Subtask C-2-3
Wafer Rinsing and Cleaning

Progress Report on Optimization of Spin Cleaning

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Presentation Outline

- Motivation
- Introduction to particle adhesion
  - Ideal systems
  - Real systems
- Particle removal – A review
- Simulation of particle removal
- Spin cleaning – Modeling
- Conclusions
- Future work

Motivation

- Particle contamination causes device failure and lower process yields
- To predict the conditions necessary for particle removal via hydrodynamics (spin cleaning), it is vital to estimate the adhesion force that holds a particle on a surface
- The rotating disc cleaner is used to remove particles from wafers
    - Undercutting and hydrodynamics contribute to removal
        - Particle removal studied under non-flow conditions (undercut)
        - Particle removal studied under flow conditions (hydrodynamics)
- Goal: model the removal and predict optimal conditions for the spin cleaning system and examine the applicability to systems of different chemistries and flow patterns

Particle Adhesion: Ideal Systems

DLVO Theory

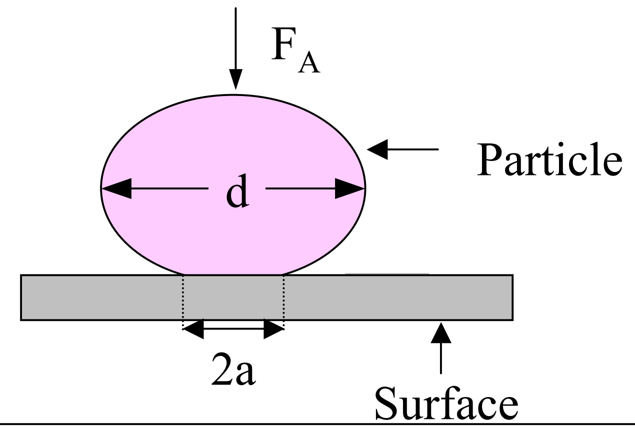
$$F_A = F_{vdW} + F_{EDL}$$

- F_A: Total Adhesion Force
- F_{vdW}: van der Waals Force
- F_{EDL}: Electrostatic Double Layer Force

$$F_{vdW} = \frac{A_{132} d}{12 h^2}\left(1 + \frac{2a^2}{hd}\right)$$

$$F_{EDL} = \frac{\varepsilon\varepsilon_0 d\left(\psi_p^2 + \psi_s^2\right)}{4} \cdot \frac{\kappa e^{-\kappa h}}{1 - e^{-2\kappa h}} \cdot \left[\frac{2\psi_p\psi_s}{\psi_p^2 + \psi_s^2} - e^{-\kappa h}\right]$$

The Clean 1 System



A = System Hamaker constant

d = Particle diameter

a = Contact radius

h = Particle-surface separation distance

ε = Medium dielectric constant

ζ = Zeta potential (*f(I,pH)*)

κ = Reciprocal double-layer thickness

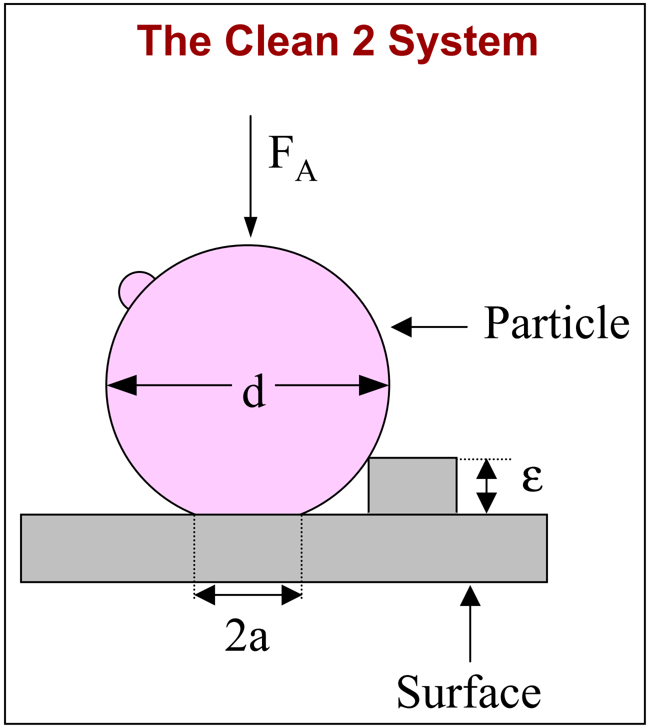
I = Medium ionic strength

Particle Adhesion: Real Systems

$$F_A = F_{vdW}(A, h, E, P, f_s, \varepsilon_s, \sigma_s, f_p, \varepsilon_p, \sigma_p, a, d)$$

Cooper et al. (2001)

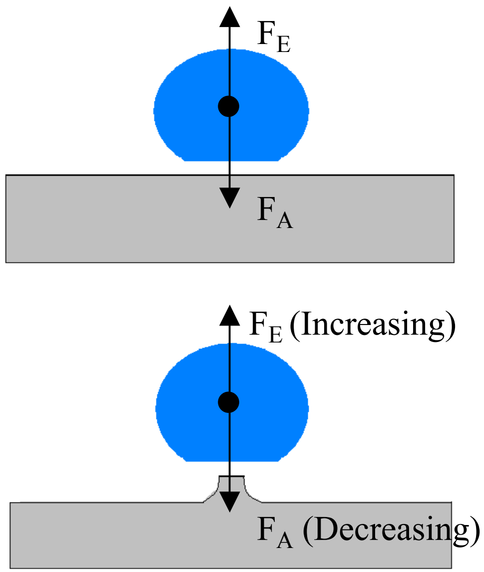
A = System Hamaker constant
h = Particle-surface separation distance
E = Elastic modulus
P = Applied load
f_s = Fraction of substrate covered by asperities
ε_s = Average asperity height on substrate
σ_s = Standard deviation in asperity height on substrate
f_p = Fraction of particle covered by asperities
ε_p = Average asperity height on particle
σ_p = Standard deviation in asperity height on particle
a = Contact radius
d = Particle diameter



