TU Clausthal

Institut für
Technische Mechanik

Transport of solid-liquid suspensions in wellbore drilling: multiscale modeling and experimental validations

Institute of Applied Mechanics

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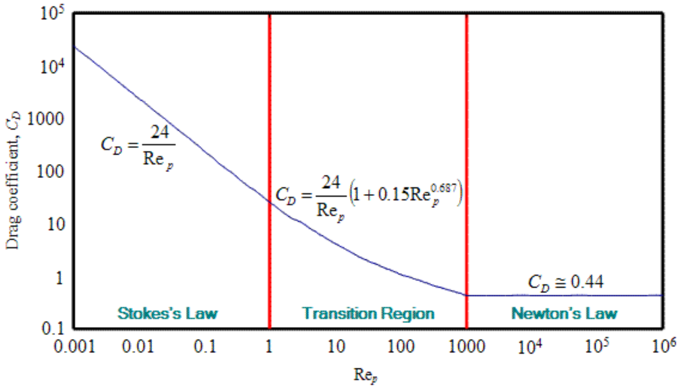
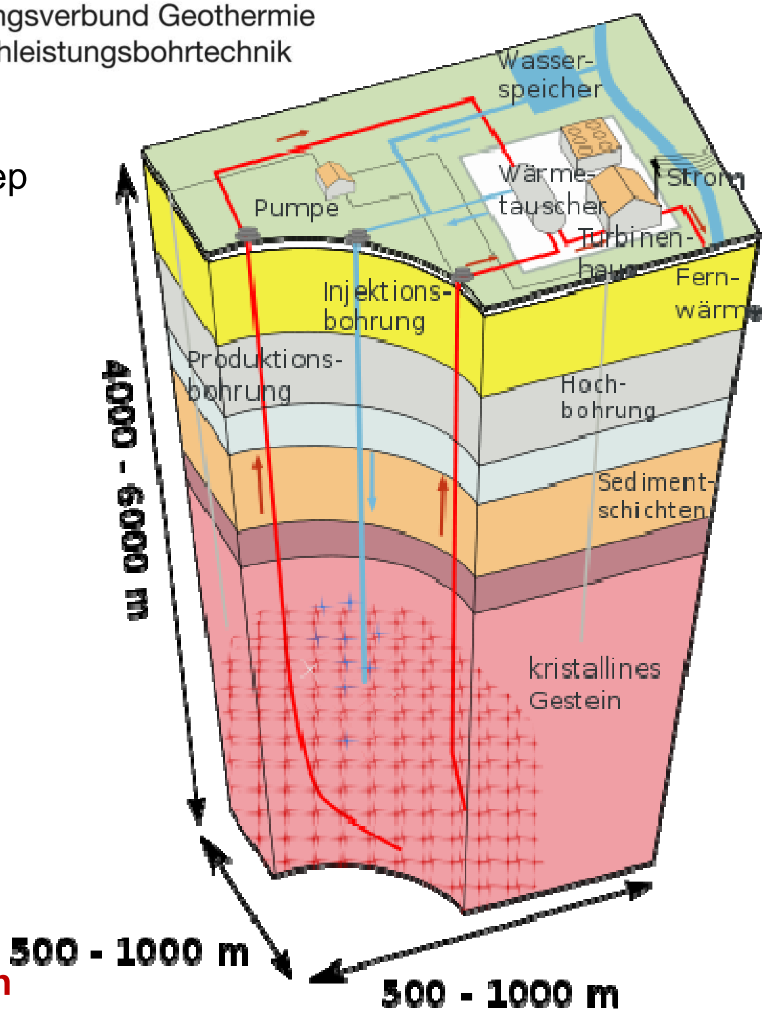
Motivation

gebo Forschungsverbund Geothermie und Hochleistungsbohrtechnik

- Deep geothermal drilling
  - Construction of wellbores up to 10.000 meter deep
  - Cost reduction - 3.000 €/Meter
- Hole-cleaning challenges
  - Variable operating conditions and geometries
  - Complex rheology
  - Multiphase flow (non-Stokesian suspensions)





Source: *Geothermie_Prinzip01.jpg: "Siemens Pressebild" http://www.siemens.com

Understanding and modeling of interactions between dispersed (solid) and continuous (liquid) phases are still unclear

Multiscale approach

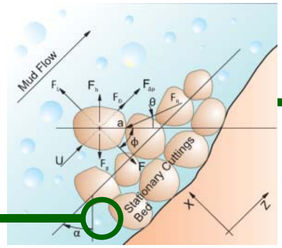
Simulation/Experiment for physical phenomena quantification

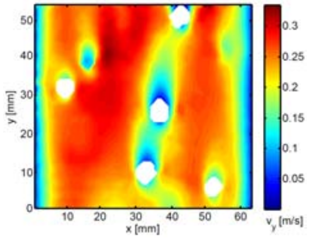
Prediction
Control
Optimization

Rheology

Microscale

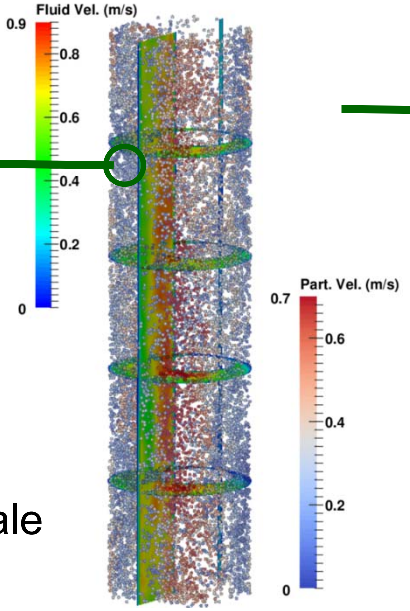
Granular flow
Sediment



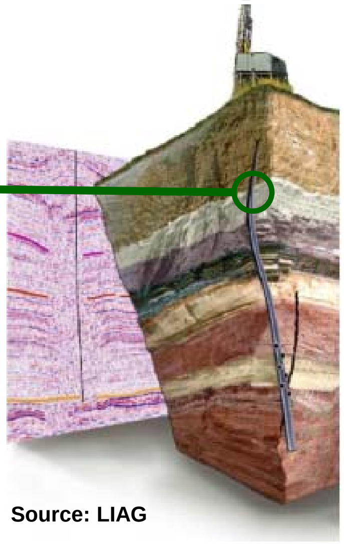


Mesoscale

Well-bore section
Bottom-hole zone



Well-bore system



Source: LIAG

Macroscale

<10^{-6} 10^{-3} 10^{0} 10^{3} meters

Modeling at system-level

- 1D-Drift-flux Model (unsteady): Formulation

  - Continuity (mixture)

$$\frac{\partial A\rho_m}{\partial t} + \frac{\partial A\rho_m V_m}{\partial s} = 0$$

  - Momentum (mixture)

$$\frac{\partial A\rho_m V_m}{\partial t} + \frac{\partial A\rho_m V_m^2}{\partial s} = -A\frac{\partial p}{\partial s} + A\rho_m g\cos\phi - A\Delta p_v$$

  - Continuity (dispersed phase)

$$\frac{\partial \rho_d \alpha_d}{\partial t} + \frac{\partial \rho_d \alpha_d V_d}{\partial s} = 0$$

V_m	average velocity of the mixture
V_d	average velocity of the dispersed phase
p	pressure

Modeling at system-level

- 1D-Drift-flux Model: Closures

- Pressure loss

$$\Delta p_v = \frac{L}{2A}\, f\, \rho_m V_m |V_m|$$

Pilehvari & Serth (2009)
power law fluid

$$f_L = 64/\mathrm{Re}_{\mathrm{eff}} \quad \text{Laminar}$$

$$f_T{}^{-0.5} = -4\log_{10}\mathrm{A} \quad \text{Turbulent}$$

$$Re_{eff0} = \frac{D_{eff}^{n'} U^{2-n'} \rho}{8^{(n'-1)} K'}$$

$$D_{eff} = \frac{\omega' D_O^{(3n'+1)/n'}}{(D_I + D_O) D_h{}^{\frac{n'+1}{n'}} (R')^{1/n'}}$$

