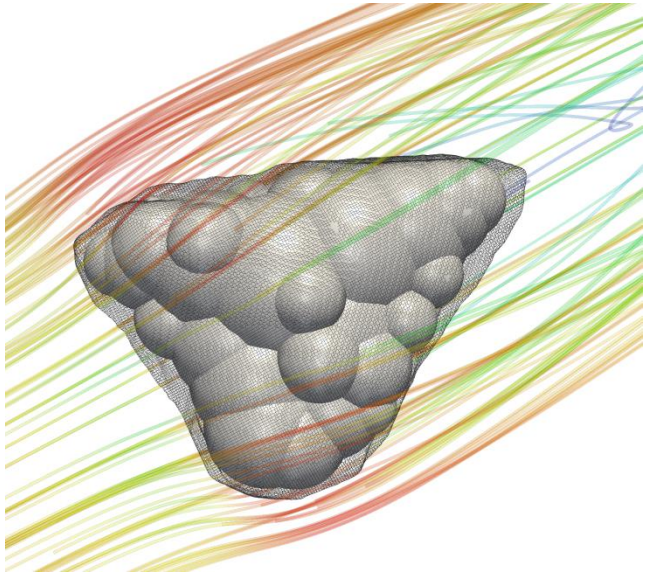
Weimar Institute of Applied Construction Research (IAB Weimar gGmbH)

Drag model for coupled CFD-DEM simulation of non-spherical particles

Rolf Lohse, Ulrich Palzer



Bundesministerium für Wirtschaft und Technologie

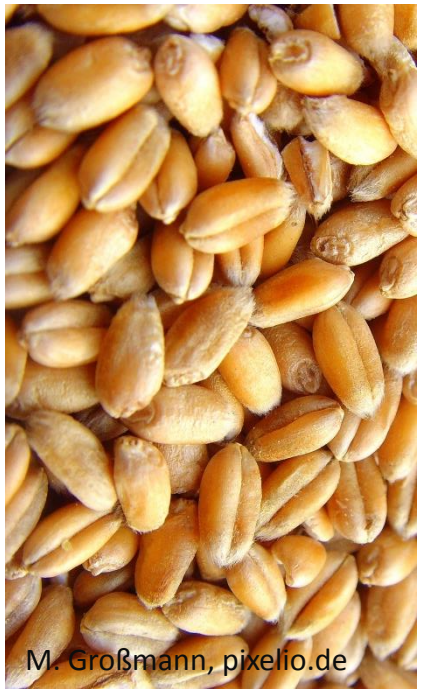
sponsored by the Federal Ministry of Economics and Technology within the funding program “INNO-KOM-Ost"

Outline

- Introduction
- Modelling of non-spherical particles
- Drag of non-spherical particles
  - CFD simulations
  - Wind tunnel tests
- Drag model based on multi-sphere approach
- Use within CFD-DEM simulation
- Outlook

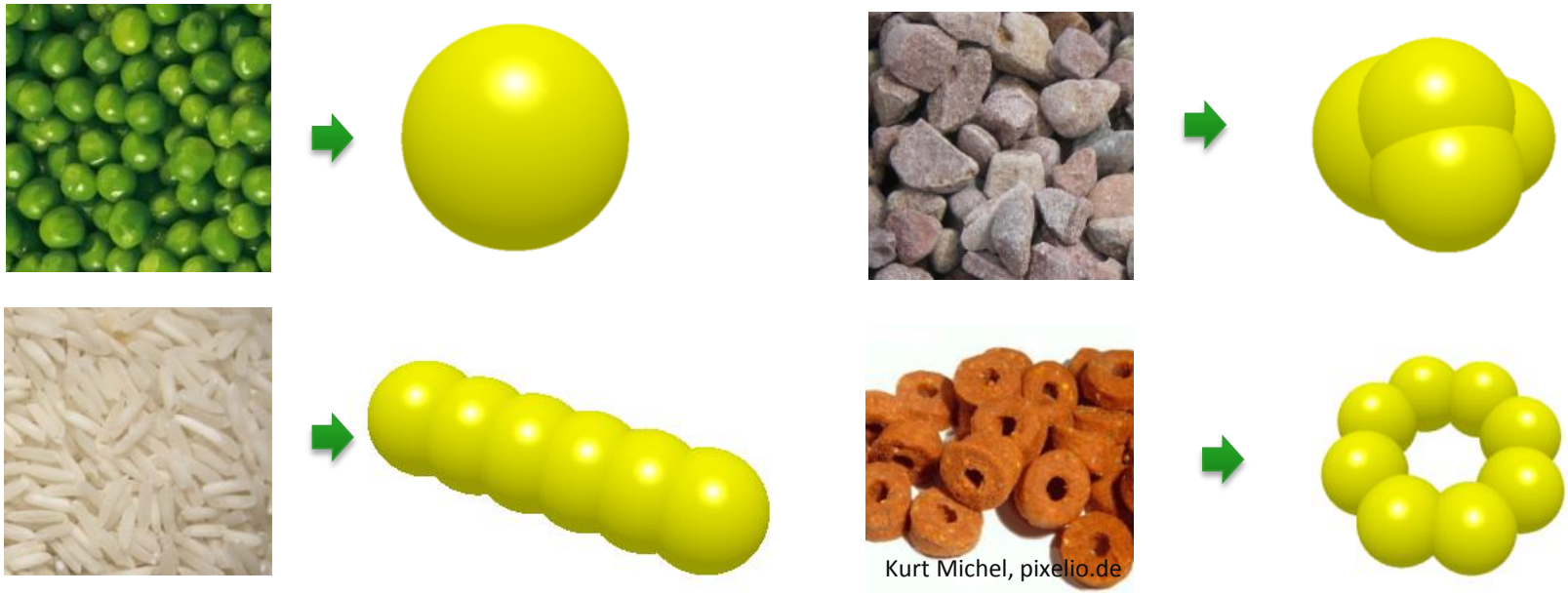
Non-spherical particles

- Many granular products are non-spherical, wide range of shape and size
  - food, pet food, mining, pharmaceuticals, agriculture
- Important for many industrial applications



Modelling of non-spherical particles

- Multi-sphere approach for modelling of non-spherical products with DEM (Discrete Element Method)



