

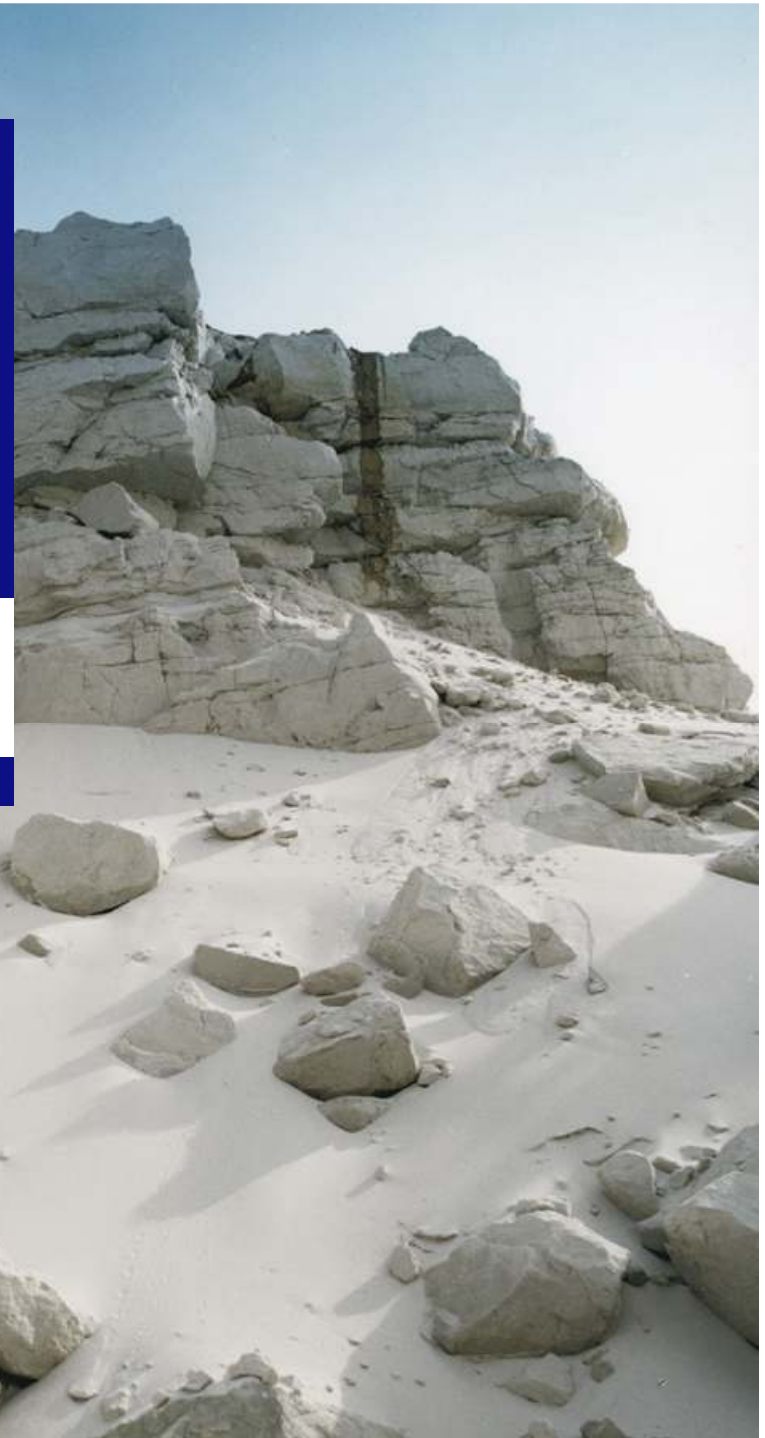
# Particle removal in linear shear flow

Model prediction and experimental validation

TNO | Knowledge for business



**Marco Zoeteweyj**  
Jacques van der Donck  
Richard Versluis



# Structure of presentation

- Scope of the project
- Model on particle – flow interaction
- Experiments
- Validation
- Discussion
- Conclusion





# 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

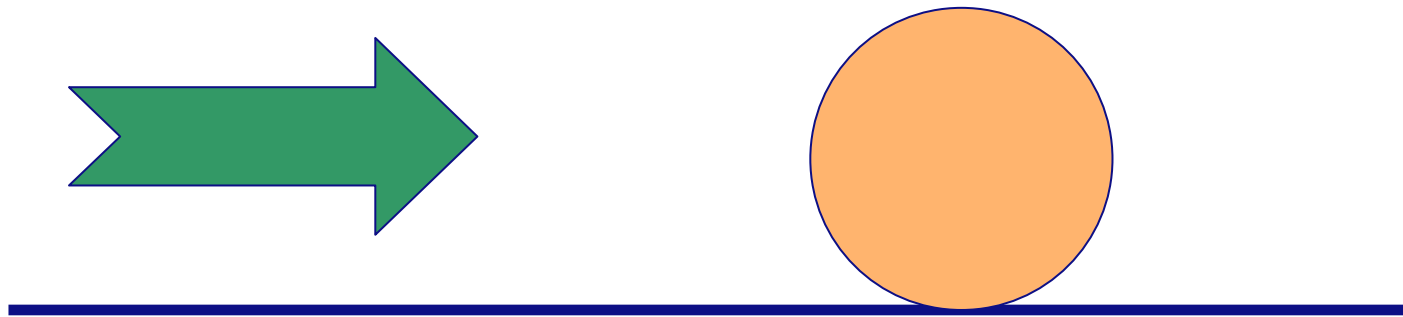


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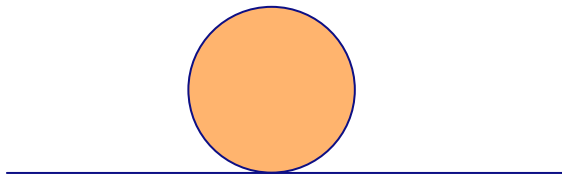
# Particle motion in flow