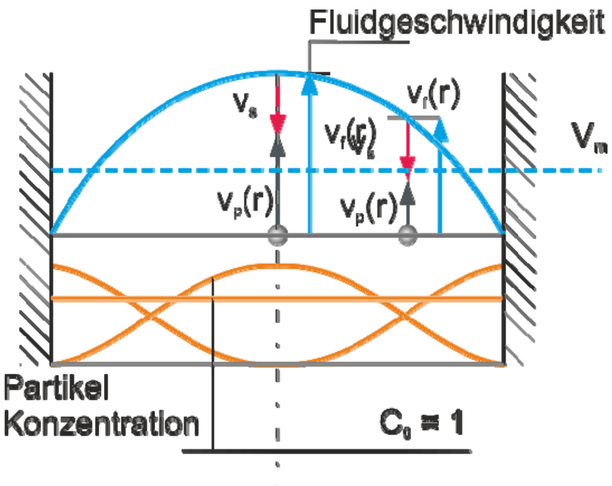
$$A = \left\{ (0.27\ \varepsilon/D_{eff}) + 1.26^{(n')^{-1.2}} / \left[\mathrm{Re}_{\mathrm{eff}}\, f_T{}^{(1-n'/2)}\right]^{(n')^{-0.75}} \right\}$$

- disperse Phase

$$V_d = C_0 V_m + V_{dj}$$

$$\frac{\partial \rho_d \alpha_d}{\partial t} + \frac{\partial \rho_d \alpha_d V_m C_0}{\partial s} = -\frac{\alpha_d \rho_d V_{dj}}{\partial s}$$

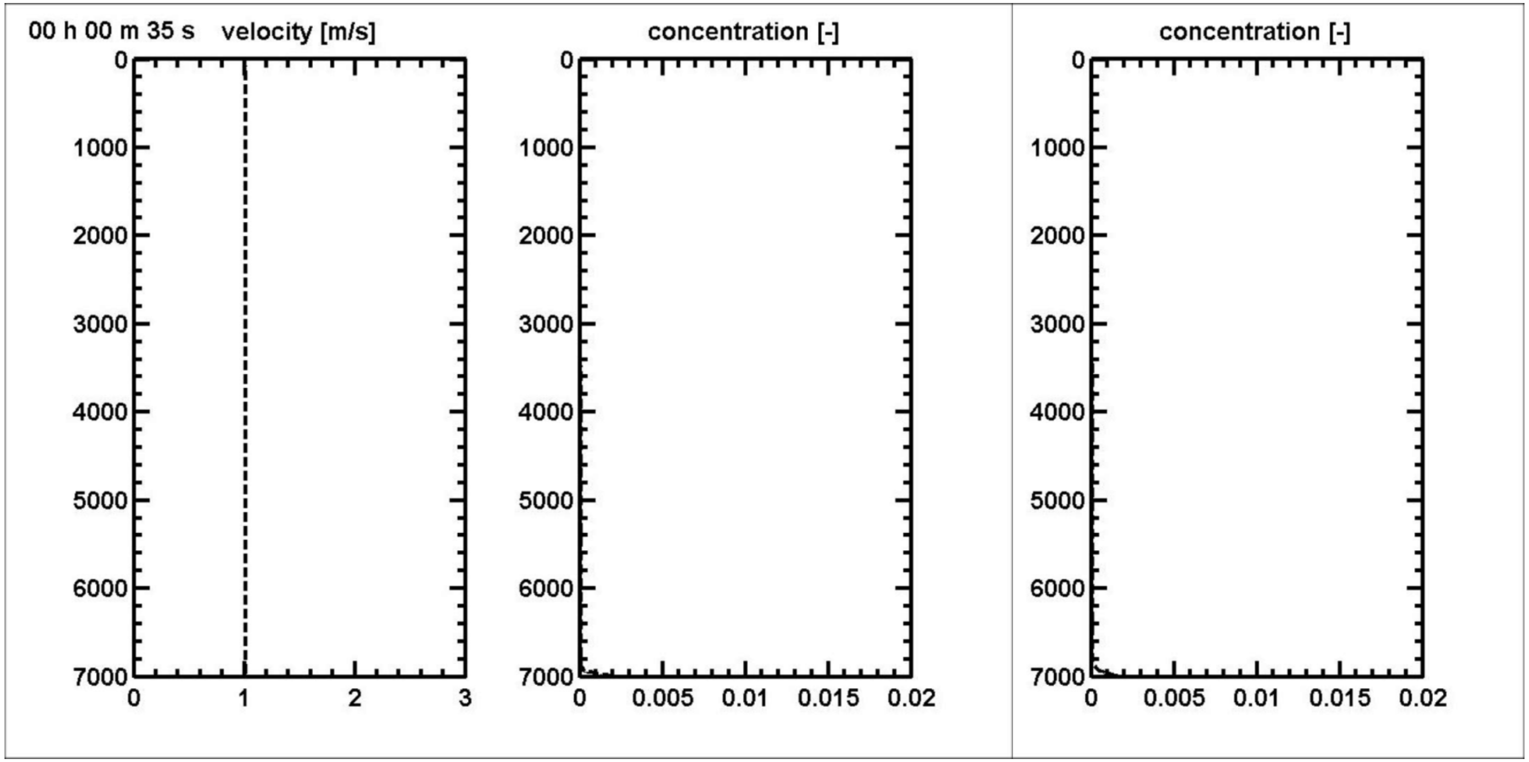
Empirical parameters $\begin{cases} C_0 & \text{Distribution Coefficient} \\ V_{dj} & \text{Drift Flux Velocity} \end{cases}$

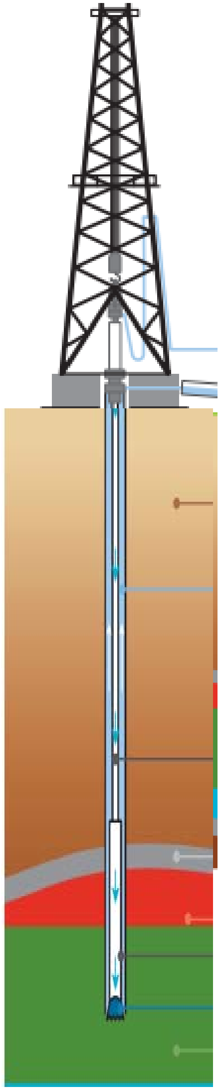


Modeling at system-level

- 1D-Drift-flux Model: Distribution Coefficient sensitivity

$C_0 = 0.8$ $\quad$ $C_0 = 1.2$





Experimental benchmark

PARAMETERS

Particles (Soda lime glass and Borosilicate)

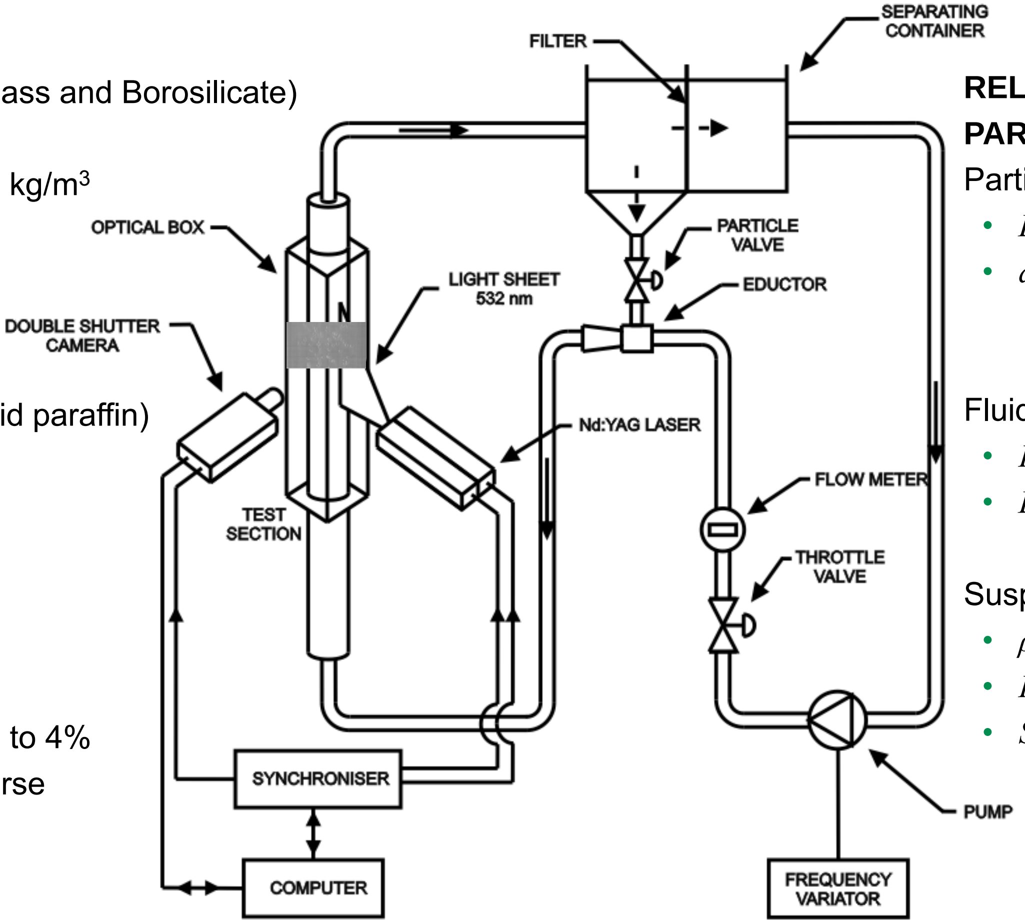
- Shape: spherical
- ρ_p = 2230 and 2580 kg/m^3
- $d_p = 2 \div 6$ mm