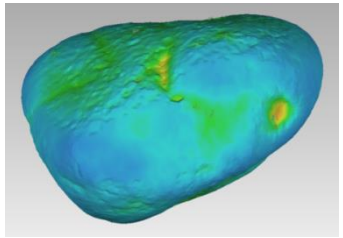
Modelling of non-spherical particles

- DEM simulation of non-spherical products

Particle

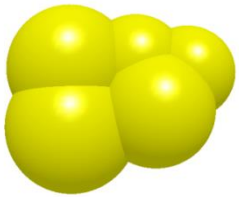
3d scanner

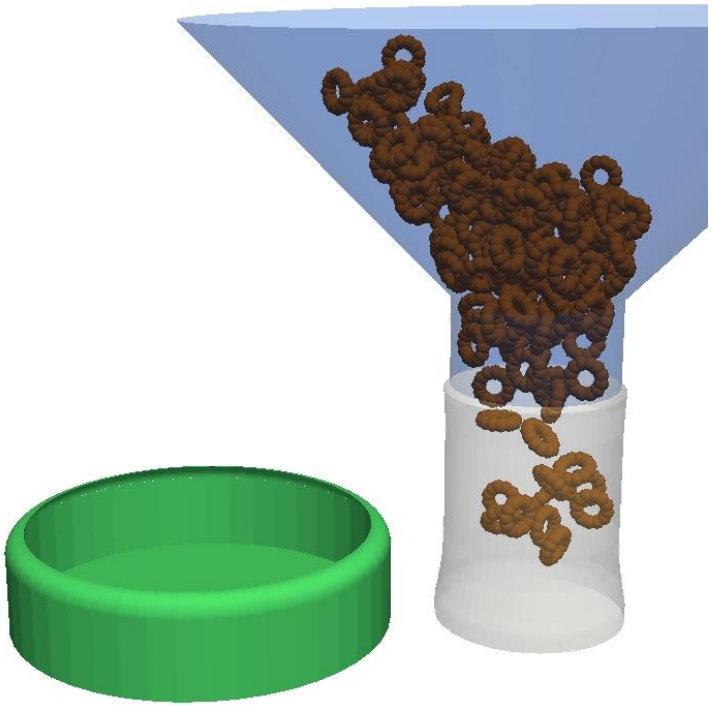
Surface model



Approximation

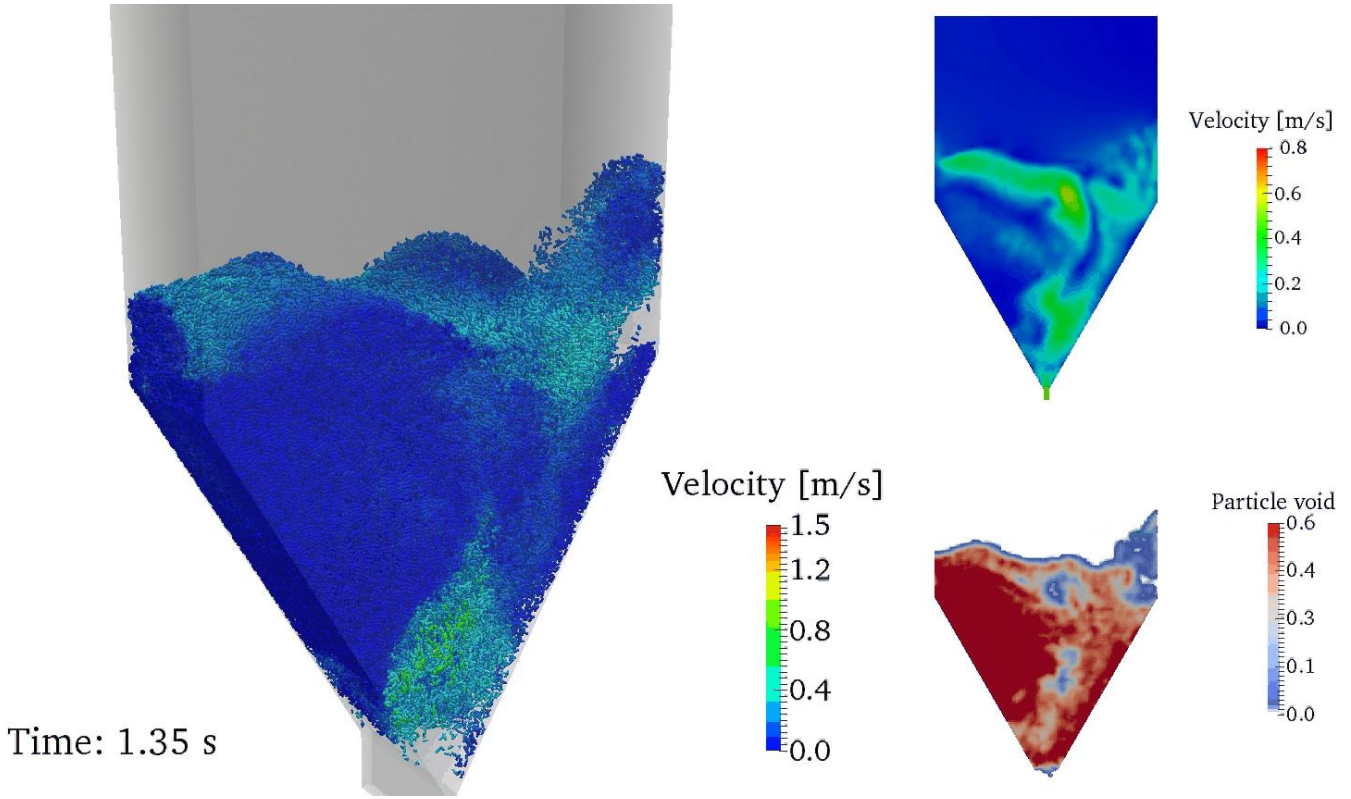
Multi-sphere (Clump)





Modelling of non-spherical particles

- Using multi-sphere approach for drag modelling within CFD-DEM

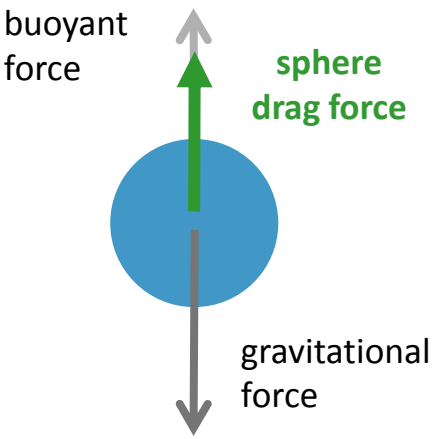


Spouted bed CFD-DEM simulation (CFDEM®coupling), 140.000 cylindrical particles (700.000 spheres)

Modelling of non-spherical particles

- Characterization of particles by sphericity (crosswise and lengthwise) [Hölzer/Sommerfeld]
- **New concept**: using multi-sphere approach for drag modelling

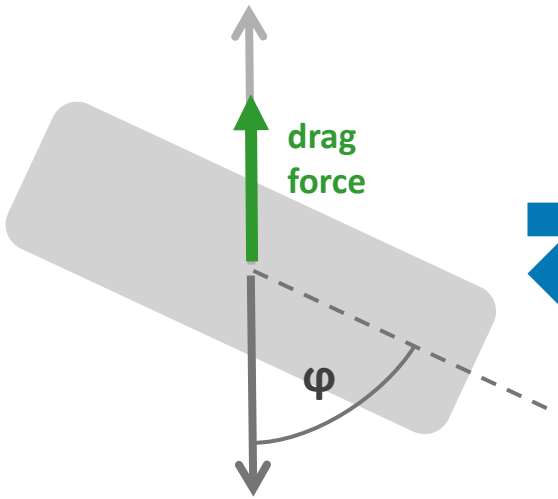
Sphere



$$F_{\mathrm{D,S}} = \frac{C_{\mathrm{D,S}}\rho}{2} U^2 \frac{\pi}{4} {d_S}^2$$

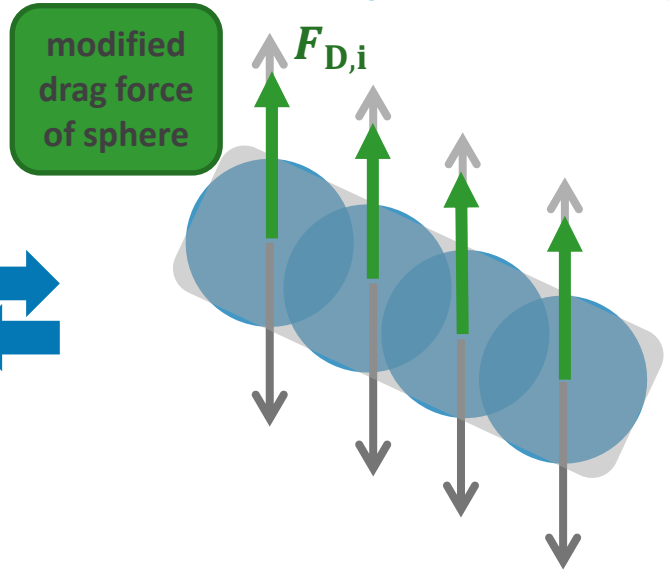
Fluid velocity

Non-spherical particle



Fluid velocity

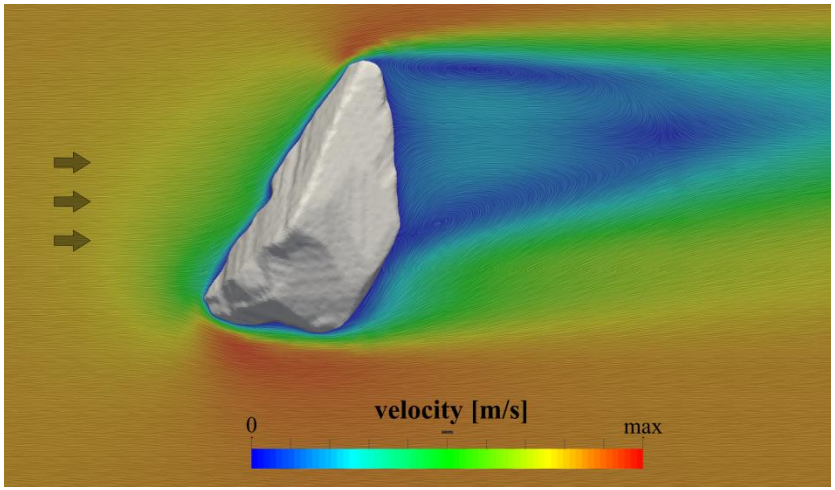
Multi-sphere clump



$$F_{\mathrm{D,i}} = W_i F_{D,S_i}$$

$$F_{\mathrm{D}} = \sum_i F_{\mathrm{D,i}}$$

Drag of non-spherical particles



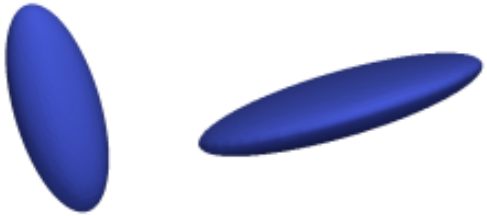
- RANS simulation with SST $k-\omega$ turbulence model
- Fluid velocity and orientation
- $Re_p \leq 10.000$
- Drag force calculated by pressure /viscous stresses integration over particle surface
- OpenFOAM® 2.3.x