Particle Removal: A Review

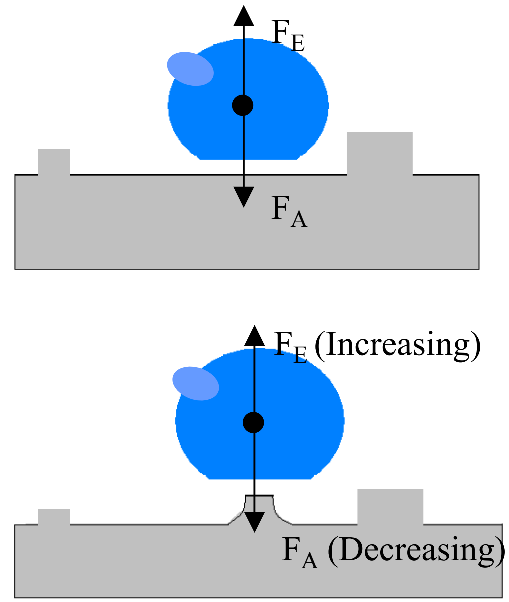
Particle removal can be modeled using various mechanisms

Undercut Cleaning (Clean 1)



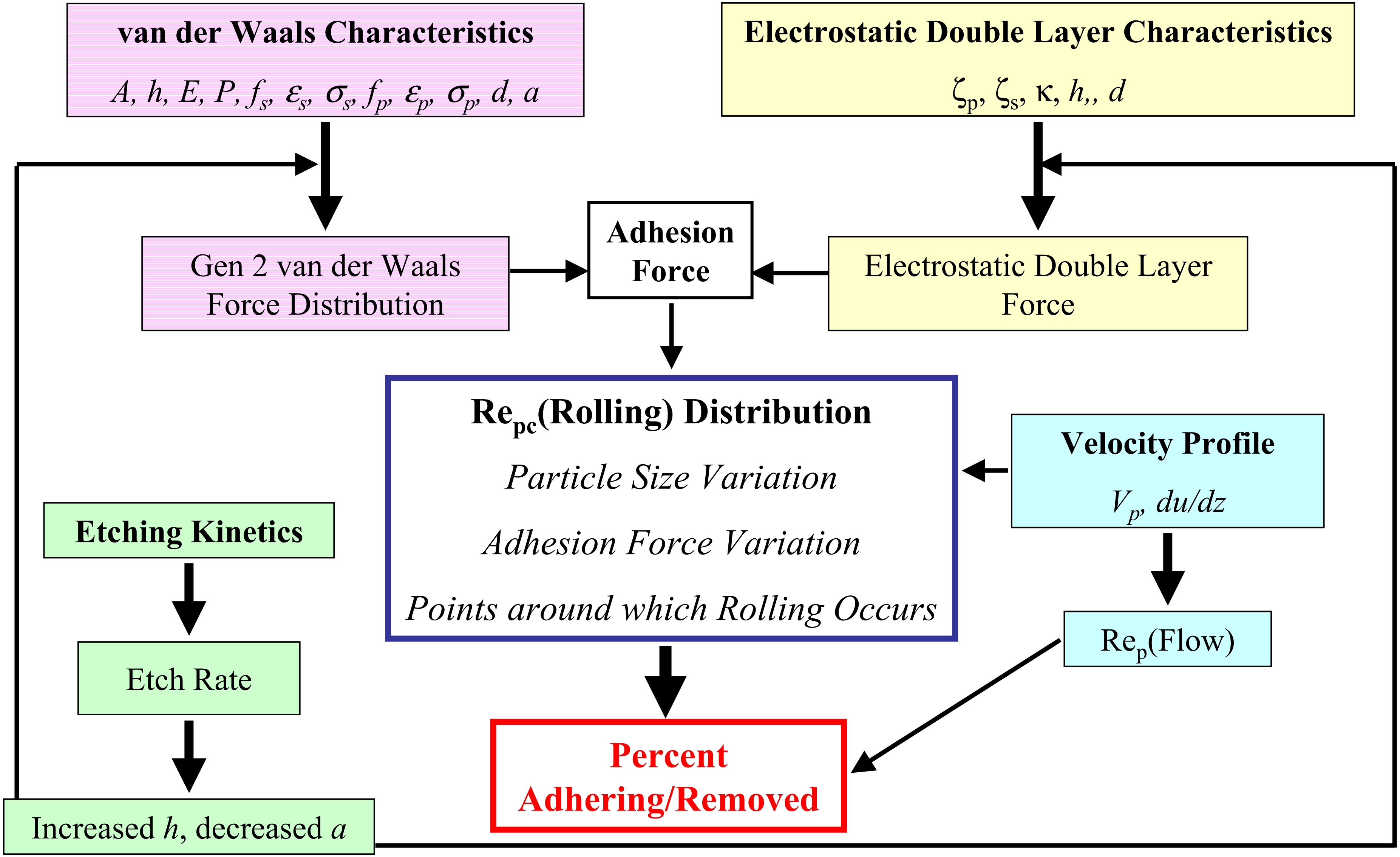
- The system consists of a smooth deforming particle on a smooth surface.
- Particle removal occurs solely due to undercutting (decreasing contact area).
- The forces acting on the particle are calculated using the DLVO theory.

