5-25-2016

CFDEM® modelling of particle coating in a three-dimensional prismatic spouted bed

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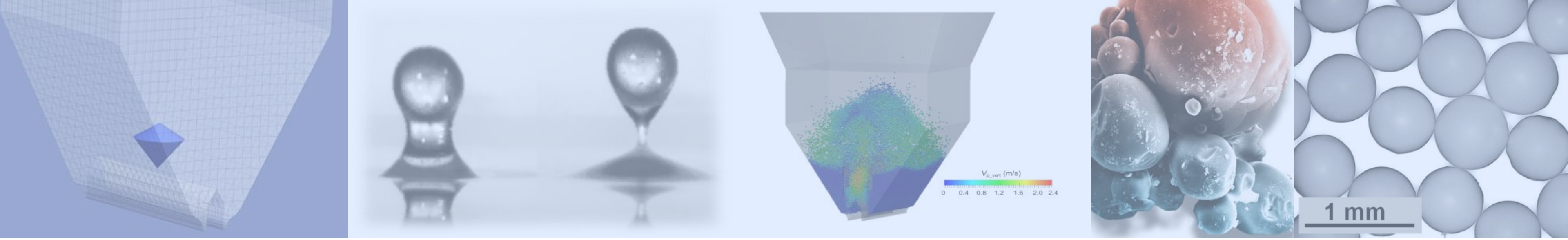

CFD-DEM modeling of a three-dimensional prismatic spouted bed

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BASF The Chemical Company

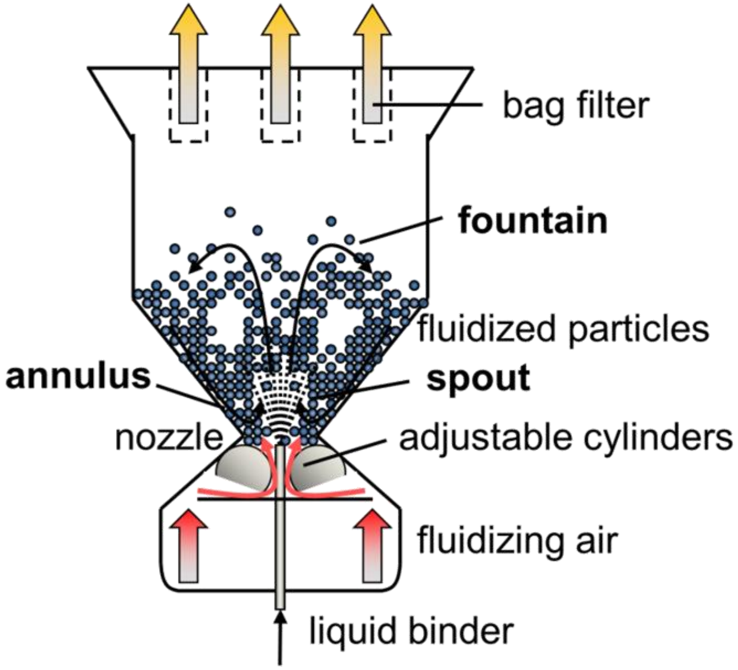
Theory
Flow pattern in a spouted bed

- Comparison to fluidized beds:
  - Fluidization of non-spherical / very big / very small / cohesive particles possible
  - Improved heat and mass transfer
- Former investigations mostly on conical or pseudo-2D prismatic spouted beds [1, 2]

⬇ **Actual study**

Prismatic laboratory plant for practical applications (e.g. spray granulation)

- Prismatic form enables scale-up in depth
- Movable cylinders for variation of gas velocity



