Influence of Electric Field and Hydrodynamic Interactions in Removal of Uniformly Charged Abrasive Particles in Post-CMP Cleaning

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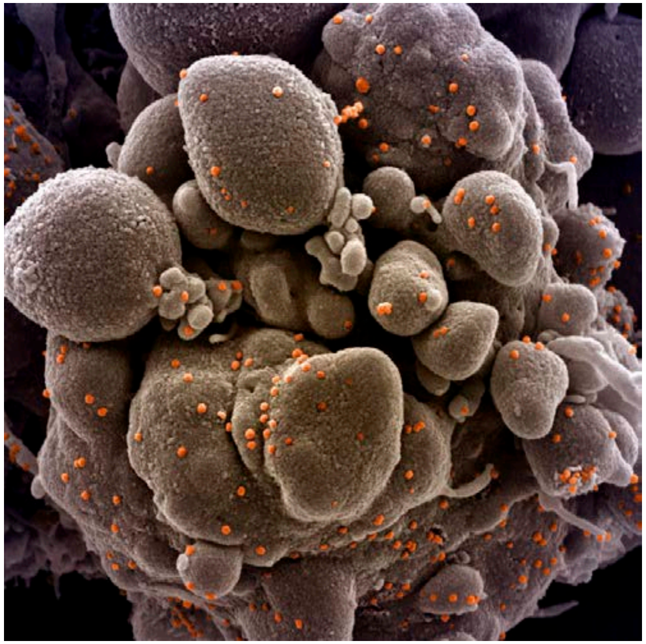
Overview

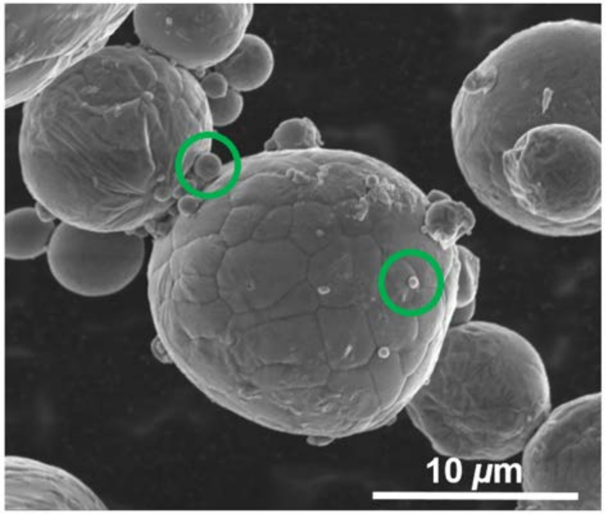
- Objectives
- Surface Features
- Particle Adhesion Model
- Charging Mechanisms
- Electrostatic Interactions
- Hydrodynamic Interactions
- Rolling Detachment Mechanism
- Critical Shear Velocity
- Results and Discussion
- Conclusions

Objectives

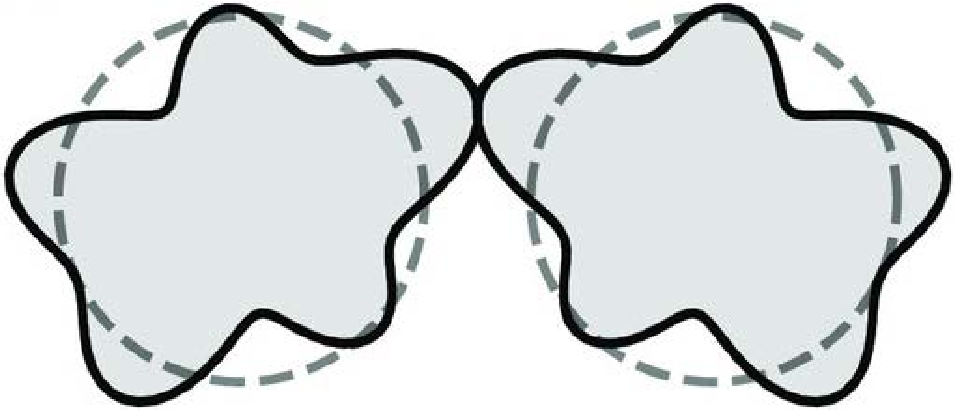
- Develop a model for the detachment of charged abrasives in turbulent flows.
- Study the removal of small, irregularly shaped particles from rough surfaces.
- Investigate Interactions between adhesion, electrostatic, and hydrodynamic forces.
- Assess size, charge, surface roughness, and irregularity effects on particle removal.