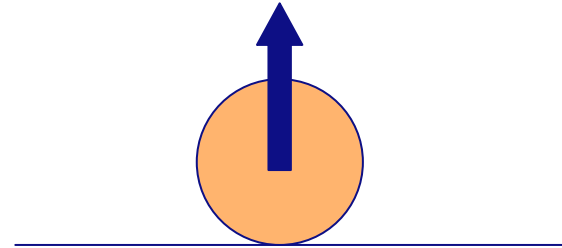
What kind of motion to expect ?

# Particle motion – 4 possible types

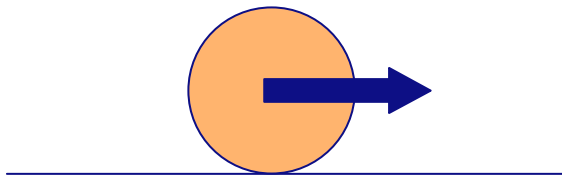
At rest



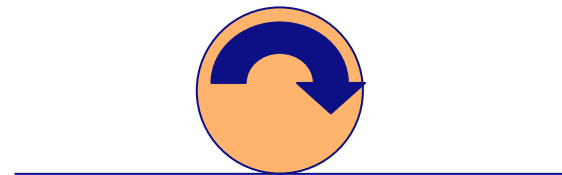
Lift



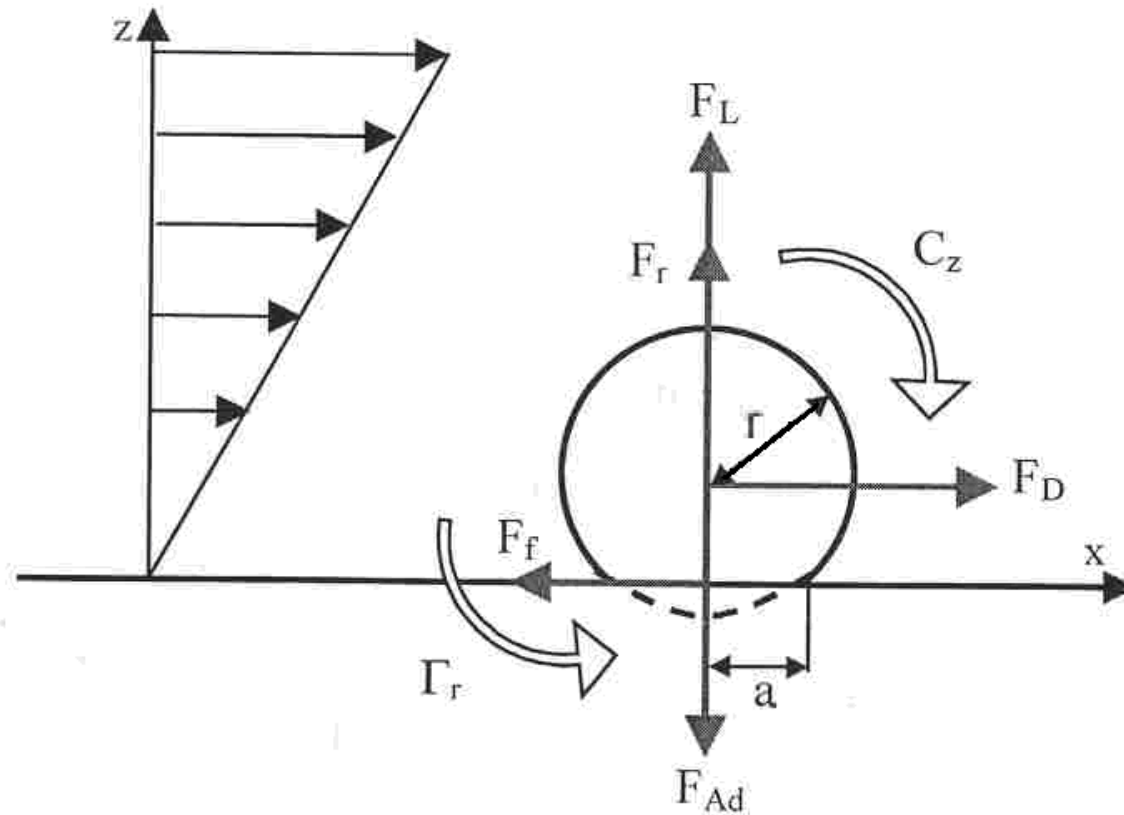
Sliding



Rotation



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



P. Schmitz, J. Cardot (2002)

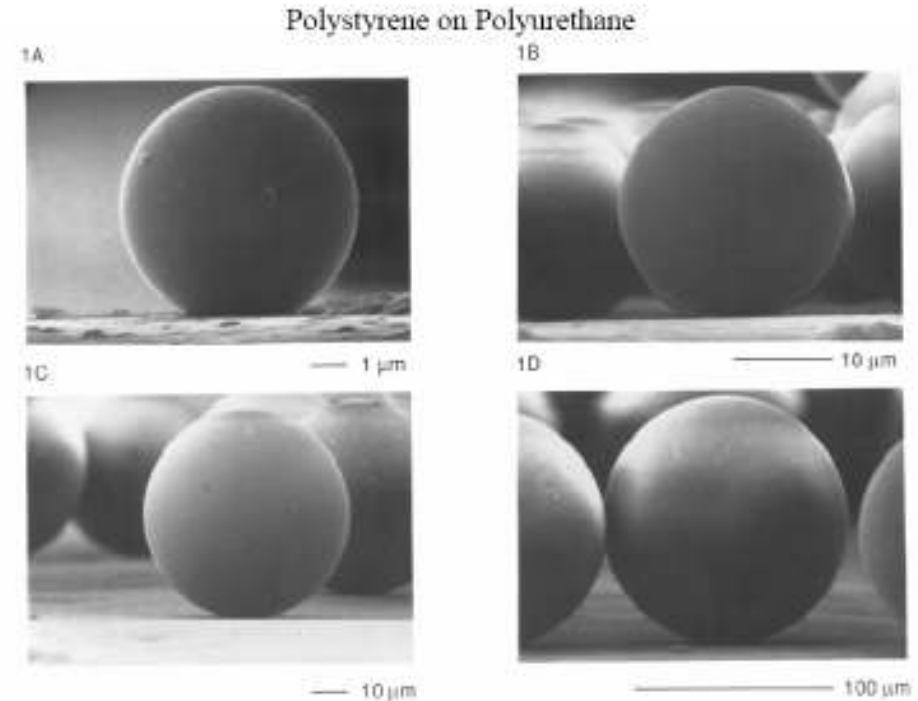
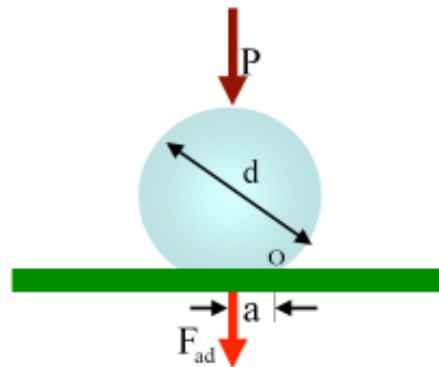
# Forces acting on the particle – Attraction

- Gravity

