An Analytical Study on the Effect of Hydrodynamic and Electrostatic Forces on Particle Removal

Abbas Khanmohammadi and Goodarz Ahmadi

Department of Mechanical and Aerospace Engineering,
Clarkson University, Potsdam, NY, USA

August 2024

Overview

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

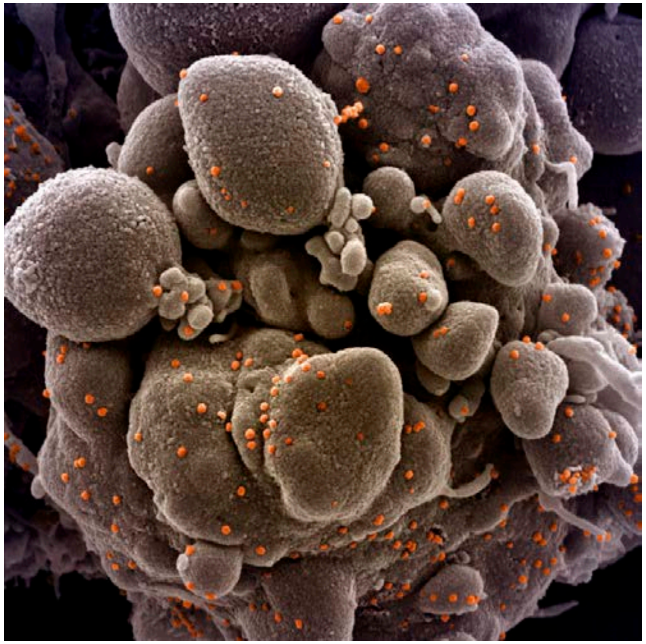
Objectives

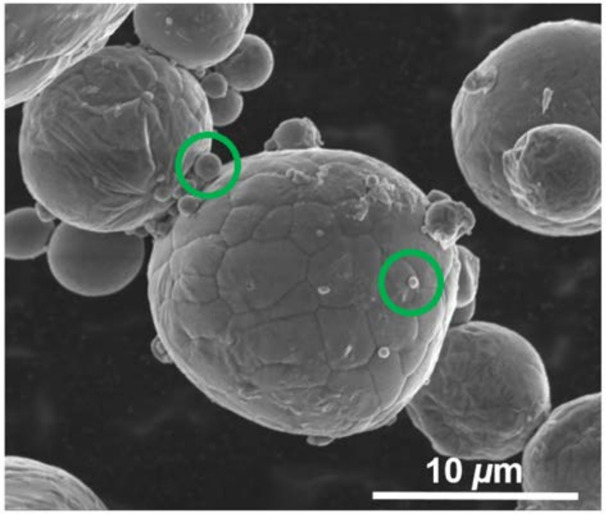
- Develop a model for detachment of triboelectrically charged particles in turbulent flows.
- Analyze the removal of small, irregularly shaped charged particles from rough surfaces.
- Investigate Interactions between adhesion, electrostatic, and hydrodynamic forces.
- Assess effects of particle size,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

Applications and Significance

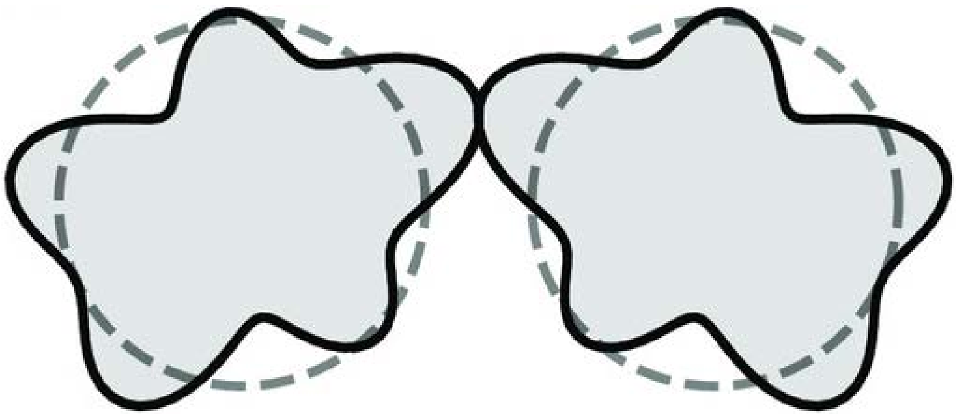
- Semiconductor Fabrication
- Clean Rooms
- Surface Cleaning
- Post-CMP Cleaning
- Cleaning Heat Exchangers and Pipelines
- Solar Energy
- Aerospace Industries
- Environmental Science and Pollution Control