- Wind tunnel Göttingen-type v = 1…40 m/s
- Fluid velocity and orientation
- Re_p = 10.000 – 40.000
- Particle production with 3d printer

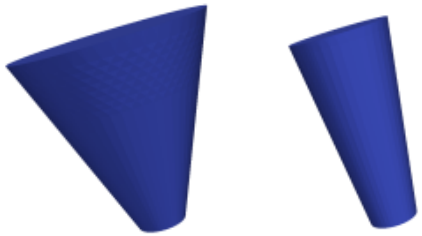
Drag of non-spherical particles

Investigated particle shapes (CFD)

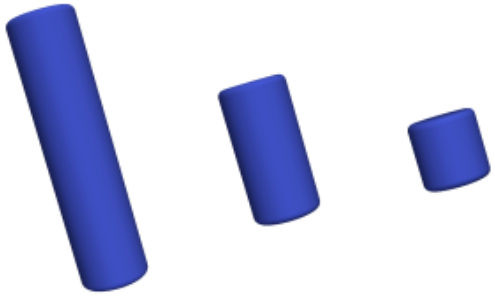
Ellipsoid / disc



Truncated cones

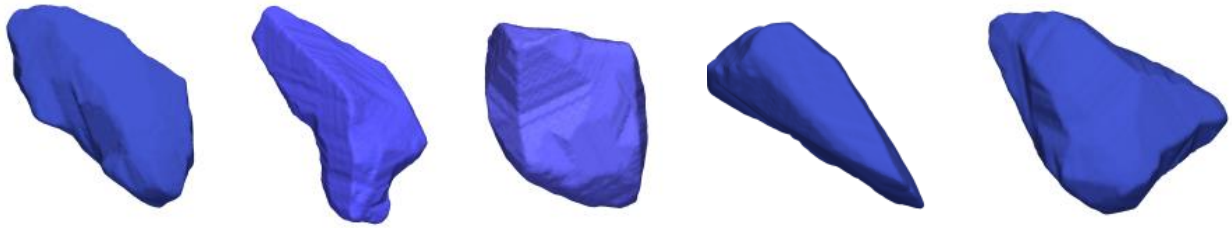


Cylinder



Torus

Real particles

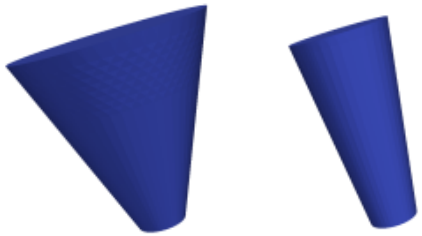


Drag of non-spherical particles

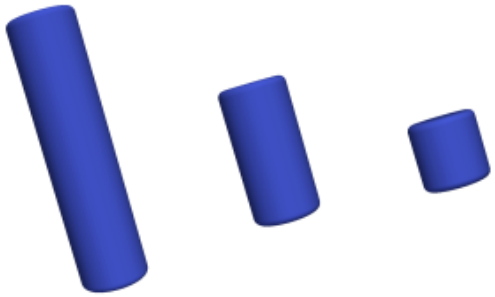
Investigated particle shapes (wind tunnel)

