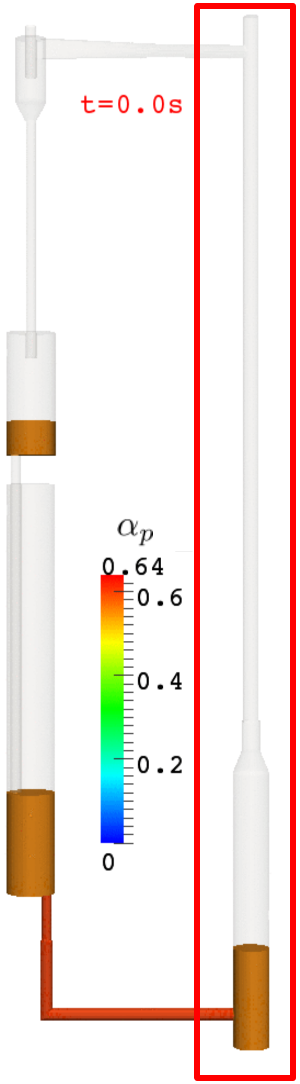
NATIONAL ENERGY TECHNOLOGY LABORATORY

Investigation of a turbulent fluidized bed and riser in an interconnected dual fluidized bed reactor system

August 7th, 2013

Arthur Konan, E. David Huckaby, Justin Weber, Ronald Breault

General Context
(e.g. Chemical Looping Reactor system)



Performance Parameters of interest

- material circulation
- pressure drop

(common to several industrial processes)

Physical Modeling Challenges

- Frictional Flow (L-valve)
- Elutriation/Entrainment
- Chaotic transport

Estimate error in material circulation prediction ?
Focus on Elutriation

Outline

1. **NETL Chemical-Looping cold flow experiment**

2. **Air reactor (+Riser) flow modeling approach**

3. **Results**

   - diameter approximation & elutriation/entrainment

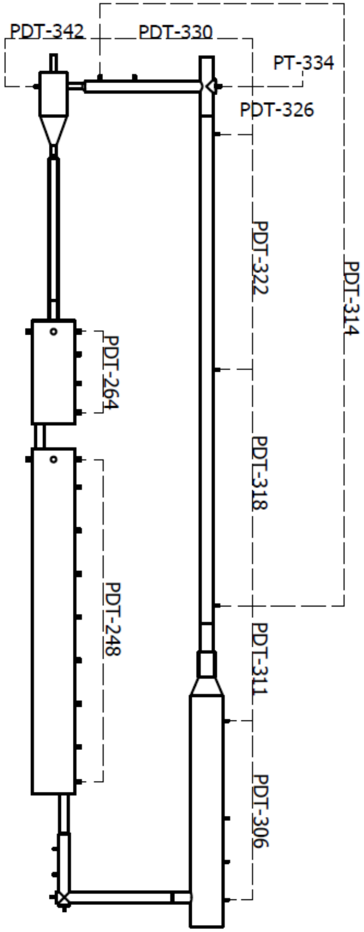
   - non-spherical particle/wall collision & gravitational settling

   - mesh resolution

4. **Conclusions – Future plans**

Experiments
(Chemical Looping Cold Flow Unit)

Cold Unit



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Measurements (available)

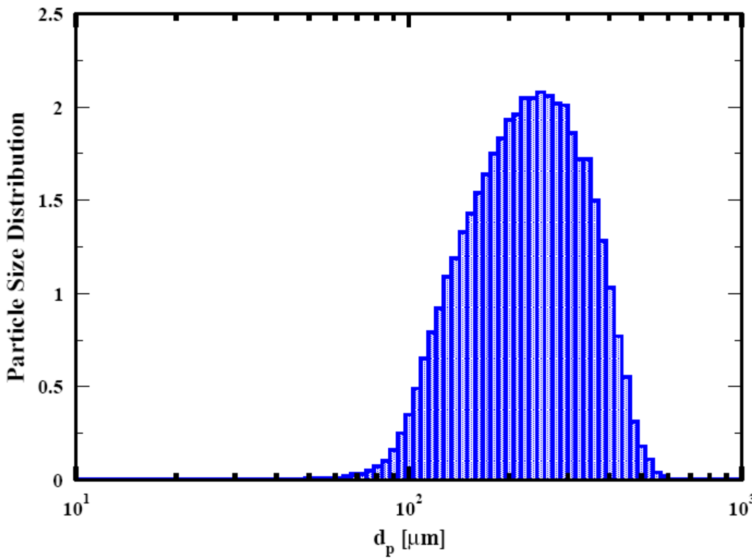
- pressure drop
- circulation rate

Operating Condition B / Mass Flow Rate [SLPM]

Air Reactor	Loop Seal	Fuel Reactor	Aeration / Inductor	Sec. Low / High
200	120	120	5 / 10	800 / 200

Experiments (Materials - Hematite)

Size distribution



$$50\ \mu m \leq d_p \leq 600\ \mu m$$

$$0.58 \leq \text{Sphericity} \leq 0.888$$

Properties	
Density (kg/m^3)	4701
Geldart type	B
d_{50} (μm)	234
d_{32} (μm)	210
Span (PSD)	1.06
Sphericity (mean)	0.847