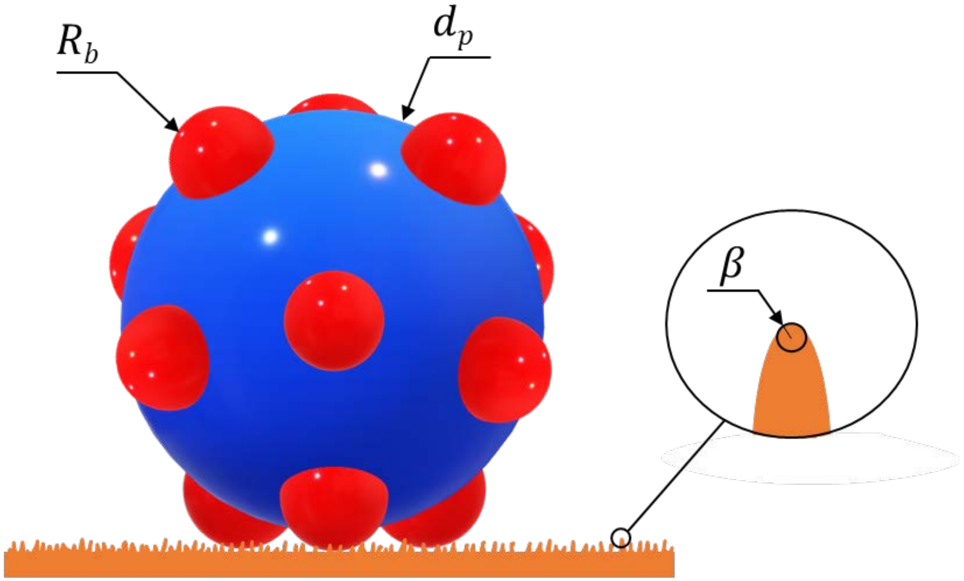
Surface Features





Non-Spherical Particles





Charging Mechanism

- Triboelectric Charging

  - Charges are concentrated on the bumps
  - No charge on the surface
  - Uniform charge distribution on the bumps

Electrostatic Interactions

- Coulomb+ Force
  - Coulomb + dielectrophoretic
  - Effect of charge and electric field
  - Attractive or repulsive
- Polarization Force
  - Induced dipoles & corresponding images
  - Effect of electric field
  - Always attractive
- Image Force
  - Force of contact & noncontact bumps
  - Effect of image charge
  - Always attractive

Electrostatic Interactions

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

radius of bump

electric charge

electric field strength

dielectric constant

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

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

thermodynamic work of adhesion

diameter of particle

roughness parameter

distribution of bumps

average spacing between bumps

number of bumps

composite Young's modulus

standard deviation of roughness height

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 $2.14y^+$.

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

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

Hydrodynamic Interactions

Stokes drag:

correction factor

density

shear velocity

$$F_h = \frac{2.76\pi f \rho d_p^2 {u^*}^2}{C_c}$$

Cunningham factor

Hydrodynamic Interactions

Hydrodynamic moment:

correction factor

density

shear velocity

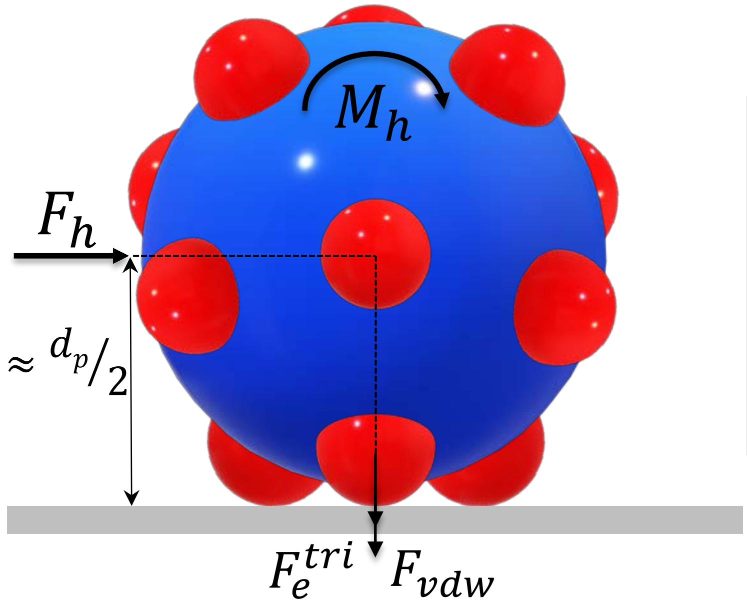
$$M_h = \frac{1.84\pi f_m \rho d_p^3 {u^*}^2}{C_c}$$

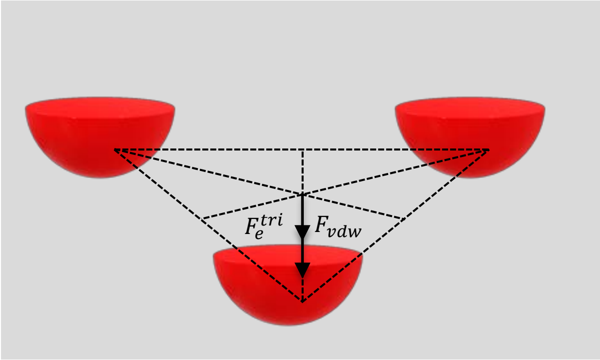
Cunningham factor

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.
- 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





$$M_h + F_h \frac{d_p}{2} \geq \frac{\sqrt{3}}{3}\, n_b\, R_b \left(F_{vdw} + F_e^{tri}\right)$$

Critical Shear Velocity

Shear Velocity:

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

$$u^* = \left(\frac{\sqrt{3}\, n_b\, R_b\, C_c\, \left[F_{vdw} + F_e^{tri} \right]}{5.52\, \pi\, \rho d_p^3\, [f_m + 0.75\, f\,]} \right)^{1/2}$$

Results and Discussion

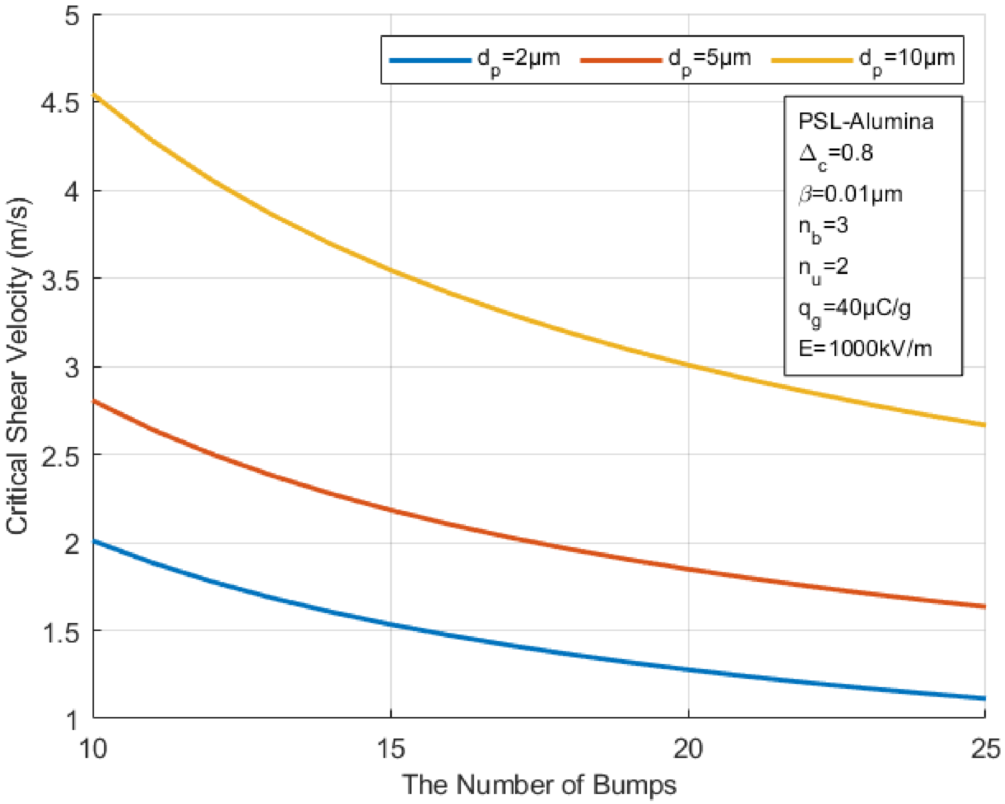
- The turbulent burst/inrush model is used to predict the shear velocity required to remove charged irregular and rough particles from rough surfaces, in the presence of an electric field in dry air flows.