Fluid Phase (Light liquid paraffin)

- ρ_f = 865 kg/m^3
- μ = 72 mPa.s
- D = 64 mm
- Length = 2000 mm

Suspension

- ϕ (volume load) up to 4%
- Mono- and bidisperse



RELEVANT DIMENSIONLESS PARAMETERS

Particles

- $D / d_p = 12.8 \div 32$
- $d_l / d_s = 1.25 \div 2$

Fluid Phase

- $Re_D = 25 \div 300$
- $L_r / D = 1 \div 13$

Suspension

- ρ_p / ρ_f = 2.5 and 2.9
- $Re_p = 1 \div 28$
- $St = 0.5 \div 7.5$

MEASURING EQUIPMENT

- Laser system: Solo PIV double-pulsed Nd:YAG, 30 mJ at 532 nm
- Camera: PCO sensicam qe, 1.376 x 1.040 pixels and 12-bit resolution
- Lens: Nikon Micro-NIKKOR 55 mm

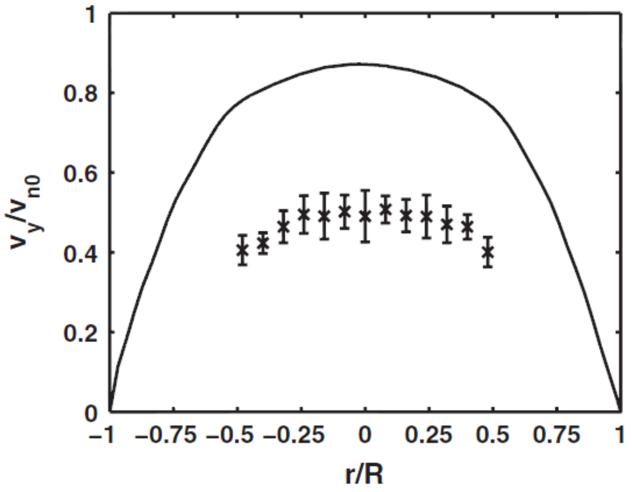
Aragall, R., Mulchandani, V., & Brenner, G. (2015). *IJMF*, *69*, 63-80.

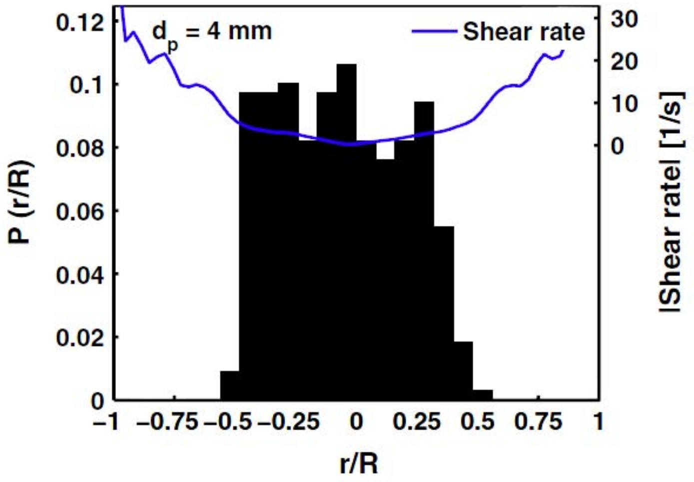
Experimental results – monodisperse flow: experiments #7 and #10

Velocity

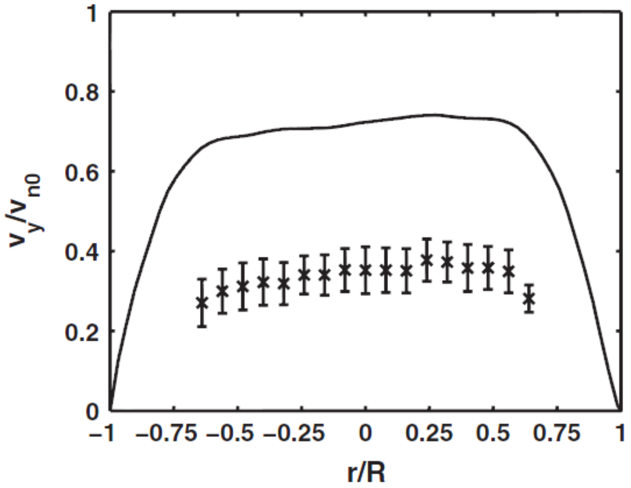
Particle distribution

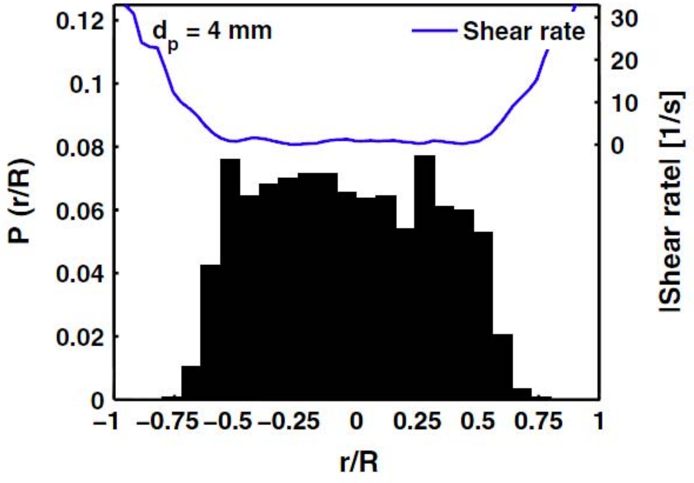
$Re_D = 289$
$\phi_4 \approx 0.12\%$
$\overline{\sigma_4} = 15$ mm/s





