costs [7–9]. Microbial adhesion could also corrode water piping system and simultaneously improve the reproduction of pathogenic microorganisms, deteriorating drinking water production [10]. Meanwhile, microbial clustering and biofilm formation in the injection system in oil industry induce several serious troubles including iron corrosion, flow reduction, and sulfide contamination [11]. It is believed that, microbial clustering or biofilm formation is initialled by the interfacial interactions between small particles/microbes [5,12]. Therefore, detailed knowledge regarding the interaction that occurs between particles/microbes and the solid surfaces is urgently needed.

Accordingly, a great interest has been grown for information that will enable regulation and manipulation of these interface behaviors. It is generally accepted that, interfacial interaction gives a measure of the susceptibility of a surface to adhesion to another surface, providing a way to regulate these interface behaviors [13–17]. In the literature, theoretical framework to quantify interfacial interaction between two surfaces is presented by the extended Derjaguin-Landau-Verwey-Overbeek (XDLVO) theory [18–21]. While XDLVO theory is effective and only feasible for quantifying interfacial interaction between two ideally smooth surfaces [3,21], real surfaces of any natural substances including microbes are heterogeneous and randomly rough [1,22,23]. Hence, it is difficult to identify interfacial interaction between two real substances (particularly between two rough particles) by the classical XDLVO theory. In other words, the real rough surface (surface topography) provides a challenge for quantification of interfacial interaction, as well as for regulation and manipulation of these interface behaviors.

The development of surface element integration (SEI) method represents a breakthrough in quantification of interfacial interactions between two curved surfaces [24,25]. In theory, this method can quantify interfacial interactions between any two rough surfaces. However, applications of this method encounter formidable hurdles, particularly for interaction between two particles with rough topography. There exist at least 3 formidable hurdles limiting applications of this method including the long and complicated expressions of double integrals [24], obtaining a continuous function reflecting the complex spatial relationship between two rough surfaces [3], and massive computations involved in SEI method [26].

With atomic efforts, Cai et al. [27] have recently proposed a sound solution dealing with the aforementioned hurdles. Accordingly, they introduced conceptions of differential geometry and composite Simpson's rule into SEI method, and realized quantification of interfacial interactions between a rough particle and a smooth flat surface for the first time to our knowledge. Hong et al. [28] further extended the method proposed by Cai et al. [27], and realized quantification of interfacial interactions between a rough particle and a rough flat surface. Bradford et al. [29] have recently used simple linear expressions to calculate mean colloid-colloid interactions although these expressions didn't involve the complicated surface topography of colloids. While these studies posed significant insights into interface behavior research, pursuing literature showed that quantification of interfacial interactions between two rough particles is still challenging and has been not previously explored.

The objective of this paper is to realize quantification of interfacial interaction between two rough particles. The surface topography of a microbial aggregation was firstly constructed by a rigorous mathematical equation. Following this, the spatial relationship between two rough microbial aggregations were significantly explored. Thereafter, the spatial relationship, together with composite Simpson's approach, were included into SEI method, leading to a new solution to assess the interfacial interaction between two rough microbial aggregations. Effects of frequency of the ripples and the radius of particles on interfacial interaction were investigated. The application prospect of this solution was discussed.