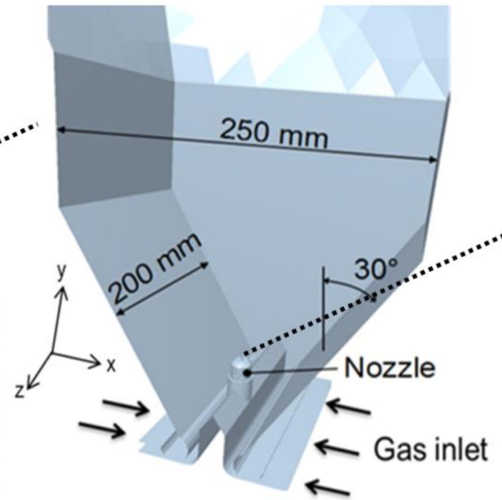
Spouted bed

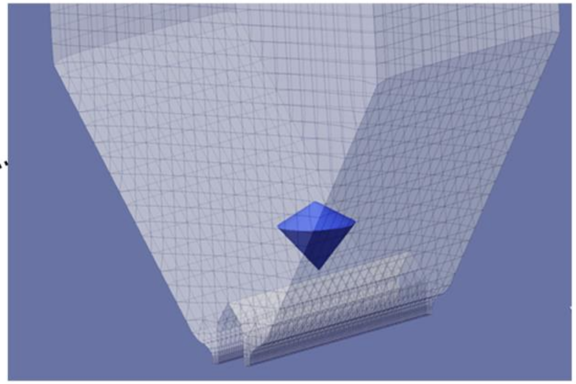
[1] V. Salikov, S. Heinrich, S. Antonyuk, V.S. Sutkar, N.G. Deen, J.A.M. Kuipers; Advanced Powder Technology, 26 (2015), 718-733.

[2] V. Salikov, S. Antonyuk, S. Heinrich, V.S. Sutkar, N.G. Deen, J.A.M. Kuipers; Powder Technology, 270 (2015), 622-636.

Material and methods

Experimental set-up

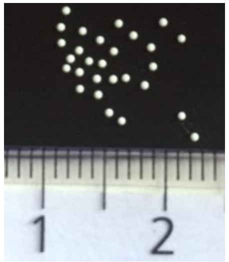


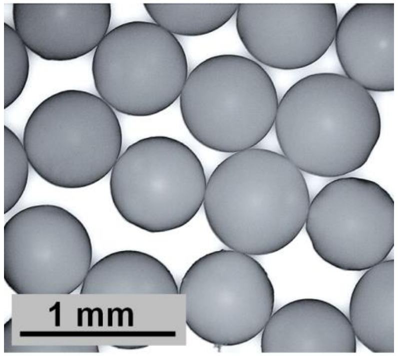


Spray zone

ProCell 5, Glatt Ingenieurtechnik

- Three-dimensional bed
- Gas inlet slots in 0° position
- Two-fluid nozzle in bottom spray configuration
- $\gamma - Al_2O_3$ particles, $d_{p,mean} = 656\ \mu m$





$\gamma - Al_2O_3$ particles, light microscope image

Simulations

Mathematical background

OpenFOAM

- Computational Fluid Dynamics (CFD)

→ Navier-Stokes equations (Eulerian)

- Discrete Element Method (DEM)

→ Newton's equations (Lagrangian)

CFD-DEM:

- CFD with momentum sources
- DEM with forces on particles coming from CFD
  - + Later on with liquid injection [1]

Navier-Stokes equations for the fluid in presence of particles:

$$\frac{\partial \alpha_f}{\partial t} + \nabla \cdot (\alpha_f \boldsymbol{u}_f) = 0$$

$$\frac{\partial (\alpha_f \boldsymbol{u}_f)}{\partial t} + \nabla \cdot (\alpha_f \boldsymbol{u}_f \boldsymbol{u}_f) = -\alpha_f \nabla \frac{p}{\rho_f} - \boxed{\boldsymbol{R}_{pf}} + \nabla \cdot \boldsymbol{\tau}$$

α_f	Fluid volume fraction	p	Pressure, Pa
$\boldsymbol{u}_f$	Fluid velocity, m/s	ρ_f	Fluid density, kg/m³
$\boldsymbol{\tau}$	Stress tensor, Pa	$\boldsymbol{R}_{pf}$	Fluid solid transfer momentum exchange

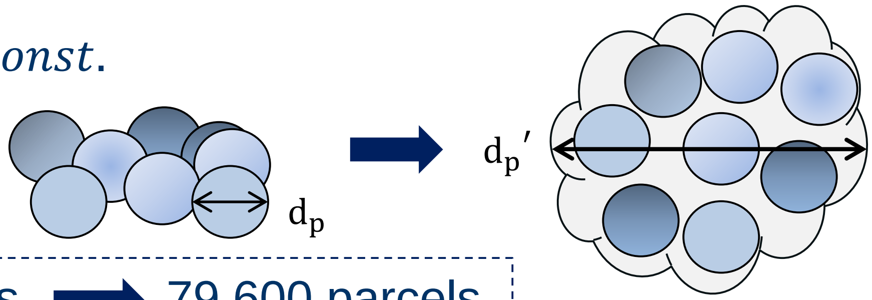
→ Several empirical, half-empirical and theoretical correlations for fluid solid momentum exchange term (drag correlations)

[1] V. S. Sutkar, N. G. Deen, A. V. Patil, V. Salikov, S. Antonyuk, S. Heinrich, J.A.M. Kuipers; Chemical Engineering Journal, 288 (2016), 185-197.