➘ Broad PSD ⇨ broad distribution of terminal velocity (but will attempt to approximate with mean diameter terminal velocity)

➔ Non-negligible non-sphericity of the materials

Flow timescales: a priori analysis

▶ Fluid-particle interactions

d_p $[\mu m]$	$d_{50}\,(=234)$	$d_{32}\,(=210)$
τ_{ps} $[s]$	0.79	0.64
V_t $[m/s]$	7.79	6.28
τ_f^t/τ_{ps}	5.8×10^{-3}	7.1×10^{-3}

$$\tau_{ps} = \frac{\rho_p}{\rho_f}\frac{d_p^2}{18\nu_f}$$

$$\tau_f^t = C_\mu \frac{3}{2}\frac{k}{\varepsilon}$$

$$V_t = \tau_{ps}\, g$$

➔ Turbulence would not influence the disperse phase motion (for the current mono-disperse approximation)

➔ Difference in particle mean response time (or terminal velocity) might influence elutriation/entrainment

▶ Particle-wall interactions

d_p $[\mu m]$	$d_{50}\,(=234)$	$d_{32}\,(=210)$
τ_{ps}/τ_ω	96.4	63.3

$$\tau_\omega = \frac{D}{V_t}$$

➔ Flow in the riser dominated by particle/wall collisions

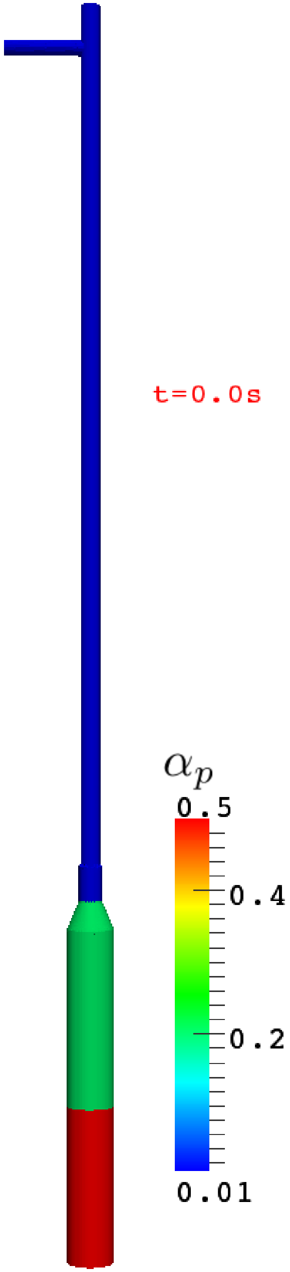
➘ Possibly significant influence of the non-spherical particle/wall collisions

Numerical modeling

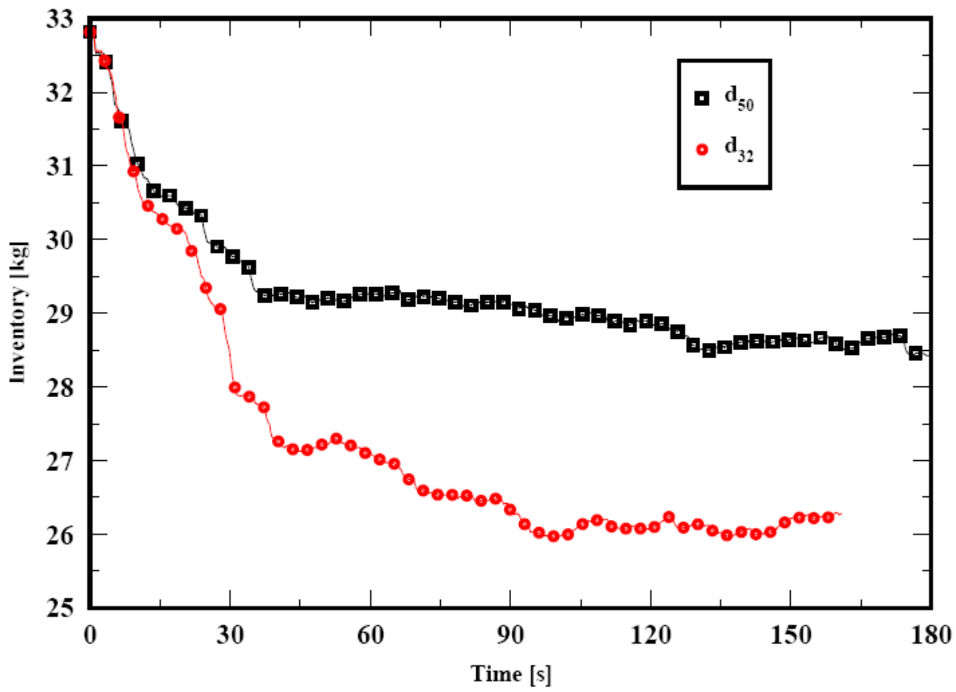
- **Euler-Euler**
  - KTGF: Gourdel, Simonin & Brunier (1999)
  - Diverging RDF (modified Mansoori) & max. packing=0.64
  - Drag: Wen & Yu and Ergun (Gobin et al., 2003)
  - Particle-wall boundary conditions: Konan, Simonin & Squires (2006)