Material characteristics of particles and surface

Particle-Surface	$\boldsymbol{W_A}$ $(\mathbf{10^{-3}\,J/m^2})$	$\boldsymbol{K}$ $(\boldsymbol{GPa})$	$\boldsymbol{E_i}$ $(\boldsymbol{GPa})$	$\boldsymbol{\rho_i}$ $(\boldsymbol{kg/m^3})$	$\boldsymbol{\nu_i}$
PSL– Alumina	17.13	4.16	2.8 - 370	1100 – 3960	0.33 – 0.2

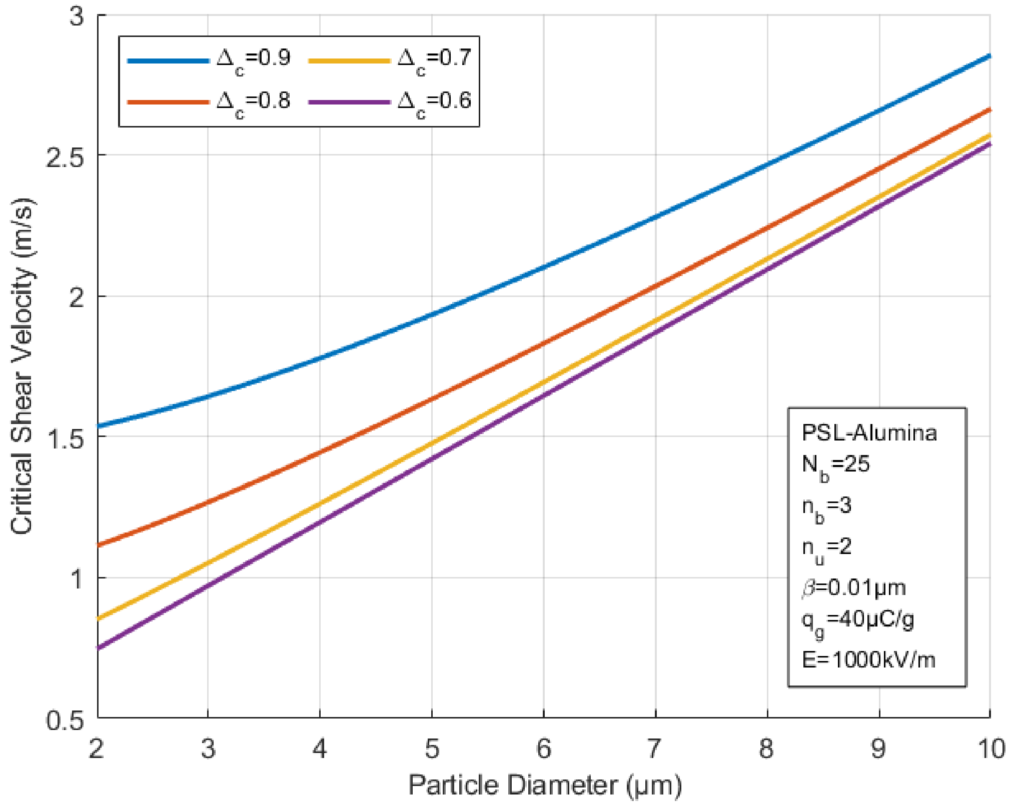
Results and Discussion

➢ Variation of critical shear velocity with number of bumps for different particle diameters



