Particle removal in linear shear flow

Model prediction and experimental validation

TNO | Knowledge for business

Marco Zoeteweij
Jacques van der Donck
Richard Versluis

Structure of presentation

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

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

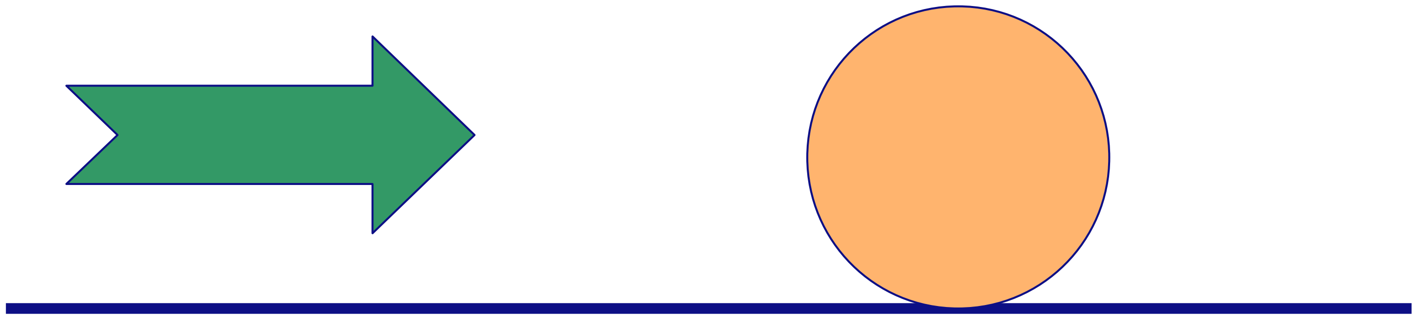
- Surface cleaning
  - Cleaning (on purpose removal) of particles from a surface using a gas flow

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

Structure of presentation

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

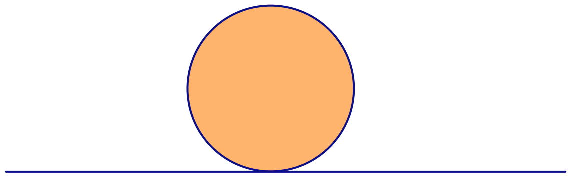
Particle motion in flow



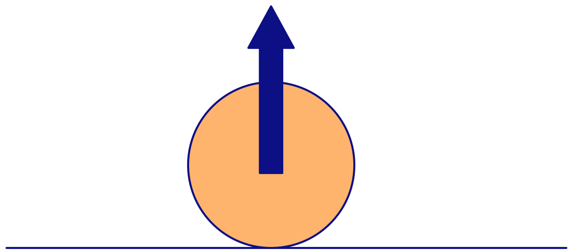
What kind of motion to expect ?