$$F_G = mg = \rho Vg$$

- Van der Waals

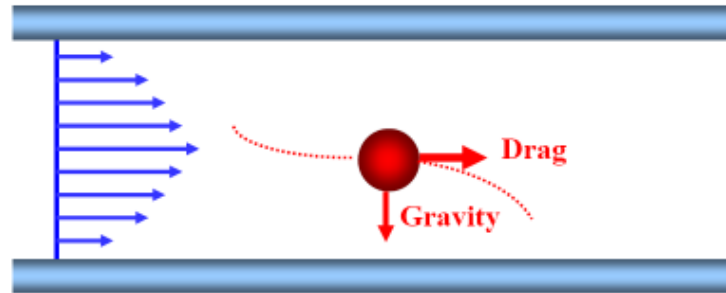
$$F_V = \frac{A_H d}{12z_0^2} \left( 1 + \frac{2a^2}{z_0 d} \right)$$



G. Ahmadi

# Forces acting on the particle – Flow induced

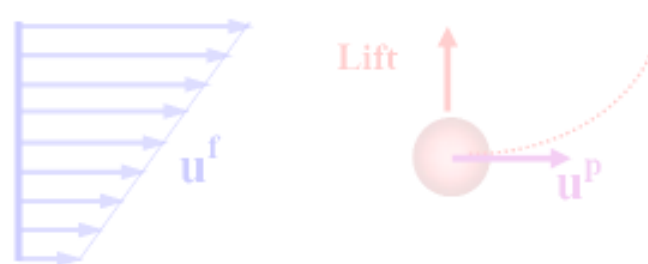
- Drag



G. Ahmadi

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

- Lift

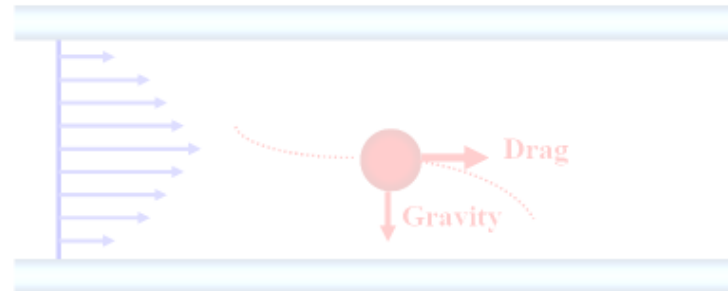


G. Ahmadi

$$F_L = 1.615 \cdot \eta \cdot d^2 \left( \frac{\rho}{\eta} \frac{\partial u}{\partial y} \right)^{1/2} (u_f - u_p)$$

