5-23-2016

Predicting gas-flow distribution in pilot-scale fluidized beds using cfd simulations

Akhilesh Bakshi
Department of Mechanical Engineering, Massachusetts Institute of Technology, USA, abakshi@mit.edu

C. Altantzis
Department of Mechanical Engineering, Massachusetts Institute of Technology ; National Energy Technology Lab, Morgantown, USA

A. F. Ghoniem
Department of Mechanical Engineering, Massachusetts Institute of Technology, USA

L. R. Glicksman
Department of Mechanical Engineering, Massachusetts Institute of Technology, USA

Gas-Flow Distribution in Bubbling Fluidized Beds: CFD-Based Analysis and Impact of Operating Conditions

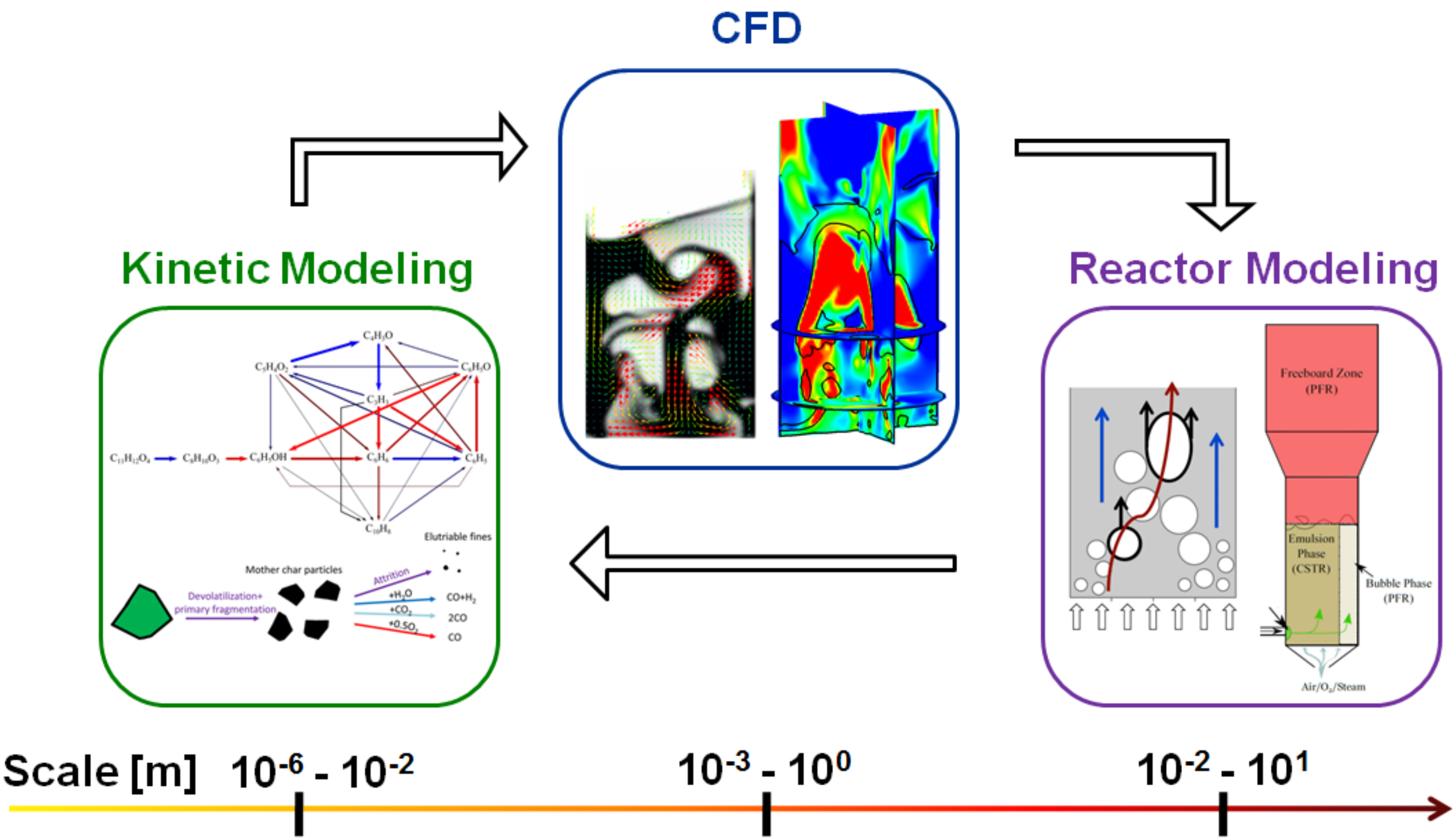
Akhilesh Bakshi, Dr. Christos Altantzis
Prof. Leon R. Glicksman, Prof. Ahmed F. Ghoniem

Department of Mechanical Engineering
Massachusetts Institute of Technology, USA

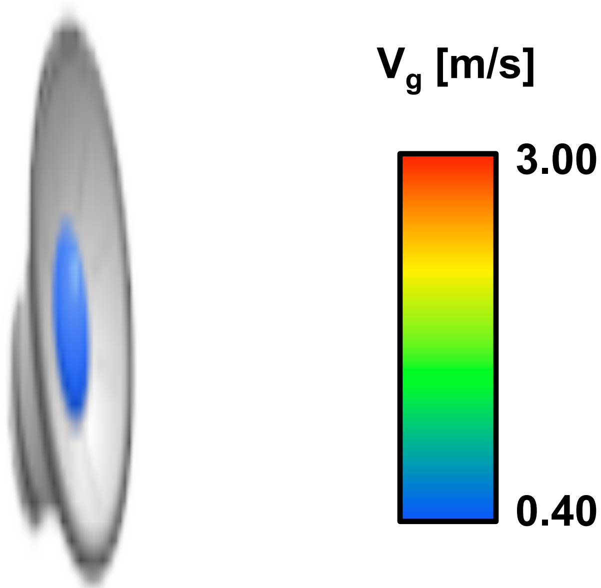
Fluidization XV
May 23, 2016

The authors gratefully acknowledge BP for funding this research

Multi-Scale Approach for Modeling Fluidized Bed Gasification



Present Study



D = 50 cm
H_0 = 50 cm

U = 0.72 m/s
LLDPE
(1.15 mm, 800 kg/m^3)

0.2x real time

Objective:

Establish computational framework for distribution of gas-flow and time-scales of different components

Take-Aways:

- Substantial fraction of gas escapes through bubbles and has significantly lower residence time
- Throughflow related to voidage distribution around bubbles and the rate of bubble rise

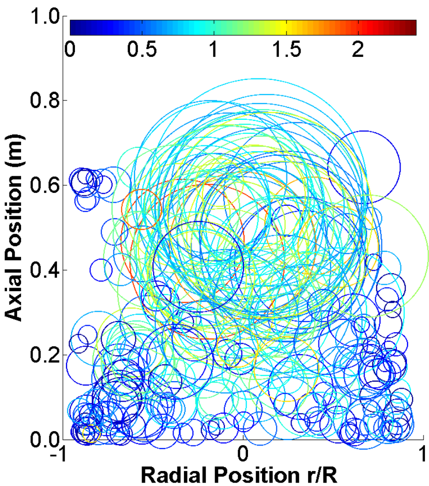
Outline

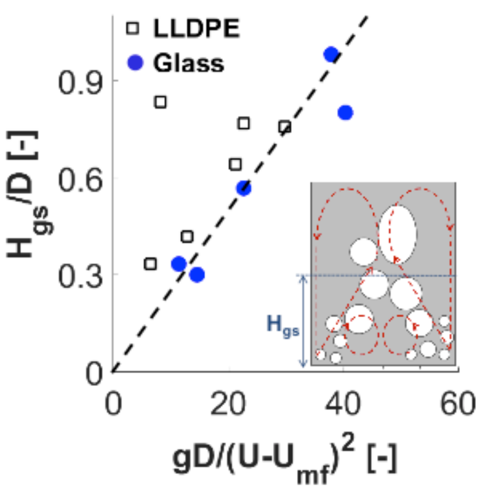
Model & Tools

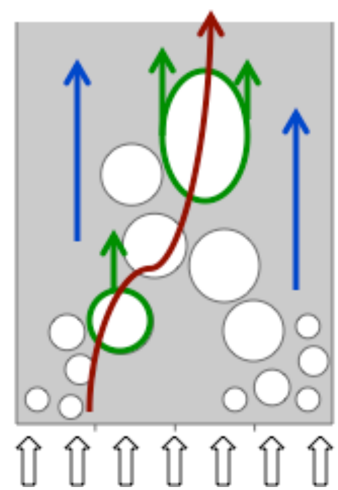
- Two Fluid Model
- Bubble Statistics
- Validation
- Bubbling in large beds