Particle motion – 4 possible types

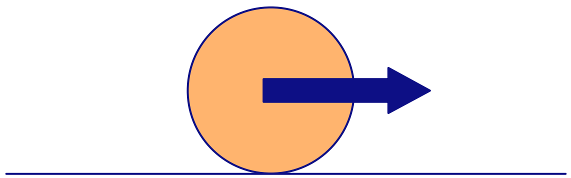
At rest



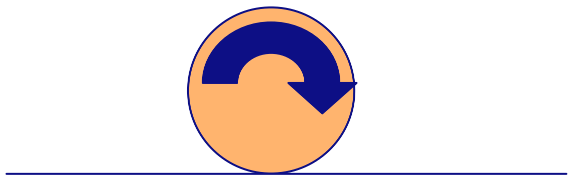
Lift



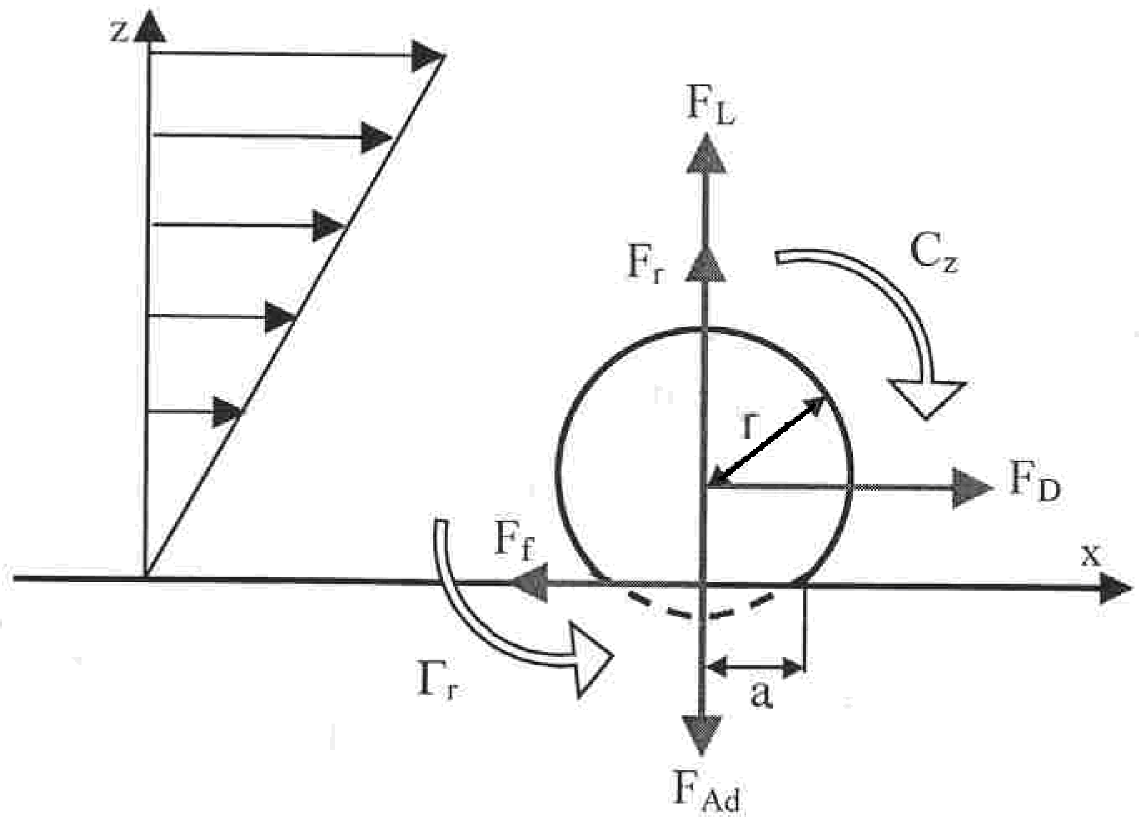
Sliding



Rotation



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



P. Schmitz, J. Cardot (2002)

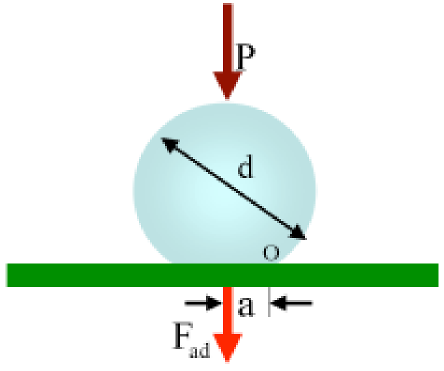
Forces acting on the particle – Attraction