- **Discretization**
  - Spatial: linearUpwind (velocity, volume fraction, pressure) and Superbee (granular temperature)
  - Temporal: First order Euler
  - Mesh topology: Hex-dominant (92%)
  - Algorithm: PIMPLE in OpenFOAM with alpha-pressure coupling correction

- **Simulation parameters**
  - particle/particle restitution coefficient: e_c=0.97
  - particle/wall friction and restitution coefficients: μ_w=0.1 and e_w=0.97
  - Domain: 4.08m height, AR-diam.=15.24cm , Riser-diam.=6.35cm



Results: Mean diameter approximation (solid inventory)



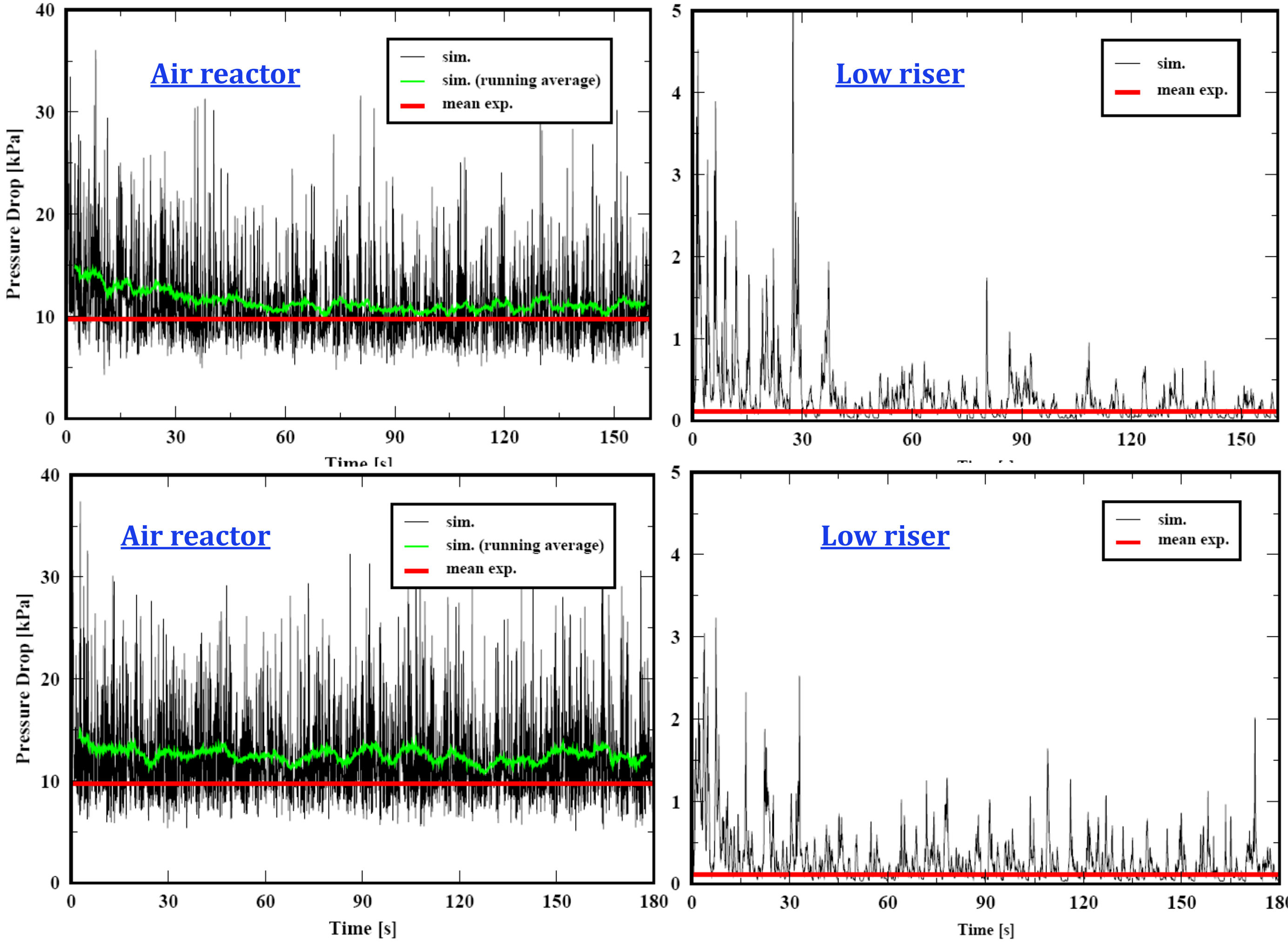
➔Inventory in bed appears sensitive to the choice of the mean diameter

➔ Air Reactor dynamics seems to be driven by the elutriation: d_{32} particles can much easily be elutriated than d_{50} particles for a specific superficial velocity