$Re_D = 261$
$\phi_4 \approx 0.50\%$
$\overline{\sigma_4} = 19$ mm/s

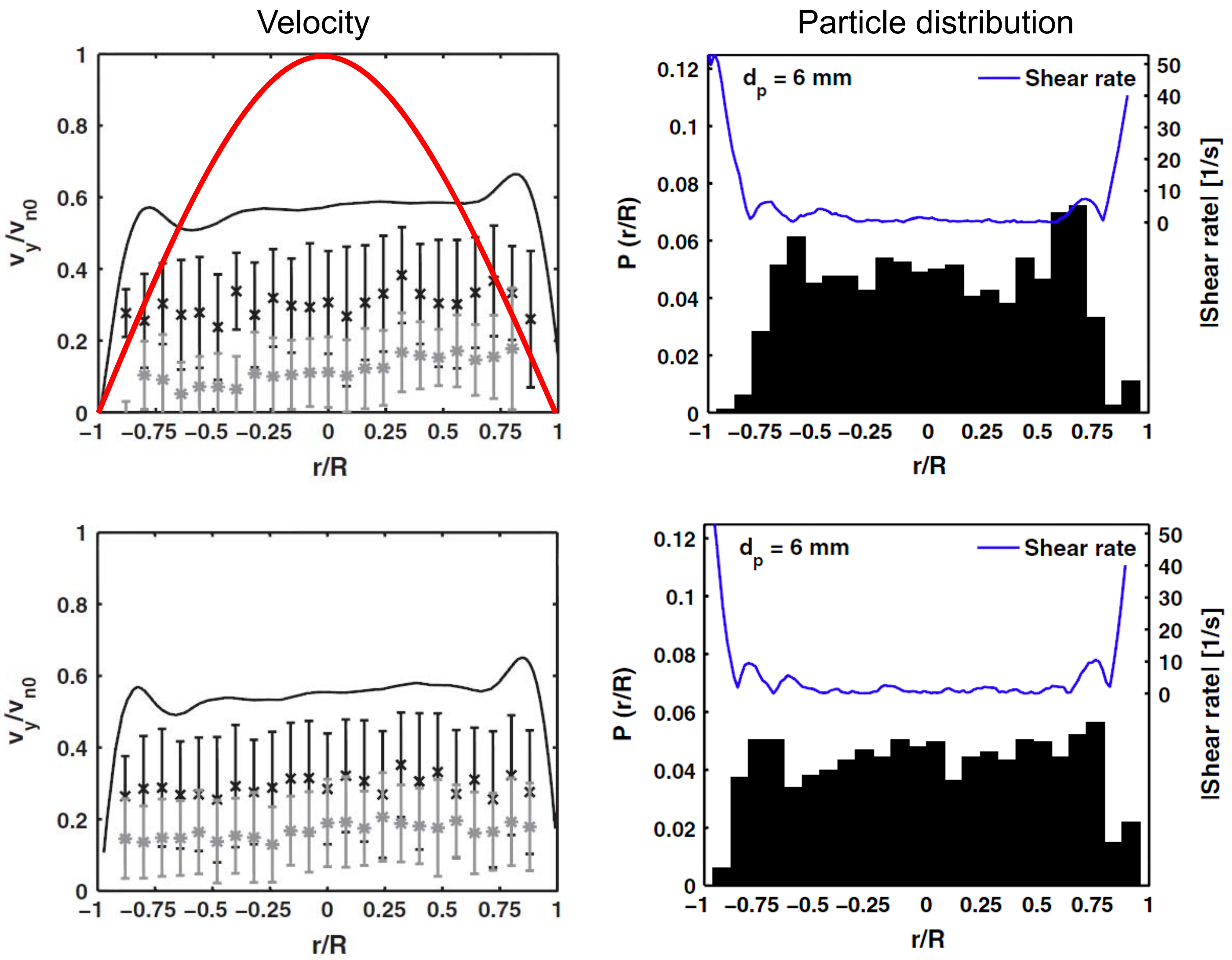




Experimental results – bidisperse flow: experiments #46 and #62

$Re_D = 224$
$\phi_4 \approx 1.00\%$
$\overline{\sigma}_4 = 69$ mm/s
$\phi_6 \approx 1.00\%$
$\overline{\sigma}_6 = 37$ mm/s

$Re_D = 235$
$\phi_4 \approx 2.00\%$
$\overline{\sigma}_4 = 77$ mm/s
$\phi_6 \approx 2.00\%$
$\overline{\sigma}_6 = 49$ mm/s


Velocity

Particle distribution

Modeling at meso- level – CFD-DEM coupling

CFD part

$$\frac{\partial}{\partial t}(\rho_f\alpha_f)+\nabla\cdot(\rho_f\alpha_f u_f)=0$$

$$\frac{\partial}{\partial t}(\rho_f\alpha_f u_f)+\nabla\cdot(\rho_f\alpha_f u_f u_f)=-\alpha_i\nabla p+\rho_f\alpha_f g+\nabla\cdot\tau_i+n f_i$$

DEM part

$$m_i\frac{dv_i}{dt}=f_{pf,i}+\sum_{j=1}^{k_c}(f_{c,ij}+f_{d,ij})+m_i g \qquad I_i\frac{d\omega_i}{dt}=\sum_{j=1}^{k_c}(M_{t,ij}+M_{r,ij})$$

α_f	fluid volume fraction
u_f	fluid velocity
τ, p	fluid stress tensor, pressure
ρ_f	fluid density
n f_i	number of particles per unit volume and local mean value of the force on particle *i* by its surrounding fluid

m_i	mass of the particle *i*
v_i	translational velocity particle *i*
I_i	moment of inertia of particle *i*
f_i	force acting on particle *i*
M_{ij}	torque acting on particle *i* by particle *j*
pf, c, d	particle-fluid, elastic and viscous forces
t, r	tangential force and rolling friction torque

CFDEM solver – cfdemSolverPiso

Solver for unresolved CFD-DEM coupling. OpenFOAM Piso algorithm for CFD and LIGGGHTS for DEM.

Interfacial models: several empirical models for drag force (Schiller-Naumann, Gidaspow, Di Felice)

Lift force with Saffman-Mei model and virtual mass force with constant coefficients.