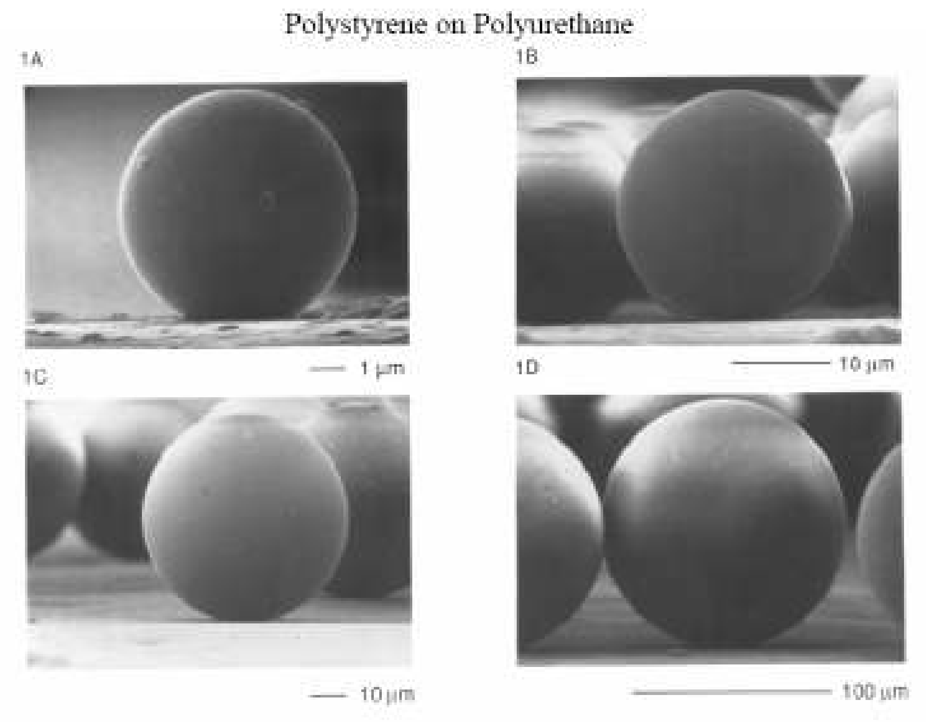
- Gravity

$$F_G = mg = \rho V g$$

- Van der Waals

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

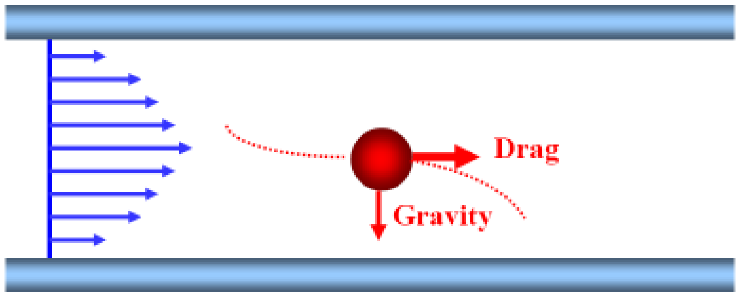




G. Ahmadi

Forces acting on the particle – Flow induced

- Drag



G. Ahmadi

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

- Lift

G. Ahmadi

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

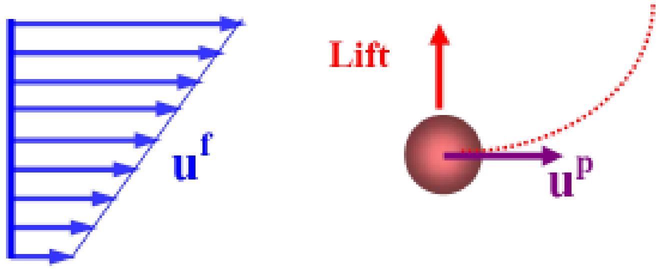
Forces acting on the particle – Flow induced