Ellipsoid / disc

Truncated cones



Cylinder

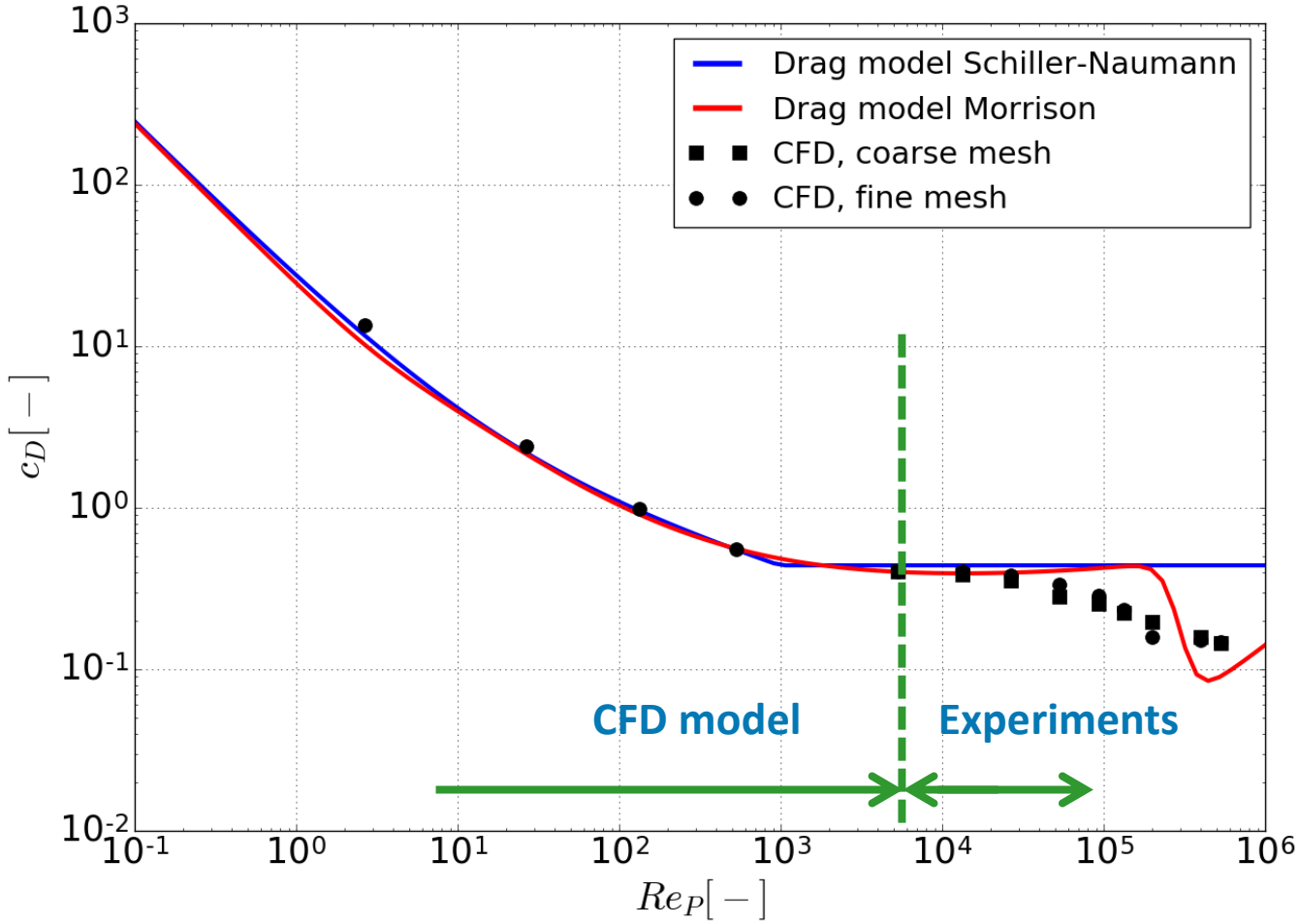


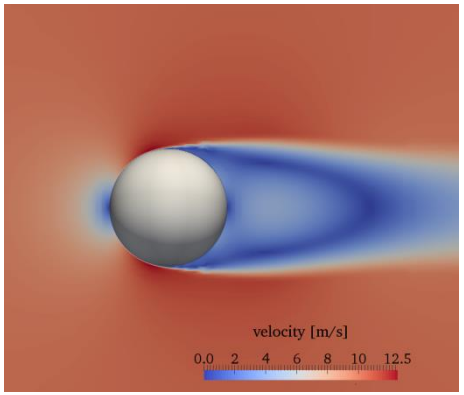
Torus

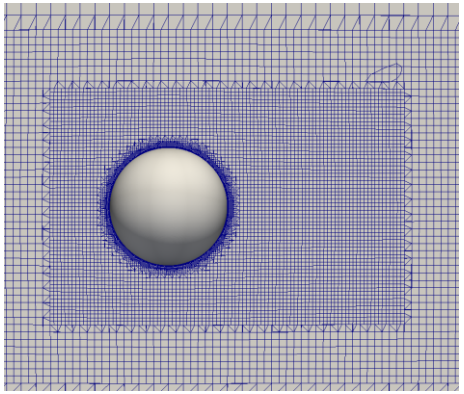
Real particles

Drag of non-spherical particles

Validation CFD model for flow around sphere

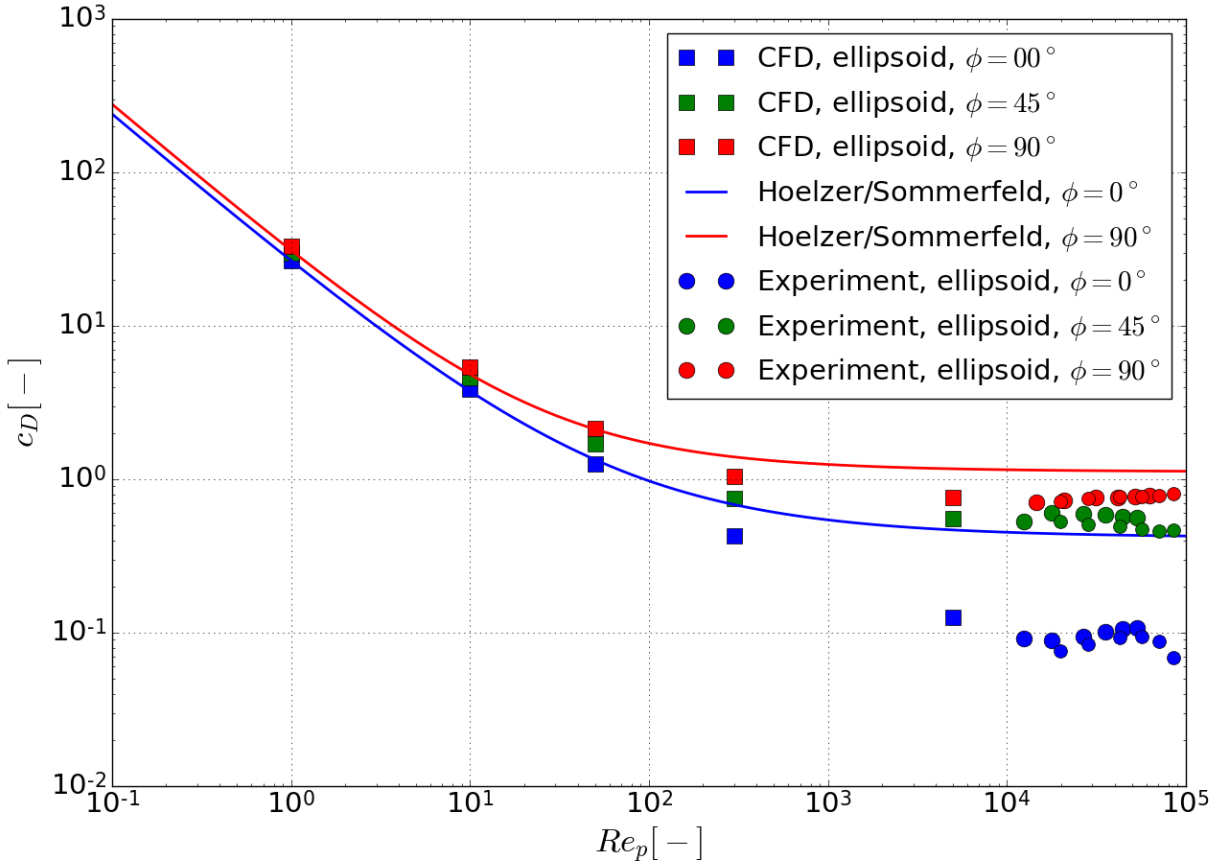


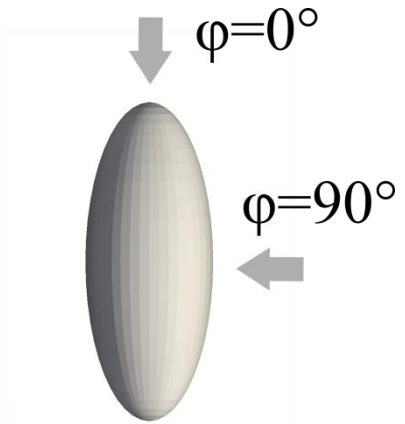




Drag of non-spherical particles

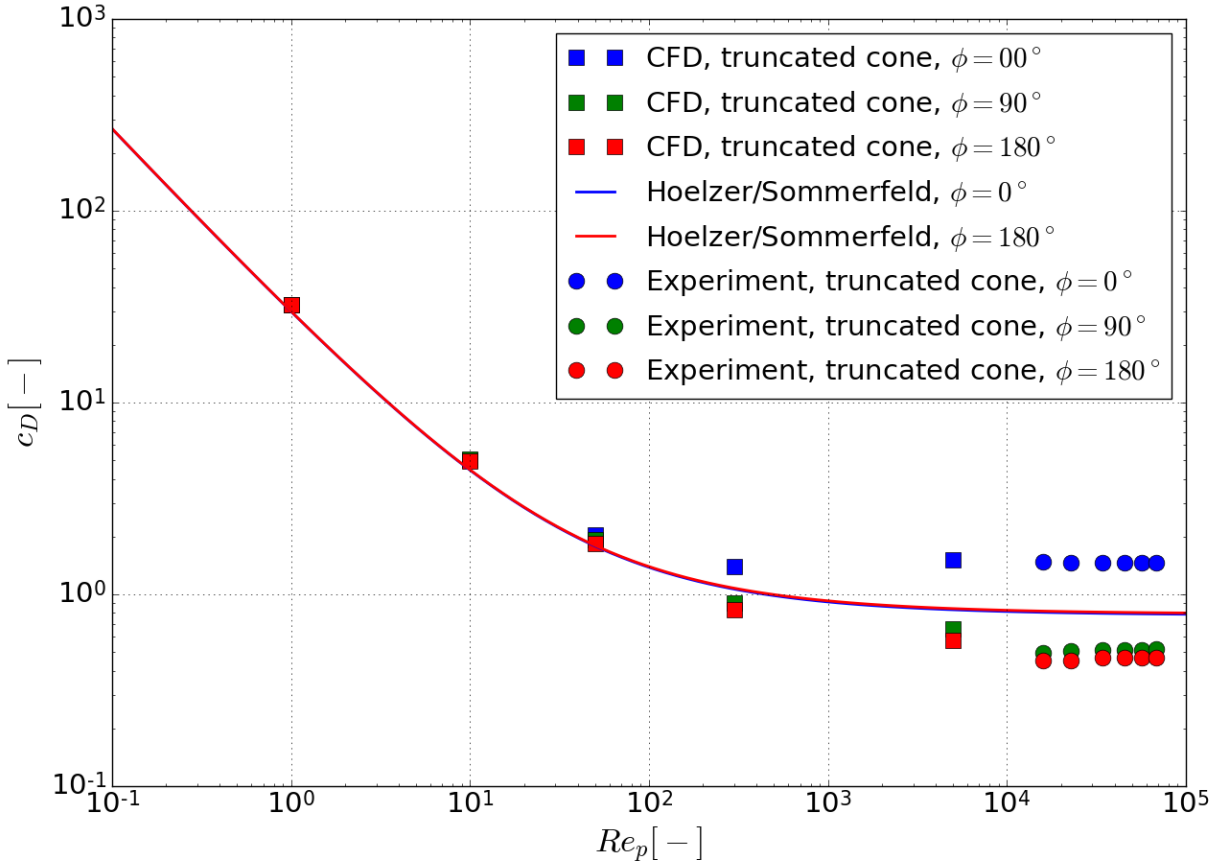
Results for ellipsoid

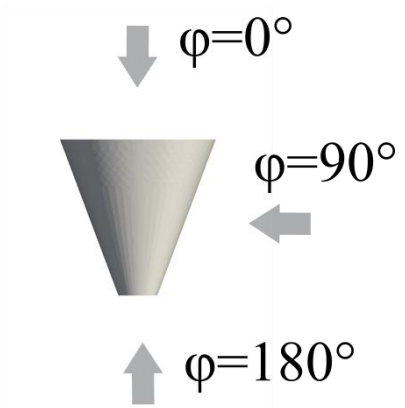




Drag of non-spherical particles

Results for truncated cone





Drag model for multi-sphere approach

Sphere drag coefficient [Morrison]

$$C_{\mathrm{D,S}} = \frac{24}{Re} + \frac{2.6\left(\frac{Re}{5.0}\right)}{1+\left(\frac{Re}{5.0}\right)^{1.52}} + \frac{0.411\left(\frac{Re}{263000}\right)^{-7.94}}{1+\left(\frac{Re}{263000}\right)^{-8.00}} + \frac{Re^{0.80}}{461000}$$