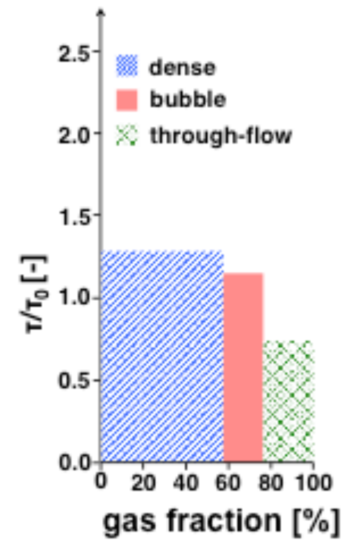
Gas Distribution

- Bubble phase
- In and around bubbles
- Throughflow
- Operating Conditions









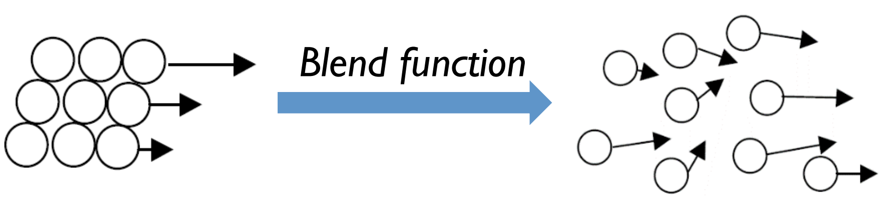
Two-Fluid Model

- Solid and gas phases fully interpenetrating continua using generalized NS equations
- Computationally efficient
- Conservation equations coupled with constitutive relationships

$$\frac{\partial}{\partial t}\left(\varepsilon_k\rho_k\vec{V}_k\right)+\nabla\cdot\left(\varepsilon_k\rho_k\vec{V}_k\vec{V}_k\right)=\nabla\cdot\bar{\bar{S}}_k-\varepsilon_k\nabla P_g+\varepsilon_k\rho_k\vec{g}+\left(\delta_{km}\vec{I}_{gm}-\delta_{kg}\vec{I}_{gm}\right)$$

Solid Phase Stress Tensor

Particle-Particle Interactions

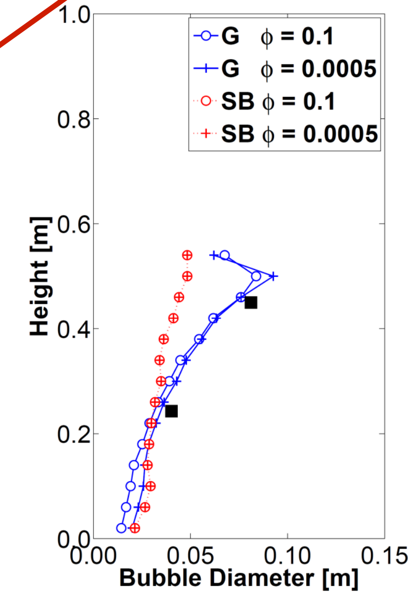


Plastic Flow
(Frictional Theory)

Viscous Flow
(KTGF)

Drag Law

Gidaspow Model more suited to lower fluidization velocities

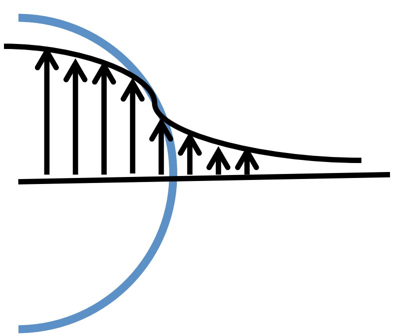


The TFM has been implemented using **MFiX** *(Multiphase Flow with Interphase eXchanges)*

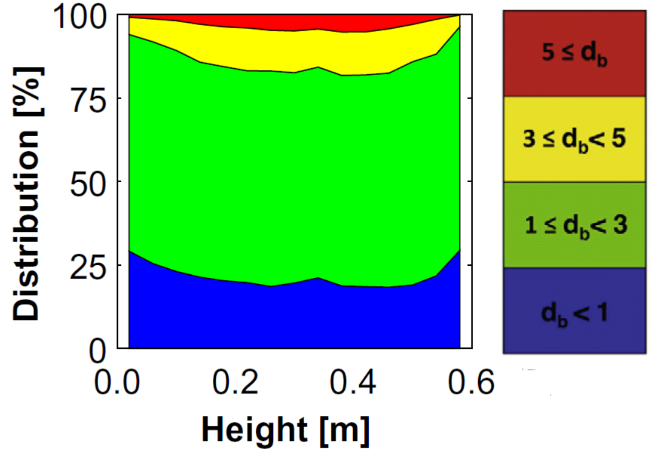
3D Bubble Statistics

MS3DATA (Multiphase-flow Statistics using 3D Detection & Tracking Algorithm): tool for accurate and scalable bubble statistics using time-resolved volumetric void fraction

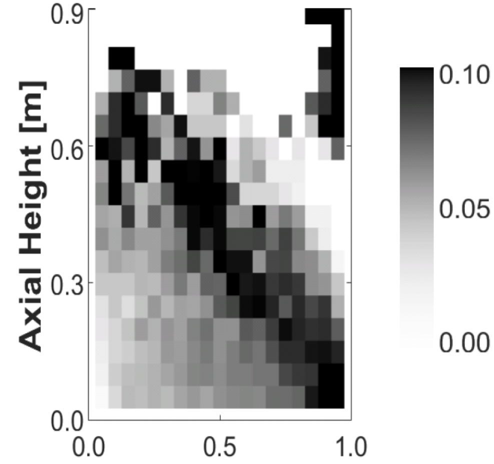
- ✓ Eliminates need for image processing software
- ✓ Flexible - can be integrated with other variables to investigate flow field in detail



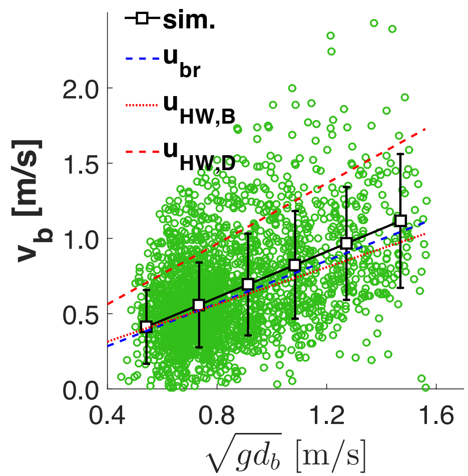
Size distribution

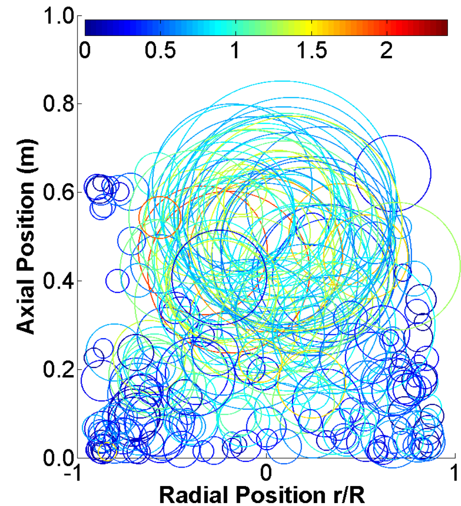


Spatial distribution



Velocity distribution





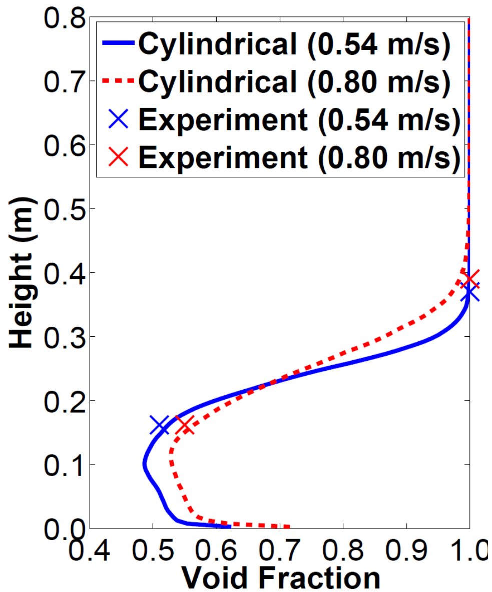
Validation

Validation with independent experiments – global parameters, bubble dynamics and solids motion

Critical sub-models – wall boundary condition (lab-scale beds), gas-solid drag model

