Particle removal in linear shear flow

Model prediction and experimental validation

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Structure of presentation

• Scope of the project

• Model on particle – flow interaction

• Experiments

• Validation

• Discussion

• Conclusion
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Scope of the project

- Contamination control
  - Prevention of the unwanted detachment of particles from wall surface due to gas flows in the system, e.g. in lithographic processing

- Surface cleaning
  - Cleaning (on purpose removal) of particles from a surface using a gas flow

- Relevant in High-End & Semiconductor industry
  - High throughput of gasses gives large velocities and increased risk of particle contamination
  - High requirements on cleanliness
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Particle motion in flow

What kind of motion to expect?
Particle motion – 4 possible types

At rest

Lift

Sliding

Rotation
Forces on a particle in linear (wall-) shear flow

Forces acting on the particle – Attraction

- Gravity

\[ F_G = mg = \rho Vg \]

- Van der Waals

\[ F_V = \frac{A_H d}{12 z_0^2} \left( 1 + \frac{2a^2}{z_0 d} \right) \]
Forces acting on the particle – Flow induced

- **Drag**

\[ F_D = \frac{1}{2} \rho U^2 \left[ 1.7009 \frac{2\eta}{Ud\rho} \right] \frac{\pi d^2}{4} = 1.7009 \cdot 3\pi \cdot \eta \cdot d \cdot (u_f - u_p) \]

- **Lift**

\[ F_L = 1.615 \cdot \eta \cdot d^2 \left( \frac{\rho}{\eta} \frac{\partial u}{\partial y} \right)^{1/2} (u_f - u_p) \]
Forces acting on the particle – Flow induced

• Drag

\[ F_D = \frac{1}{2} \rho U^2 \left[ 1.7009 \frac{24\eta}{Ud\rho} \right] \frac{\pi d^2}{4} = 1.7009 \cdot 3\pi \cdot \eta \cdot d \cdot (u_f - u_p) \]

• Lift

\[ F_L = 1.615 \cdot \eta \cdot d^2 \left( \frac{\rho}{\eta} \frac{\partial u}{\partial y} \right)^{1/2} (u_f - u_p) \]
Forces acting on the particle - Overview

For micron-sized particles $F_G \ll F_V$, so NOT depending on orientation of surface.

Glass particles in air flow at atmospheric pressure
Reynolds number analysis

- \[ \text{Re}_p = \frac{U_p d \rho}{\eta} \]

- \[ \text{Re}_{\text{lift}} = \frac{F_{\text{attraction}}}{1.615d} \frac{\rho}{\eta} \sqrt{\frac{\rho}{\eta}} \frac{\partial u}{\partial y} \eta^2 \]

- \[ \text{Re}_{\text{sliding}} = \frac{\mu_s F_{\text{attraction}}}{1.7009 \cdot 3\pi + \mu_s 1.615d} \frac{\rho}{\eta} \sqrt{\frac{\rho}{\eta}} \frac{\partial u}{\partial y} \eta^2 \]

- \[ \text{Re}_{\text{rotation}} = \frac{F_{\text{attraction}} \cdot L_2}{0.94399 \cdot 2\pi d + 1.7009 \cdot 3\pi L_1 + 1.615d} \frac{\rho}{\eta} \sqrt{\frac{\rho}{\eta}} \frac{\partial u}{\partial y} L_2 \eta^2 \]
Reynolds number analysis (1)

Glass particles in air flow at atmospheric pressure

Diameter [m]

Reynolds [-]

Rest Rotation Lift

Particle
Lift
Sliding
Rotation

100 micron
80 micron
1.6 micron
Reynolds number analysis (2)

Hard materials, Steel and Glass behave similar
The soft PSL has a much larger critical diameter at the same shear rate

Different materials, rotational motion only
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Experimental validation – Set-up

- Flow-cell with 10 mm slit-height
- Turbulent flow conditions
  \((\text{Re} > 10^4)\)
- Shear rates at the lower surface ranging from \(7\cdot10^4 \text{ s}^{-1}\) to \(2\cdot10^6 \text{ s}^{-1}\)
- Linear velocity gradient in wall region (for \(z<0.1 \text{ mm}\))
Removal efficiency for different shear rates

![Graph showing removal efficiency for different shear rates. The graph plots residual percentage against diameter (micron) for various shear rates. The graph includes multiple curves representing different shear rates, with markers indicating specific diameters such as $d_{50}$ and $d_{30}$.](image-url)
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### Critical diameters for particle motion

<table>
<thead>
<tr>
<th>Gradient [1/s]</th>
<th>$d_{lift}$ [µm]</th>
<th>$d_{rot}$ [µm]</th>
<th>$d_{50}$ [µm]</th>
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<tr>
<td>$1.93 \cdot 10^6$</td>
<td>101</td>
<td>1.7</td>
<td>4.1</td>
</tr>
</tbody>
</table>
Several micron under prediction

![Graph showing particle removal in linear shear flow]

- **Shear rate [1/s]**
- **Diameter [micron]**

**Experiment**

**Model**
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Discussion

- Rotation diameter is a good estimator for the critical particle release diameter

- Not included in the model
  - Electrostatic interaction
  - Capillary effects
  - Non-spherical particles
  - Surface roughness

- Implementation of these effects will improve accuracy
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Conclusions

• Particle rotation responsible for initial motion and removal

• Model based on Van der Waals interaction and drag force predicts the experimentally obtained value within several micron

• The distribution in diameters of removed particles is wide, which is not implemented in the model. The model indicates the average diameter for which 50% of the particles is removed

• When including other effects in the model (e.g. electrostatic and capillary interaction, particle and surface shapes), the accuracy of the predictions will improve