Drag force of sphere within clump

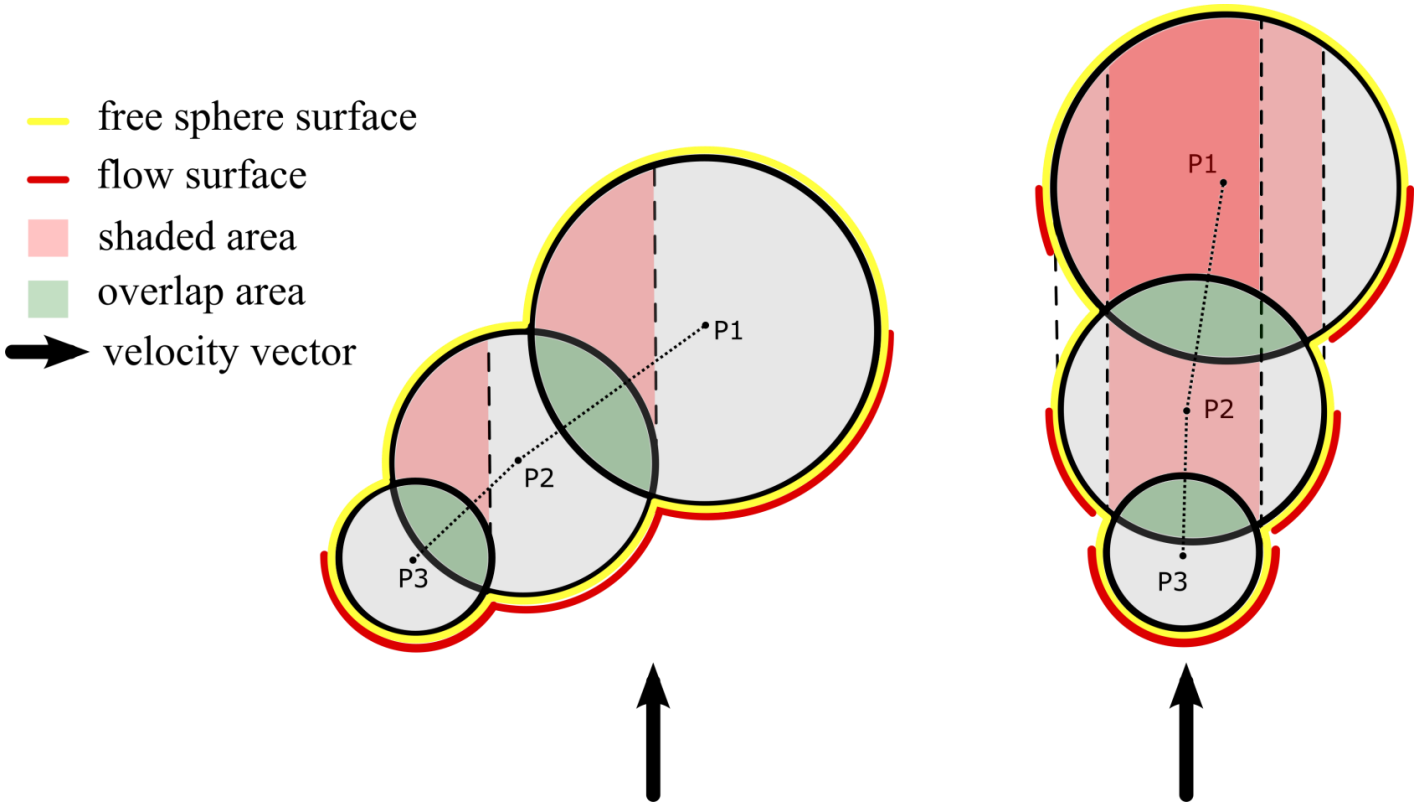
$$F_{\mathrm{D,S}} = \boldsymbol{W}\frac{C_{\mathrm{D,S}}\rho}{2}U^2\frac{\pi}{4}{d_S}^2 \qquad \boldsymbol{W} = f(Re, \ldots, ?)$$

Drag coefficient clump (non-spherical particle)

$$C_{\mathrm{D}} = \frac{\sum F_{\mathrm{D,S}}}{\frac{\rho}{2}U^2\frac{\pi}{4}{d_V}^2}$$

Drag model for multi-sphere approach

Parameters

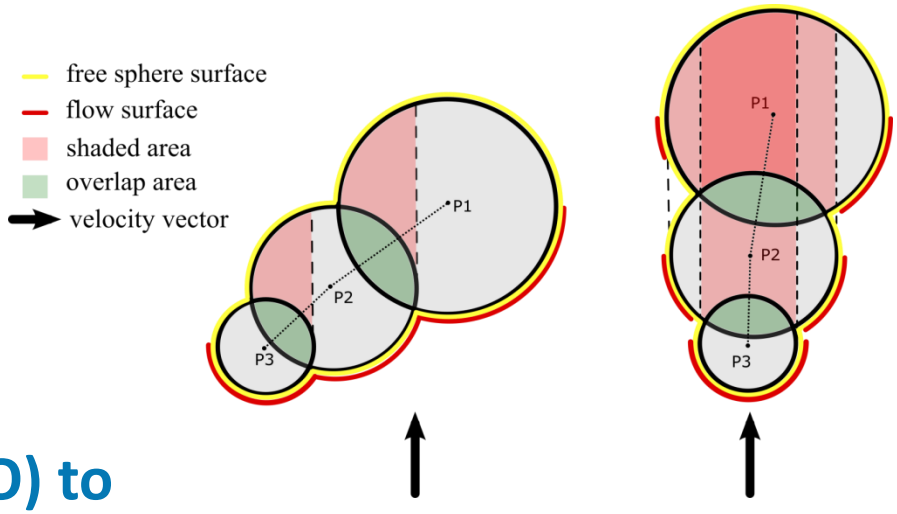


Drag model for multi-sphere approach

Parameters / coefficients

$$W = (A - B\,a_{Sh}{}^{C}) + Re^{D}(E - F\,a_{Sh}{}^{G})\,(H\,a_{bs}{}^{I}) + Re^{J}(K - L a_{Sh}{}^{M}) s^{N} (O - P\,a_{bs}{}^{Q}) + Re^{R}(S - T\,a_{Sh}{}^{U})\,(V - X a_{f}{}^{Y})$$

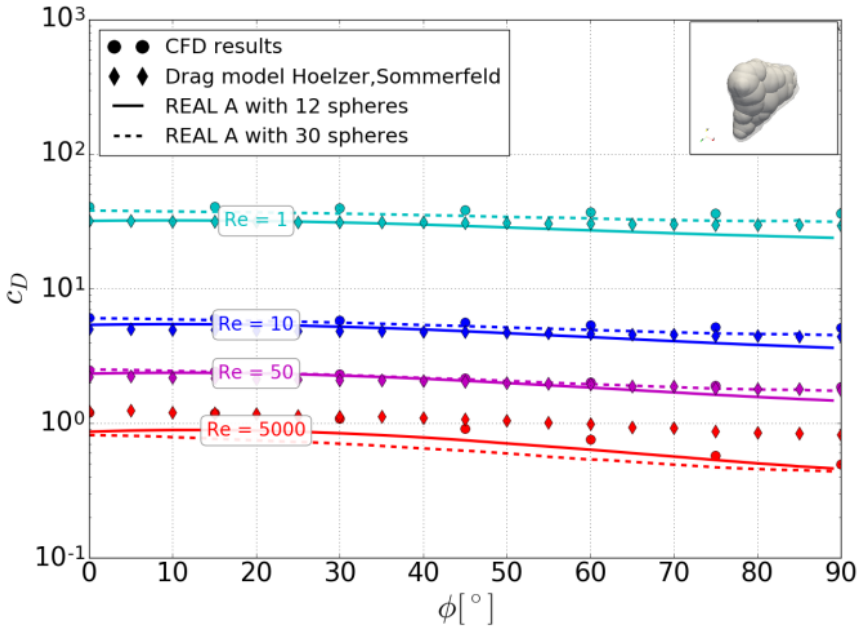
- a_{Sh} shading ratio
- a_{bs} shading ratio with reverse velocity vector
- a_f free surface ratio
- s distance to leading sphere