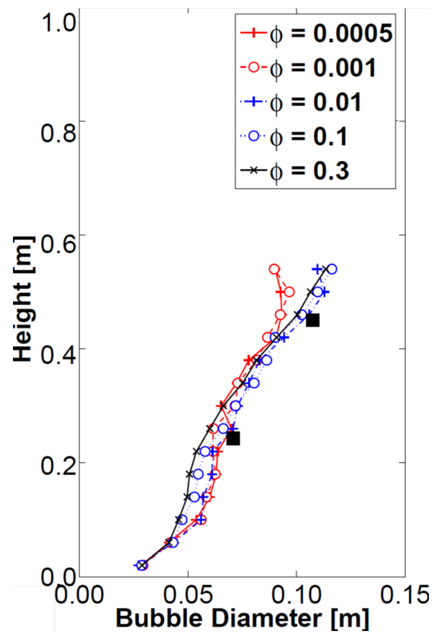
ECT measurements by Makkawi et al 2004

Glass (0.35 mm, 2500 kg/m³)
Bed Diameter = 13.8 cm



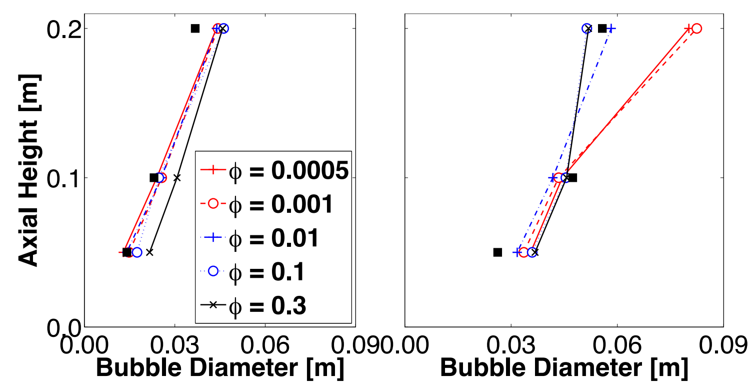
Optical probe measurements by Rüdisüli et al 2012

Alumina (0.29 mm, 1350 kg/m³)
Bed Diameter = 14.5 cm



X-Ray measurements by Verma et al 2014

(~1.0 mm, 800-2500 kg/m³)
Bed Diameter = 10.0 cm



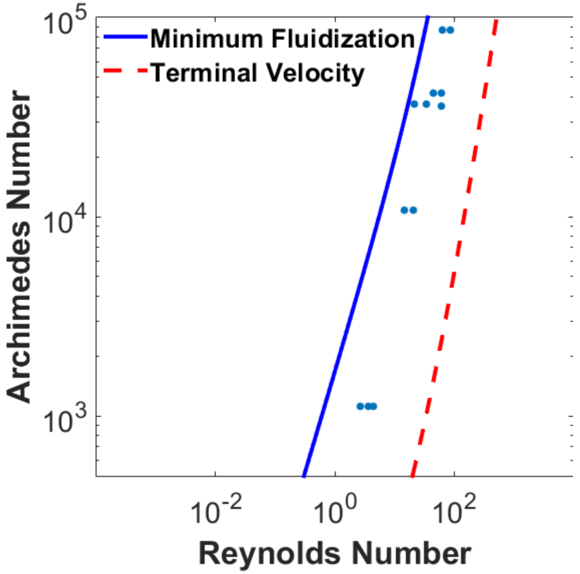
Validation

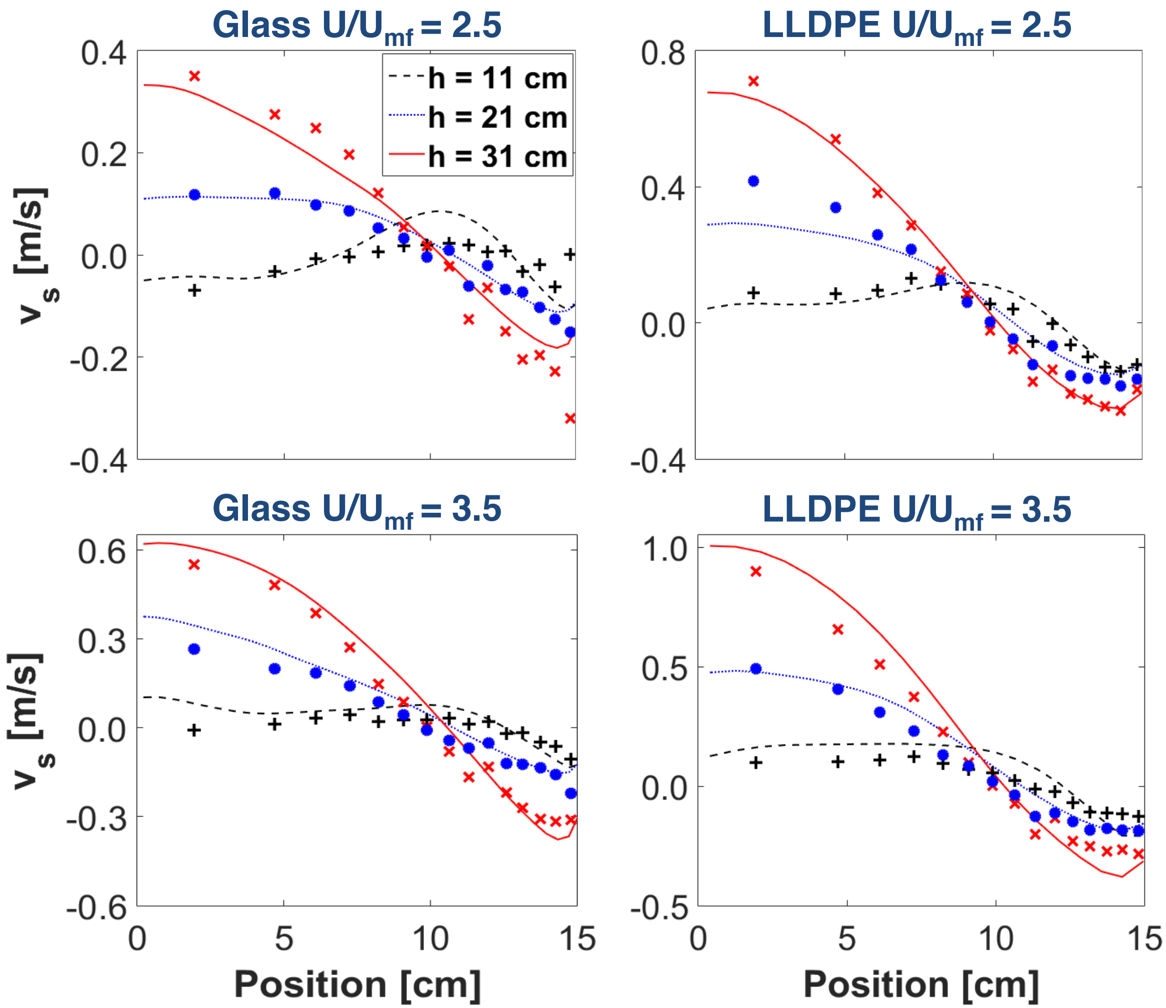
Validation with independent experiments – global parameters, bubble dynamics and solids motion

PEPT measurements by
Laverman et al 2012

Glass (0.5 mm, 2500 kg/m^3)
LLDPE (1.15 mm, 800 kg/m^3)
Bed Diameter = 30 cm

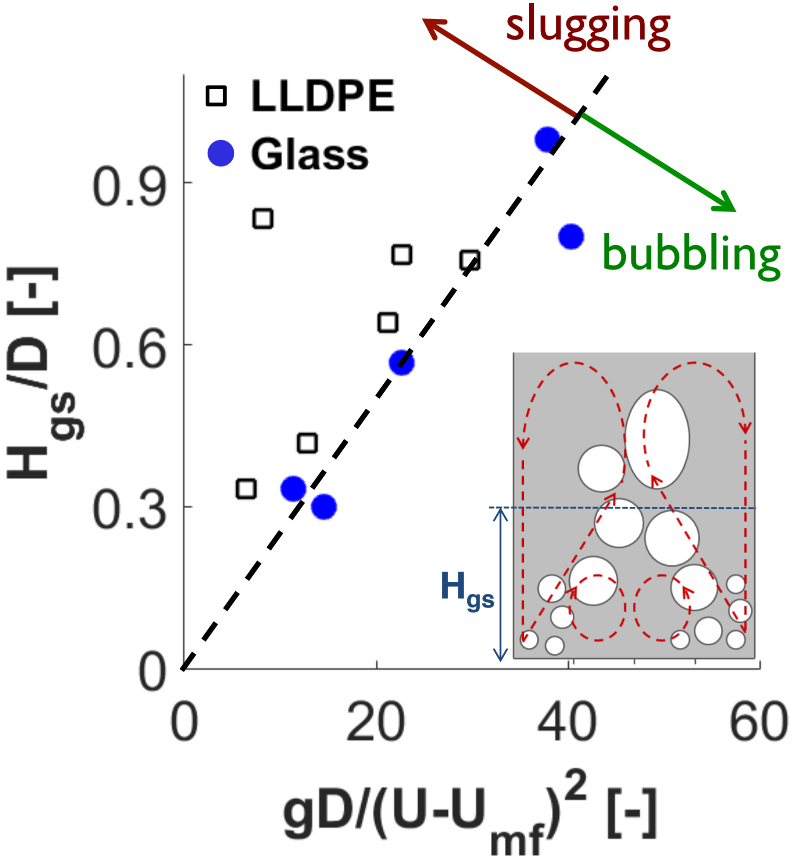
Exhaustive validation for bubbling fluidization of Geldart B particles