Modeling at meso-level

Numerical Simulation of the benchmark through CFDEM

<u>Bidisperse Suspension</u>

Re_D = 257

d_p= 4 mm, Φ_4 = 0.62 %

d_p= 5 mm, Φ_5 = 0.50 %

<u>Numerical set-up</u>

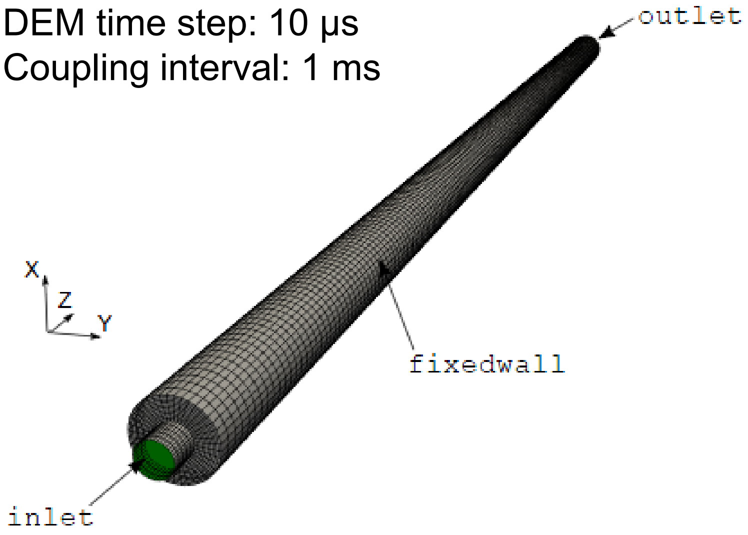
model type: A

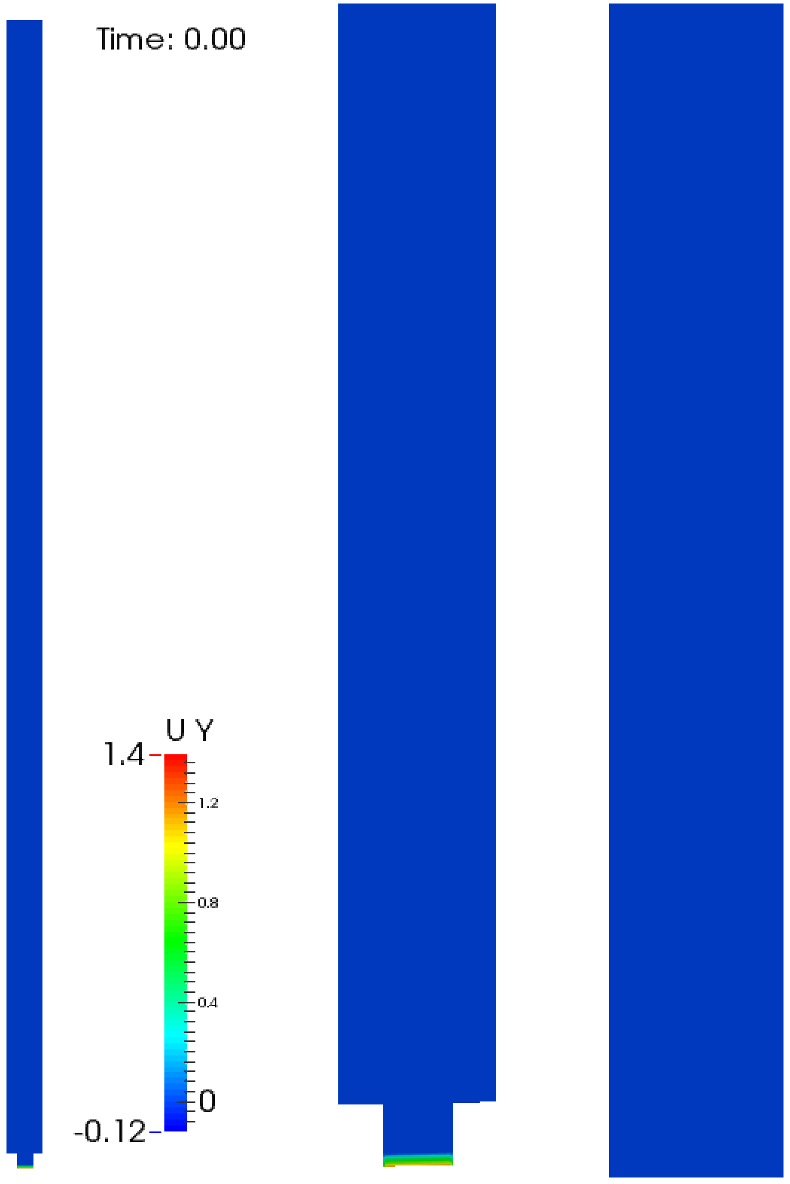
void Fraction Model: divided

CFD time step: 1 ms

DEM time step: 10 µs

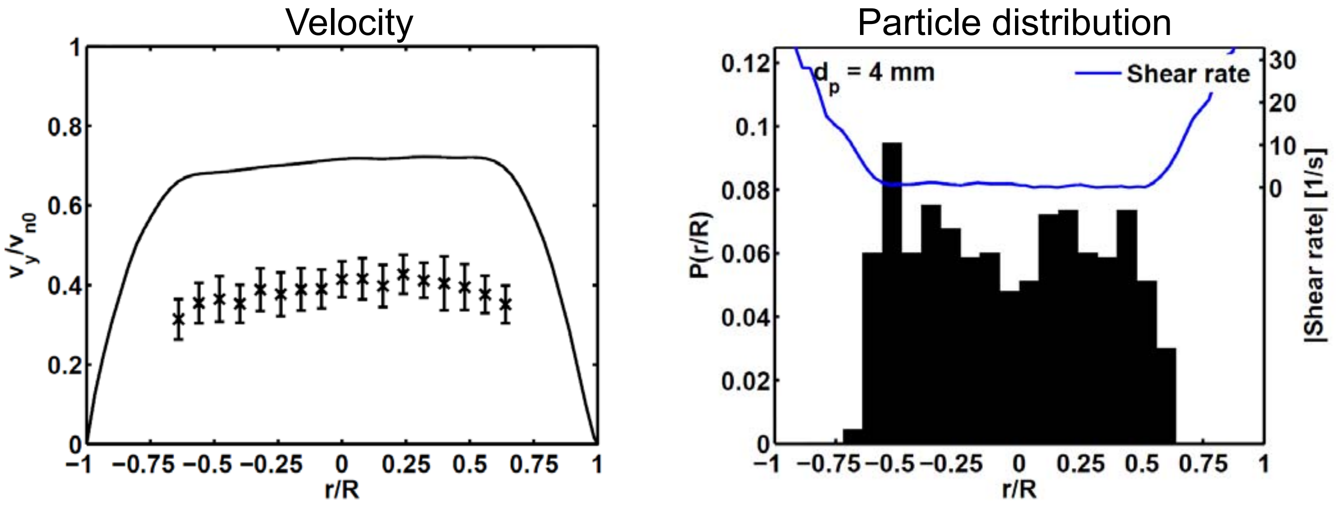
Coupling interval: 1 ms



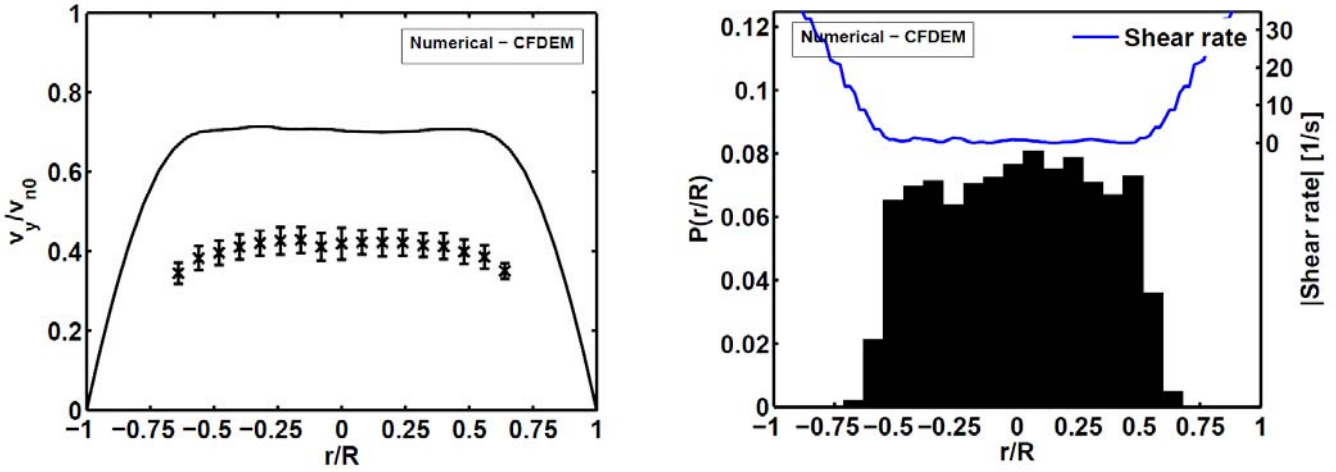


Comparison – monodisperse flow: experiment #15

PIV + PTV
Re_D = 270
$\phi_4 \approx 0.62\%$
$\overline{\sigma}_4$ = 22 mm/s



CFD DEM
Re_D = 270
$\phi_4 = 0.62\%$
$\overline{\sigma}_4$ = 15 mm/s

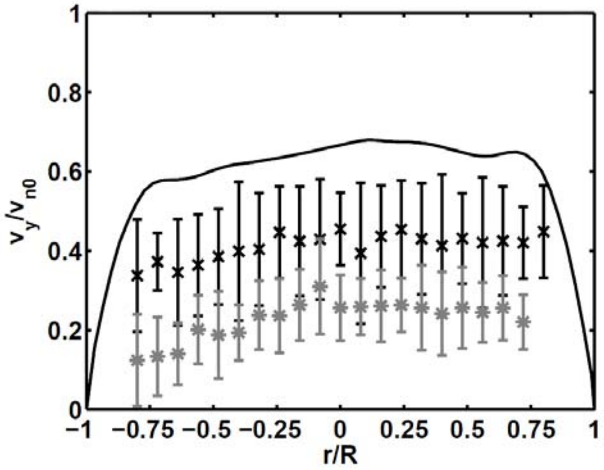


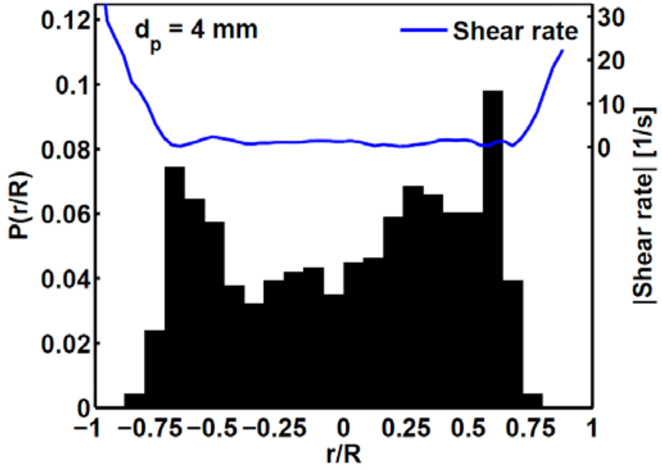
Comparison – bidisperse flow: experiment #6