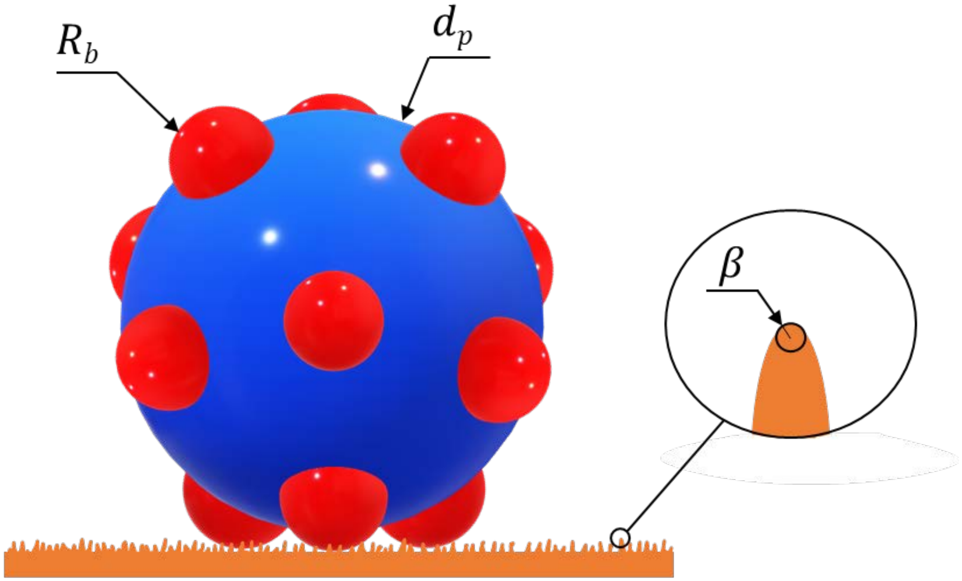
Surface Features





Non-Spherical Particles

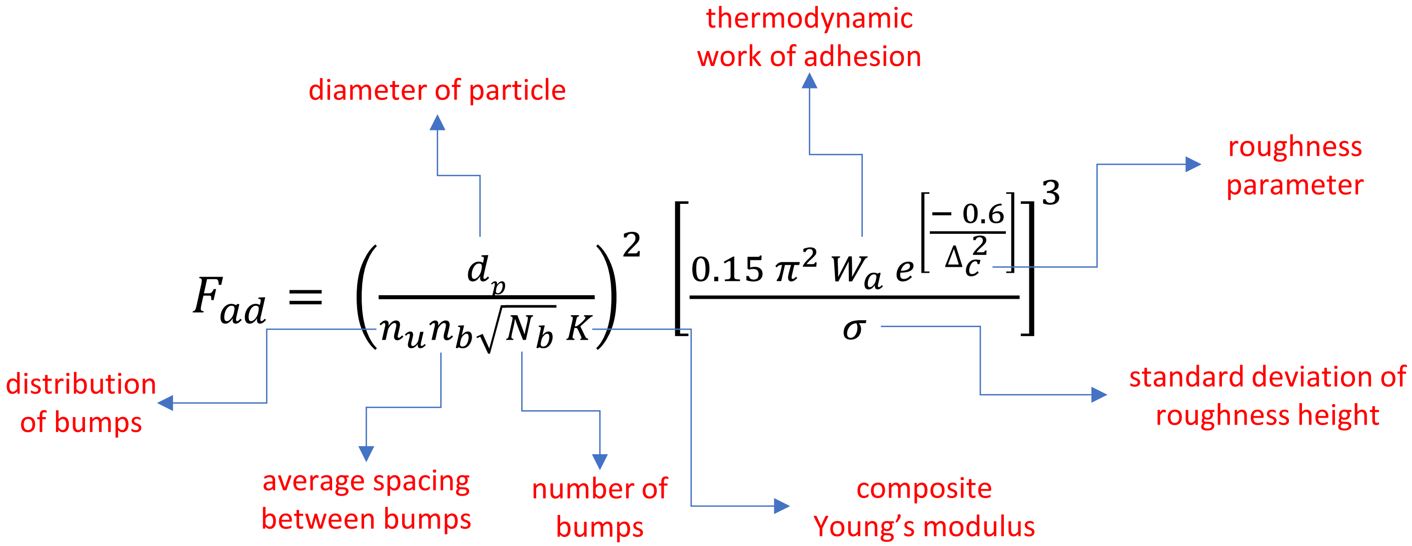




Particle Adhesion Model

- Van der Waals molecular forces in the absence of charge
- JKR adhesion model
- Elastic contact deformation
- Microparticles
- Three contact bumps
- Effects of surface feature and material properties on particle adhesion

Particle Adhesion Model



$$F_{ad} = \left(\frac{d_p}{n_u n_b \sqrt{N_b}\, K}\right)^2 \left[\frac{0.15\,\pi^2\, W_a\, e^{\left[\frac{-0.6}{\Delta_c^2}\right]}}{\sigma}\right]^3$$

thermodynamic work of adhesion

diameter of particle

roughness parameter

distribution of bumps

standard deviation of roughness height

average spacing between bumps

number of bumps

composite Young's modulus

Charging Mechanisms

- Triboelectric Charging
  - Charges are concentrated on the bumps
  - Nonuniform charge distribution on the surface
- Corona Ion Charging
  - Charges are distributed on the entire surface
  - Uniform charge distribution on the surface

Electrostatic Interactions

➢ Coulomb^{+} Force	• Coulomb + dielectrophoretic • Effect of charge and electric field • Attractive or repulsive
➢ Polarization Force	• Induced dipoles and corresponding images • Effect of electric field • Always attractive
➢ Image Force	• Force of contact and noncontact bumps • Effect of image charge • Always attractive