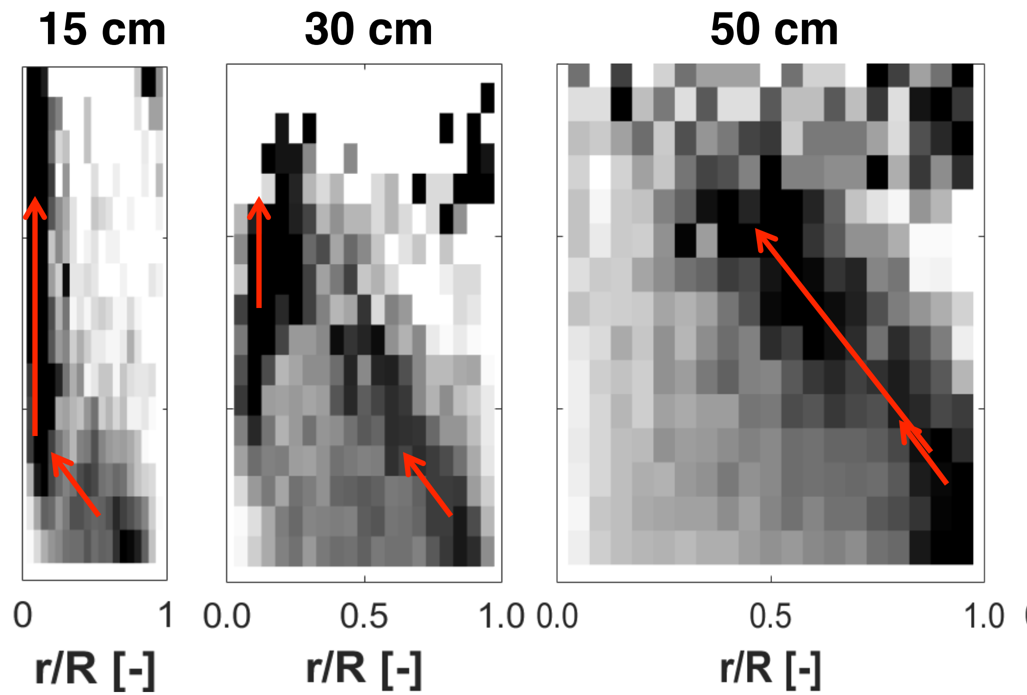




Bubbling in Large Beds

LLDPE (1150 microns)
Sand (500 microns)
D = 15 cm – 70 cm
H_0 = 10 cm – 75 cm
U/U_{mf} = 2, 3





Takeaways –

1. Predictions scalable when (a) bubbles small compared to bed dimensions and (b) solids circulation consistent across scales
2. Hydrodynamics in 50 cm bed (H/D ~ 1) are independent of wall effects

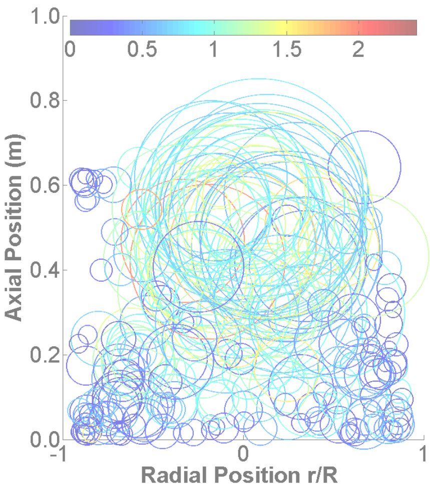
Outline

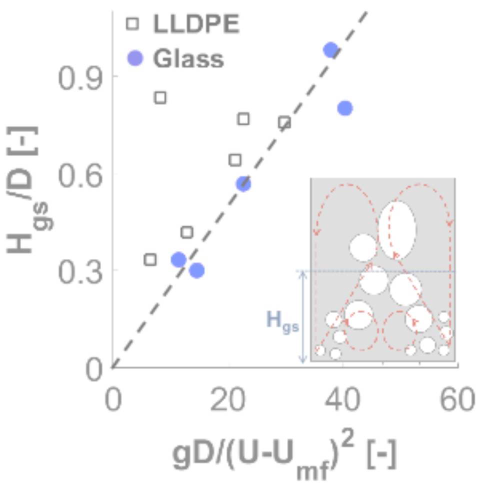
Model & Tools

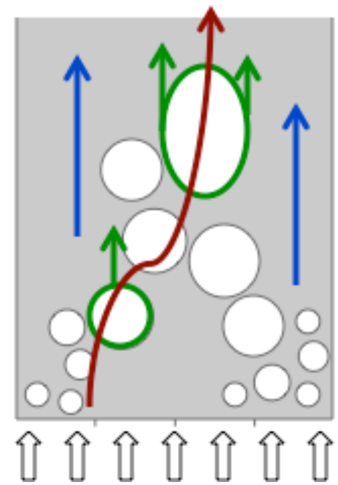
- Two Fluid Model
- Bubble Statistics
- Validation
- Bubbling in large beds

