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Modeling of the initial deposition of individual particles during the cross-flow membrane filtration

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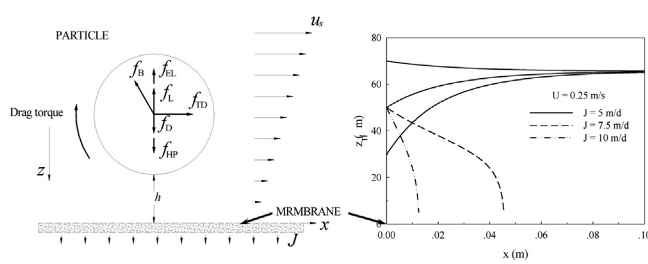
HIGHLIGHTS

- ► Comprehensive force analysis was conducted on initial particle deposition on membrane.
- ► Semi-Brownian particles are mostly likely the membrane foulants.
- ► The effect of hydraulic factors on the deposition of individual particles can be simulated.
- ► Critical flux exists for semi-Brownian and Brownian particles during water filtration.

GRAPHICAL ABSTRACT

The particle within the viscous sub-layer may be exerted by three groups of forces, which include hydrodynamic forces (drag forces and lift force, f_{TD}, f_D and f_L), inherent force (the random Brownian force, f_B) and interfacial forces (hydrophobic force, f_{HP}, and electrostatic force, f_{EL}). The particle transport trajectories can be simulated. Under otherwise identical conditions, there exists a critical flux for a non-Brownian particle, above which the particle will be transported to and attached on the membrane surface, causing particle deposition.



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ABSTRACT

This study is devoted to the modeling of the deposition of individual particles onto a clean membrane surface in cross-flow filtration systems. Comprehensive force analysis approach is applied, which accounts for the random Brownian force and the polar component of the particle–membrane interactive forces. The inclusion of the polar interactive force is important in that when a hydrophilic membrane is involved, it can easily predominate over the rest of lateral forces in the near-field. The repulsive polar particle–membrane interaction can greatly decrease the stability of the particle on the membrane surface. In the far-field that is about 0.1 μm or farther away from the membrane, the particle transport is primarily dictated by the hydrodynamic lift and drag forces and the Brownian force. In sharp contrast to semi- or non-Brownian particles, the transport trajectory of Brownian particle is hardly definitive. The filtration flux and the cross-flow velocity can influence the particle transport trajectory of all sizes. Nevertheless, the existence of critical flux or critical cross-flow velocity is more evident for non-Brownian particles. Above the critical cross-flow rate or below the critical flux, particle deposition is minimized. Under appropriate operational conditions, a force-balanced level exists in the viscous sub-layer for a particular particle size, which is independent of the initial position of the particle. The model can be expanded further for more complicated water filtration conditions.

1. Introduction

In the past decades, membrane filtration, especially microfiltration and ultrafiltration, has been increasingly attractive to water and wastewater treatment, primarily as the substitution for the

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Nomenclature

List of symbols

a	particle transport accelerating rate in the z direction (m/s^2)
C_f	membrane friction factor
C_L	lift coefficient of the hydrodynamic lift force
$C_{L,w}$	C_L when the particle is in contact with the membrane wall
D	inner diameter of the membrane tubular flow channel (m)
d_p	particle diameter (m)
e	elementary charge (1.602×10^{-19} C)
F	Faraday constant (96485.3 C/mol)
F_{at}	the net force responsible for the particle attachment (N)
F_{dt}	the net force responsible for the particle detachment (N)
f_{AB}	force of Lewis acid–base particle–membrane interaction (N)
f_B	Brownian force on a particle (N)
f_D	hydrodynamic drag force on a particle (N)
f_{EL}	force of electrostatic particle–membrane interaction (N)
f_{HP}	force resulted from hydrophobic effect, i.e. the sum of f_{LW} and f_{AB} (N)
f_L	hydrodynamic lift force on a particle (N)
f_{LW}	force of Lifshitz–van der Waals particle–membrane interaction (N)
ΔG_{AB}	*AB* free energy per unit area of two parallel plates at a distance of h_0 (J/m^2)
ΔG_{LW}	*LW* free energy per unit area of two parallel plates at a distance of h_0 (J/m^2)
h	separation distance between the membrane and a particle (m)
h_0	minimum separation distance between plates due to Born repulsion (0.157×10^{-9} m)
I	ionic strength (mol/L)
i	electrolyte charge number
J	apparent filtration flux ($m^3/m^2/s$)
k_B	Boltzmann constant (1.381×10^{-23} J/K)
R	gas constant (8.314 J/K/mol)
Re	Reynolds number
Re_p	particle Reynolds number
s	surface roughness of the membrane tube (m)
T	absolute temperature (K)
t	time (s)
U	average cross-flow velocity in the filtration tube (m/s)
u	local water velocity (m/s)
u_x	local water velocity in the x direction (m/s)
u_z	local water velocity in the z direction (m/s)
u^*	membrane wall friction velocity (m/s)
v	particle velocity (m/s)
v_x	particle velocity in the x direction (m/s)
v_z	particle velocity in the z direction (m/s)
x	cross-flow direction (Fig. 1)
Z	normalized distance from the membrane in the filtration direction
z	distance from the membrane in the filtration direction (Fig. 1)