Electrostatic Interactions

electric charge

$$F_e = \pm 1.5\, q\, E \ + \frac{q^2}{4\pi\varepsilon_0[(n_u n_b)^2+1]^2}\left[\frac{\left[(n_u n_b)^2-1\right]^2}{d_p^2} + \frac{4\left(1-\left(\frac{3}{N_b}\right)\right)^2}{d_p^2} + \frac{\left[\sqrt{\left(4n_b^2+1\right)^3}+2\right]\left(\frac{3}{N_b}\right)^2}{3\, R_b^2\, \sqrt{\left(4n_b^2+1\right)^3}}\right] + \ 72\, \pi\, \varepsilon_0\, R_b^2\, E^2$$

electric field strength

dielectric constant

Hydrodynamic Interactions

- Hydrodynamics drag and moments are the primary cause of particle detachment in fluid.
- The viscous sublayer is unsteady and disturbed by turbulent burst/inrush and coherent vortices.
- The burst/inrush increases the local turbulent flow velocity acting on particles.

Hydrodynamic Interactions

- The maximum velocity in the streamwise direction ranges between $1.6y^{+}$ and $2.14y^{+}$:

$$u_M^{+} = 1.72y^{+} + 0.1{y^{+}}^{2}$$

- The highest velocity at the particle's center $\left(y_c^{+} = \frac{d_p u^{*}}{2\nu}\right)$ is estimated as:

$$u_{c,max}^{+} = 0.86d_p^{+} + 0.025{d_p^{+}}^{2}$$

Hydrodynamic Interactions

- Nonlinear drag force:

correction factor density Reynolds number shear velocity

$$F_h = \frac{2.58\pi f \rho d_p^2 {u^*}^2}{C_c}\left(1 + 0.15Re^{0.678}\right)\left(1 + 0.029\frac{d_p u^*}{\nu}\right)$$