Undercut Cleaning (Clean 2)

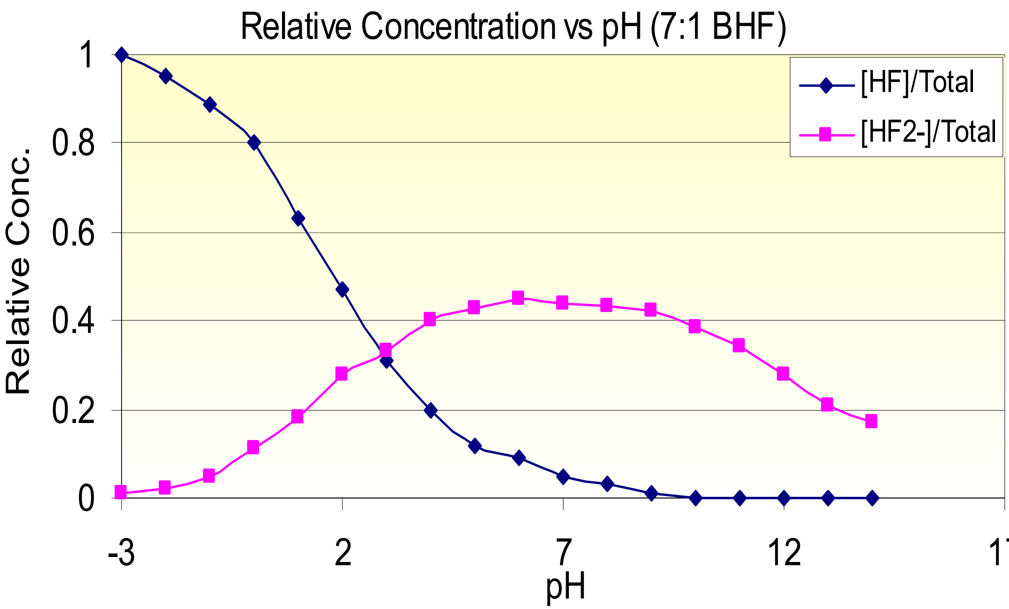


- The system consists of a rough particle on a rough surface.
- Particle removal occurs solely due to undercutting (decreasing contact area).
- The forces acting on the particle are calculated using the model by Cooper et al. (2001).

Analysis Procedure



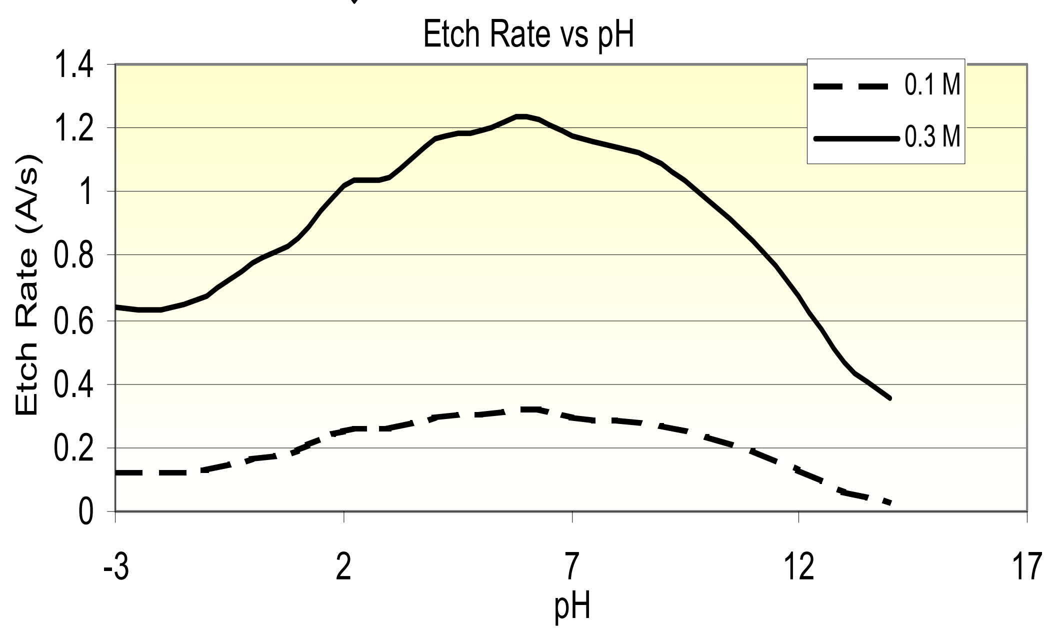
Etch Rate Calculation (7:1 BHF, 25^{o}C)



