Effects of Hydrodynamics on Attachment Efficiency in Colloid Deposition Under Unfavorable Chemical Conditions

Chongyang Shen[1], Yan Jin[2], Yuanfang Huang[1], and Baoguo Li[1]

[1]Department of Soil and Water Sciences, China Agricultural University, Beijing, 100094, China
[2]Department of Plant & Soil Sciences, University of Delaware, Newark, DE 19716-2170, USA

INTRODUCTION

- Accurate understanding of the mechanisms that control the attachment and transport of colloids is of great importance in many environmental processes
- Classic filtration theory (CFT) separate overall filtration process under unfavorable chemical conditions into two components: the rate of particle collisions with collectors of porous media (denoted as single collector remove efficiency) and the probability that a collision produces attachment (denoted as attachment efficiency)
- Attachment efficiency is not influenced by hydrodynamics and only controlled by chemical factors (e.g., solution ionic strength and surface potential of colloids and collectors) in CFT
- Recent experimental studies showed attachment efficiency is also influenced by a physical factor (flow velocity) under unfavorable chemical conditions.
- The role of hydrodynamics in attachment efficiency for colloid deposition under unfavorable chemical conditions has not been clearly understood to date

OBJECTIVES

- To study the effects of hydrodynamics on attachment efficiency in colloid deposition under unfavorable chemical conditions via theoretical analysis and laboratory column experiments.

THEORETICAL CONSIDERATION

Attachment efficiency is considered to be determined by coupled effects of diffusion process and hydrodynamic forces

$$\alpha = f_{pri}\alpha_{pri} + f_{sec}\alpha_{sec}$$

α is attachment efficiency; α_{pri} and α_{sec} are coefficients accounting for effects of diffusion on deposition of colloids in primary and secondary minimum, respectively; f_{pri} and f_{sec} are coefficients accounting for effects of hydrodynamics on primary- and secondary-minimum deposition, respectively

- The Maxwell approach is used to quantify effects of diffusion process on attachment efficiency by coupling primary- and secondary-minimum deposition

(i) distribution of colloid velocities at the separation corresponding to a secondary minimum follows the Maxwell distribution

$$f(v) = 4\pi\left(\frac{m_p}{2\pi kT}\right)^{(3/2)} v^2 \exp\left(-\frac{m_p v^2}{2kT}\right) \qquad \int_0^\infty f(v)dv = 1$$

m_p is mass of a colloid; v is velocity of colloid; k is Boltzmann constant; T is absolute temperature

(ii) the colloids in a secondary minimum will remain there if their kinetic energies are smaller than the interaction energy of the secondary minimum

$$\alpha_{sec} = \int_0^{\sqrt{\Phi_{sec}}} \frac{4}{\pi^{1/2}} x^2 \exp(-x^2)dx \qquad x^2 = \frac{m_p v^2}{2kT}$$

α_{sec} the fraction of successful collisions that result in deposition in the secondary minimum; Φ_{sec} is secondary-minimum energy depth; x is a dimensionless kinetic energy of the colloid

(iii) the colloids in a secondary minimum will transport over the energy barrier and be deposited in the primary minimum if their kinetic energies are larger than $\Delta\Phi$

$$\alpha_{pri} = \int_{\sqrt{\Delta\Phi}}^{\infty} \frac{4}{\pi^{1/2}} x^2 \exp(-x^2)dx$$

α_{pri} the fraction of successful collisions that result in deposition in the secondary minimum; $\Delta\Phi$ is energy barrier

- The influence of hydrodynamic drag on attachment efficiency is quantitatively determined via comparing adhesive and hydrodynamic torques that act on the colloids at primary and secondary minima

$$T_A = F_A l_c \qquad T_{hyd} = 1.4 a_p F_H \qquad F_H = 10.205\pi\mu(\partial V/\partial r)a_p^2$$

T_A is adhesive torque; F_A is adhesive forces, estimated as for colloids retained in primary and secondary minima, respectively; l_c is lever arm; a_p is colloid diameter; T_{hyd} is hydrodynamic torque; F_H is hydrodynamic force; μ is the viscosity of the fluid; $\partial V/\partial r$ is the hydrodynamic shear, the Happel's sphere-in-cell model was adopted to calculate $\partial V/\partial r$

RESULTS

1 DLVO Interaction Energy calculation

I(M)	$\Phi_{max}(kT)$		Φ_{pri}				Φ_{sec}			
			depth, kT		distance, nm		Depth, kT		distance, nm	
	30nm	1156nm	30nm	1156nm	30nm	1156nm	30nm	1156nm	30nm	1156nm
0.001	31.31	1267.70	a	a	a	a	0.003	0.11	109.46	110.13
0.01	24.41	1019.47	a	a	a	a	0.04	1.54	25.71	26.03
0.1	7.83	291.8	a	a	a	a	0.51	19.60	5.15	5.12
0.2	1.97	59.95	1.47	79.9	0.29	0.29	1.05	41.3	2.87	2.81

The extended DLVO theory is used for calculation. The zeta potentials of both colloids and glass beads were adopted from the study of *Shen et al.* [2007]. *a* represents primary minimum is absent in the extended DLVO interaction energy profiles. Collector diameter= 328 μm; Hamaker constant = 1×10^{-20} J

- Calculated maximum energy barriers and secondary-minimum depths and distances using the extended DLVO theory are the same as those obtained by the classic DLVO theory

- Born repulsion only changes the depths and distances of primary minima and does not influence the values of maximum energy barrier and secondary energy minimum