- Drag

G. Ahmadi

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

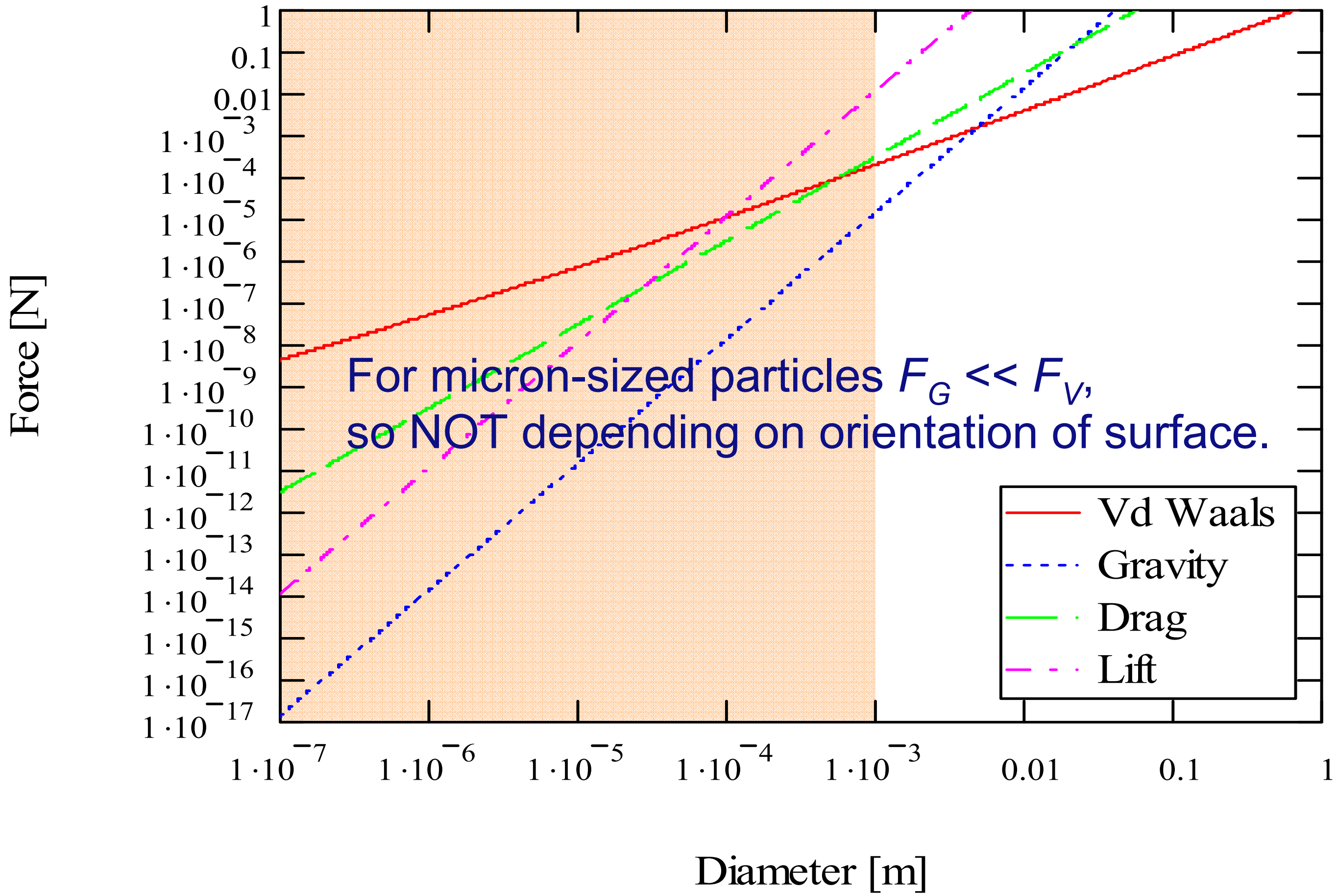
- Lift



G. Ahmadi

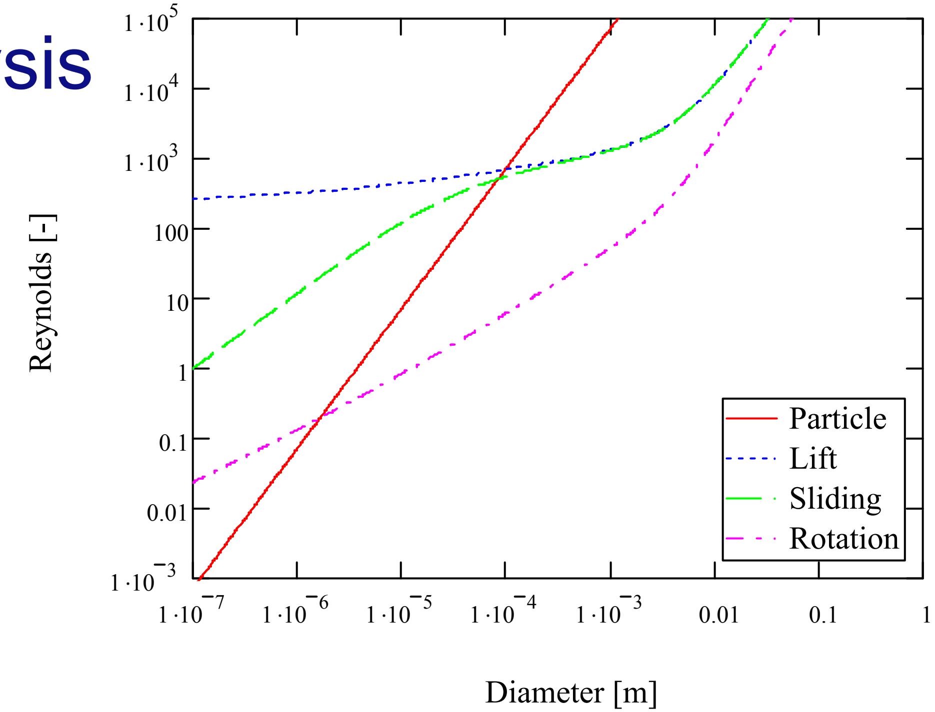
$$F_L = 1.615\cdot\eta\cdot d^2\left(\frac{\rho}{\eta}\frac{\partial u}{\partial y}\right)^{1/2}\left(u_f - u_p\right)$$