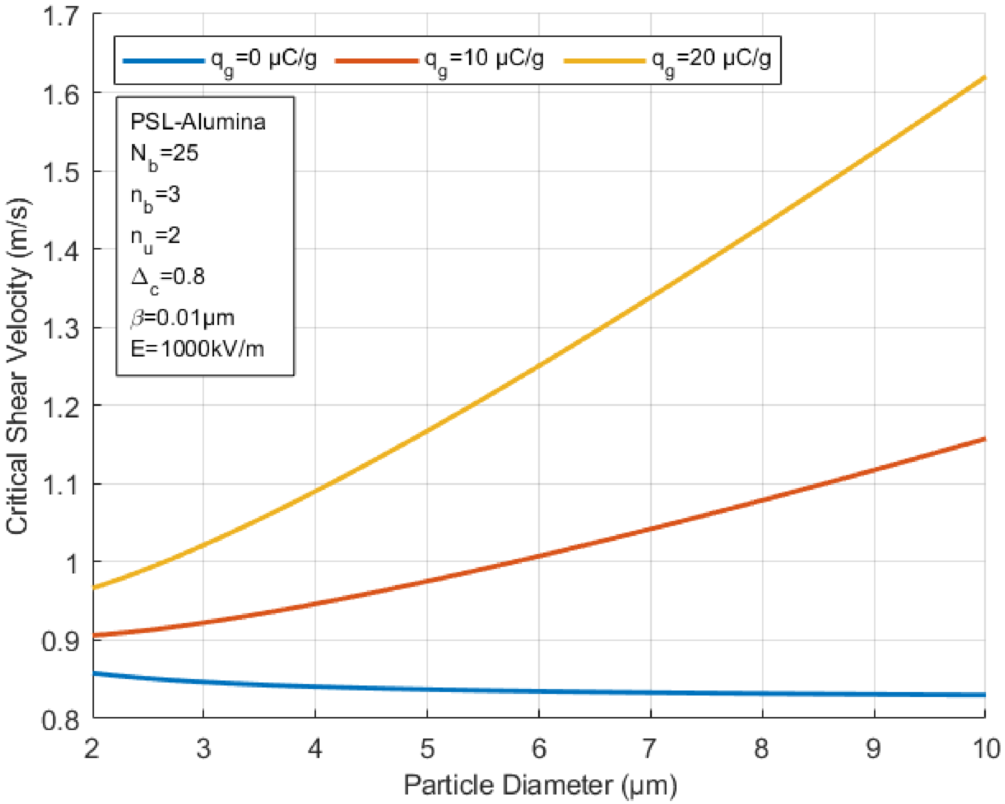
Results and Discussion

- Variation of critical shear velocity with particle diameter for different surface roughness