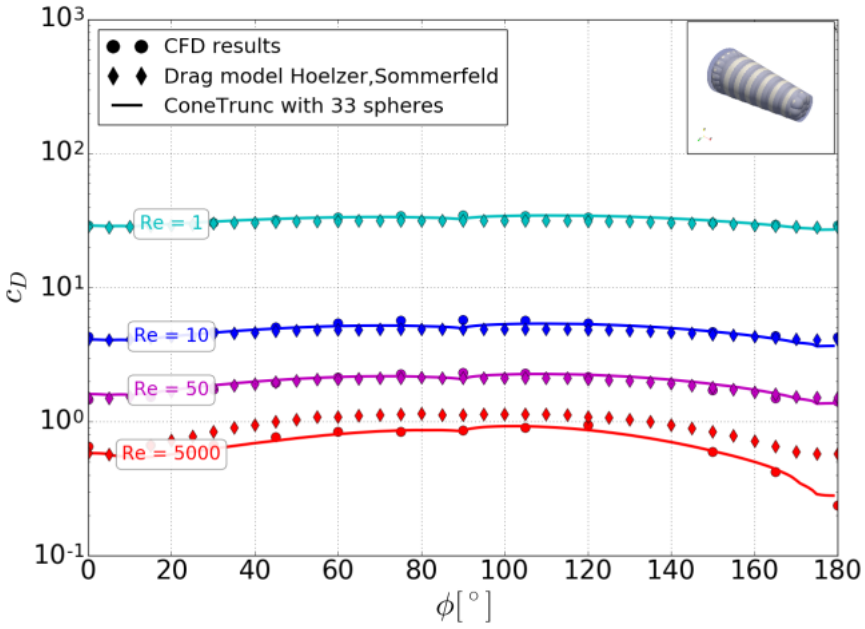


Particle Swarm Optimization (PSO) to find good model coefficients ($A - X$)

Drag model for multi-sphere approach

Results for shape independent model coefficients





CFD-DEM simulations

Simulation model

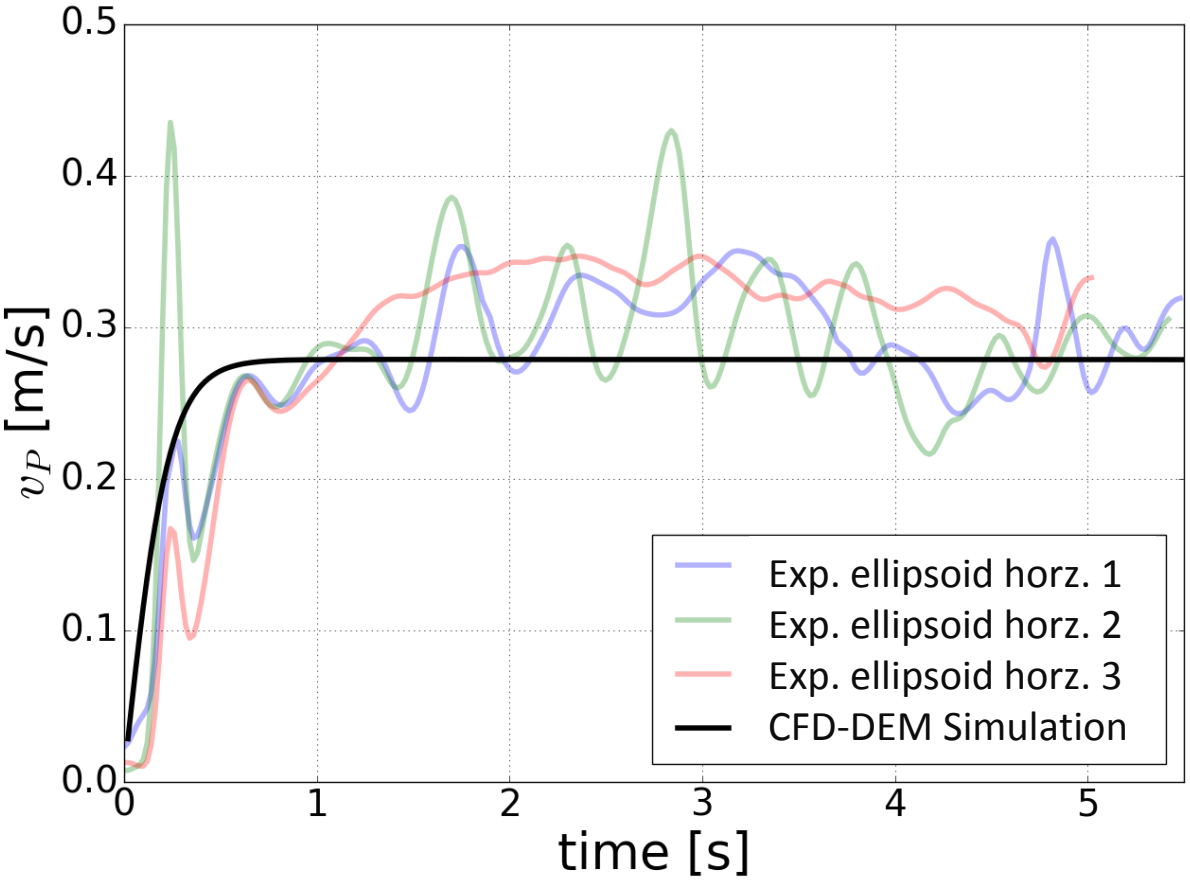
- CFDEM(R)coupling 2.9
  (OpenFOAM® 2.3.x + LIGGGHTS® 3.1)
- Momentum balance for fluid with coupling term for granular phase

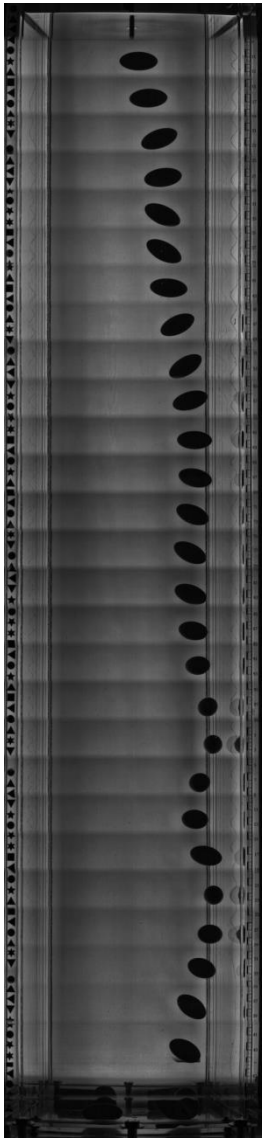
$$\frac{\partial \epsilon_f U_i}{\partial t} + \frac{\partial \epsilon_f U_i U_j}{\partial x_i} = -\epsilon_f \frac{\partial p}{\partial x_i} + \frac{\partial \epsilon_f \tau}{\partial x_i} + \epsilon_f g - K_{fs}(U_f - U_S)$$

- LIGGGHTS® modification to model multiple clumps in parallel
- Implementation of new drag model and drag model of Hölzer and Sommerfeld
- Modification regarding clumps with overlapping spheres
  - Archimedes and gravity force
  - void fraction model