Coarse-graining approach [1]

$$\Delta E_{kin} = \frac{m_{eff}}{2}\left(v_{n,rel,after}^2 - v_{n,rel,before}^2\right) = const.$$

$$\Rightarrow d_p{}' = \delta \cdot d_p = 4 \cdot d_p$$



1 kg $\gamma - Al_2O_3$ particles ≡ 5,094,386 particles ➡ 79,600 parcels

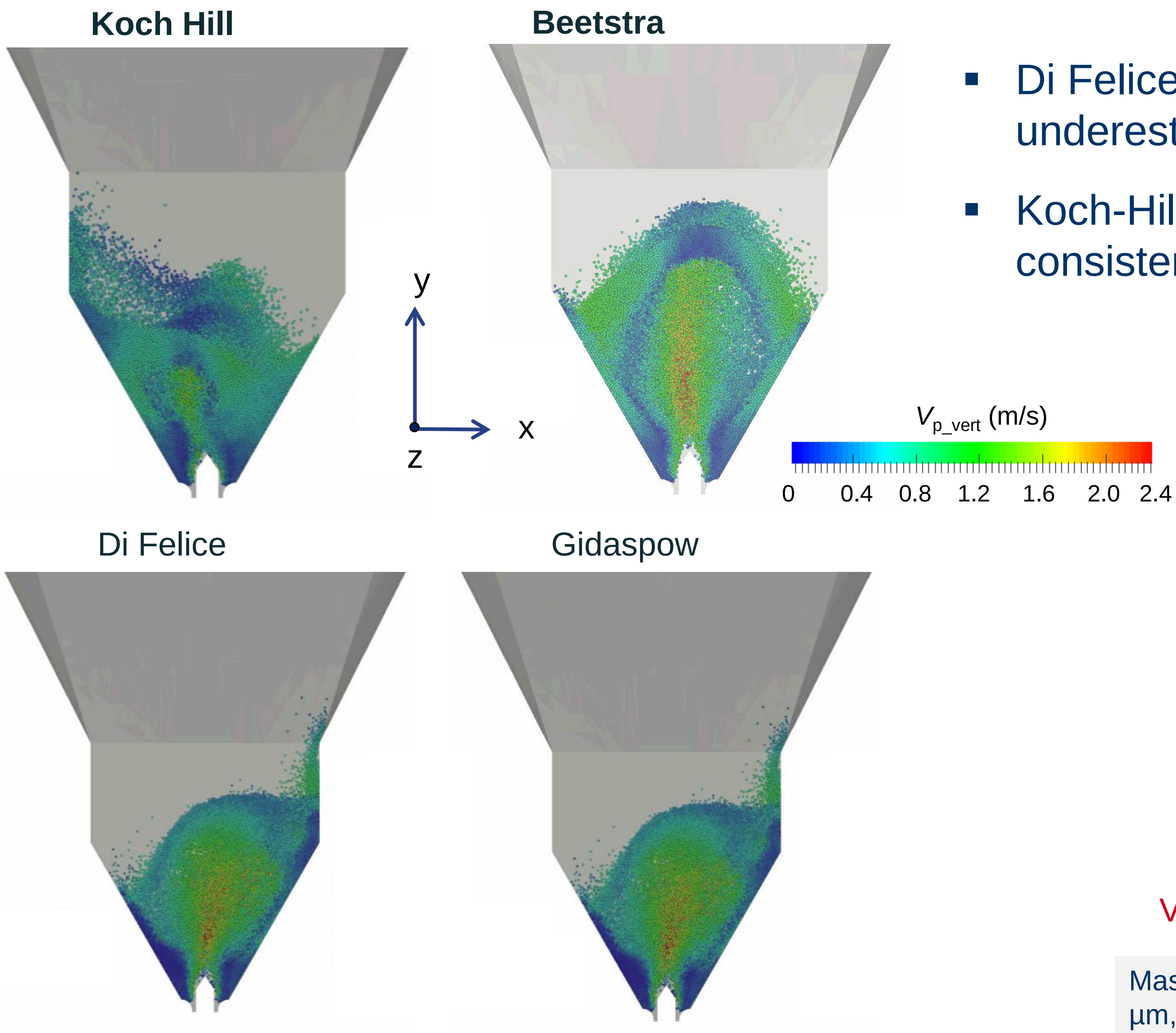
E_{kin}	Dissipated energy, kgm²/s²	m_{eff}	Reduced mass, kg
$v_{n,rel}$	Normal components of relative velocity, m/s	d_p	Particle diameter, µm
δ	Scaling factor	$d_p{}'$	Scaled particle diameter, µm