Cunningham factor kinematic viscosity

Hydrodynamic Interactions

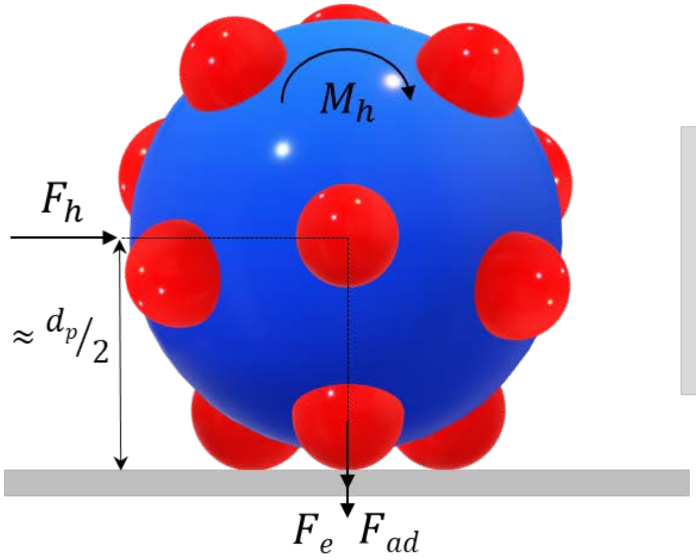
- Nonlinear hydrodynamic moment:

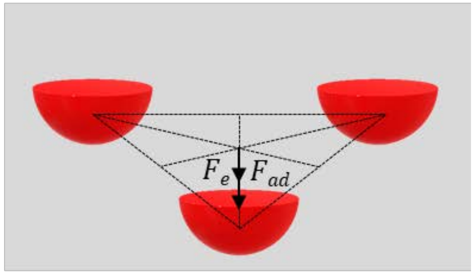
$$M_h = \frac{1.72\pi \overset{\text{density}}{\uparrow}{\rho}\, \overset{\text{correction factor}}{\uparrow}{f_m}\, d_p^3 {u^*}^2}{\underset{\downarrow\,\text{Cunningham factor}}{C_c}}\left(1 + 0.029\,\frac{d_p \overset{\text{shear velocity}}{\uparrow}{u^*}}{\underset{\downarrow\,\text{kinematic viscosity}}{\nu}}\right)$$

Rolling Detachment Mechanism

- Particles may detach by sliding, lifting off, or rolling on the surface. However, the primary removal mechanism of compact nearly spherical particles is the rolling detachment.
- A particle is detached from a surface when the hydrodynamic drag force and hydrodynamic moment overcome van der Waals and electrostatic adhesion forces in turbulent flows.
- For bumpy particle detachment, the hydrodynamic drag force and moment break the contact between one of the contact bumps and the surface at the onset of rolling removal.
- Then, the particle rolls about the axis of the two other contact bumps and is removed.

Rolling Detachment Mechanism





$$M_h + F_h \frac{d_p}{2} \geq \frac{\sqrt{3}}{3}\, n_b\, R_b\, (F_{ad} + F_e)$$

Critical Shear Velocity

Shear Velocity: $$u^* = \sqrt{\frac{\tau_w}{\rho}}$$

$$u^* = \left(\frac{\sqrt{3}\, n_b\, R_b\, C_c\, [F_{ad} \;+\; F_e]}{5.16\, \pi\, \rho d_p^3\, [f_m + 0.75\, f\, (1 + 0.15\, Re^{0.678})]\, \left[1 \;+\; 0.029\, \dfrac{d_p\, u^*}{\nu}\right]} \right)^{1/2}$$