2 Adhesive and Drag Torques

I(M)	30 nm				1156 nm			
	primary minimum		secondary minimum		primary minimum		secondary minimum	
	F_A	T_A	F_A	T_A	F_A	T_A	F_A	T_A
0.001	a	a	1.13×10^{-16}	1.34×10^{-27}	a	a	4.11×10^{-15}	5.48×10^{-25}
0.01	a	a	6.40×10^{-15}	2.93×10^{-25}	a	a	2.43×10^{-13}	1.27×10^{-22}
0.1	a	a	4.07×10^{-13}	7.45×10^{-23}	a	a	1.58×10^{-11}	3.29×10^{-20}
0.2	2.79×10^{-11}	2.09×10^{-20}	1.51×10^{-12}	4.25×10^{-22}	1.13×10^{-9}	9.85×10^{-18}	6.05×10^{-11}	1.98×10^{-19}

- Both adhesive forces and torques increase with increasing ionic strength and particle size

- For a given ionic strength, colloids deposited in the primary minimum experience much larger adhesive forces and torques compared with those in the secondary minimum
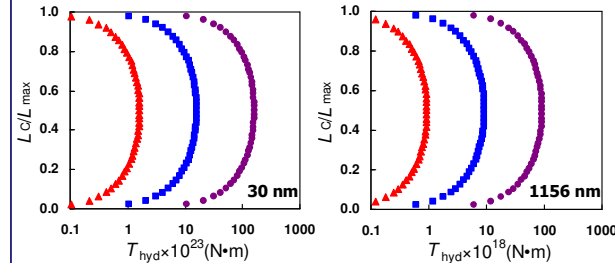

The normalized distance L_C/L_{max} is defined as the arc distance from the front toward the rear stagnant point along the collector surface (L_C) divided by the arc distance between the front and rear stagnation points (L_{max}) (triangle, 1.2×10^{-5} m/s; square, 1.2×10^{-4} m/s; circle, 1.2×10^{-3} m/s)

- The smallest drag torque is found at the front and rear stagnation point regions whereas the largest one is at the midpoint region of the collector surface

- The drag torque displays a linear dependence on the flow velocity

- The drag torque is proportional to the volume of a colloid at certain location of the collector surface

- The drag torque increases with decreasing collector diameter

RESULTS

3 DLVO Interaction Energy calculation
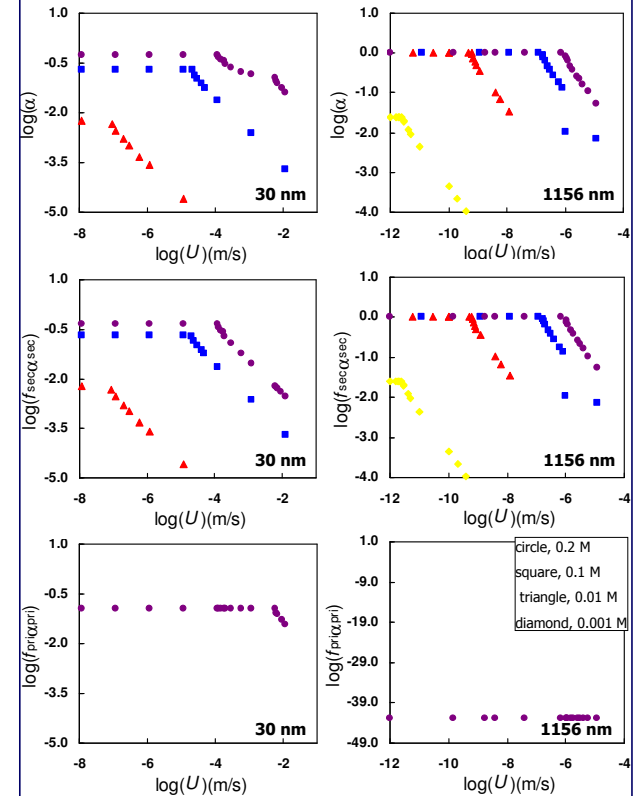
The critical flow velocity occurs when the hydrodynamic torque acting on colloids at the midpoint region of the collector surface begins to surpass the primary- or secondary-minimum adhesive torque.
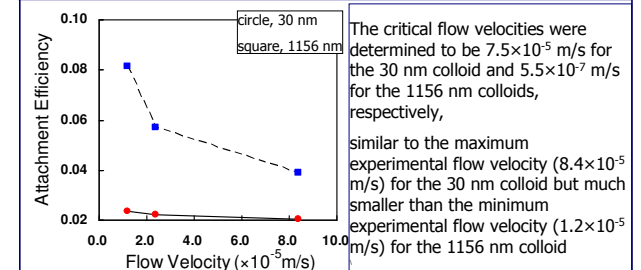
The critical flow velocities were determined to be 7.5×10^{-5} m/s for the 30 nm colloid and 5.5×10^{-7} m/s for the 1156 nm colloids, respectively,

similar to the maximum experimental flow velocity (8.4×10^{-5} m/s) for the 30 nm colloid but much smaller than the minimum experimental flow velocity (1.2×10^{-5} m/s) for the 1156 nm colloid

SUMMARY

The attachment efficiency does not change with increase in flow velocity until it reaches a critical point at which the attachment efficiency begins to decrease as flow velocity further increases

References
Shen et al., 2007. Environ. Sci. Technol. 41, 6976-6982
Torkzaban et al., 2007. Langmuir 23, 9652-9660