Input parameter / numerical settings

Parameter/setting	Symbol	Value	Unit
Time step:			
- CFD	Δt_{CFD}	1.25 · 10-4	s
- DEM	Δt_{DEM}	5 · 10-7	s
Particle density	ρ_p	1328	kg/m³
Gas density	ρ_g	1.225	kg/m³
Gas dynamic viscosity	μ_g	1.7894 · 10-5	kg/(m·s)
Gas flow rate	$\dot{V}$	25; 75; 125; 175	m³/h
Particles:			
- Young's modulus	Y_p	3.06	GPa
- Poisson's ratio	ϑ_p	0.3	-

Parameter/setting	Symbol	Value	Unit
Wall:			
- Young's modulus	Y_w	2.5	GPa
- Poisson's ratio	ϑ_w	0.3	-
Restitution coefficient:			
Particle-particle	e_{p-p}	0.72	-
Particle-wall	e_{p-w}	0.73	-
Static friction:			
- Particle-particle	$\mu_{s,p-p}$	0.06	-
- Particle-wall	$\mu_{s,p-w}$	0.05	-
Scaling factor	δ	4	-

[1] C. Bierwisch, T. Kraft, H. Riedel, M. Moseler; Journal of the Mechanics and Physics of Solids, 57 (2009), 10-31.