Results and Discussion

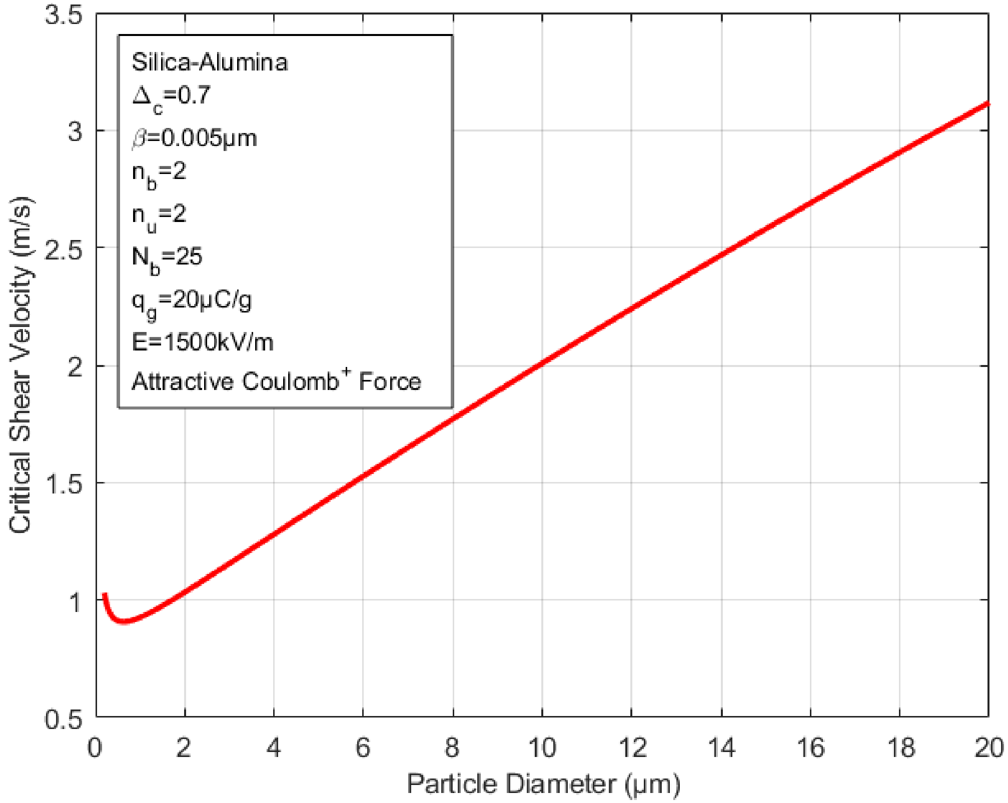
- The turbulent burst/inrush model is used to predict the shear velocity required to remove charged irregular and rough particles from rough surfaces, in the presence of an electric field in dry air flows.

Material characteristics of particles and surface

Particle-Surface	W_A $(10^{-3}\,J/m^2)$	K (GPa)	E_i (GPa)	ρ_i (kg/m^3)	ν_i
Silica– Alumina	19.79	80.77	69 - 370	2180 – 3960	0.2 – 0.2