System Kinetics

$$K_1[HF] = [H^+][F^-]$$

$$K_2[HF_2^-] = [HF][F^-]$$



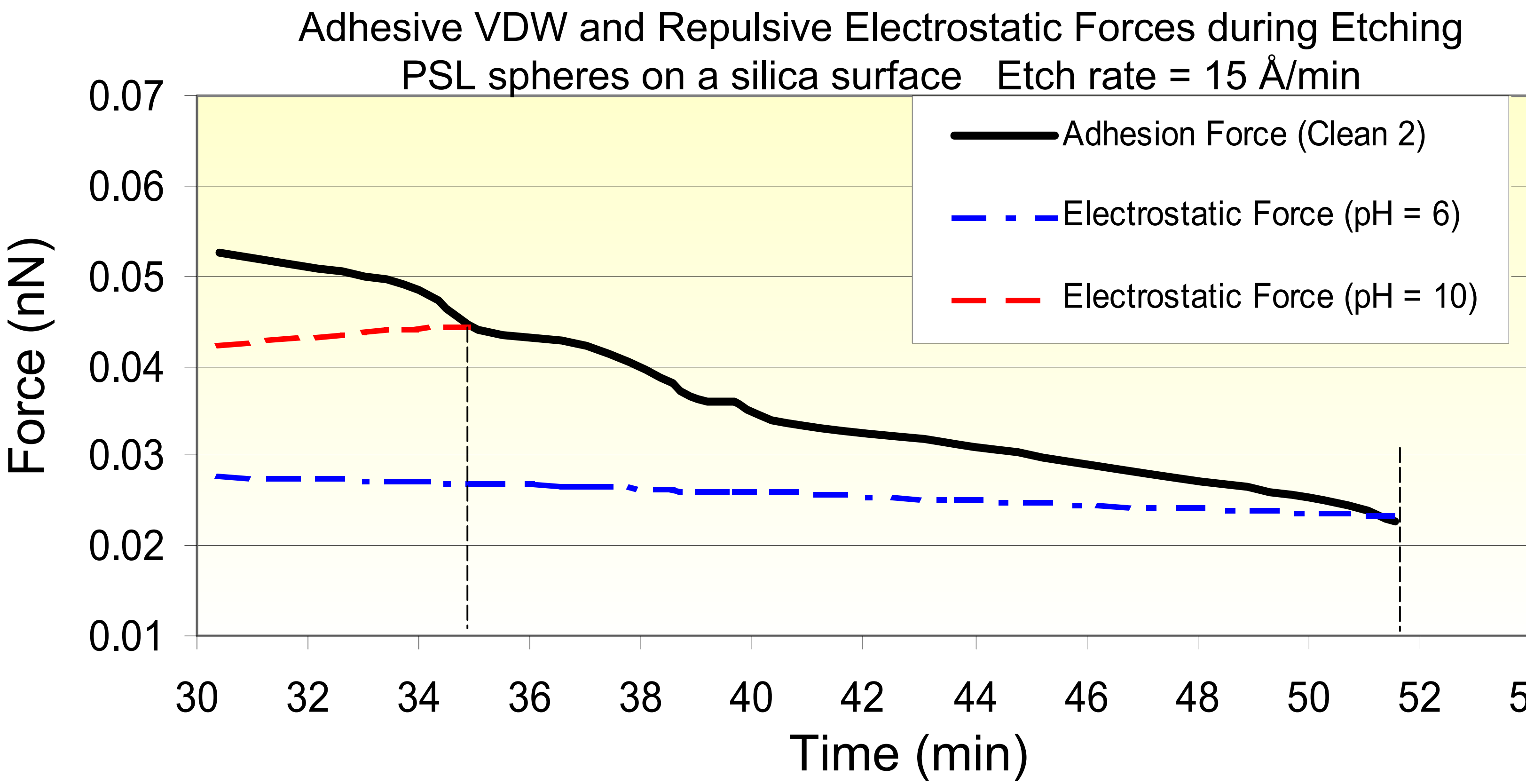
$$K_1 = 1.3 \times 10^{-3}$$

$$K_2 = 0.104$$

$$A = 2.5 \;\; B = 9.66 \;\; C = -0.14$$

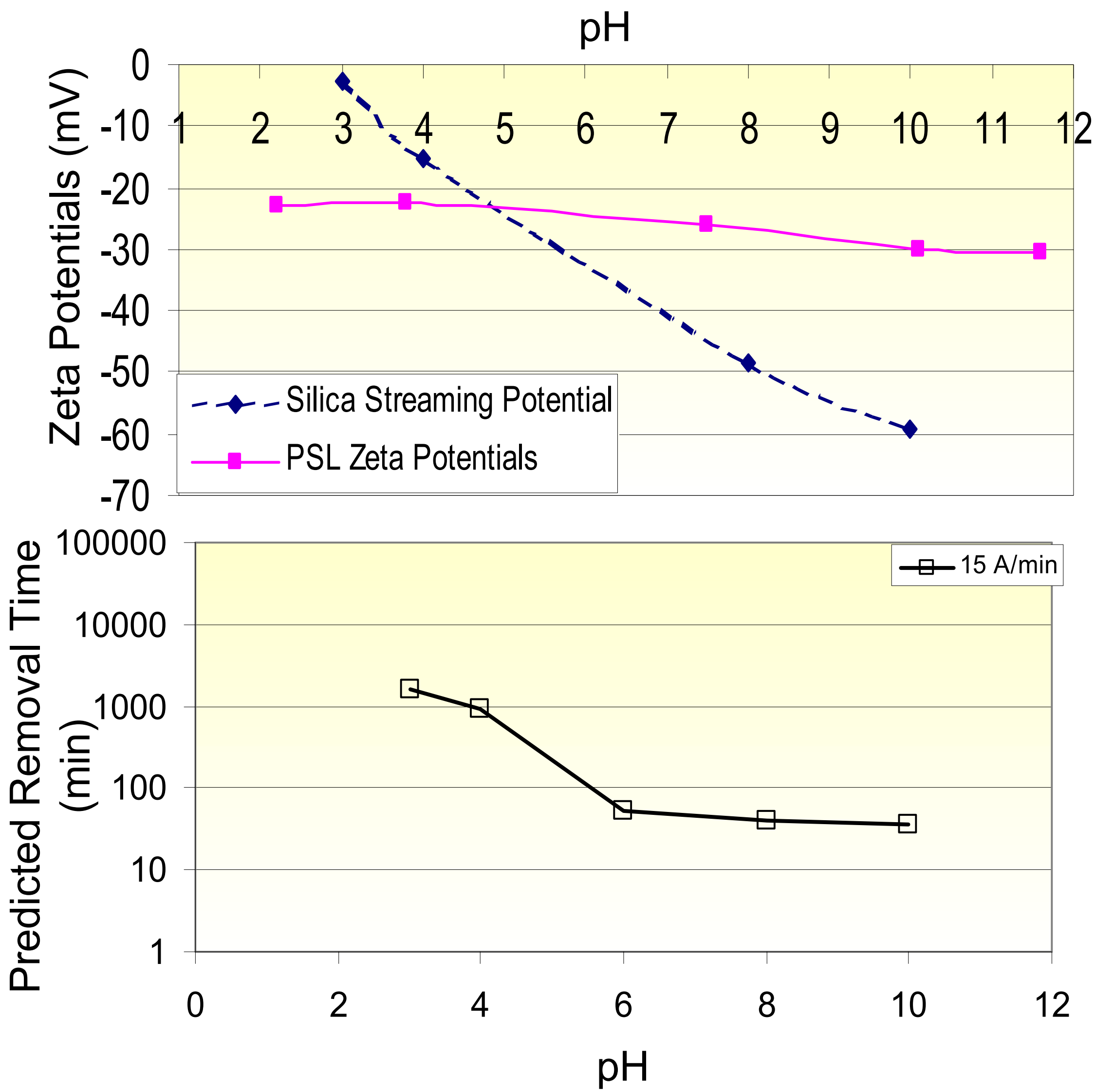
$$Etch\,Rate = A[HF] + B[HF_2^-] + C$$

Simulation Results: PSL Spheres on a Silica Surface Stagnant System