Results: Mean diameter approximation (Pressure drop)

d32

d50



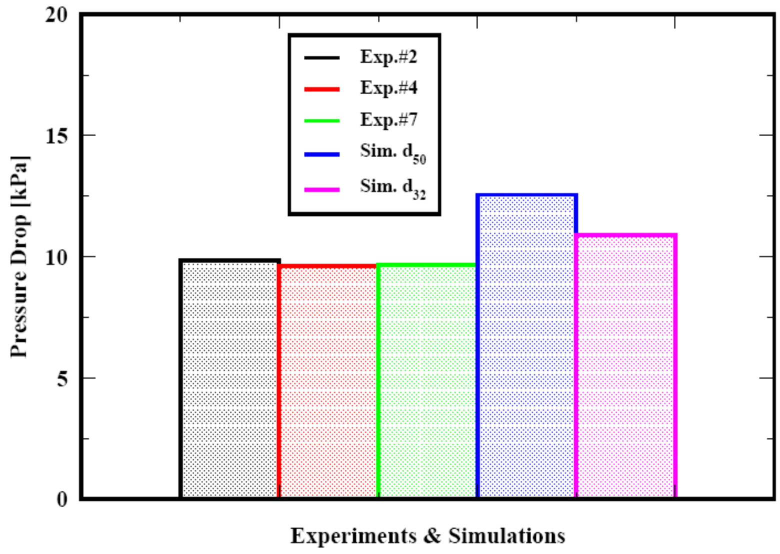
➔ **Better prediction of the pressure drop with d_{32} than d_{50}**

➔ **Can d_{32} be considered as an “effective diameter”?**

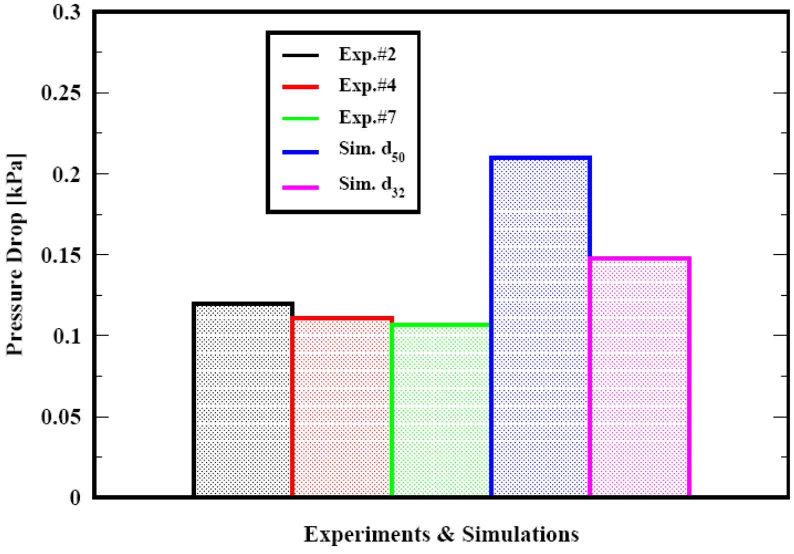
(see e.g. Loth et al., 2004 for theoretical investigation)

Results: Mean diameter approximation (mean pressure drop)