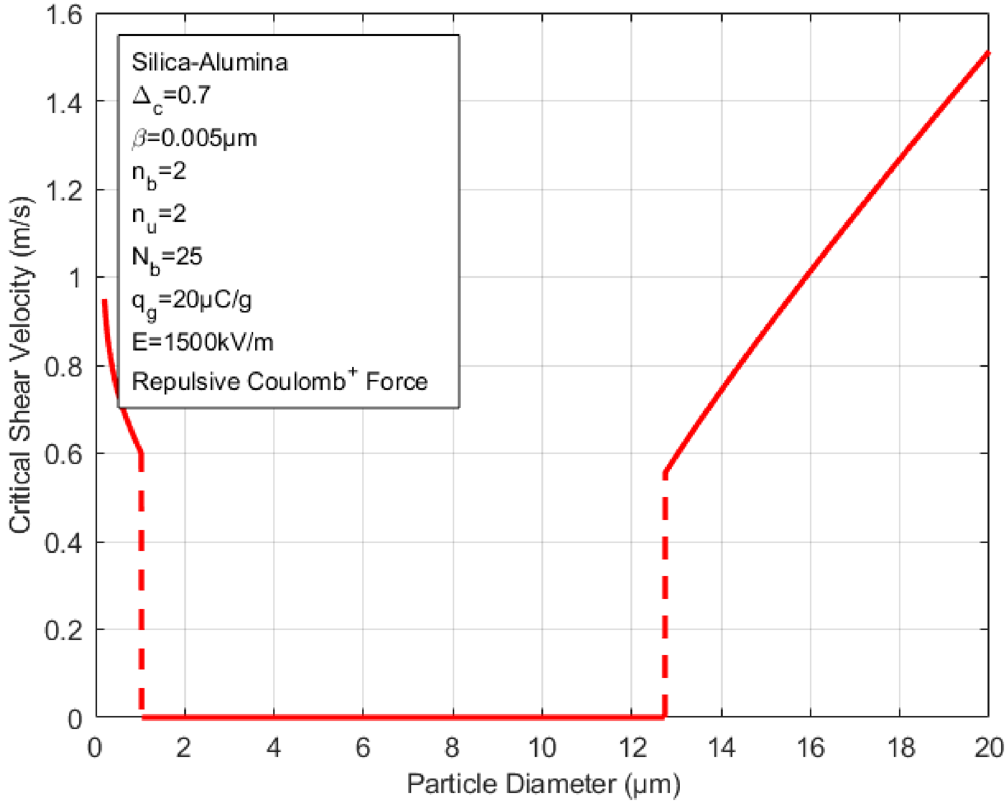
Results and Discussion

- Variation of Critical Shear Velocity Versus Particle Diameter for Attractive Coulomb$^+$ Force



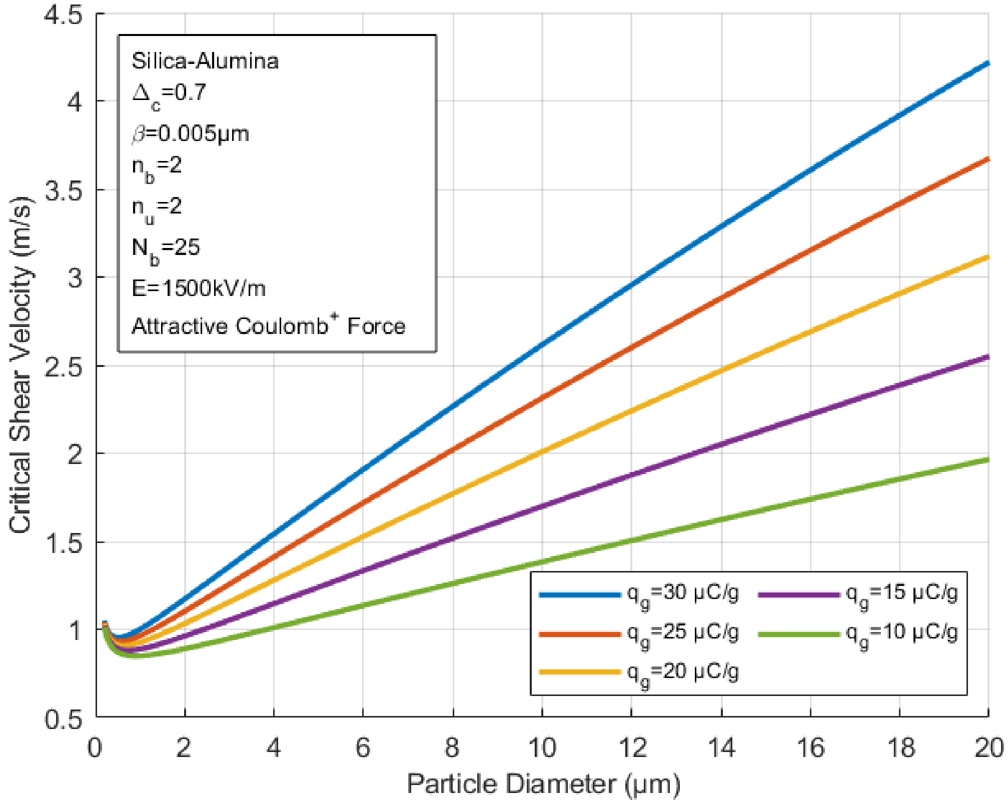
Results and Discussion

- Variation of Critical Shear Velocity Versus Particle Diameter for Repulsive Coulomb$^+$ Force



Results and Discussion

- Effect of the fixed corona ion charge (Attractive Coulomb$^+$ Force)