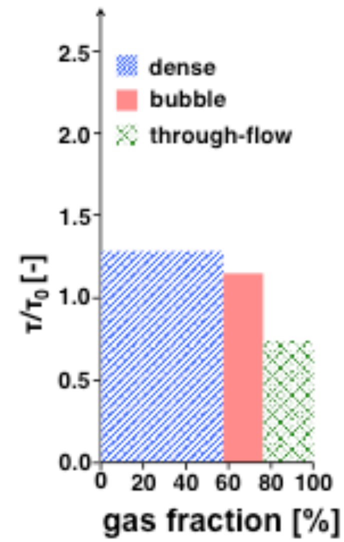
Gas Distribution

- Bubble phase
- In and around bubbles
- Throughflow
- Operating Conditions







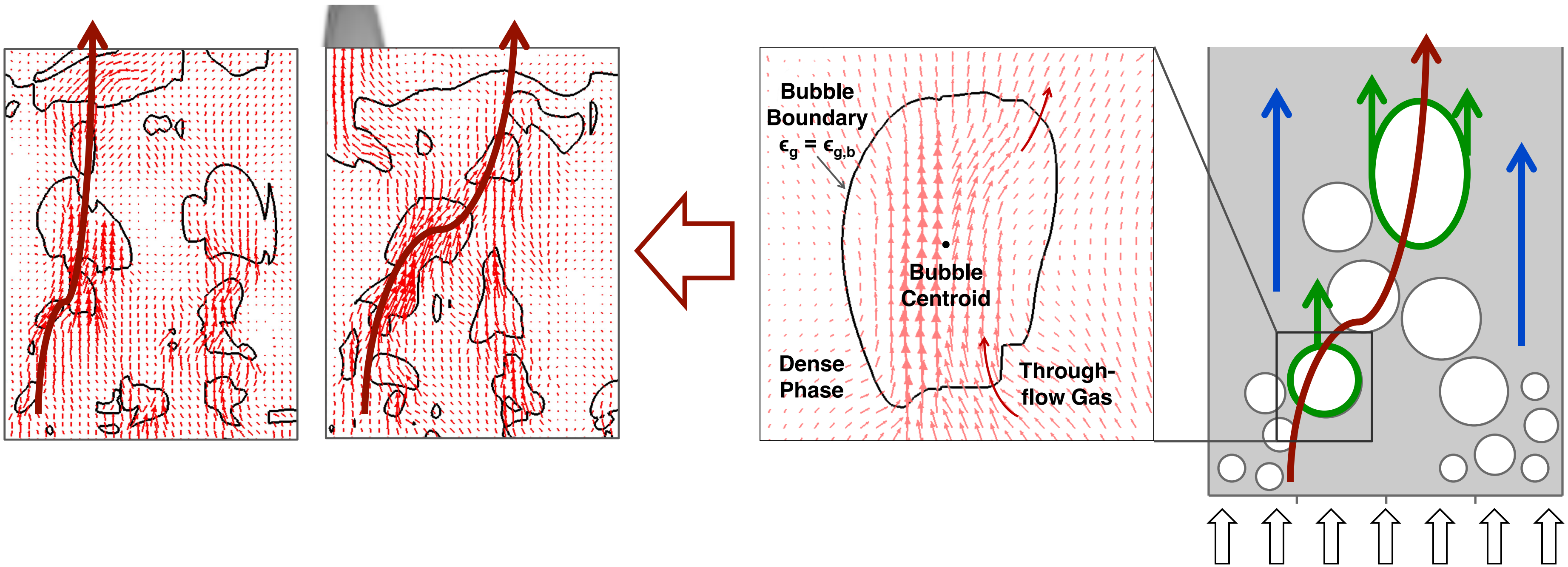


Gas Flow Distribution

Reduced Order Modeling

Total Gas Flow = dense flow + visible bubble flow + through-flow

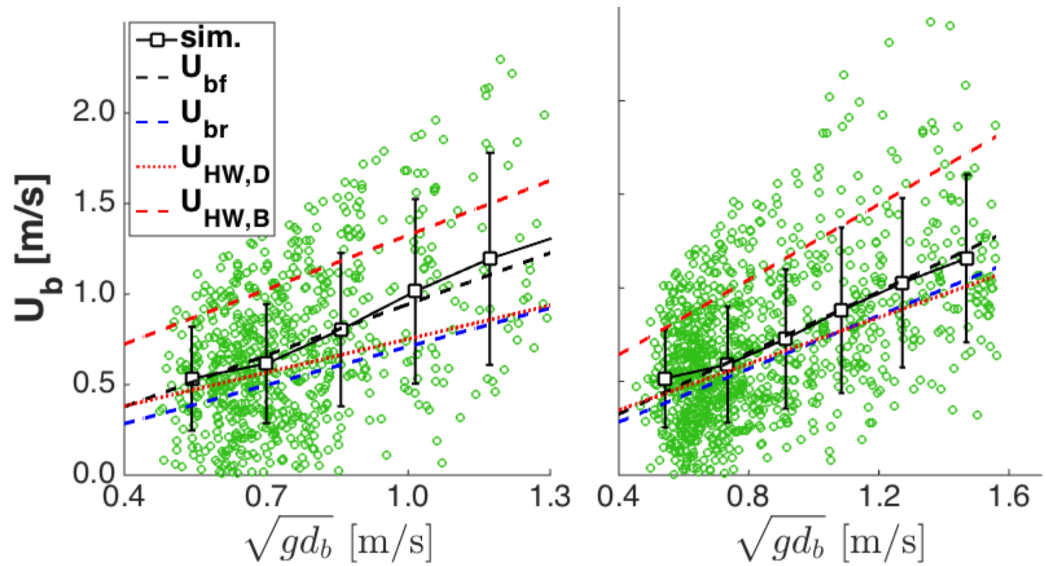
Bubble swarms offer low-resistance pathway for shortcut of gas => minimal contact with dense phase



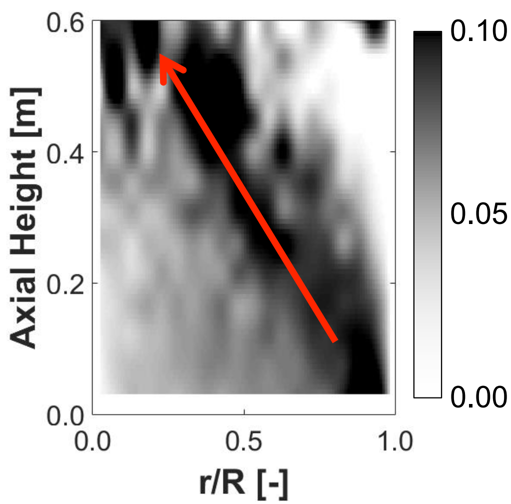
Bubble Phase

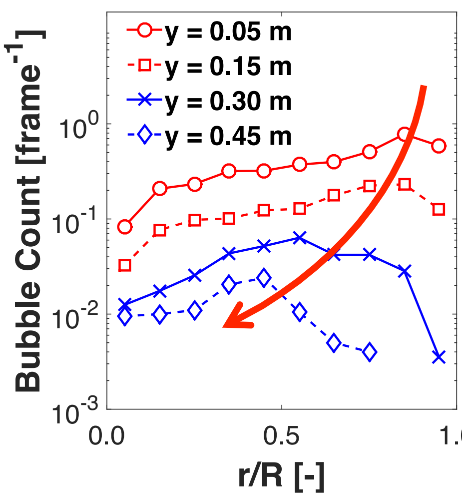
Spread in bubble velocities because of

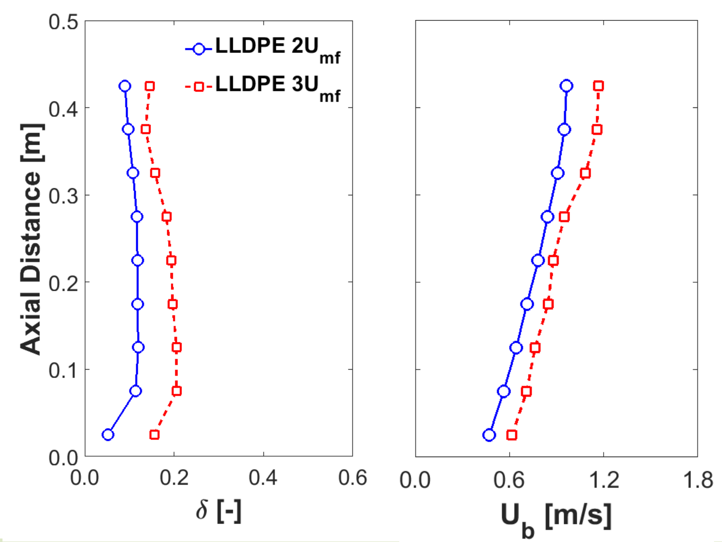
1. Bed geometry
2. Wall effects
3. Bubble interaction, coalescence
4. Local solids porosity, velocity



$U_b = \Phi(d^{0.5})$ => $\mathbf{Q_b = U_b}\,\delta$ increases

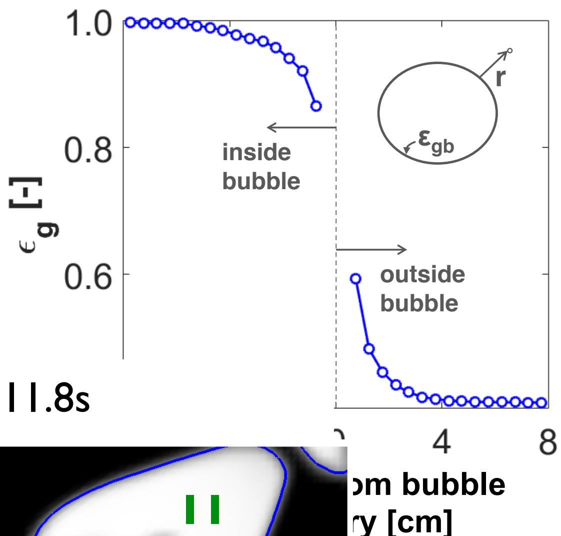


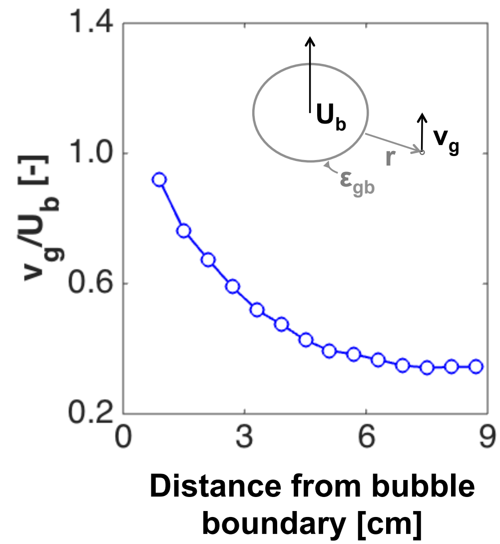




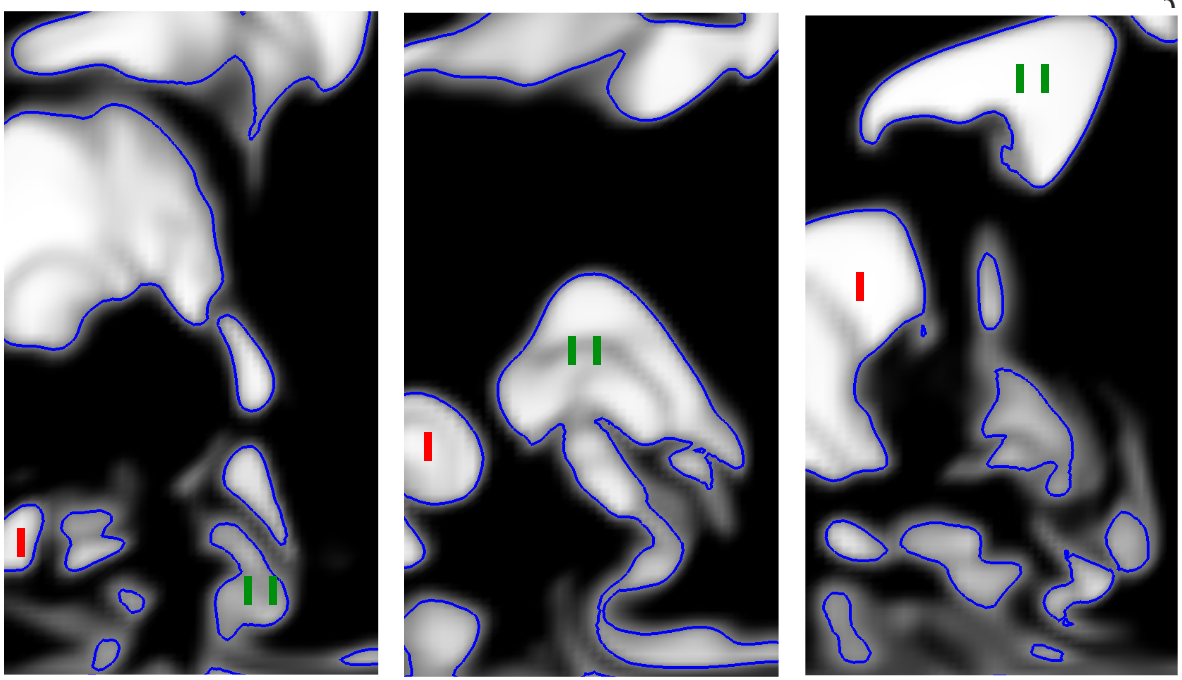
In and Around Bubbles

- Common assumption that ALL of dense-phase can be assumed to be minimally fluidized
- Exponential decay of voidage, gas velocity but **significantly higher than min. fluidization**