Forces acting on the particle - Overview



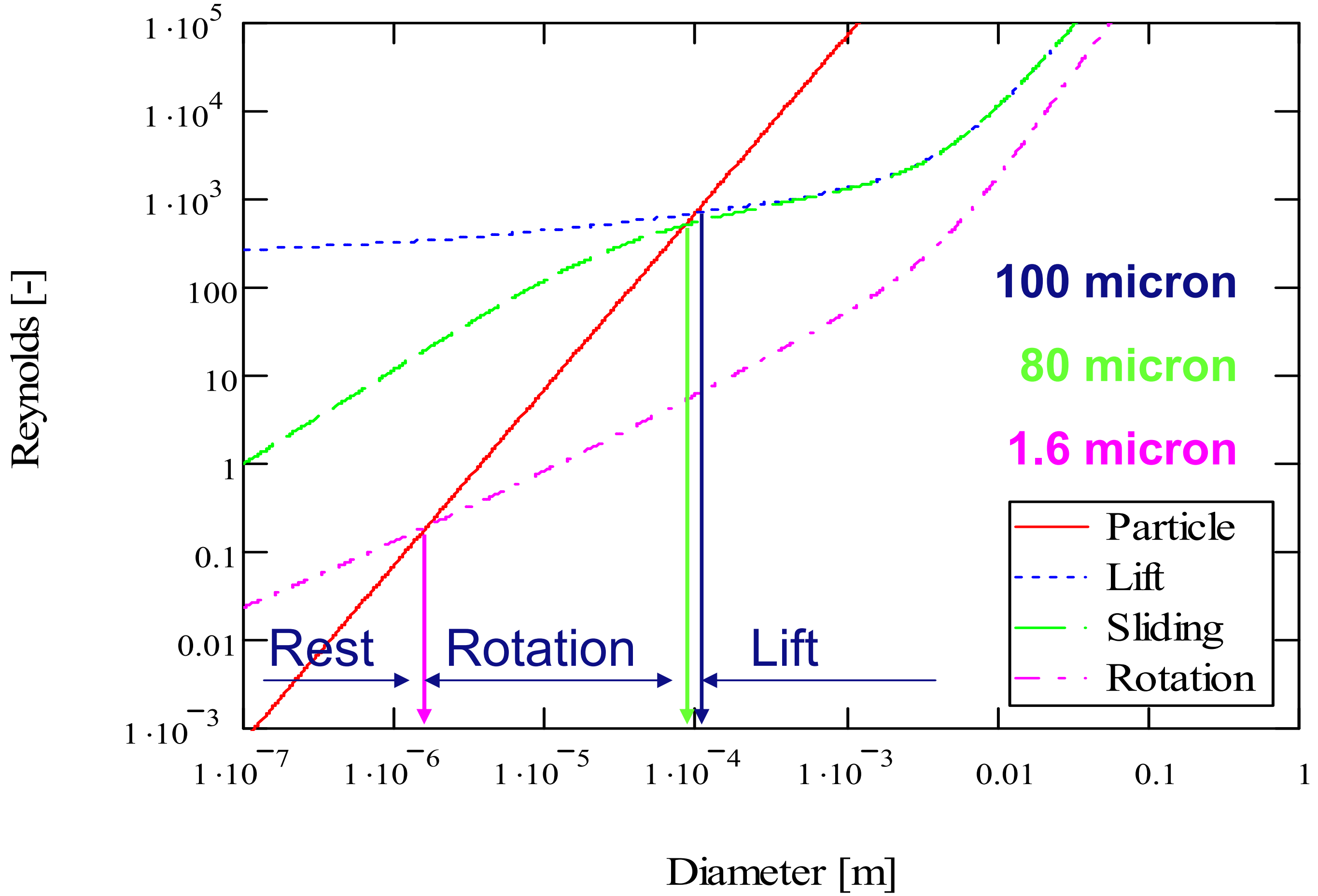
Glass particles in air flow at atmospheric pressure