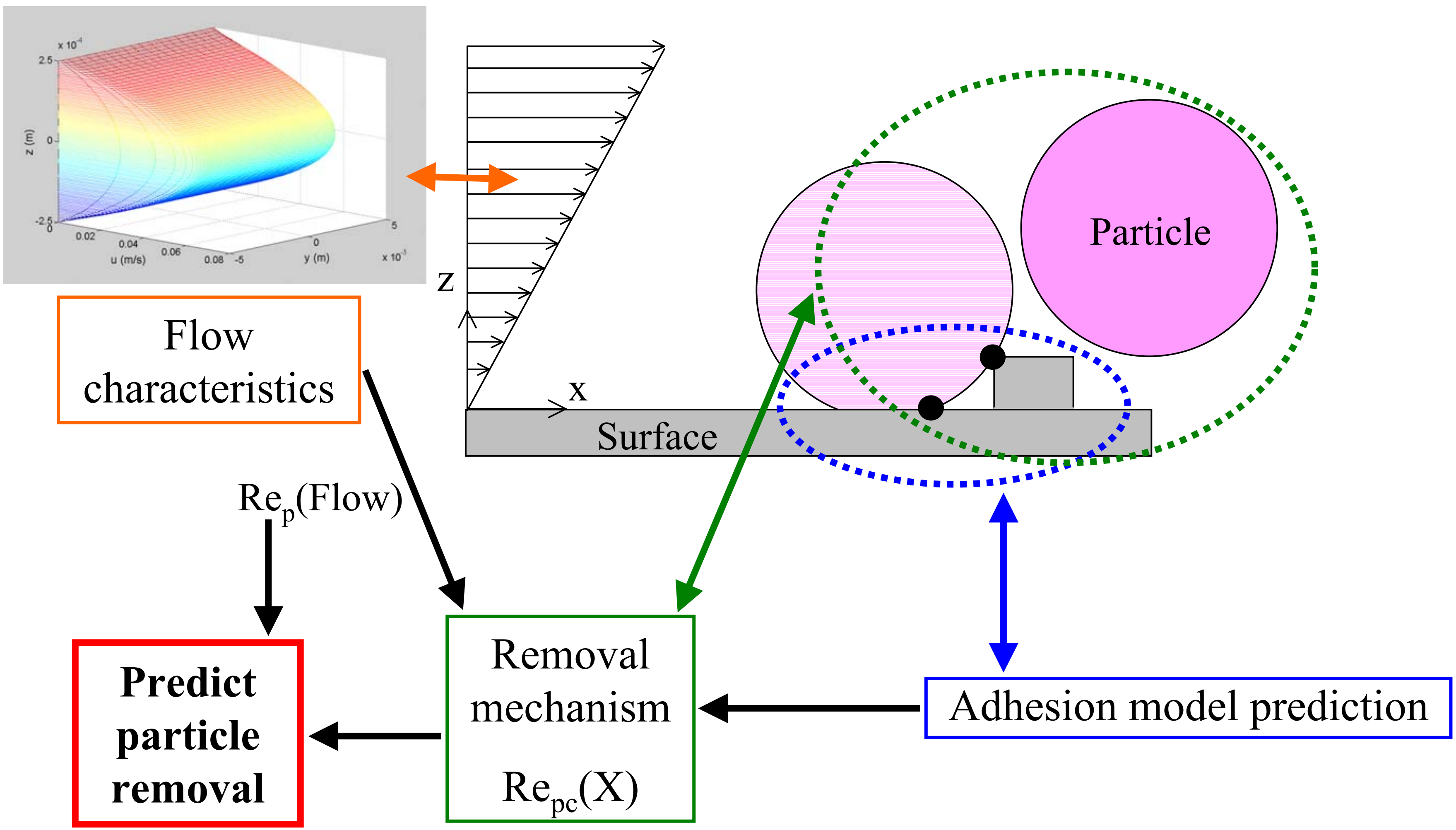
- The predicted adhesion force from the Clean 1 model is over an order of magnitude larger than that predicted by Clean 2
- The repulsive electrostatic force causes the removal of particles during undercutting and the magnitude of this force increases as the pH of the solution increases