11.0s 11.4s 11.8s

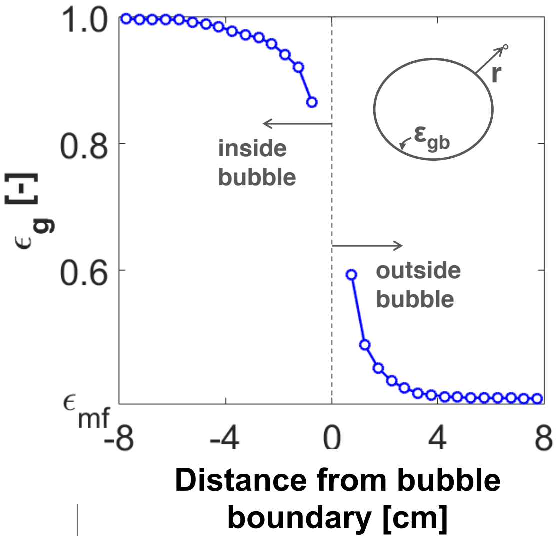


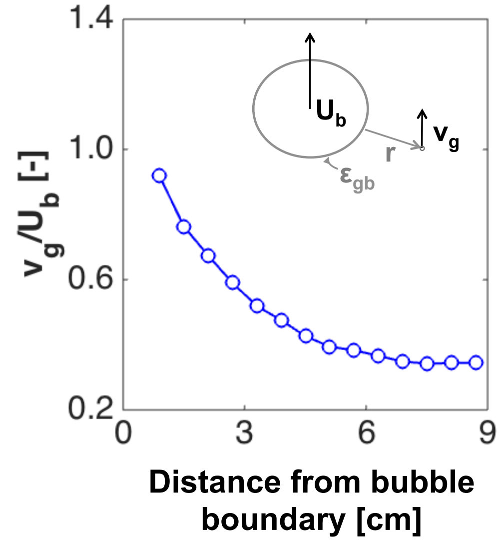
Areas frequented by bubbles have higher dense-phase voidage

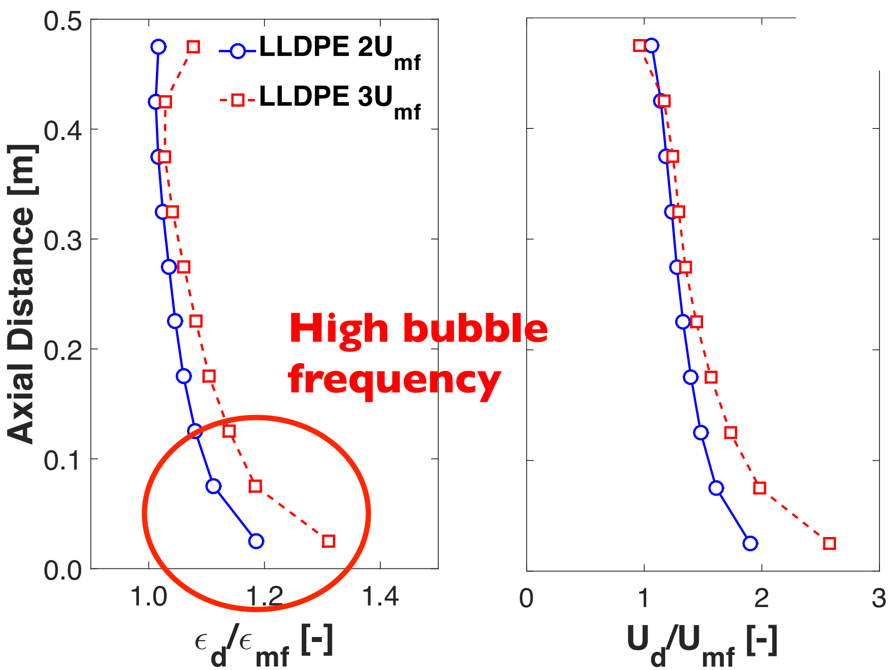
Bubbles get sucked into areas already occupied by bubbles - explains preferential pathways for bubble flow

In and Around Bubbles

- Common assumption that ALL of dense-phase can be assumed to be minimally fluidized
- Exponential decay of voidage, gas velocity but **significantly higher than min. fluidization**







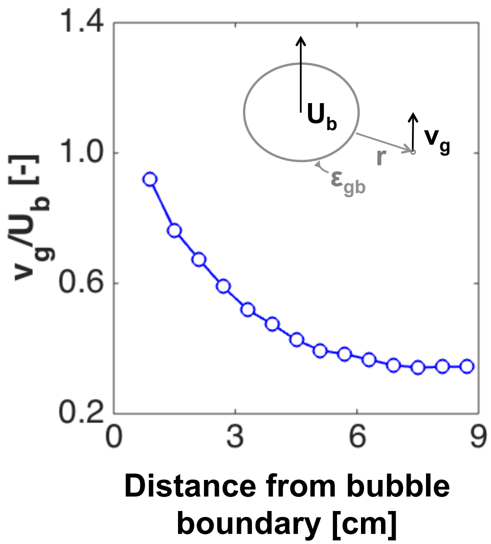
Overall, minimally fluidized dense-phase is a reasonable assumption except in areas of high bubble frequency (lower half of deep beds or shallow beds)

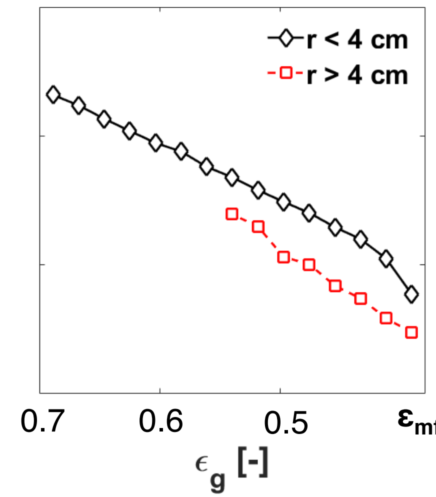
Throughflow

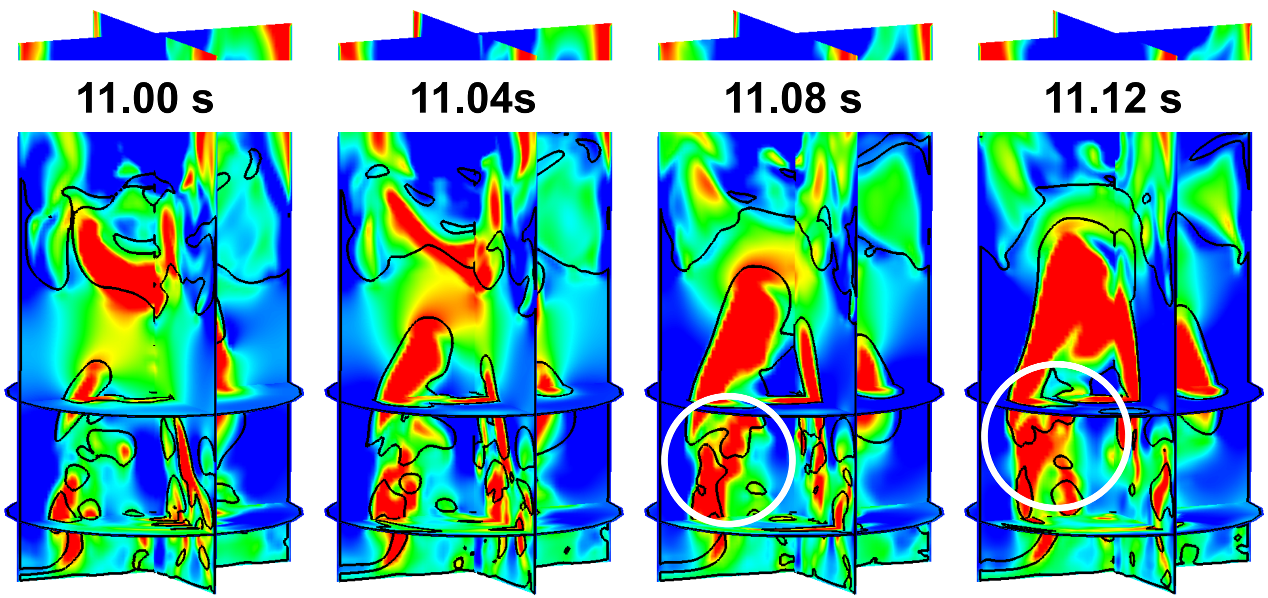
Throughflow increase related to

- Local permeability in the dense-phase (vicinity of bubbles v/s far away)

  $K \propto \varepsilon^3 d^2/(1-\varepsilon)^2$







Gas flow in the vicinity is sucked into the bubbles !