Velocity

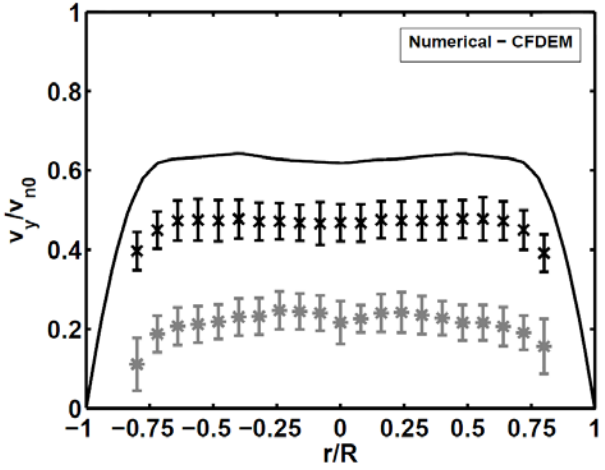
Particle distribution

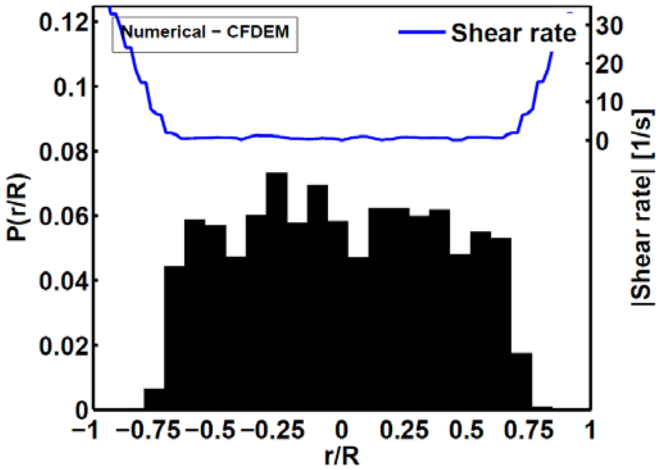
PIV + PTV
$Re_D = 177$
$\phi_2 \approx 0.37\%$
$\overline{\sigma_2} = 40$ mm/s
$\phi_4 \approx 0.62\%$
$\overline{\sigma_4} = 26$ mm/s





CFD DEM
$Re_D = 177$
$\phi_2 = 0.37\%$
$\overline{\sigma_2} = 17$ mm/s
$\phi_4 = 0.62\%$
$\overline{\sigma_4} = 17$ mm/s



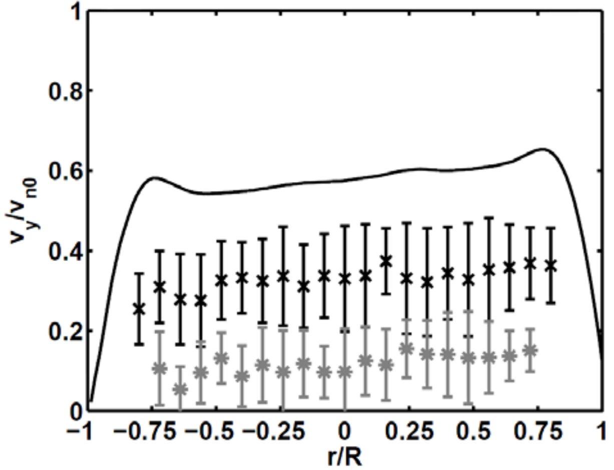


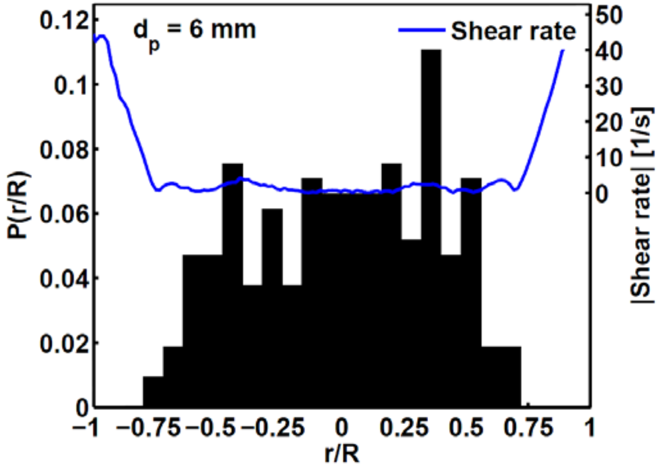
Comparison – bidisperse flow: experiment #46

Velocity

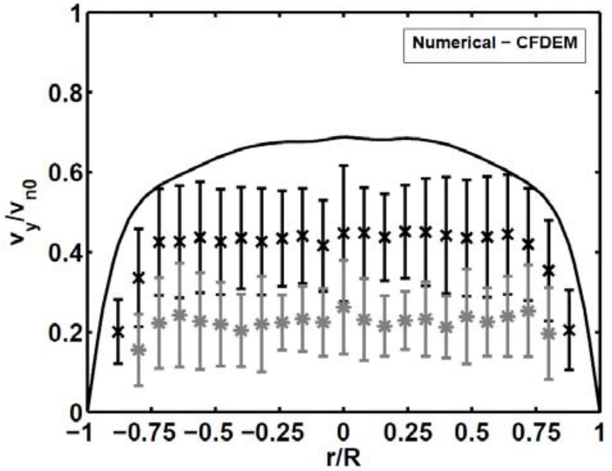
Particle distribution

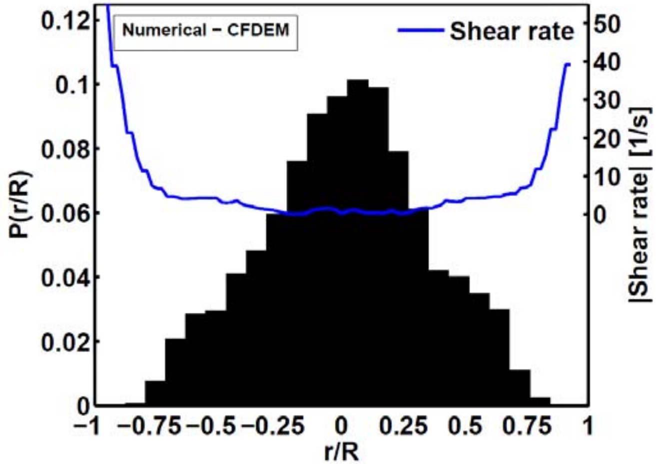
PIV + PTV
$Re_D = 246$
$\phi_4 \approx 1.00\%$
$\overline{\sigma}_4 = 42$ mm/s
$\phi_6 \approx 0.25\%$
$\overline{\sigma}_6 = 29$ mm/s





CFD DEM
$Re_D = 246$
$\phi_4 = 1.00\%$
$\overline{\sigma}_4 = 57$ mm/s
$\phi_6 = 0.25\%$
$\overline{\sigma}_6 = 44$ mm/s





Analysis of the effect of eccentricity on vertical cuttings transport

- Fixed parameters:
  - **Length** = 1,000 mm
  - **D$_o$** = 250 mm **D$_i$** = 125 mm

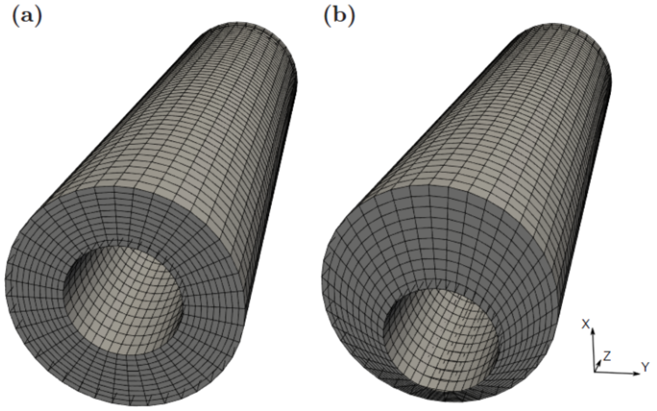
- Varied parameters:
  - **Eccentricity** = concentric, 25 and 50%