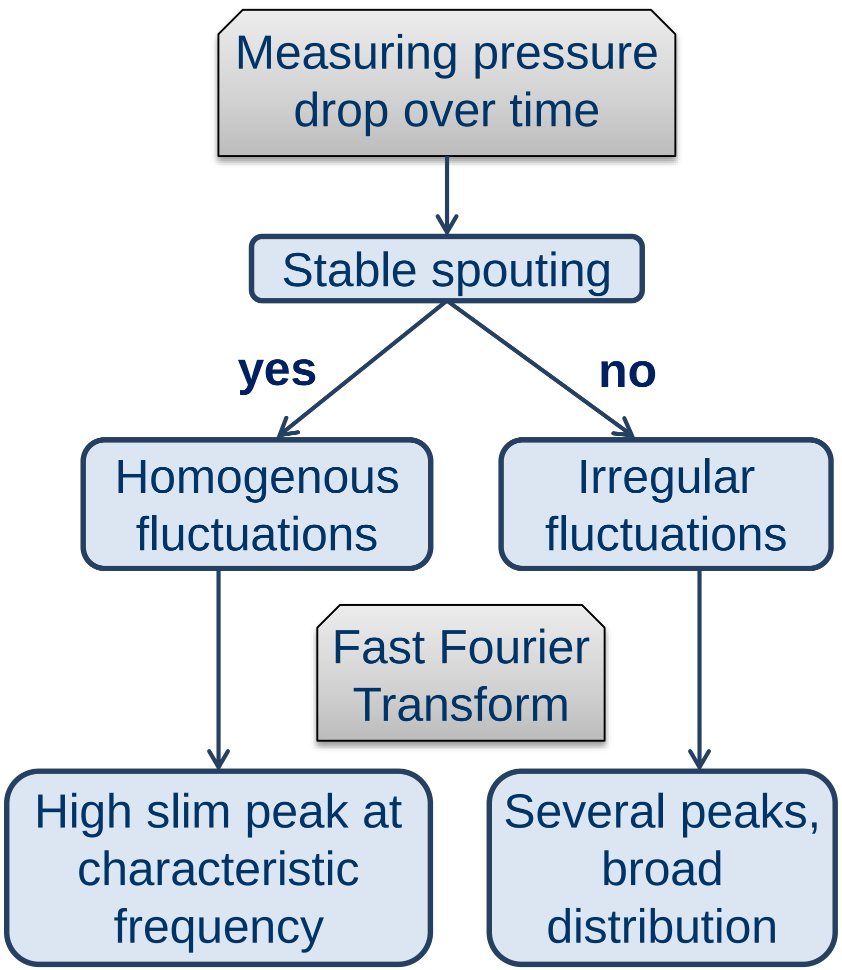


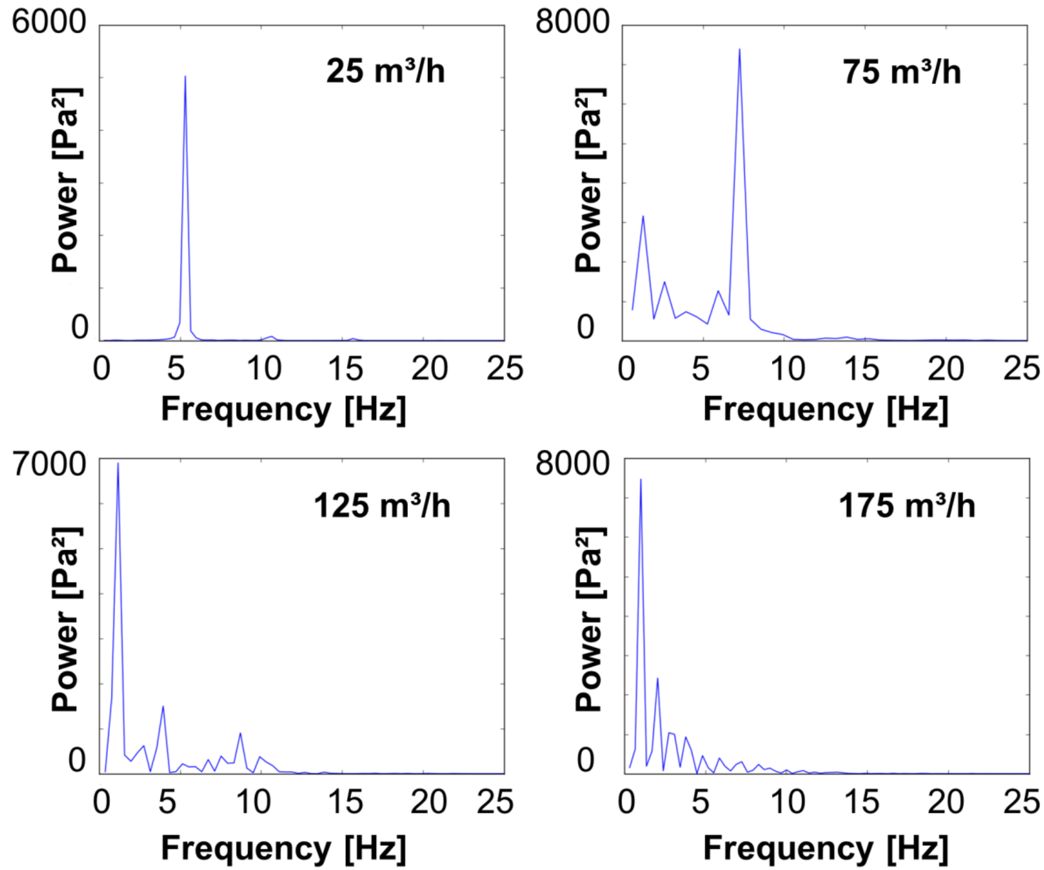
- Di Felice and Gidaspow: underestimated bed expansion
- Koch-Hill and Beetstra: qualitative consistence with experiments

Visual experimental validation

Mass: 1.0 kg $\gamma - Al_2O_3$, particle size: 656 µm, fluidization gas: air, 125 m³/h

FFT Analysis:

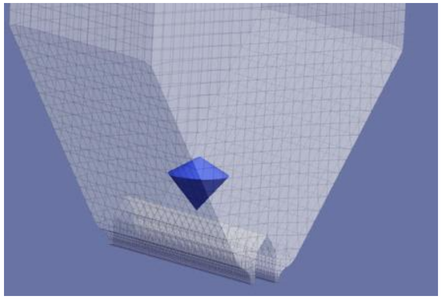




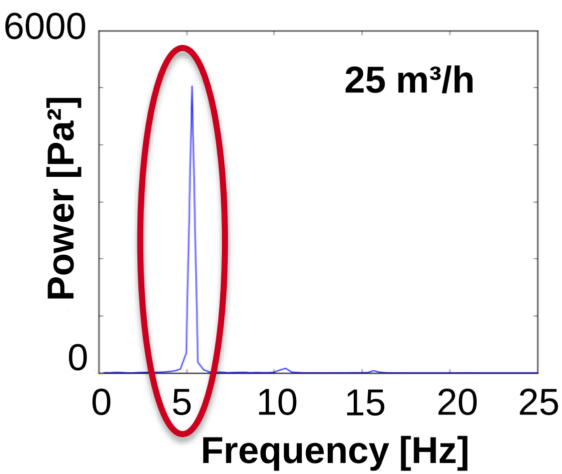
- 25 m³/h: single peak
  → homogeneous flow but weak spouting
- 125 m³/h: several peaks, broad distribution
  → inhomogeneous spouting

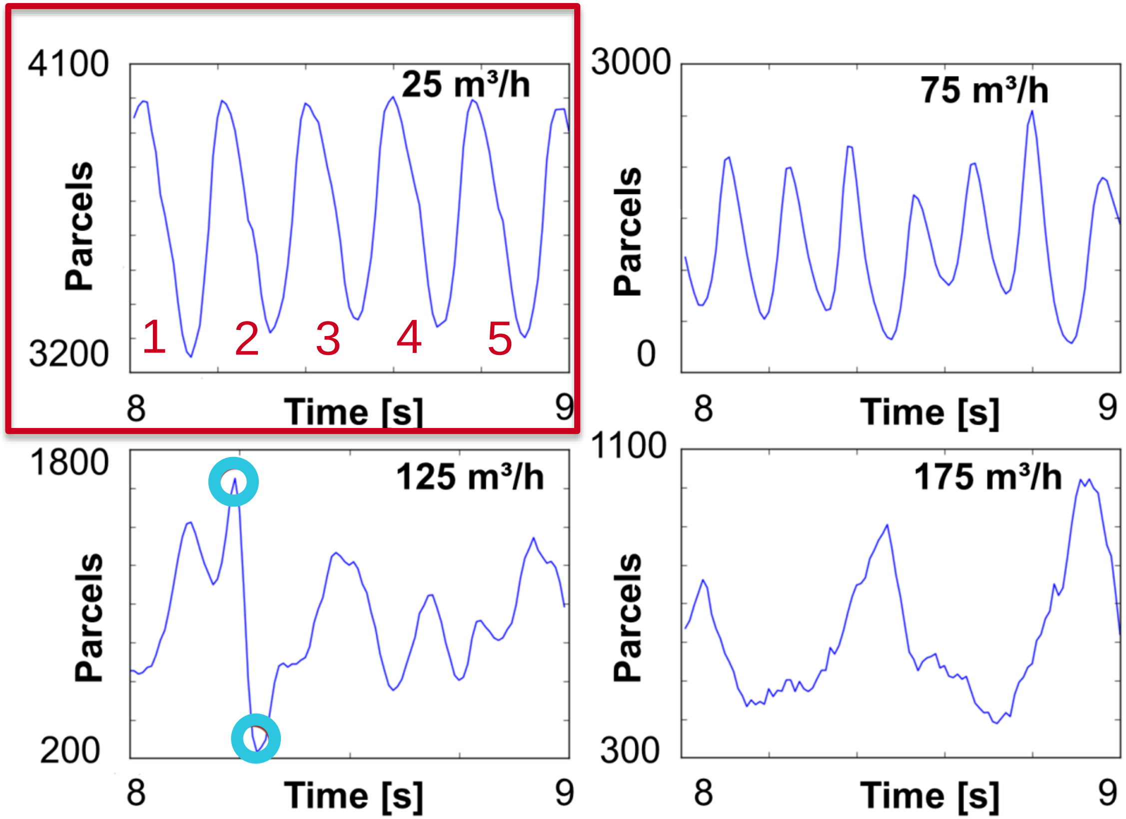
Simulation results

Residence times in spray zone



Periodic fluctuations with dominant frequency





Increasing inhomogeneity with higher gas flow rates

How can the spouting stability be improved?