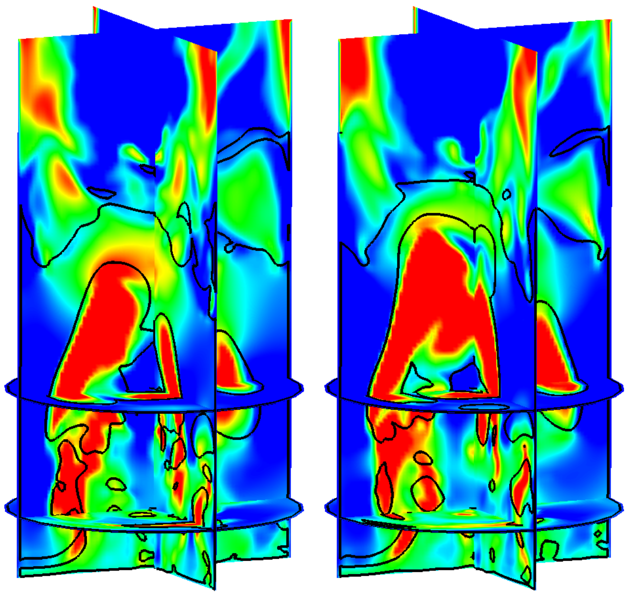
Throughflow

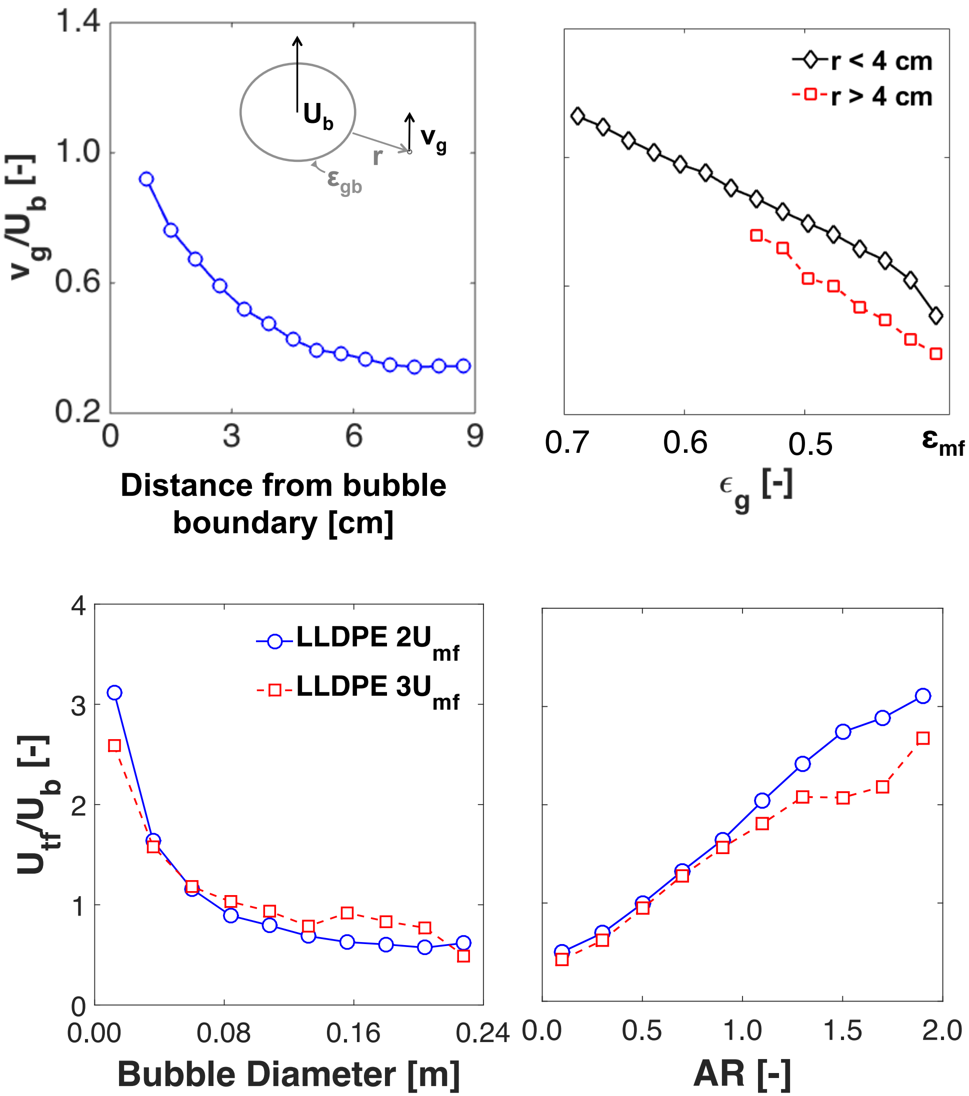
Throughflow increase related to

- Local permeability in the dense-phase (vicinity of bubbles v/s far away)

  $K \propto \varepsilon^3 d^2/(1-\varepsilon)^2$

- Bubble rise < interstitial velocity





Throughflow

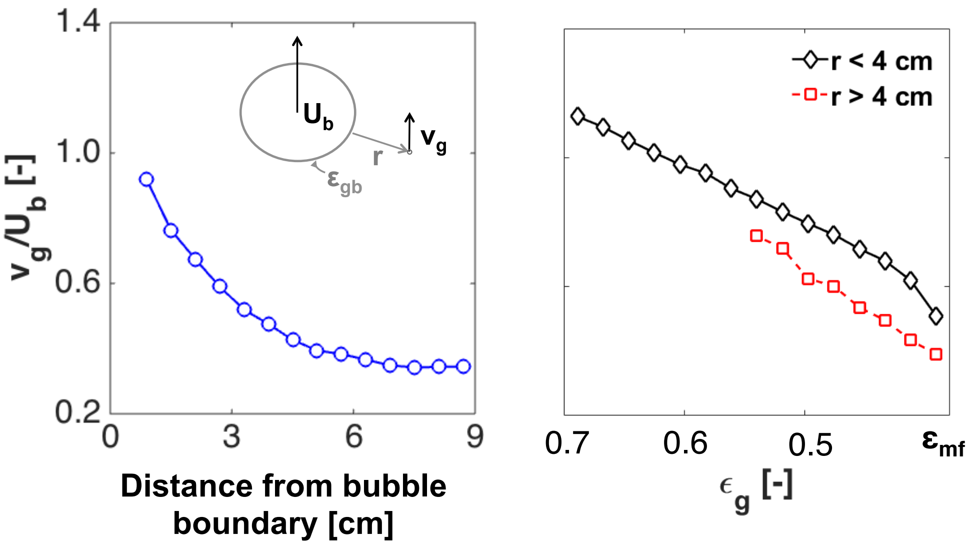
Throughflow increases related to

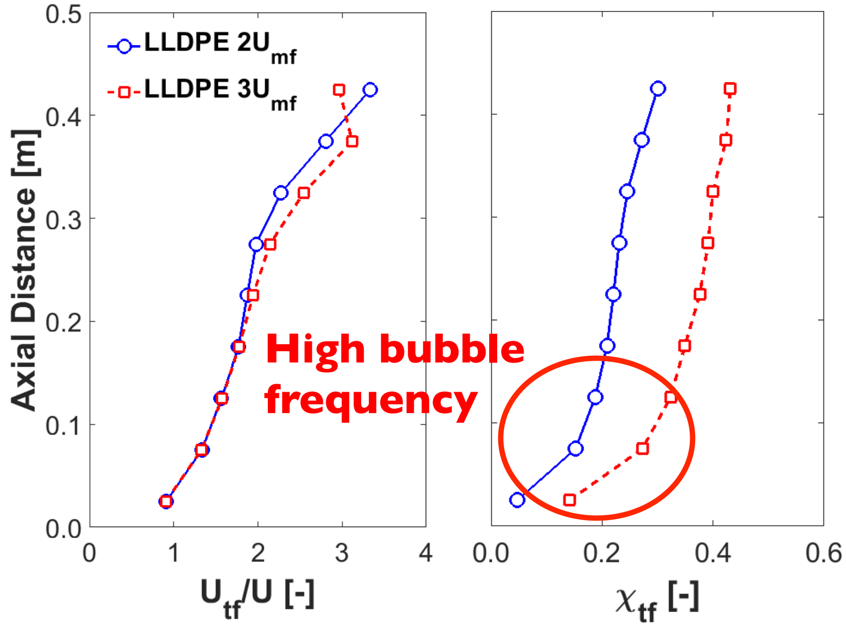
- Local permeability in the dense-phase (vicinity of bubbles v/s far away)