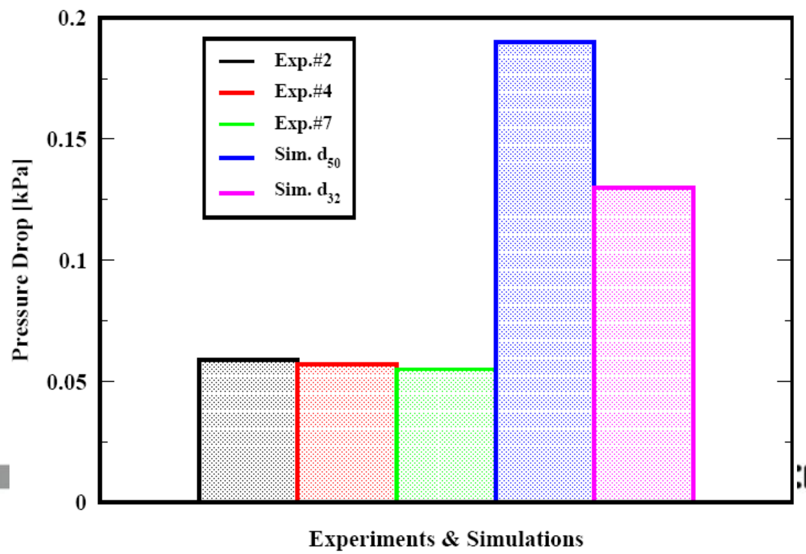
Air reactor



Low riser

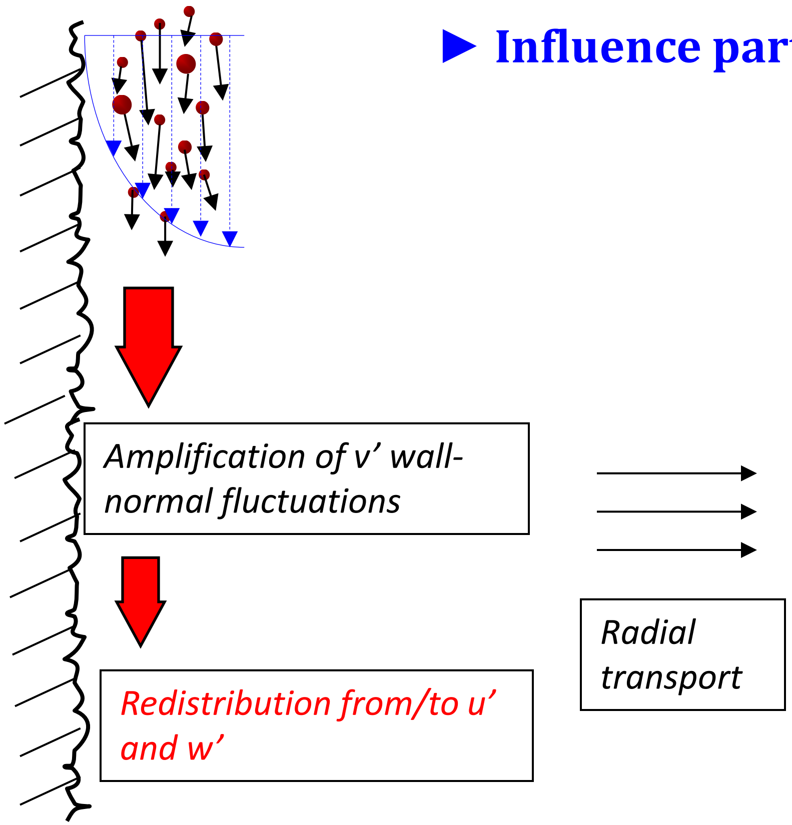


Middle riser



Gravitational settling and non-spherical particle/wall collisions

Non-spherical particle/smooth collisions ⇔ spherical particle/rough wall collisions[1]



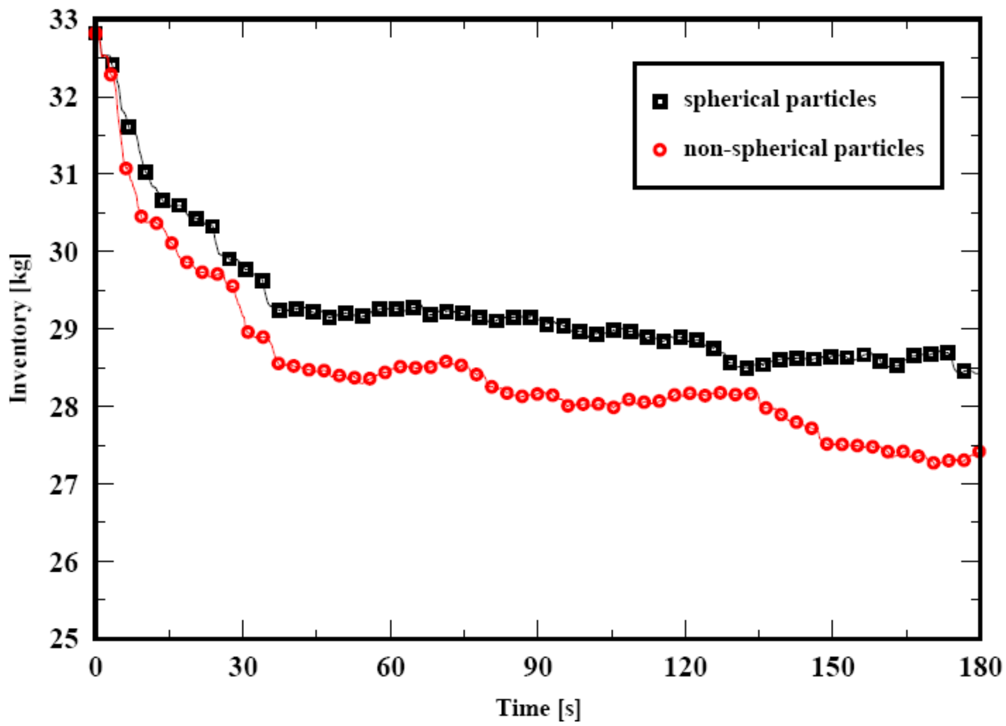
► Influence particle/rough wall collisions

- Amplification of wall-normal particle velocity variance via transfer from mean streamwise velocity (strong effect)
- Redistribution: from streamwise to wall-normal velocity fluctuation and from wall-normal to spanwise velocity fluctuation (weak effect)

➘ Mechanism accounted for in Euler/Euler wall boundary conditions (Konan et al., 2006, ASME)

[1]Sommerfeld & Huber, 1999, IJMF

Results: Non-spherical particle/wall collision effects (solid inventory)