# Forces acting on the particle – Flow induced

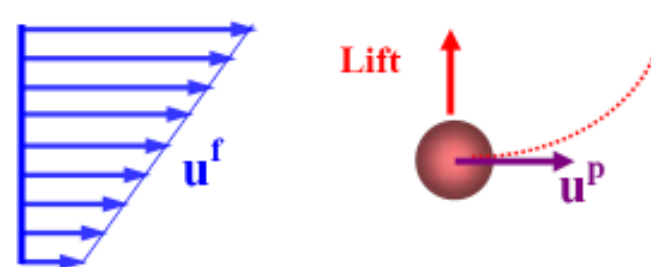
- Drag



G. Ahmadi

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

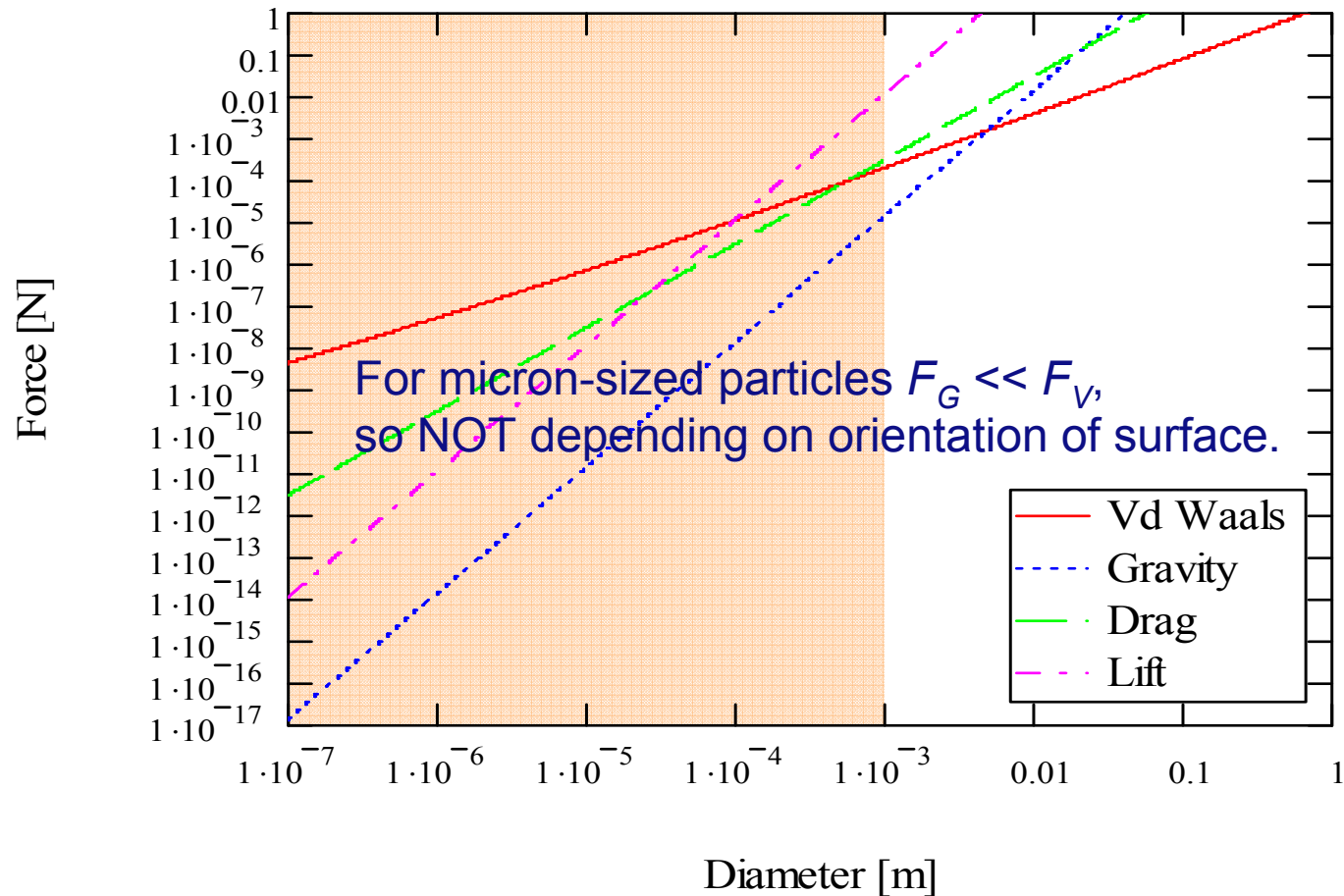
- Lift



G. Ahmadi

$$F_L = 1.615 \cdot \eta \cdot d^2 \left( \frac{\rho}{\eta} \frac{\partial u}{\partial y} \right)^{1/2} (u_f - u_p)$$