Effect of Zeta Potentials on Removal time

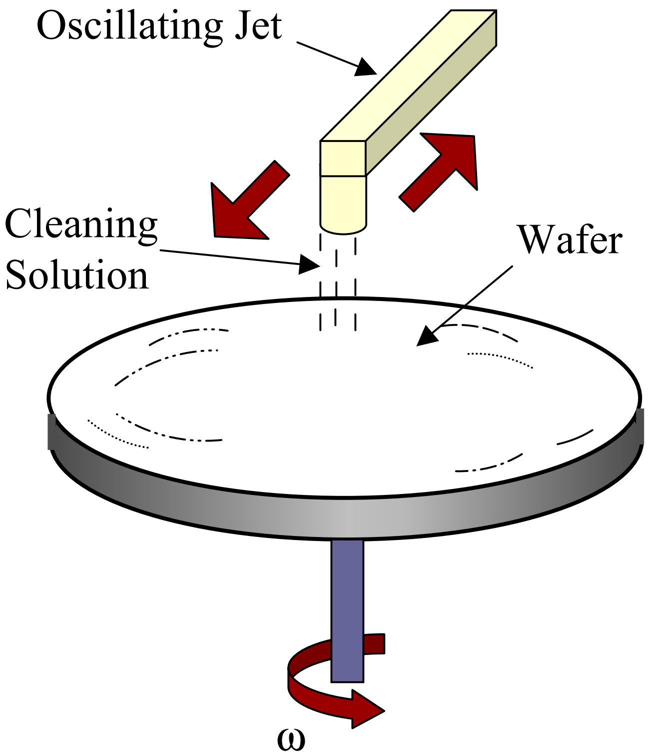


- Removal time for undercutting, is very large for low pH values and decreases rapidly as pH increases.
- Attributed to the fact that the PSL zeta potential and silica streaming potential are small at low pH values and rise as pH rises
- Predicted removal time is found to be 52, 39, and 35 min for pH values of 6, 8 and 10 respectively.

Hydrodynamic Removal Model



The Rotating Disc System



Rotating disc

- wafer rotating at a constant angular velocity
- jet impinging on the wafer surface
- jet causes hydrodynamic removal of particulate contaminants

Modeling the system

- Steady state
- Incompressible fluid
- Infinite rotating plane lamina
- Constant angular velocity
- Cylindrical co-ordinate system

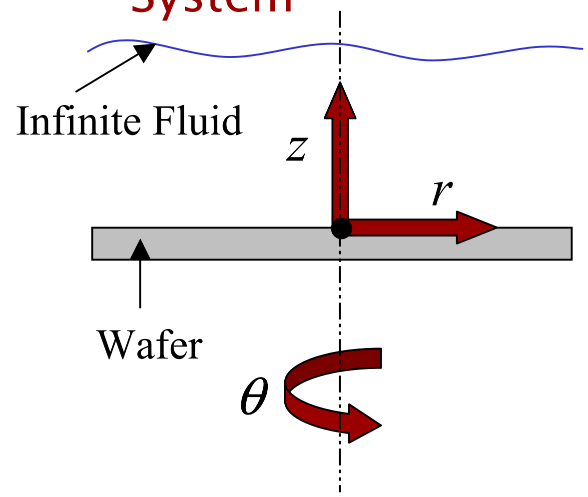
Solution: Transport Equations

Velocity Components

$$u = rf(z) \quad v = rg(z) \quad w = h(z) \quad p = p(z)$$

$$v_r \quad v_\theta \quad v_z \quad pressure$$

Co-ordinate System



System of Equations

(Derived from the equations of motion and continuity for a Newtonian fluid)