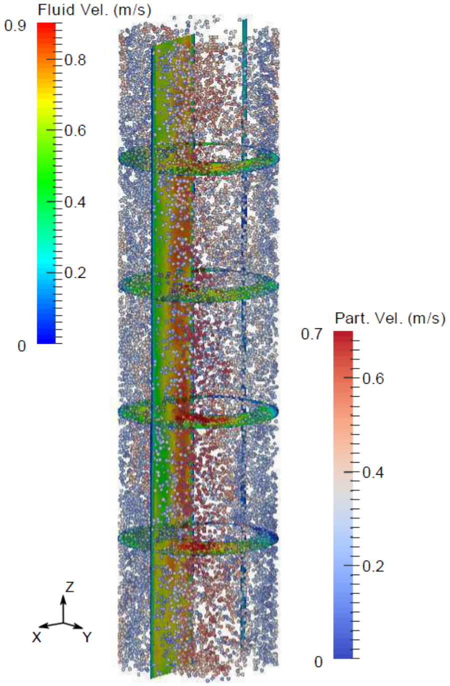
Basic Experiment	Particle Diameter d_p (mm)	Fluid average velocity u_l (m/s)	Dynamic Viscosity η (mPa·s)	Particle Volume Fraction ϕ (%)
S1	4	0.7	50	5
S2	4	0.6	75	2.5
S3	6	0.7	50	1
S4	5	0.5	30	1

- Output parameters:

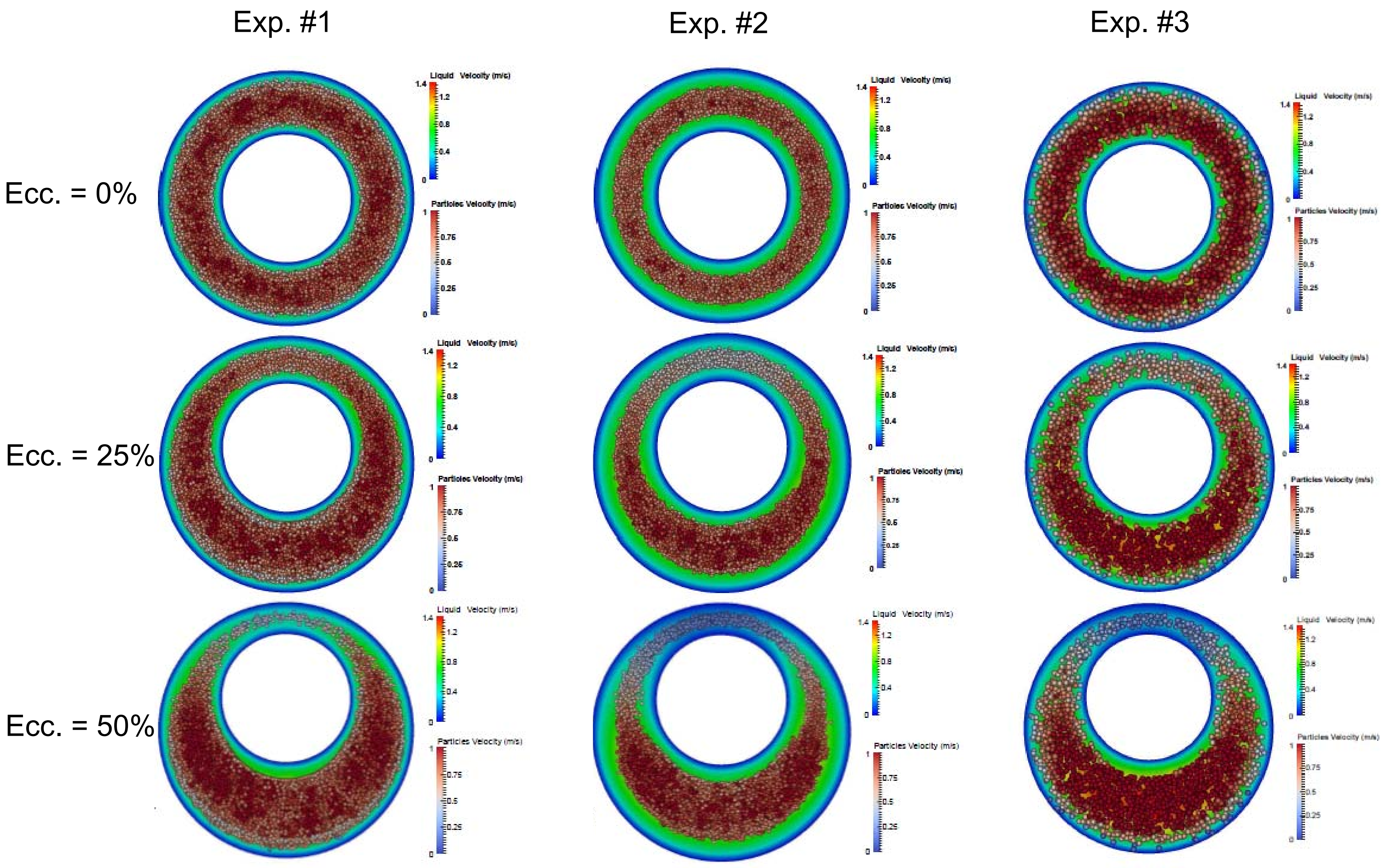
$$C_0 = \frac{\overline{\varepsilon_d j_m}}{E_d V_m} \qquad V_{dj} = \frac{\overline{\varepsilon_d v_{dj}}}{E_d}$$

- Experimental design:
  - 60 seconds to reach stability
  - 20 last seconds saved for averaging





Flow fields and particle distributions



Effect of Velocity and Concentration Profile

- Drift -flux parameters
    - Distribution coefficient

$$C_0 = \frac{\overline{\varepsilon_d j_m}}{E_d V_m} \qquad \overline{\varepsilon_d j_m} = \frac{1}{A}\int_0^A \varepsilon_d j_m dA = \frac{1}{A}\int_0^A \varepsilon_d(\varepsilon_d v_d + \varepsilon_f v_f)dA =$$

$$= \frac{1}{A}\int_0^A \varepsilon_d(\varepsilon_d v_d + (1-\varepsilon_d)v_f)dA$$

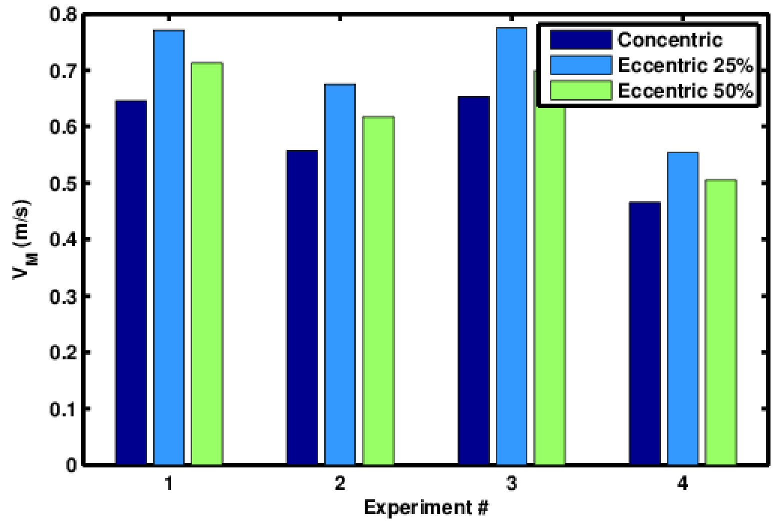
-
    - Drift flux velocity

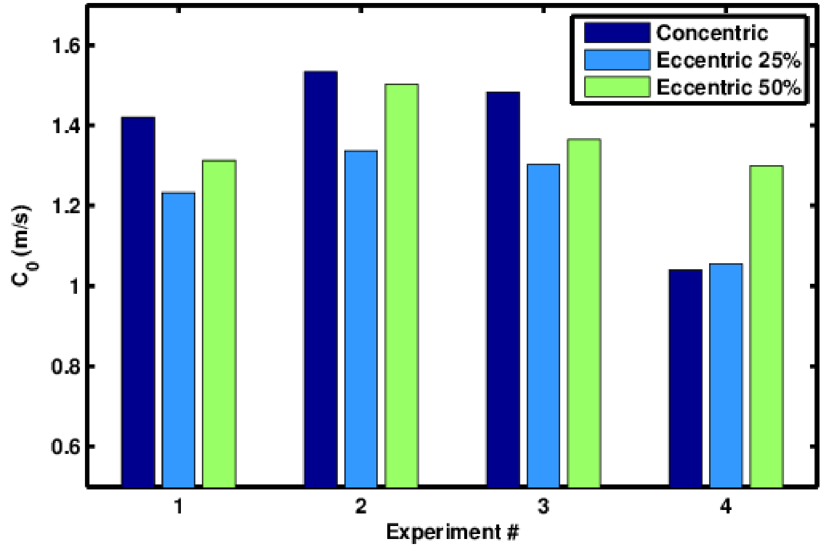
$$V_{dj} = \frac{\overline{\varepsilon_d v_{dj}}}{E_d} \qquad \overline{\varepsilon_d v_{dj}} = \frac{1}{A}\int_0^A \varepsilon_d v_{dj} dA = \frac{1}{A}\int_0^A \varepsilon_d(v_d(\varepsilon_d v_d + \varepsilon_f v_f))dA =$$