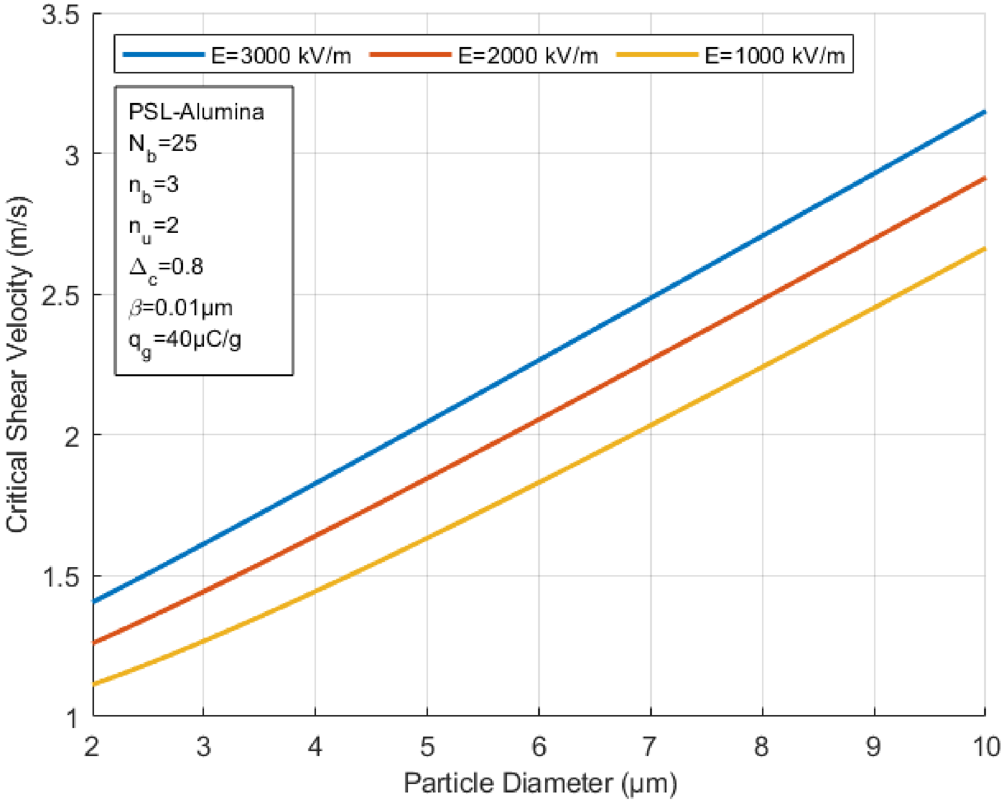
Results and Discussion

- Variation of critical shear velocity with particle diameter for different charges per unit mass



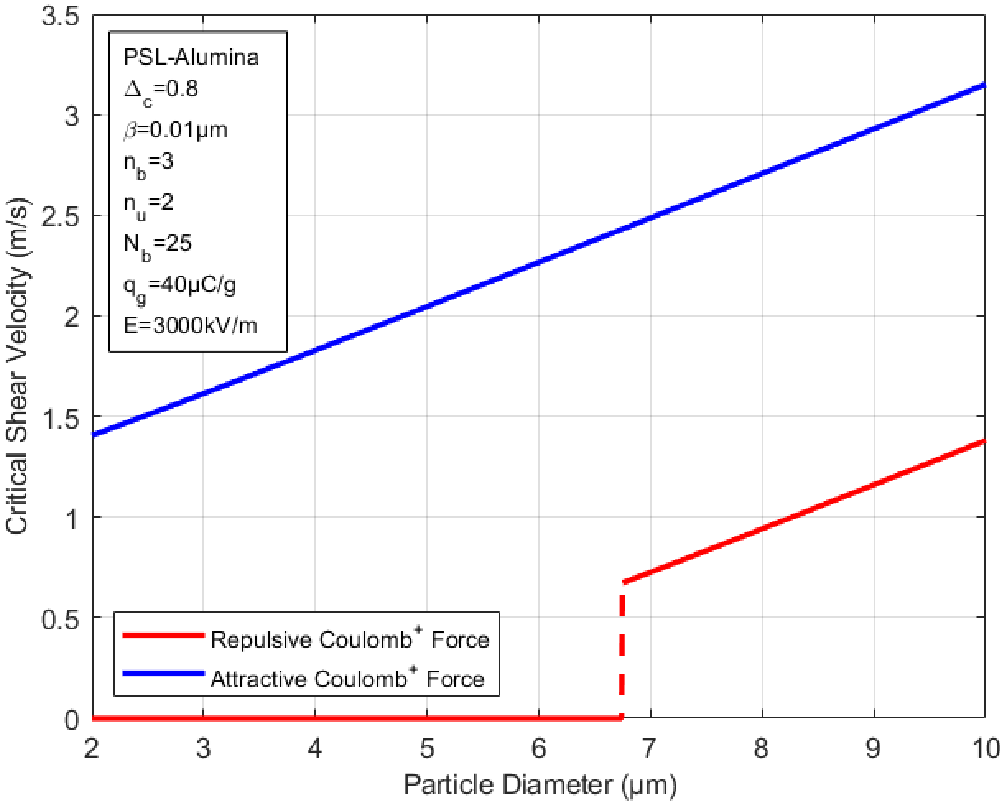
Results and Discussion

- Variation of critical shear velocity with particle diameter for different electric fields



Results and Discussion

- Variation of critical shear velocity with particle diameter for different directions of electric field



Conclusions

- Rolling is the main detachment mechanism for compact particles in turbulent airflows.
- A repulsive Coulomb^{+} force contributes to the detachment.
- 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.