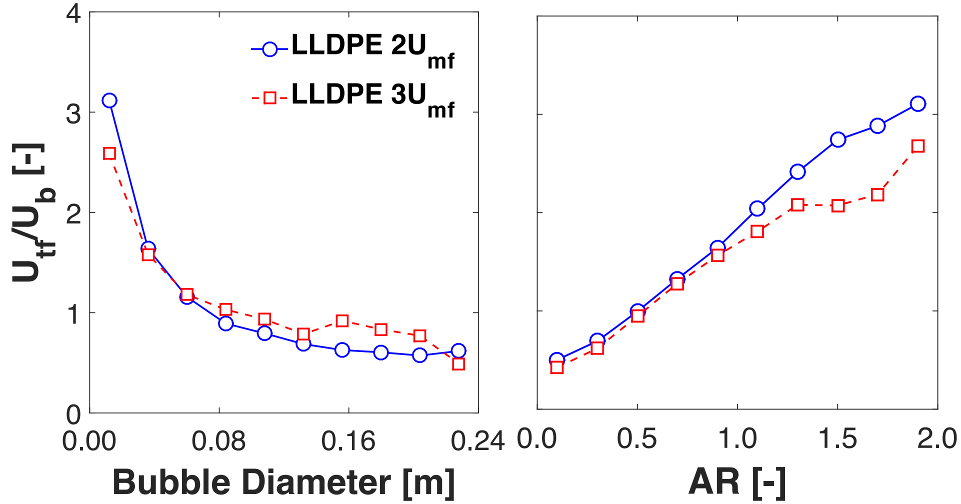
  $K \propto \varepsilon^3 d^2/(1-\varepsilon)^2$

- Bubble rise < interstitial velocity

Most of increase in gas flow constituting throughflow close to distributor !







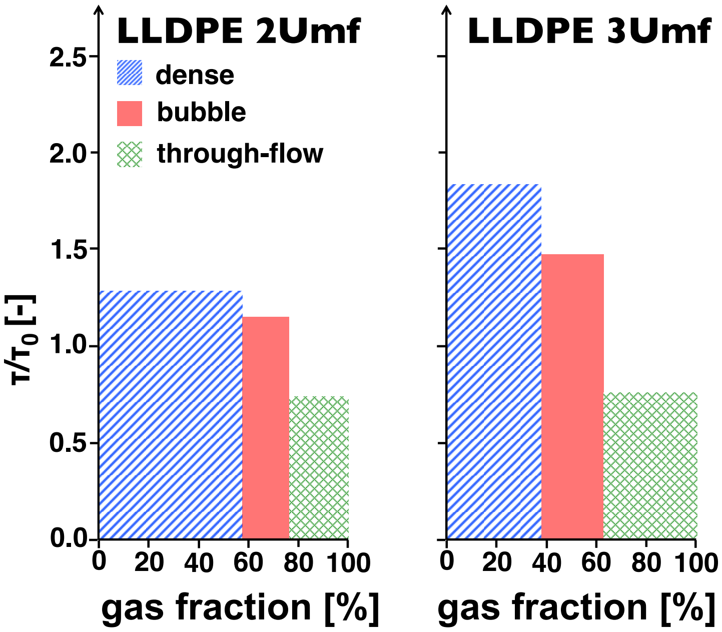
Operating Conditions

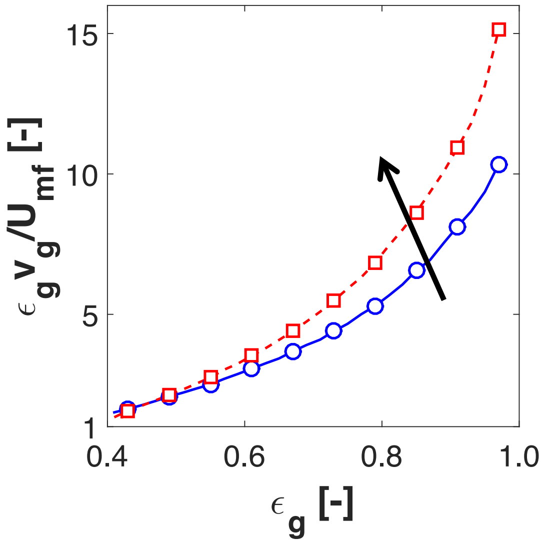
- Residence time normalized by t_0 (assuming homogeneous mixing)
- Inhomogeneity in mixing represented by (a) % throughflow and (b) t_d/t_{tf}

LLDPE 2Umf → 3Umf

- Dense phase decreases from 58% → 40%
- Throughflow increases from 23% → 39% and U_{tf}/U_d ~ 2.0-2.5

⇒ **For large particles, 70% of the additional gas supplied bypasses through bed**

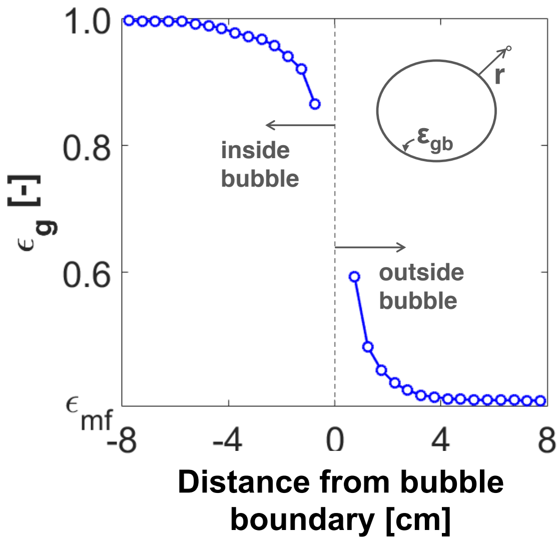




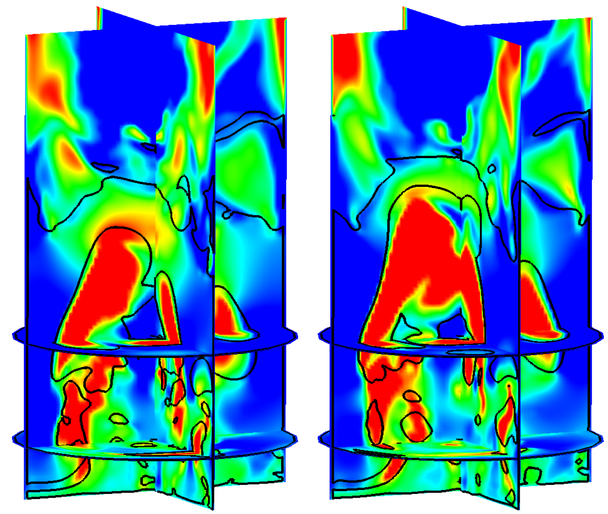
Summary

In-house bubble statistics code (MATLAB) used for detailed investigation of flow-field and computational framework for gas-flow distribution

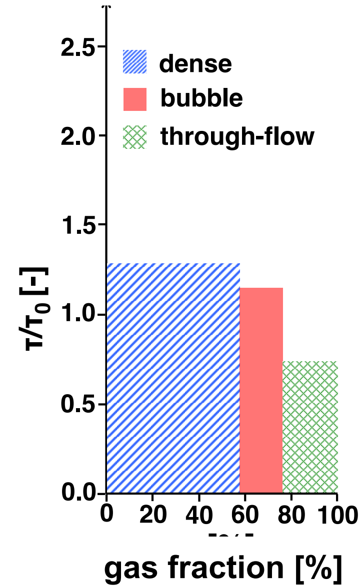
Dense-phase ~ minimally fluidized except near distributor



Throughflow depends on
(a) local permeability and
(b) bubble rise



30-40% of gas flow may have 2x shorter residence



What does this mean for reactor design ?

- Throughflow v/s mixing – better distributor/injection design to control bubble dynamics
- Multiple gas inlets because increasing U/U_{mf} for larger particles $\not\Rightarrow$ better axial mixing of solids

Publications

Bakshi et al, Study of the effect of reactor scale on fluidization hydrodynamics using fine-grid CFD simulations based on the Two-Fluid Model, *Accepted, Powder Technology*

Bakshi et al, Multiphase-flow Statistics using 3D Detection and Tracking Algorithm (MS3DATA): Methodology and application to large-scale fluidized beds, *Chemical Engineering Journal* 2016

Bakshi et al, Eulerian–Eulerian simulation of dense solid–gas cylindrical fluidized beds: Impact of wall boundary condition and drag model on fluidization., Powder Technology 2015

Altantzis et al, 3D Eulerian modeling of thin rectangular gas-solid fluidized beds: Estimation of the specularity coefficient and its effects on bubbling dynamics and circulation times, *Powder Technology* 2015

Bakshi et al, Towards accurate three-dimensional simulation of dense multi-phase flows using cylindrical coordinates , Powder Technology 2014