# Forces acting on the particle - Overview



## Glass particles in air flow at atmospheric pressure

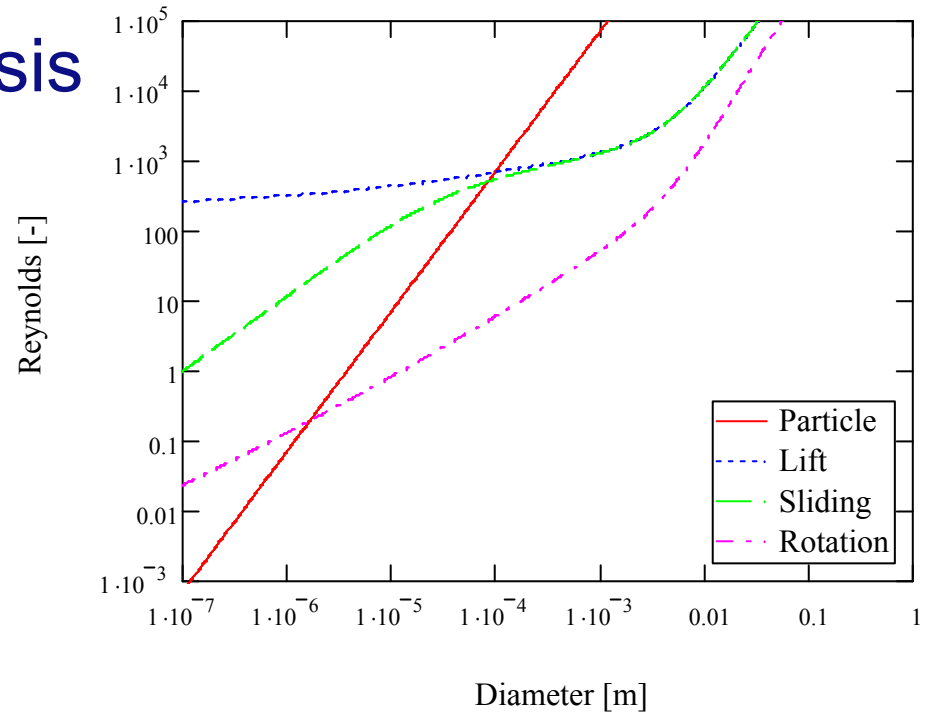
# Reynolds number analysis

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

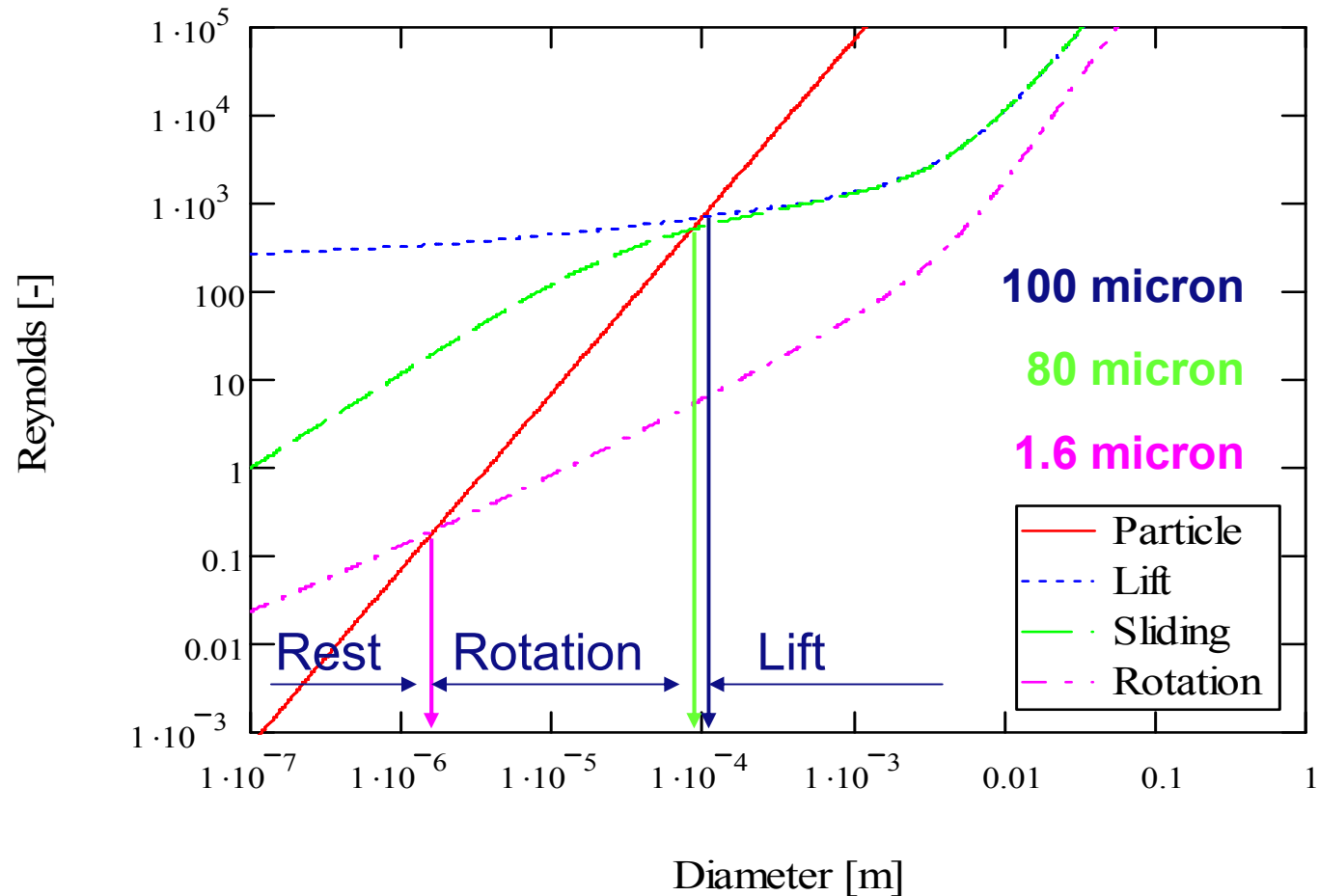
- $$\text{Re}_{lift} = \frac{F_{attraction}}{1.615d \sqrt{\frac{\rho}{\eta}} \sqrt{\frac{\partial u}{\partial y}}} \frac{\rho}{\eta^2}$$