Greek symbols

$\alpha\beta\gamma$	parameters in Eq. (11)
γ_m^{AB+}	polar component as electron acceptor of the surface tension of the membrane (J/m^2)
γ_m^{AB-}	polar component as electron donor of the surface tension of the membrane (J/m^2)
γ_m^{LW}	apolar component of the surface tension of the membrane (J/m^2)
γ_p^{AB+}	polar component as electron acceptor of the surface tension of the particles (J/m^2)
γ_p^{AB-}	polar component as electron donor of the surface tension of the particles (J/m^2)
γ_p^{LW}	apolar component of the surface tension of the particles (J/m^2)
γ_w^{AB+}	polar component as electron acceptor of the surface tension of water (J/m^2)
γ_w^{AB-}	polar component as electron donor of the surface tension of water (J/m^2)
γ_w^{LW}	apolar component of the surface tension of water (J/m^2)
δ	thickness of the viscous sub-layer (hydrodynamic boundary layer) (m)
ε	relative dielectric constant of water (78.5)
ε_0	dielectric permittivity of vacuum (8.854×10^{-12} C/V/m)
κ	Debye parameter (1/m)
λ	decay length for Lewis acid–base interactions in water (0.6×10^{-9} m)
μ	Water viscosity (Pa s)
ρ	Water density (kg/m^3)
ρ_s	particle density (kg/m^3)
τ_w	Membrane wall shear stress (Pa)
Ψ_{d1}	potential of the particle at the plane where the diffuse double layer begins (V)
Ψ_{d2}	potential of the membrane at the plane where the diffuse double layer begins (V)

conventional deep-bed filtration [1] and the secondary clarifier [2], respectively. Membrane filtration is becoming the most promising technology to polish the treated water or wastewater for better quality [3,4]. All membrane filtration processes make use of the unique separation principle that selectively allows permeation of water (and part or all of dissolved species) and therefore retention of particulate matters in the feed side [5]. However, particle retention often leads to membrane fouling, which decreases the membrane permeability [6,7]. To minimize fouling, most membrane filtration processes are operated using the cross-flow mode, which features that the water filtration is perpendicular to the bulk feed flow.

No cake formation, i.e. fouling by particle deposition, is expected if the applied filtration flux is sufficiently low [8–10]. However, if a super-critical flux is applied initially, cake formation could still be inevitable [11]. It has been realized that particle deposition is the result of the lateral transport of the particles approaching to the membrane (i.e. excessive forth-transport over the back-transport) in the far-field region, followed by the near-field phenomena of the attachment of the particles onto the membrane surface [12–14]. Both the lateral transport and the near-field phenomenon are dictated by a number of forces that have the hydrodynamic, thermodynamic, electrodynamic, electrostatic or mass-related origins [15–17]. Therefore, by using the force analysis approach, usually on a single particle in the flow regime in the filtration apparatus, membrane fouling can be simulated by deriving the particle transport “trajectories” and evaluating the particle “stability” on the membrane surface if attached [12,14,18–22].