CFD-DEM simulations

Validation single particle sedimentation

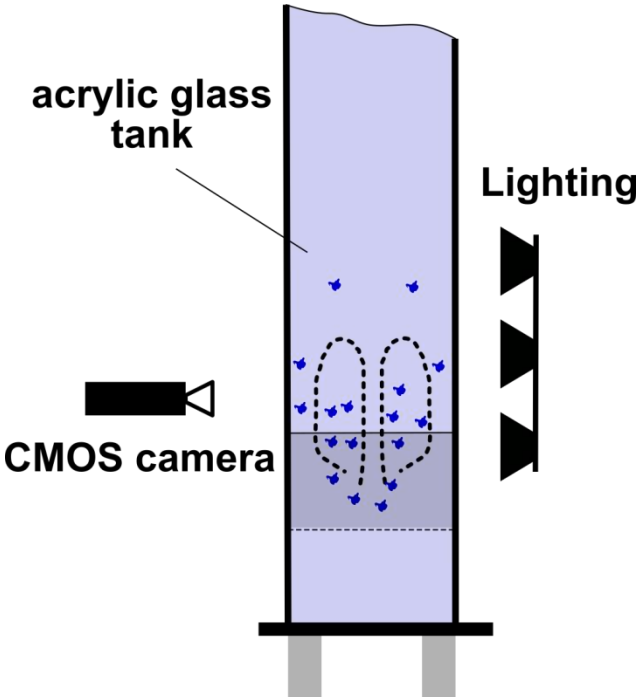




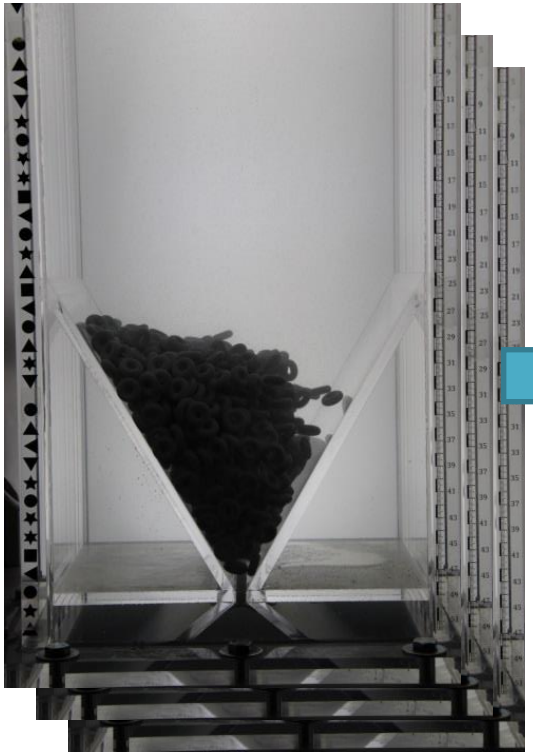
CFD-DEM simulations

Test spouted bed

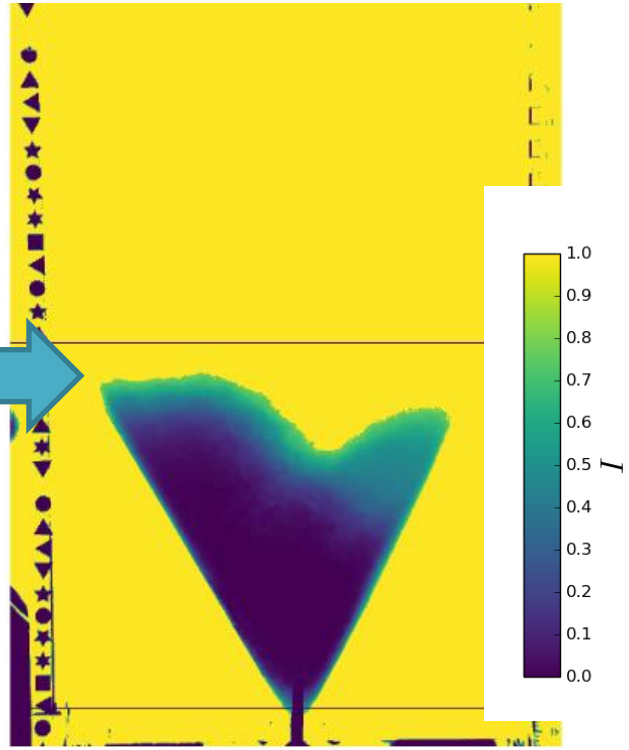
Experimental setup



Time series of images (particle positions)



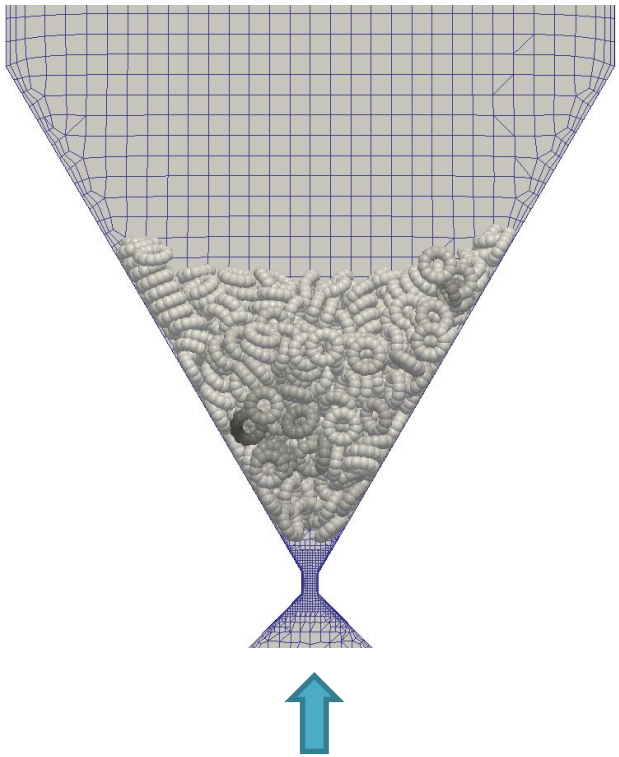
Measure for mean 2d particle distribution