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

- $$\text{Re}_{rotation} = \frac{F_{attraction} \cdot L_2}{0.94399 \cdot 2\pi d + 1.7009 \cdot 3\pi L_1 + 1.615d \sqrt{\frac{\rho}{\eta}} \sqrt{\frac{\partial u}{\partial y}} L_2} \frac{\rho}{\eta^2}$$

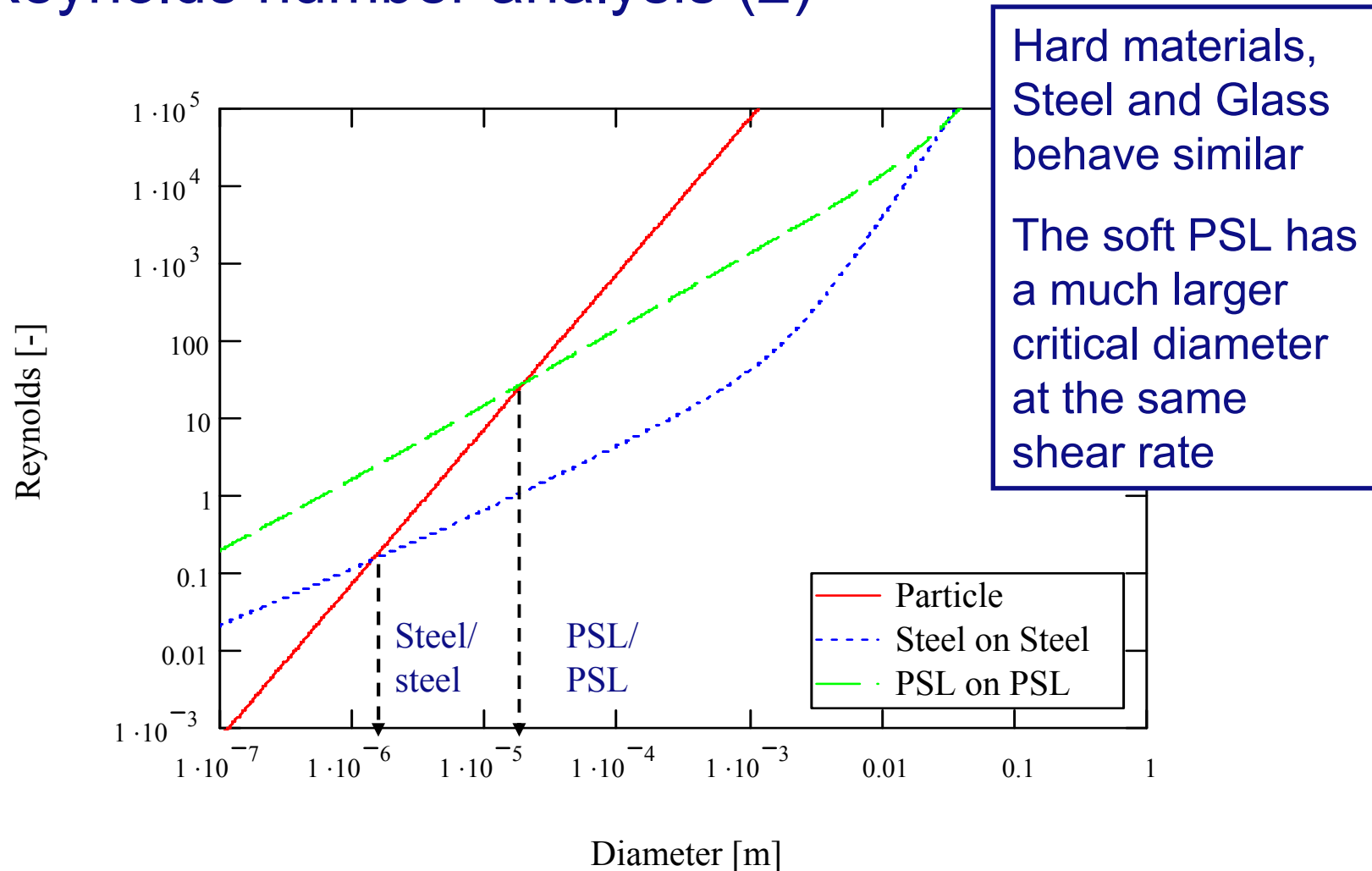


# Reynolds number analysis (1)



## Glass particles in air flow