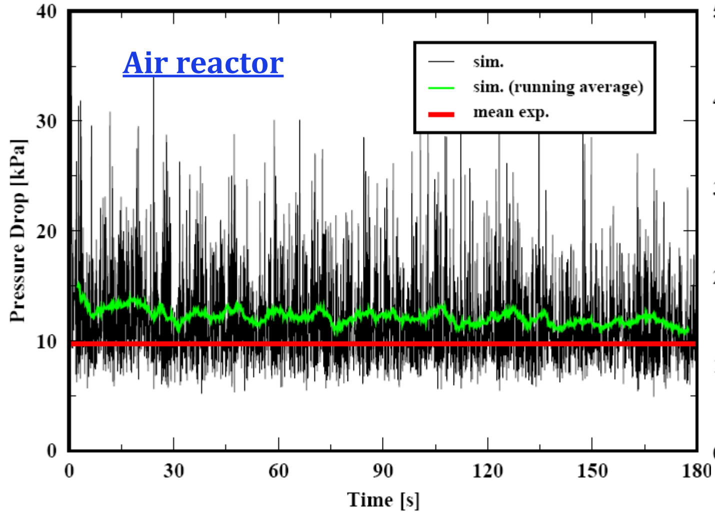


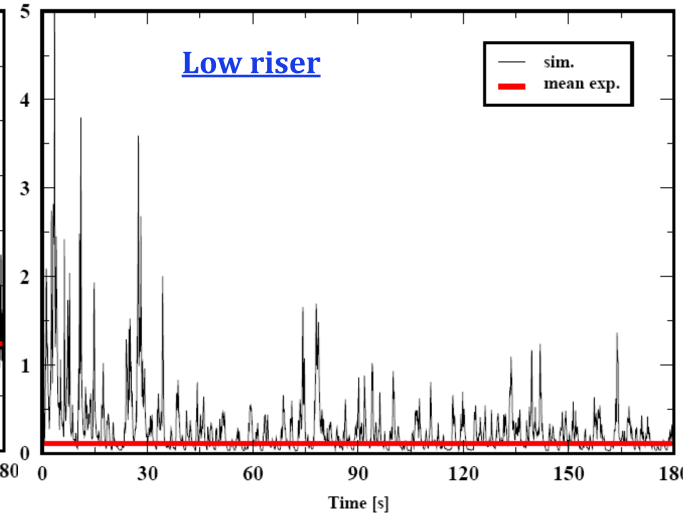
➔ Irregular bouncing at the wall resulted in decreasing of the inventory

➔ Gravitational settling is reduced and transport improved in the riser

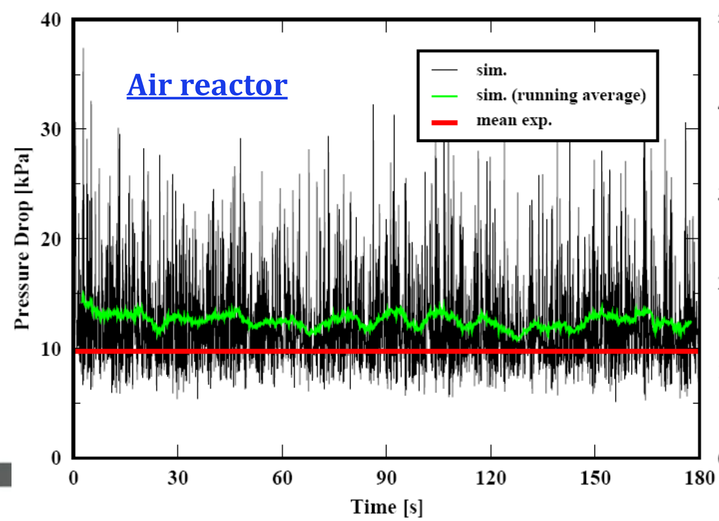
Results: Non-spherical particle/wall collision effects (mean Pressure drop)