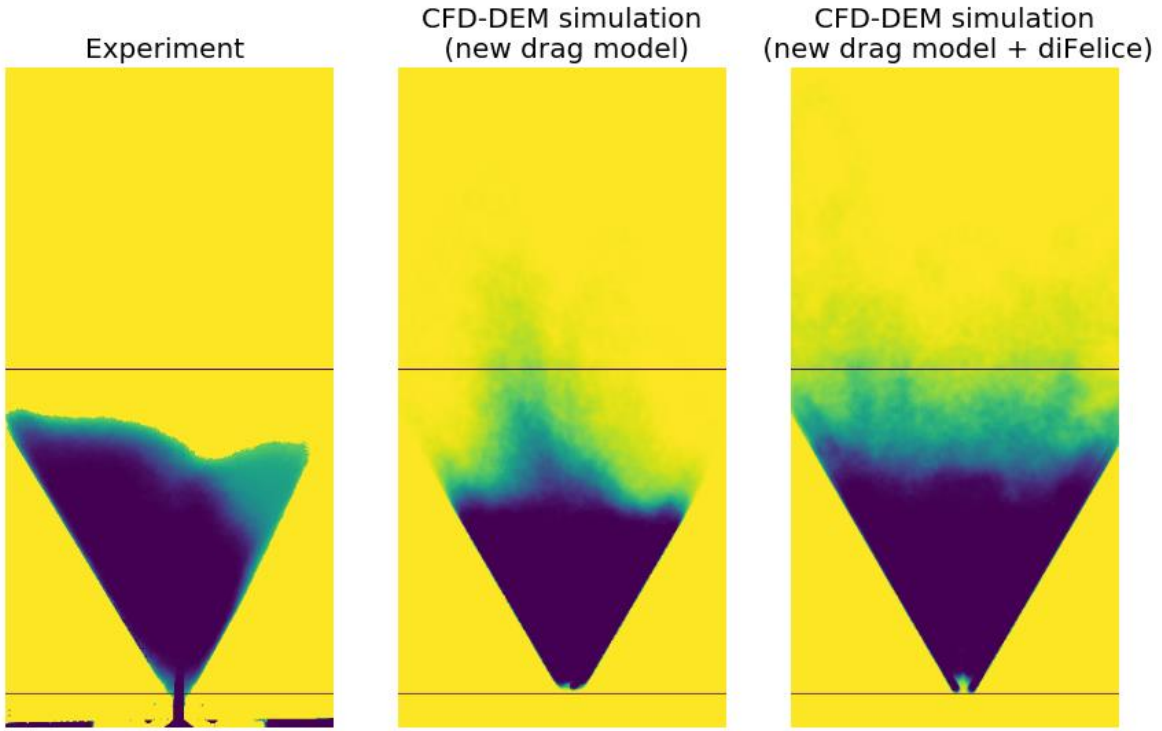


CFD-DEM simulations

Results for spouted bed

Particles: 1000 tori (12.000 spheres), $\dot{V} = 300\ \mathrm{l/min}$, water





Experimental data

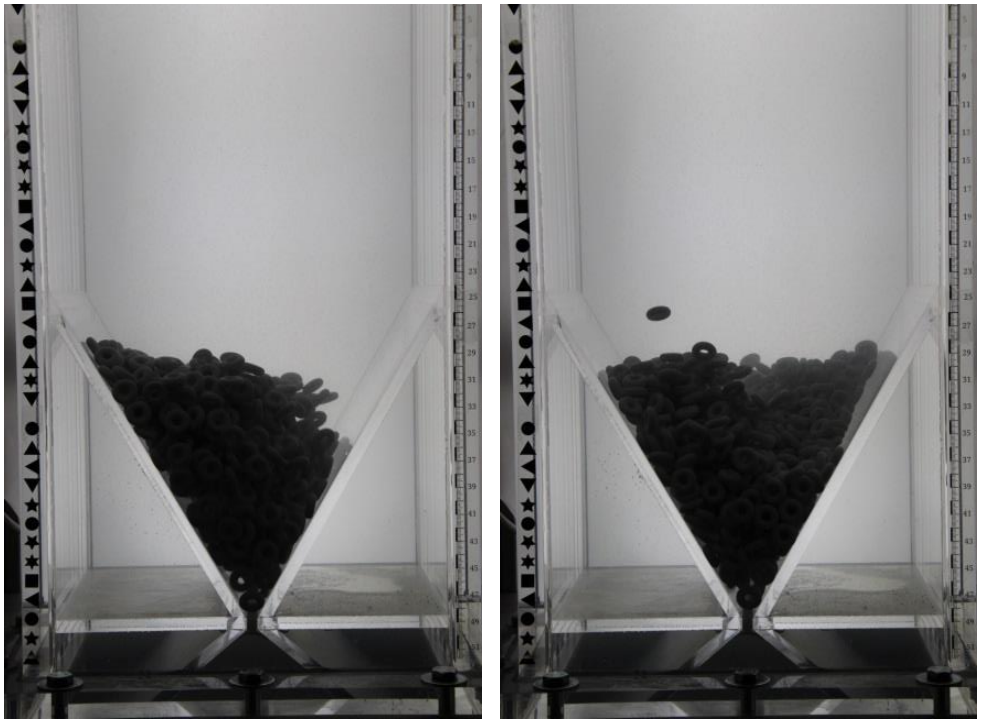
Simulation single particle drag

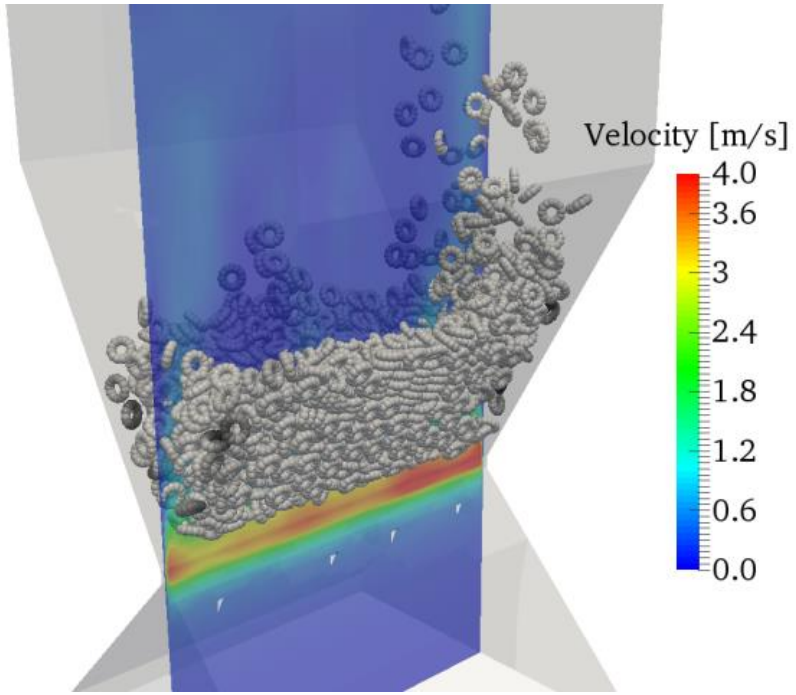
Simulation + swarm effects diFelice model

CFD-DEM simulations

Results for spouted bed

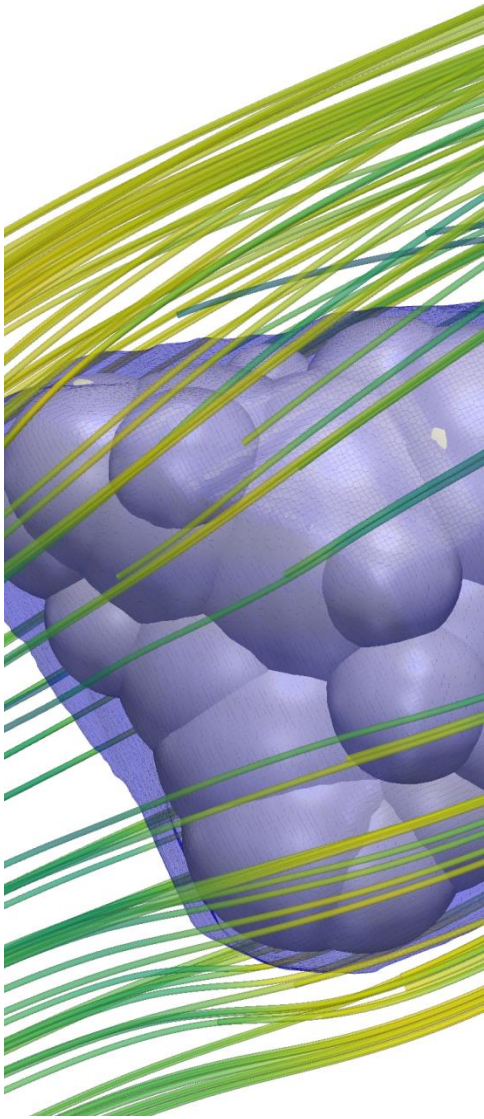
Particles: 1000 tori (12.000 spheres), $\dot{V} = 300\ \mathrm{l/min}$, water





Conclusion

- CFD simulation and wind tunnel measurements for drag force of non-spherical particles
- Development of drag model based on the multi-sphere approach
- Further improvement for the integration within CFD-DEM simulation necessary



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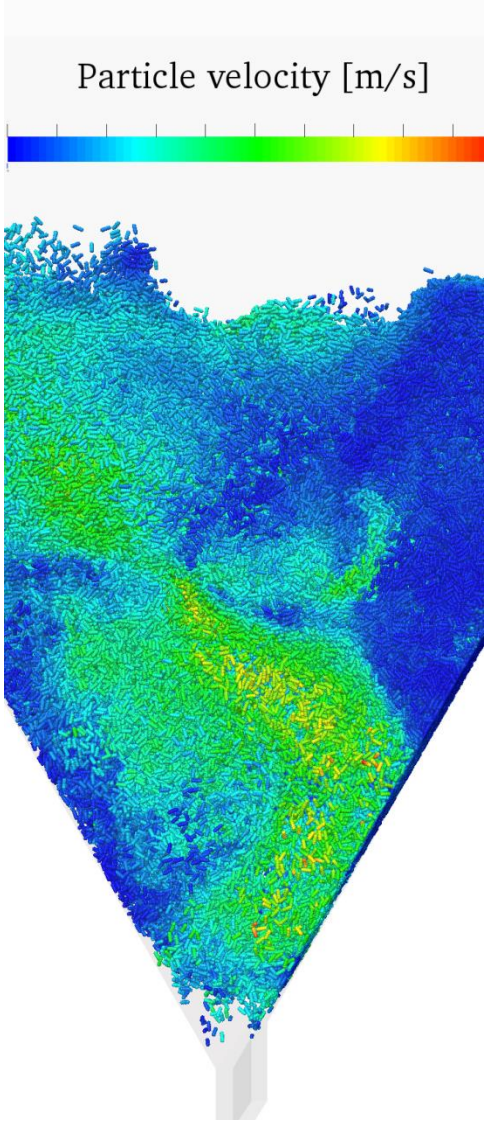
Future work

- further validations necessary
- Improvements of the drag model
  - Discretization of non-spherical particles
  - Simplify : Reduction of model coefficients
  - Integration into CFD-DEM framework
- two-mesh method for large particles (fine fluid mesh and coarse mesh for particle representation)
- Integration within resolved CFD-DEM



Thank you for your attention

Dr.-Ing. Rolf Lohse
IAB – Weimar Institute of Applied Construction Research gGmbH
Über der Nonnenwiese 1
99428 Weimar, Germany
+ 49 3643 8684-158
r.lohse@iab-weimar.de