at atmospheric pressure

## Reynolds number analysis (2)



Different materials, rotational motion only

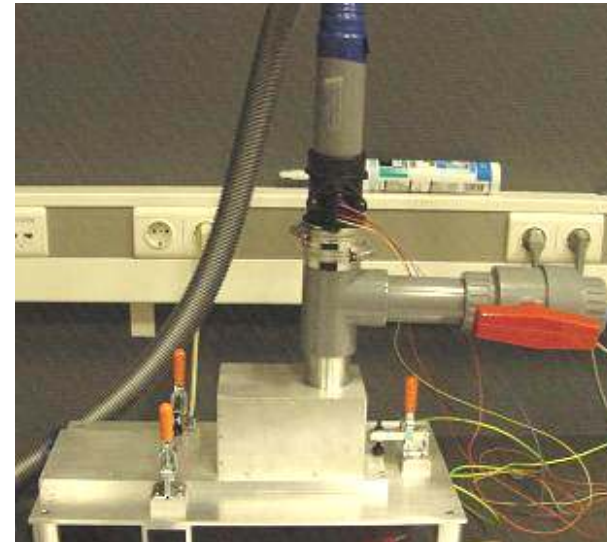
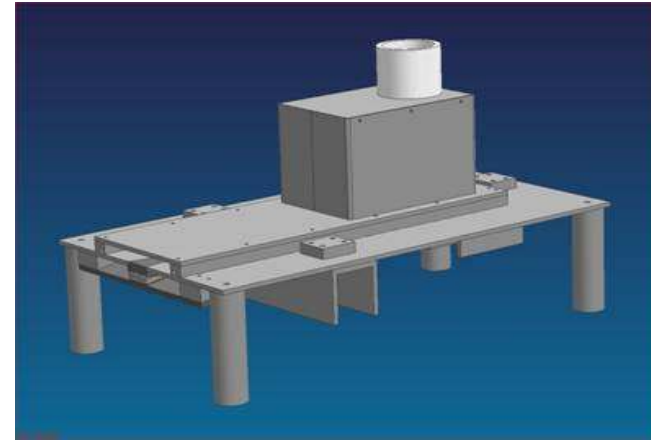
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- **Experiments**
- Validation
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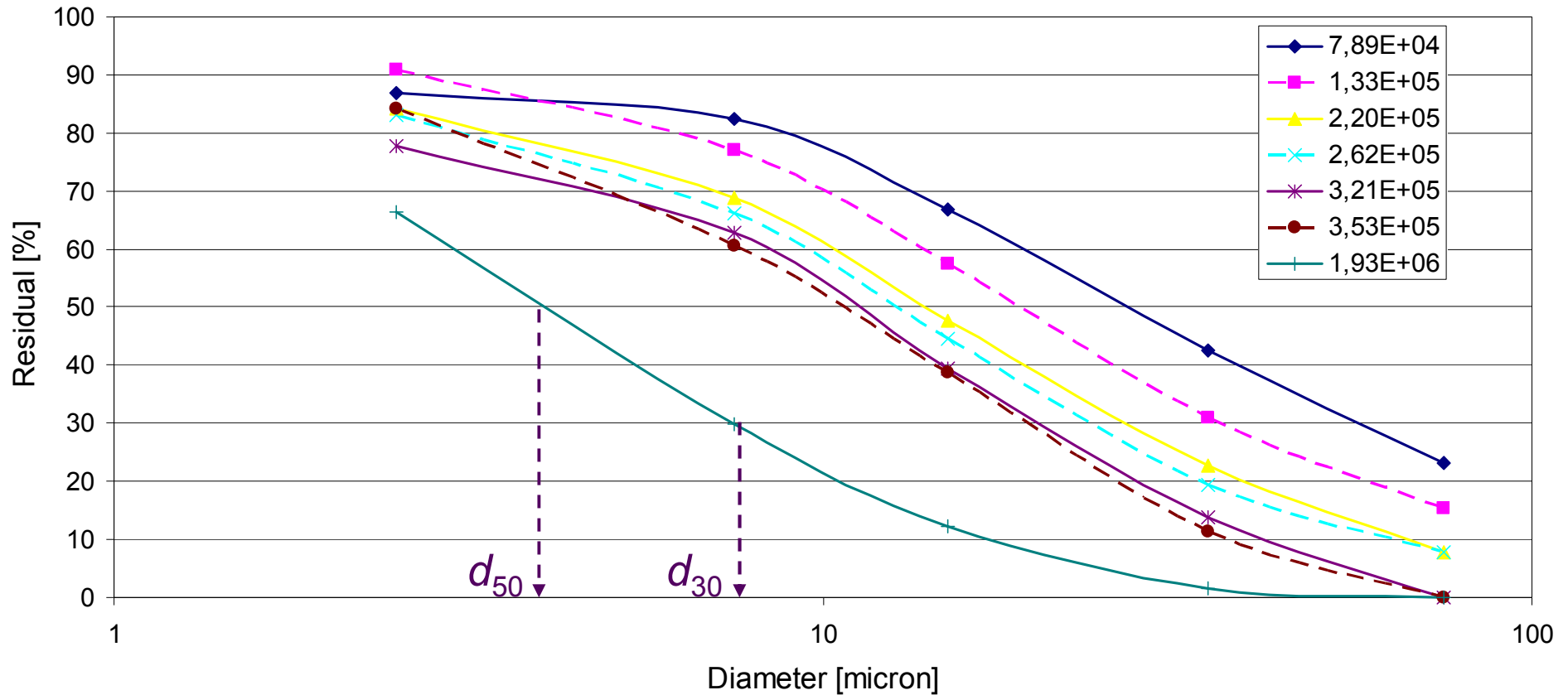