Reynolds number analysis



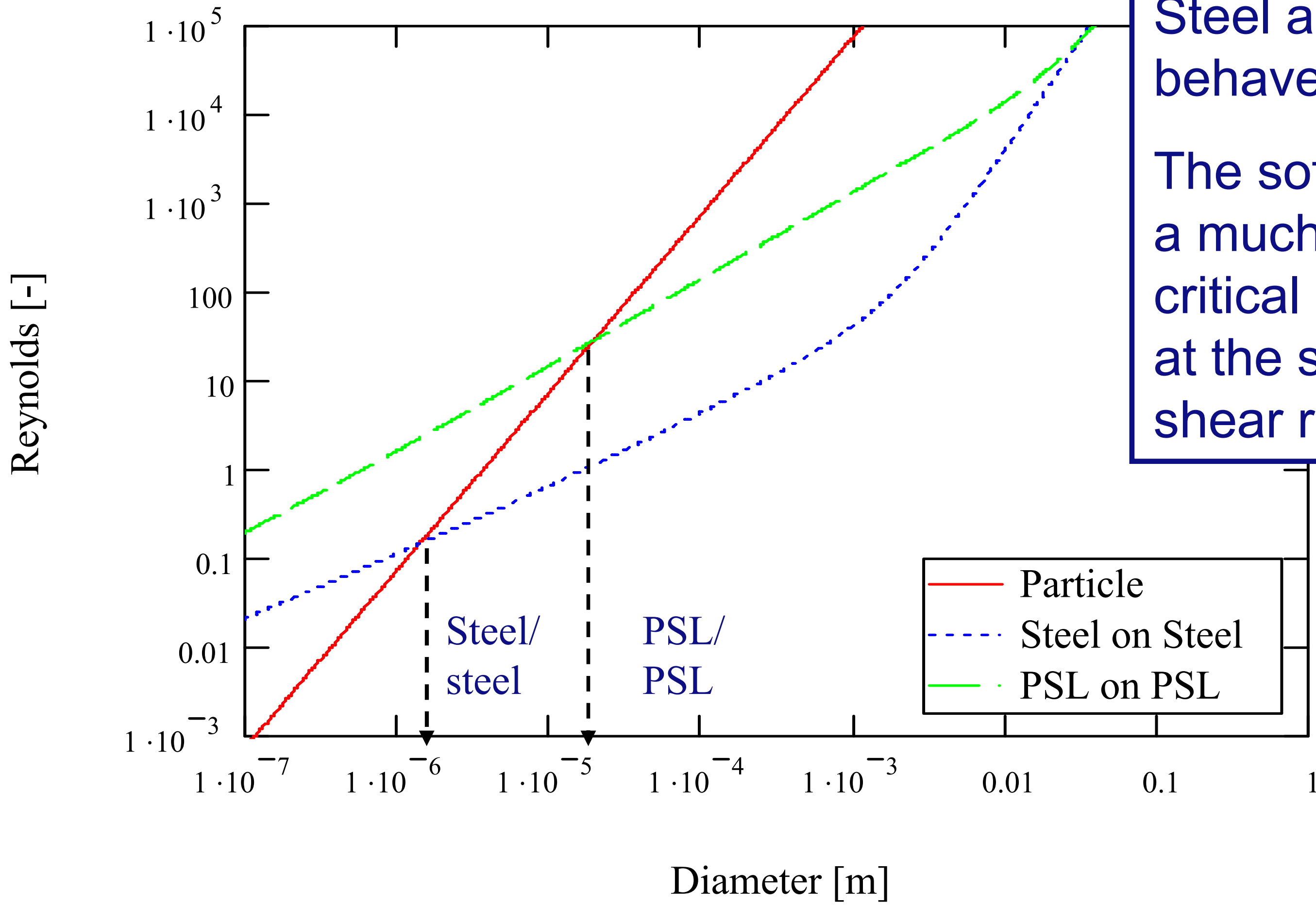
- $$\mathrm{Re}_p = \frac{U_p d\rho}{\eta}$$
- $$\mathrm{Re}_{lift} = \frac{F_{attraction}}{1.615d\sqrt{\frac{\rho}{\eta}}\sqrt{\frac{\partial u}{\partial y}}}\frac{\rho}{\eta^2}$$
- $$\mathrm{Re}_{sliding} = \frac{\mu_s F_{attraction}}{1.7009\cdot 3\pi + \mu_s 1.615d\sqrt{\frac{\rho}{\eta}}\sqrt{\frac{\partial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

Reynolds number analysis (1)



Glass particles in air flow at atmospheric pressure

Reynolds number analysis (2)



Hard materials, Steel and Glass behave similar

The soft PSL has a much larger critical diameter at the same shear rate

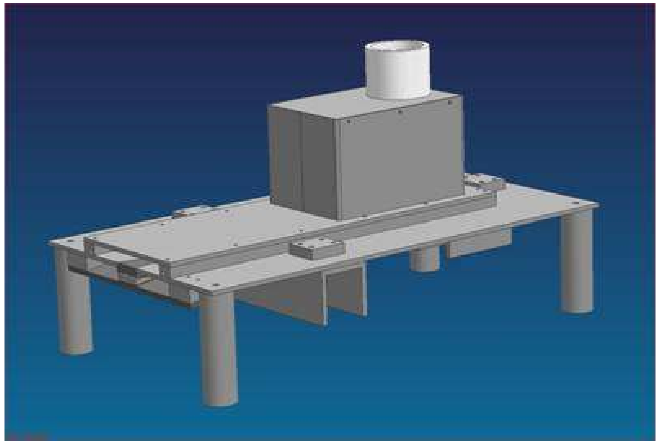
Different materials, rotational motion only