→ Installation of draft plates [1]

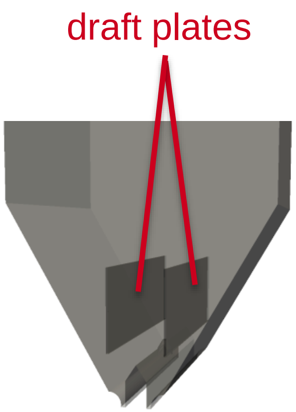
[1] V. Salikov, S. Heinrich, S. Antonyuk, V.S. Sutkar, N.G. Deen, J.A.M. Kuipers; Advanced Powder Technology, 26 (2015), 718-733.

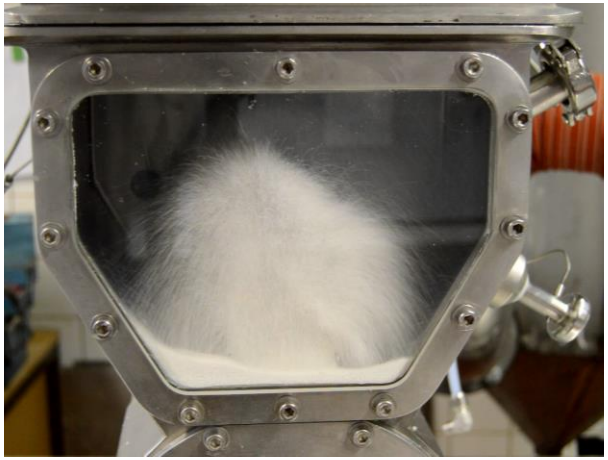
Experimental results

Installation of draft plates

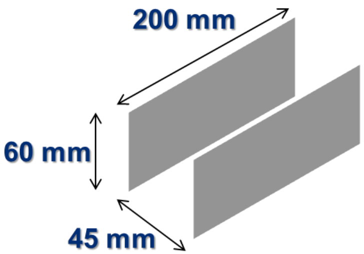
Without draft plates | **With draft plates**