# Experimental validation – Set-up

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



# Removal efficiency for different shear rates



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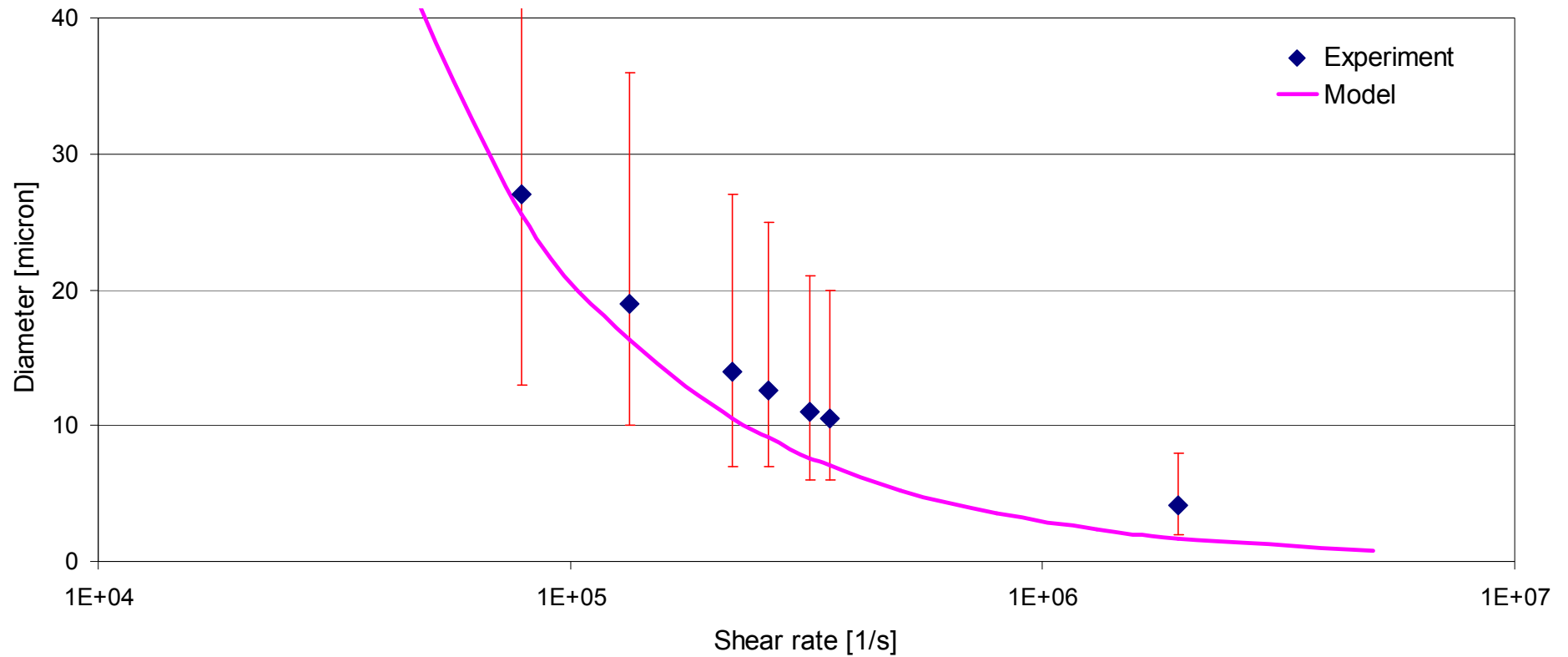


# Critical diameters for particle motion

Gradient [1/s]	$d_{lift}$ [ $\mu\text{m}$ ]	$d_{rot}$ [ $\mu\text{m}$ ]	$d_{50}$ [ $\mu\text{m}$ ]
$7.89 \cdot 10^4$	1740	25.6	27.0
$1.33 \cdot 10^5$	1047	16.3	18.7
$2.20 \cdot 10^5$	661	10.5	14.0
$2.62 \cdot 10^5$	566	9.1	12.6
$3.21 \cdot 10^5$	473	7.6	11.0
$3.53 \cdot 10^5$	436	7.0	10.5
$1.93 \cdot 10^6$	101	1.7	4.1



# Several micron under prediction



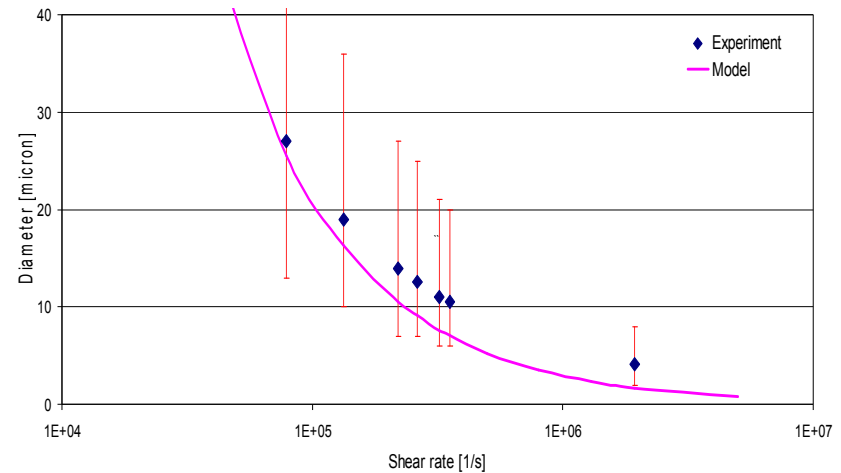
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# Discussion

- Rotation diameter is a good estimator for the for the critical particle release diameter
- Not included in the model
  - Electro static 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