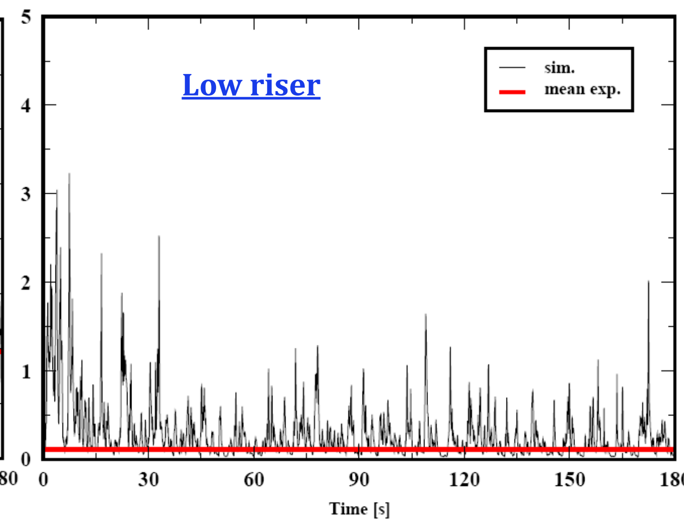
Non-Spherical particles





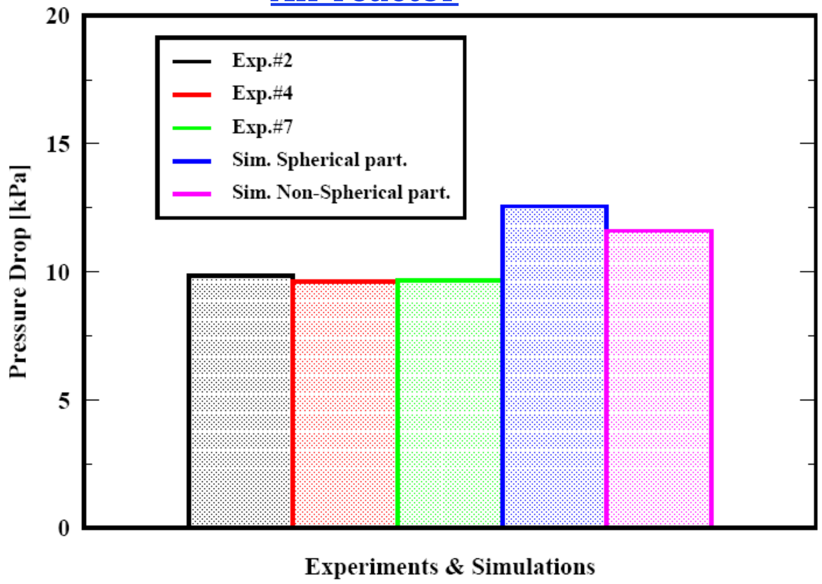
Spherical particles



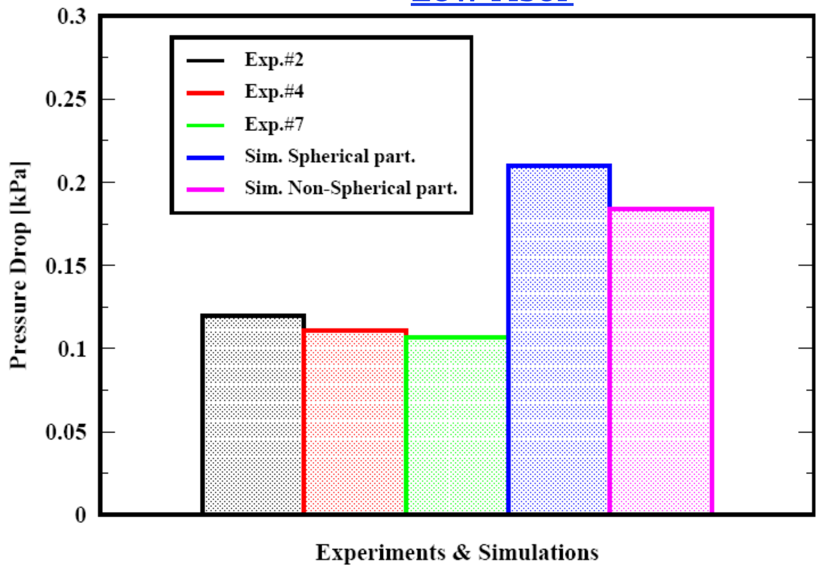


Results: Non-spherical particle/wall collision effects (Pressure drop)