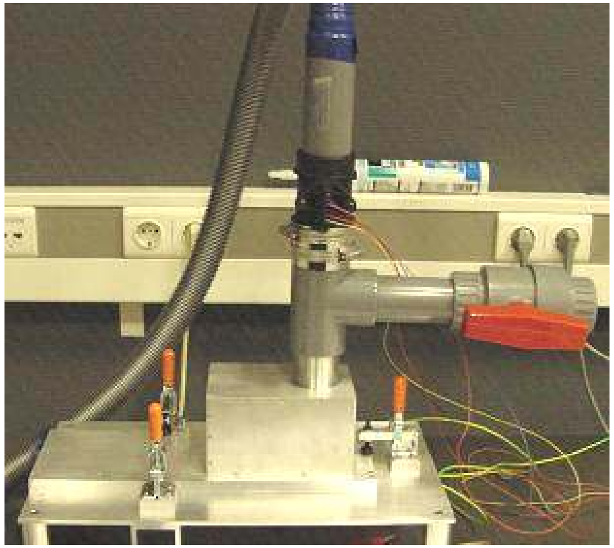
Structure of presentation

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

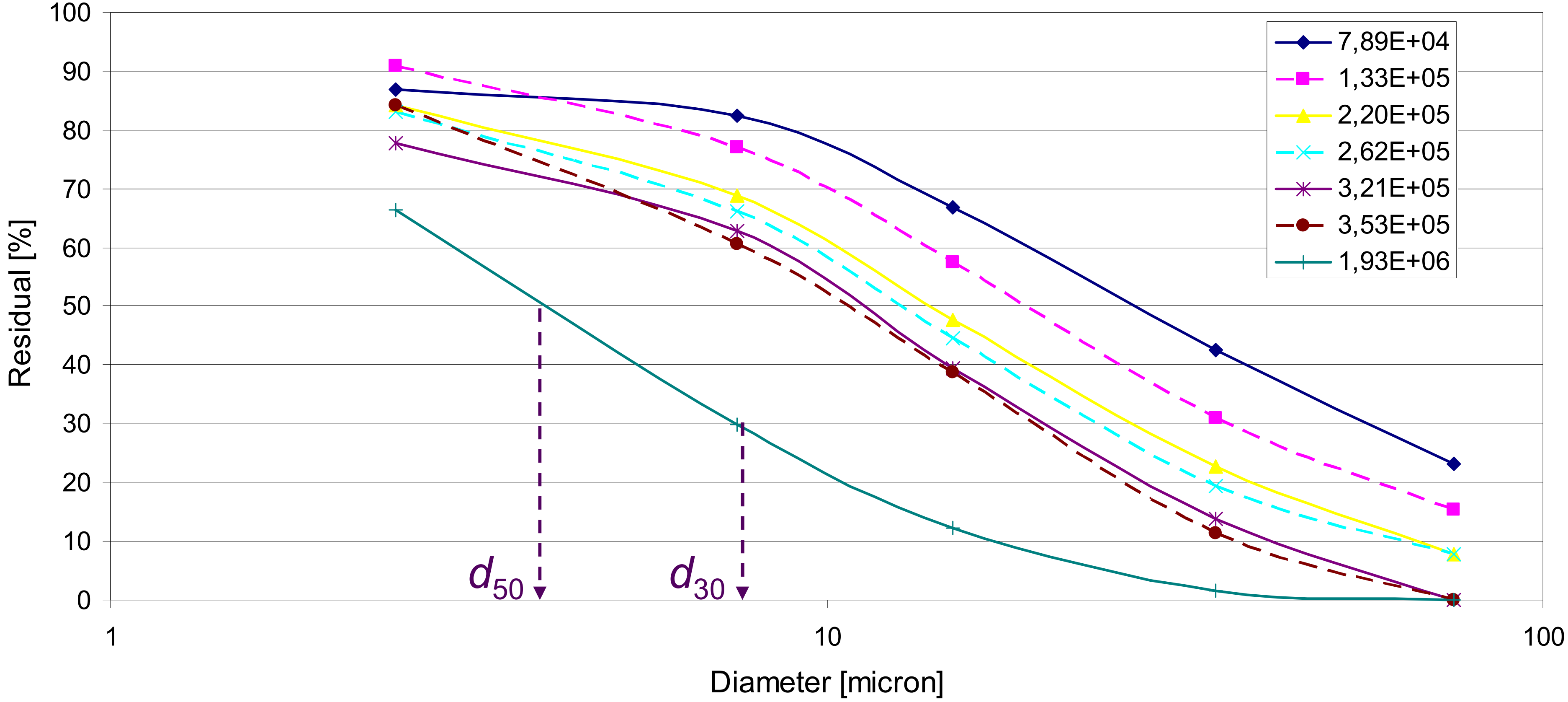
Experimental validation – Set-up

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





Removal efficiency for different shear rates



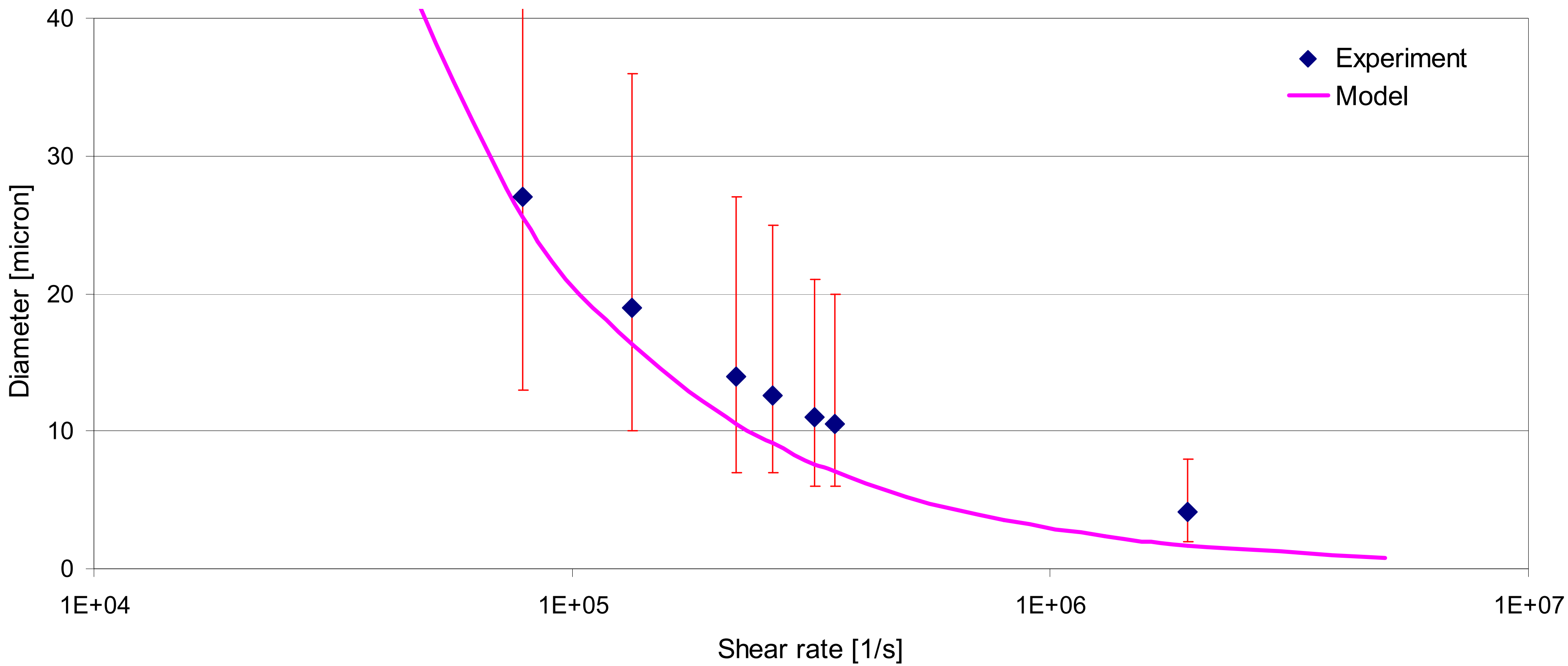
Structure of presentation

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

Critical diameters for particle motion