Results and Discussion

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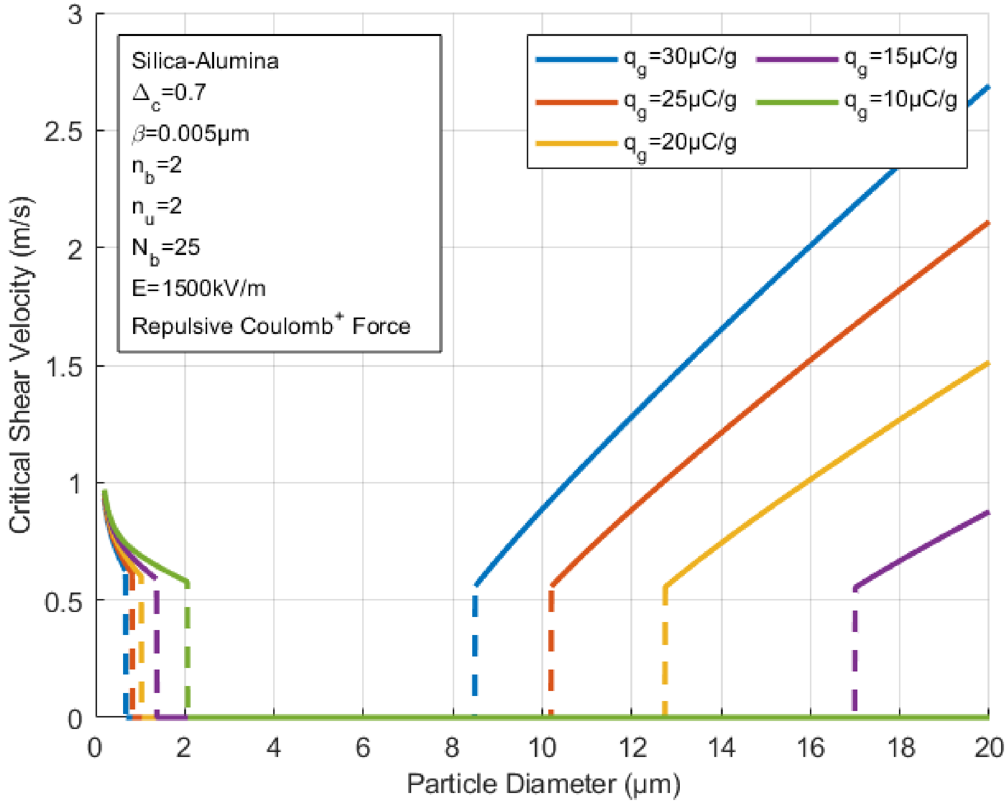
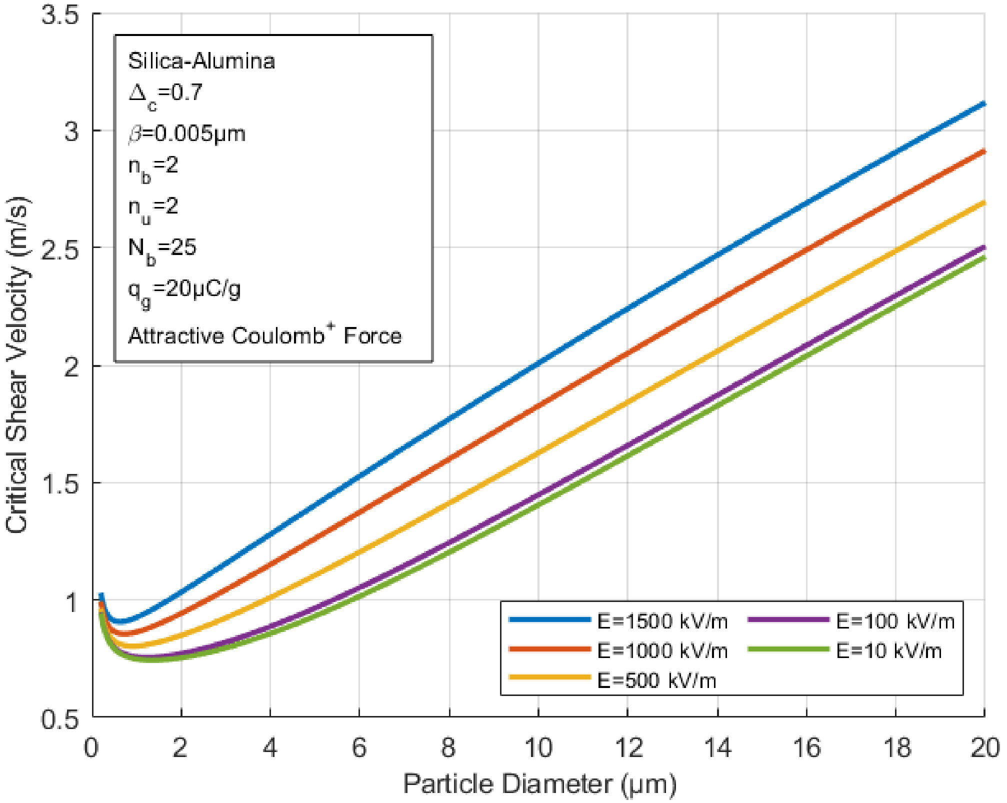