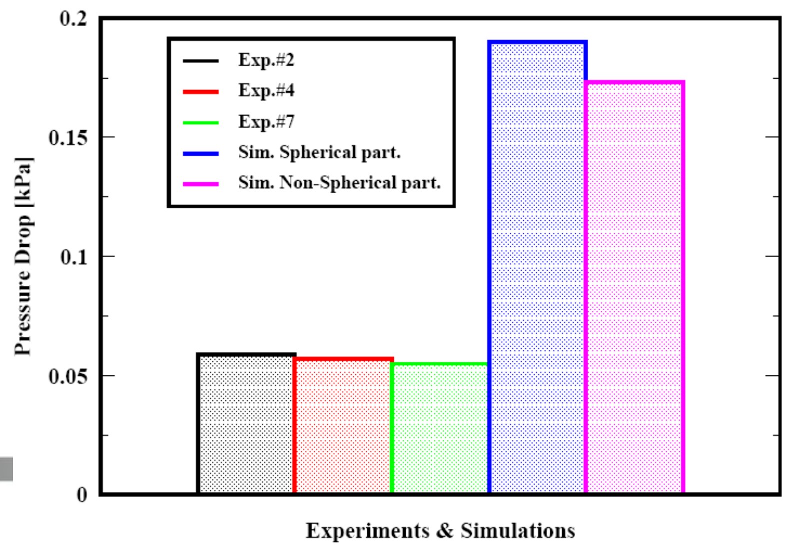
Air reactor



Low riser



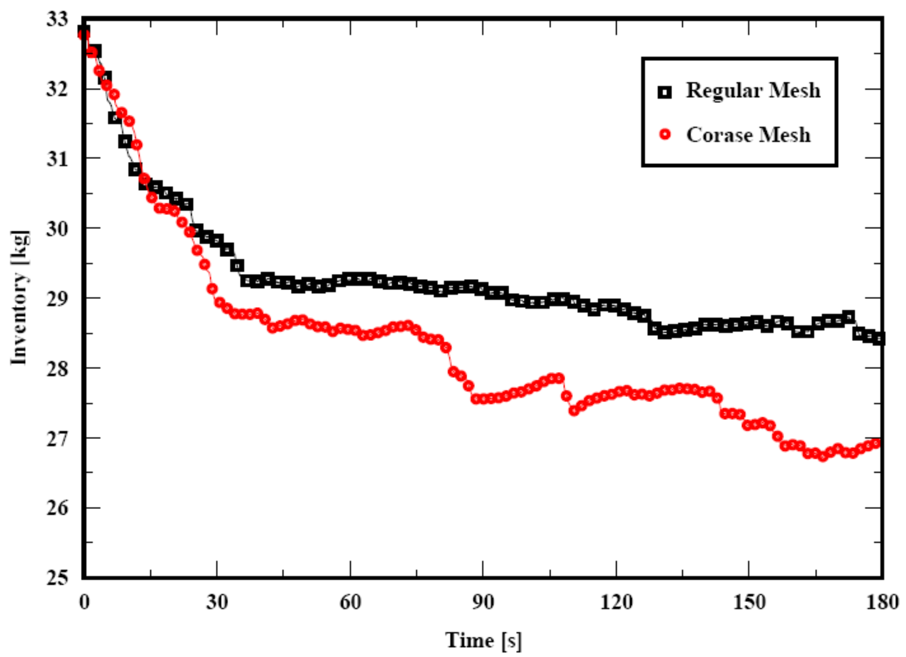
Middle riser



Results: Mesh refinement (solid inventory & Pressure drop)

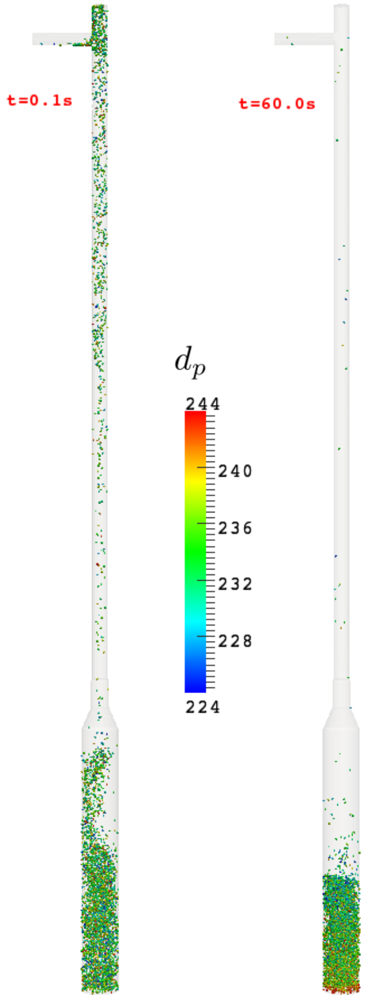
Mesh	
Coarse	85,194
Regular	181,518
Fine	445,855

Pressure (Mean) [kPa]			
	Exp.	**Sim. Coarse**	**Sim. Regular**
AR	9.712 (+/-)	11.42	12.56
LR	0.113 (+/-)	0.21	0.21
MR	0.06 (+/-)	0.187	0.19



➔ Coarse mesh over-predicts drag and subsequently the elutriation

Discussion



Barracuda's AR model

Material properties (Hematite)

Full-Loop	
d_{50} (mm)	234
d_{32} (mm)	210
Span (PSD)	1.06
Sphericity (mean)	0.847

Before Experimental Run

	AR	FR	L-valve
d_{50} (mm)	247	194	194
d_{32} (mm)	222	172	171
Span (PSD)	0.92	1.11	1.21
Sphericity (mean)	0.887	0.891	0.888

After Experimental Run

➔ Continuous change in PSD and sphericity within sub-system (attrition, break-up, ...) and maybe overall...

➘ Increases uncertainty on particle properties

➔ How those changes might affect reaction and system efficiency?

Conclusions

- **Turbulent 3D fluidized bed with a broad PSD of material is investigated in the mono-disperse mean diameter framework for elutriation/entrainment and transport**

- **The mean diameter approximation under-estimates elutriation (which drives the dynamics of the system). But the choice of the mean diameter approximation is critical as mean pressure drop is over-estimated by:**
  - Median diameter (d_{50}) of more than 30%
  - Sauter Mean diameter (d_{32}) of about 13%

- **Non-Spherical particle/wall collisions (or irregular bouncing) reduces gravitational settling and improves the transport in the riser**

- **Increasingly uncertainty on the material properties with the number of cycles**

Future work

- **Experiments**
  - systematic experimental design targeted to investigate phenomena and general operation
    - current experiments were to develop an operating envelope for cold unit and estimate the operating envelope for the reacting unit.
  - glass beads to alleviate issues with particle variation
    - but.. (static electricity)
- **Simulations**
  - additional operating conditions to:
    - support more general conclusions on predictive capabilities
    - address uncertainty in material properties and measurements (e.g. circulation rate)

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