125 m³/h



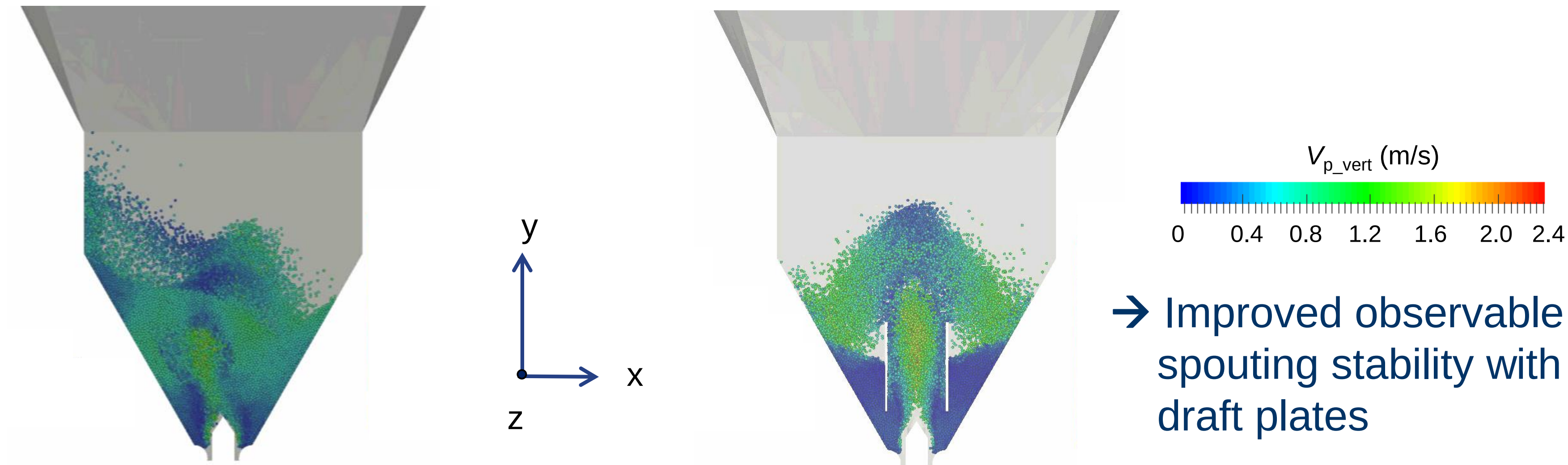


200 m³/h

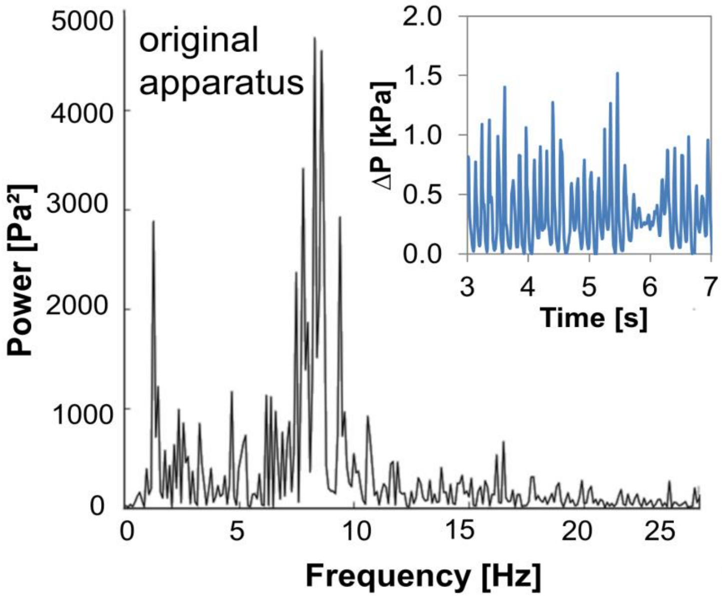


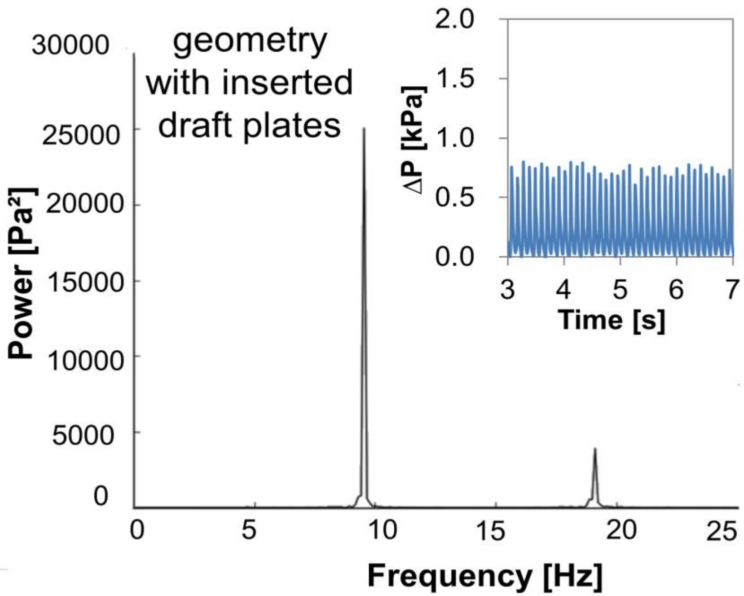
→ Visual evaluation: improved spouting stability with draft plates

Without draft plates | **With draft plates**



→ Improved observable spouting stability with draft plates



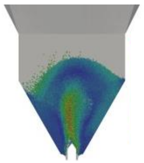


→ Single slim peak at about 9 Hz and harmonic at about 18 Hz

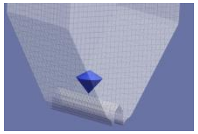
→ System is quantitatively less chaotic

Summary and outlook

Summary



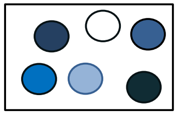
- A spouted bed was modeled with coupled CFD-DEM approach
- Drag models of Koch and Hill and Beetstra represent spouting behavior
- Influence of spouting stability on the spray zone was studied

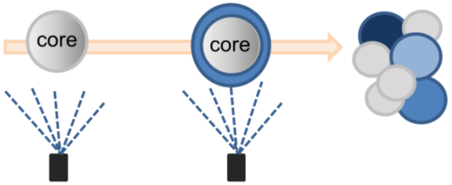


- Spouting stability is improved by inserting draft plates into the process chamber

Outlook

- Development and implementation of models in CFD-DEM simulations for liquid injection and particle growth (droplet generation, evaporation, sticking criteria, cohesion, change of particle properties due to liquid layer etc.)





- Implementation of continuous process

Thank you.