Results and Discussion

- Effect of the electric field (Attractive Coulomb$^+$ Force)



Results and Discussion

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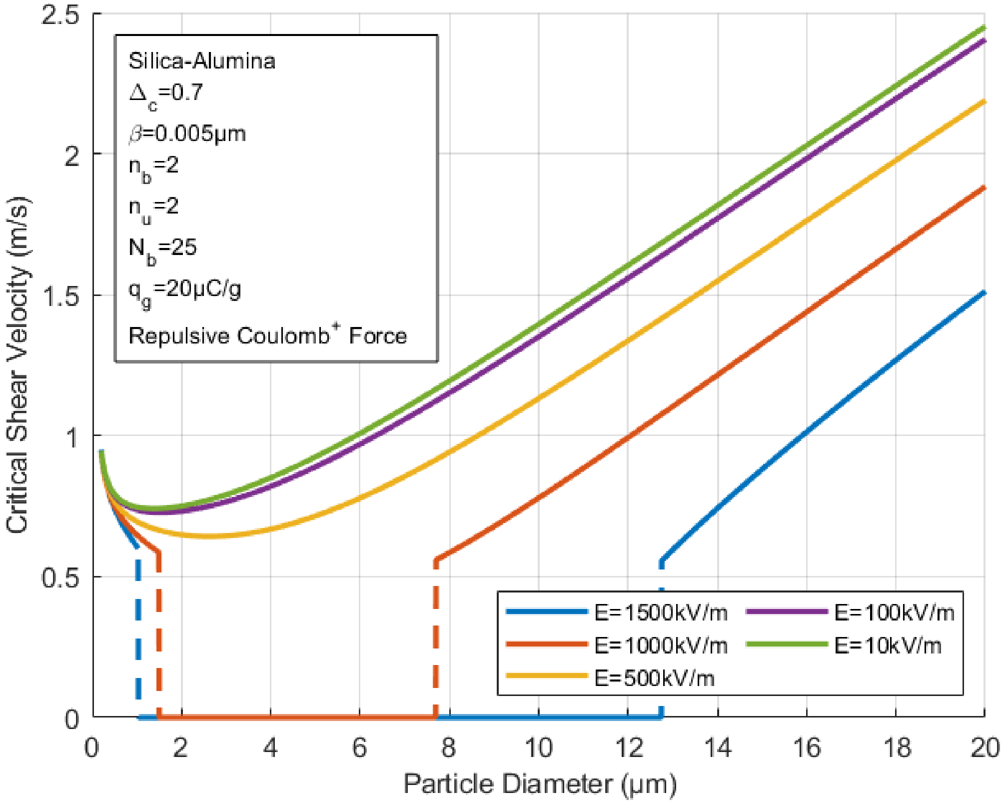

Conclusions

- Rolling is the main detachment mechanism for compact particles in turbulent airflows.
- A repulsive Coulomb$^+$ force significantly (by 50%, depending on the particle size) lowers the critical shear velocity compared to the attractive case.
- Increasing the number of bumps and roughness decreases the critical shear velocity.
- Higher charge and electric field increase the critical shear velocity when the electrical forces are attractive.

Questions and Discussion

Thanks for your attention.