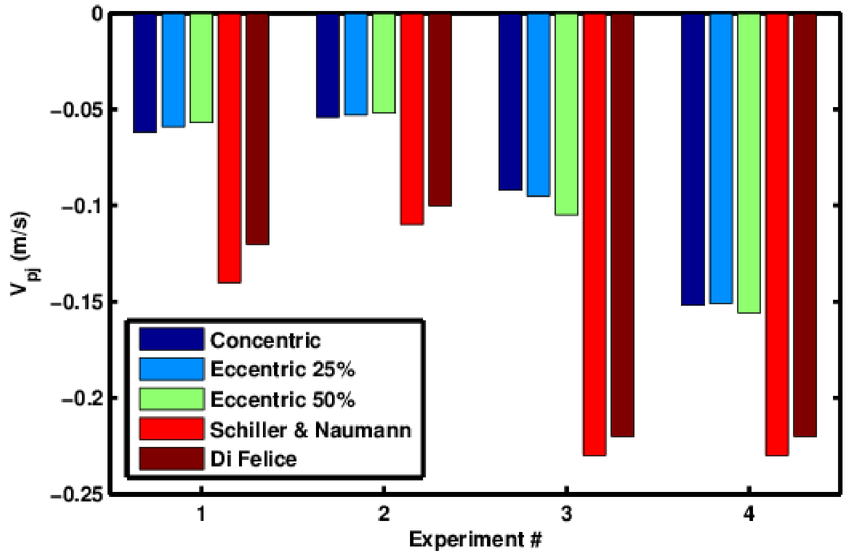
$$= \frac{1}{A}\int_0^A \varepsilon_d(v_d(\varepsilon_d v_d + (1-\varepsilon_d)v_f))dA$$

Distribution coefficients and drift-flux velocities

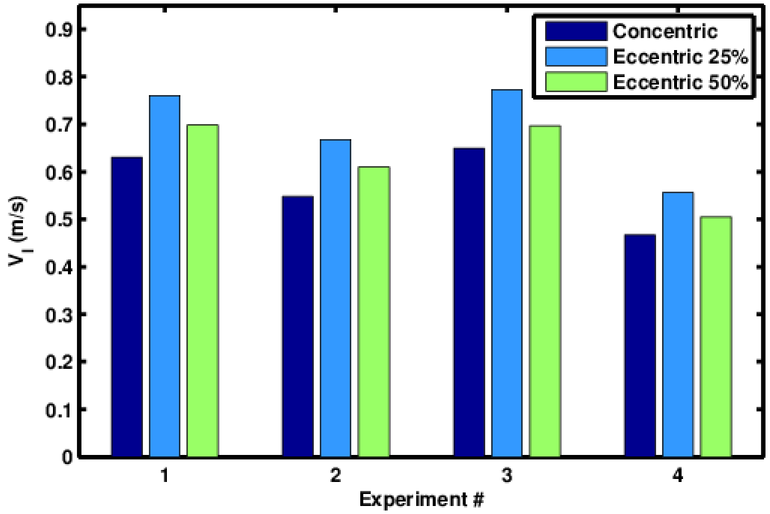
$$V_d = C_0 V_m + V_{dj}$$

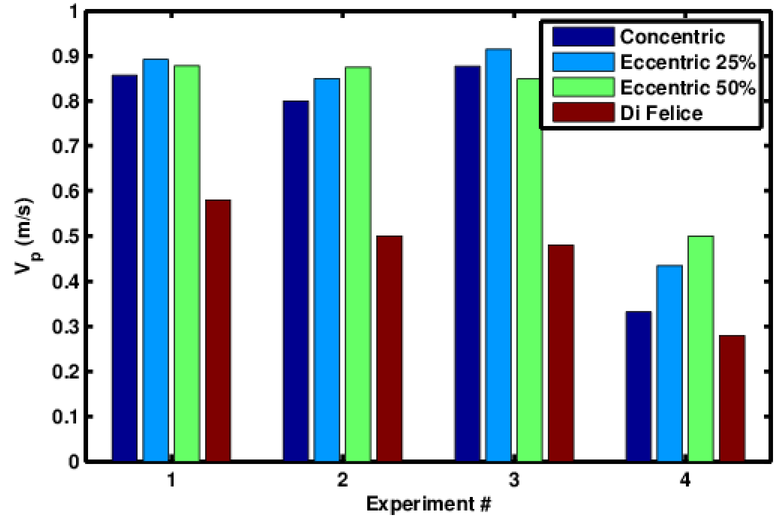


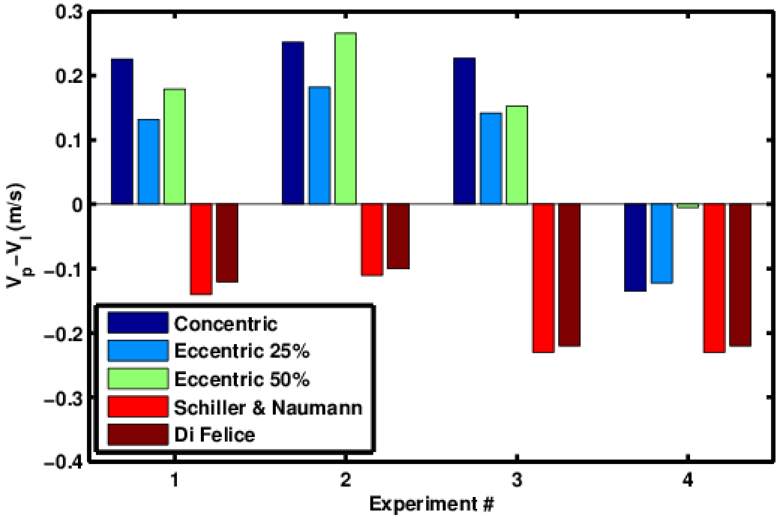


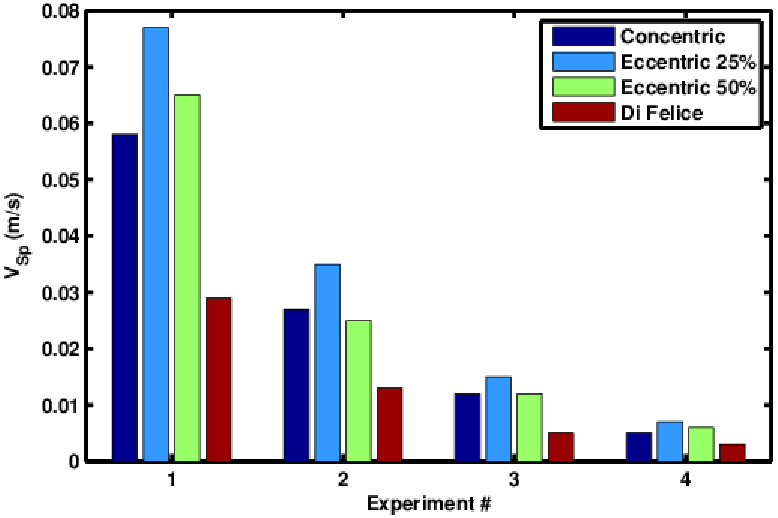


Distribution coefficients and drift-flux velocities









Conclusions and Outlook

- Conclusions
  - System scale models require information from lower scales
  - Numerical simulations are becoming a real alternative to full scale physical experiments
  - Detailed physical experiments focused on fundamental phenomena are still required for the validation phase

- Outlook
  - Development of correlations to predict superficial velocity of the cuttings as a function of operating conditions
  - Further experiments concentrated on pseudoplastic fluids
  - Development of the CFDEM library to include pseudoplastic rheology

Thank you for your attention

gebo Forschungsverbund Geothermie
und Hochleistungsbohrtechnik

BAKER HUGHES

Niedersächsisches Ministerium
für Wissenschaft und Kultur