$$f^2 - g^2 + h\frac{df}{dz} = \upsilon\frac{d^2 f}{dz^2}$$

$$2fg + h\frac{dg}{dz} = \frac{d^2 g}{dz^2}$$

$$h\frac{dh}{dz} = -\frac{1}{\rho}\frac{dp}{dz} - 2\upsilon\frac{df}{dz}$$

$$2f + \frac{dh}{dz} = 0$$

Boundary Conditions

$$u = 0, v = \omega r, w = 0 \quad \text{at} \quad z = 0$$

$$u = 0, v = 0 \quad \text{at} \quad z = \infty$$

$$w = \textit{finite} \quad \text{at} \quad z = \infty$$

Cochran's* Solution

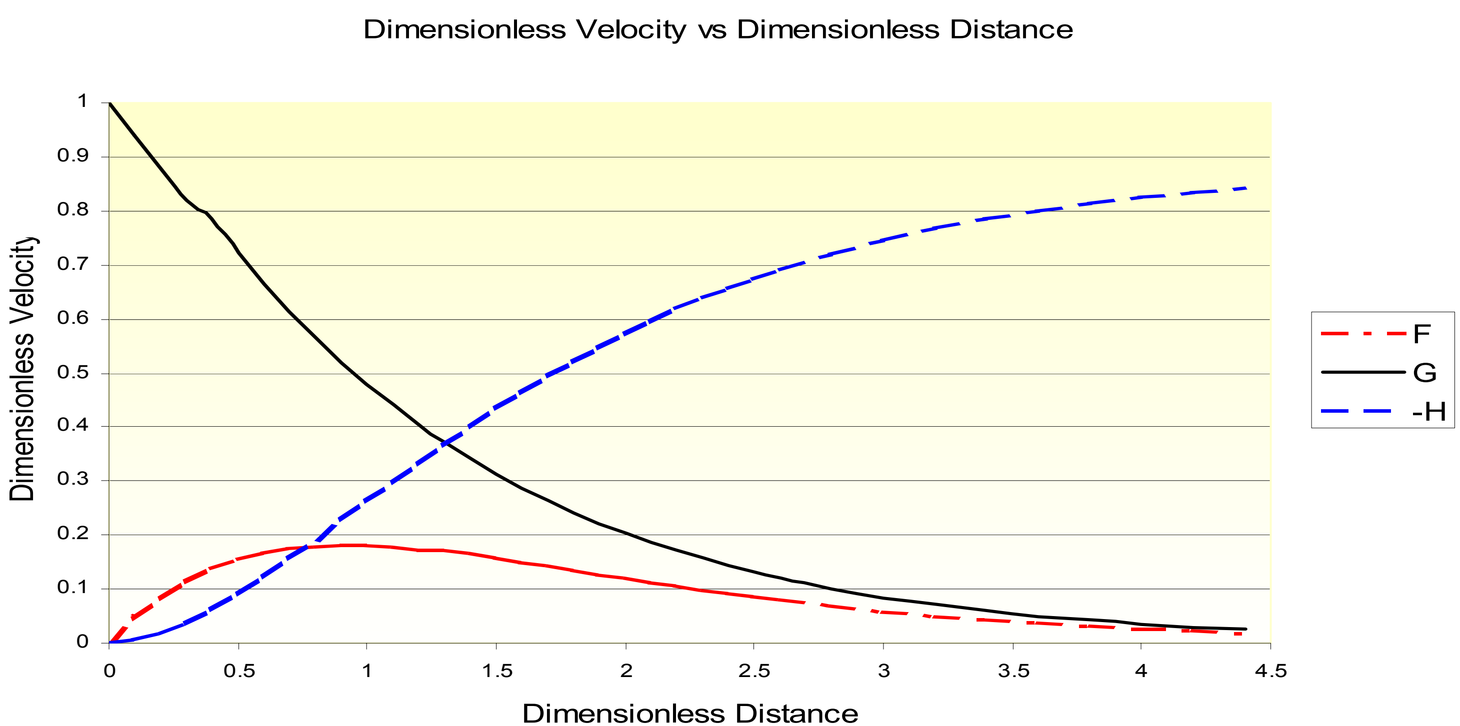
Dimensionless distance (ζ) = $(\upsilon/\omega)^{1/2}\zeta$