Gradient [1/s]	d_{lift} [μm]	d_{rot} [μm]		d_{50} [μm]
$7.89 \cdot 10^4$	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

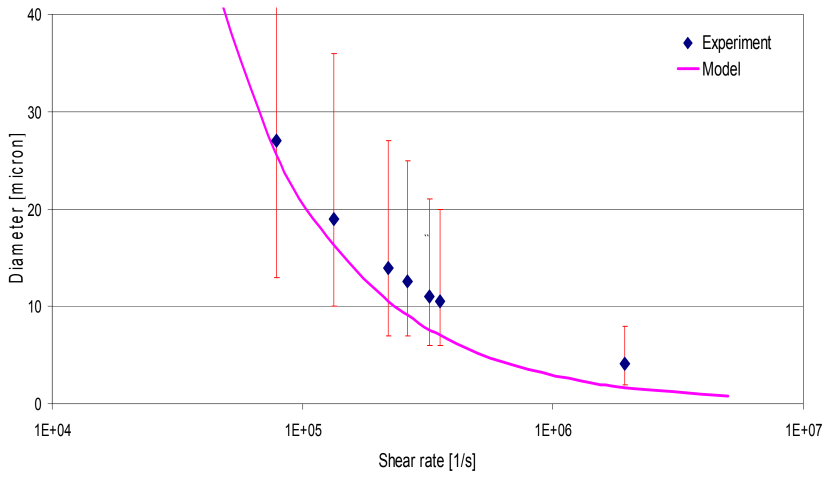


Structure of presentation

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

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

Structure of presentation

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

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