Dimensionless velocity components

$$f = \omega F$$

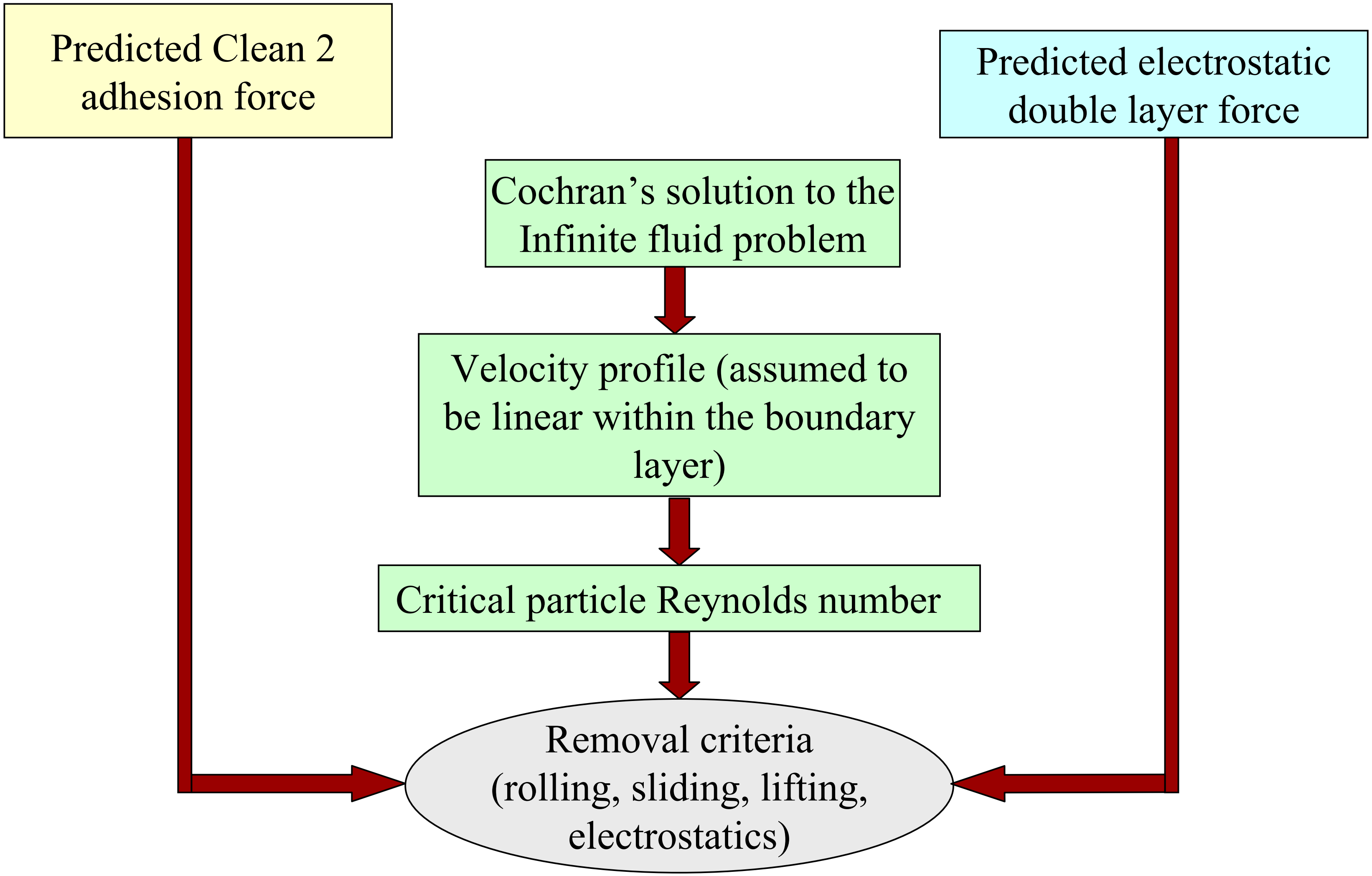
$$G = \omega G$$

$$h = (\upsilon\omega)^{\frac{1}{2}} H$$

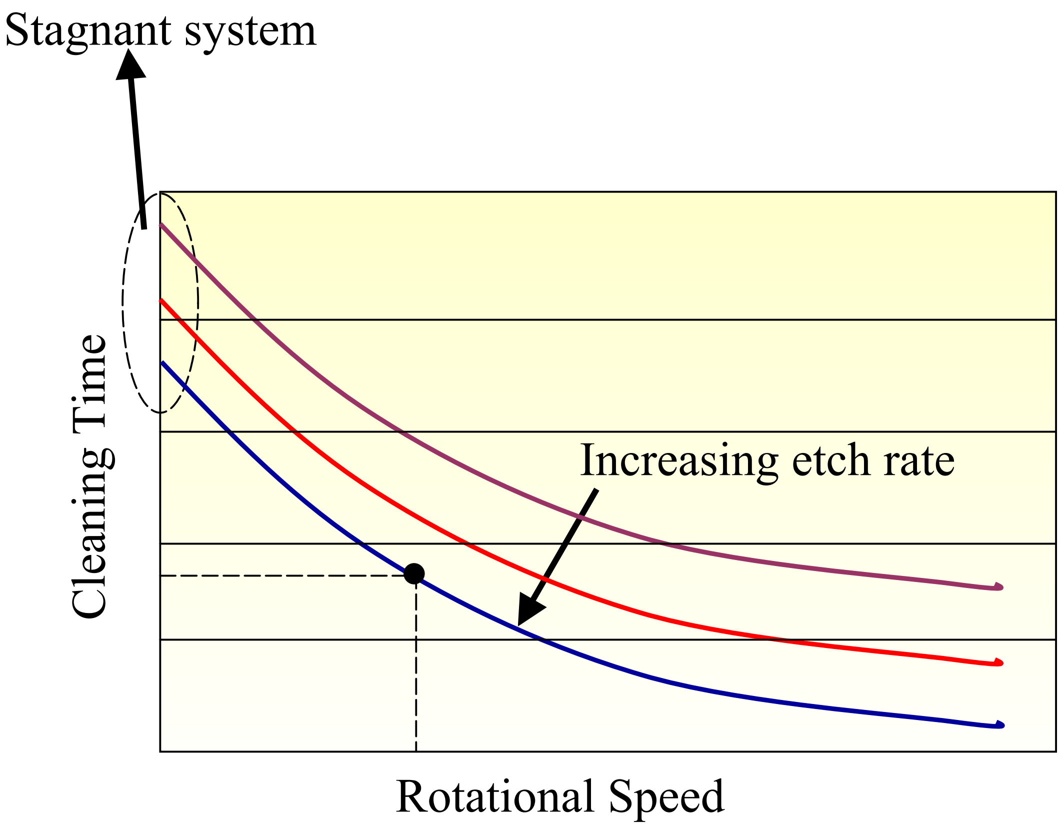


*Cochran, W.G. (1934), The flow due to a rotating disk, *Proc. Cambridge Philos. Soc.*, **30**(3), *365-75*

Removal Model (Spin Clean System)



Envisioned Outcome



- Modeling goal: Generalized approach to wafer cleaning
- Experimentally-validated models to predict cleaning conditions required for particle removal
- Model to be examined for varying chemistries and flow patterns

Cleaning curves functions of particle size and composition, wafer composition, solution composition

Summary/Conclusions

- Adhesion force is a function of the particle diameter, separation distance, contact area, particle roughness, and surface roughness
- The electrostatic force is a function of the composition of the etching solution, the particle-wafer separation distance and the zeta potentials of the particle and surface
- Particle removal is determined by balance of van der Waals attraction, electrostatic repulsion (etching), and fluid flow
- In the rotating disc system, all three velocity components need to be examined in order to predict the flow velocity at the wafer-solution interface

Future Work

- Combine hydrodynamic, electrostatic, and van der Waals force model to determine effects of fluid flow on particle removal during undercutting
- Determine the adhesion force of particles of interest (PSL, silica, Si_3N_4) using atomic force microscopy and compare the predicted adhesion force and the experimental adhesion force
- Predict particle removal conditions using the simulation above for different etching solutions used in the rotating disc system
- Validate model predictions

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