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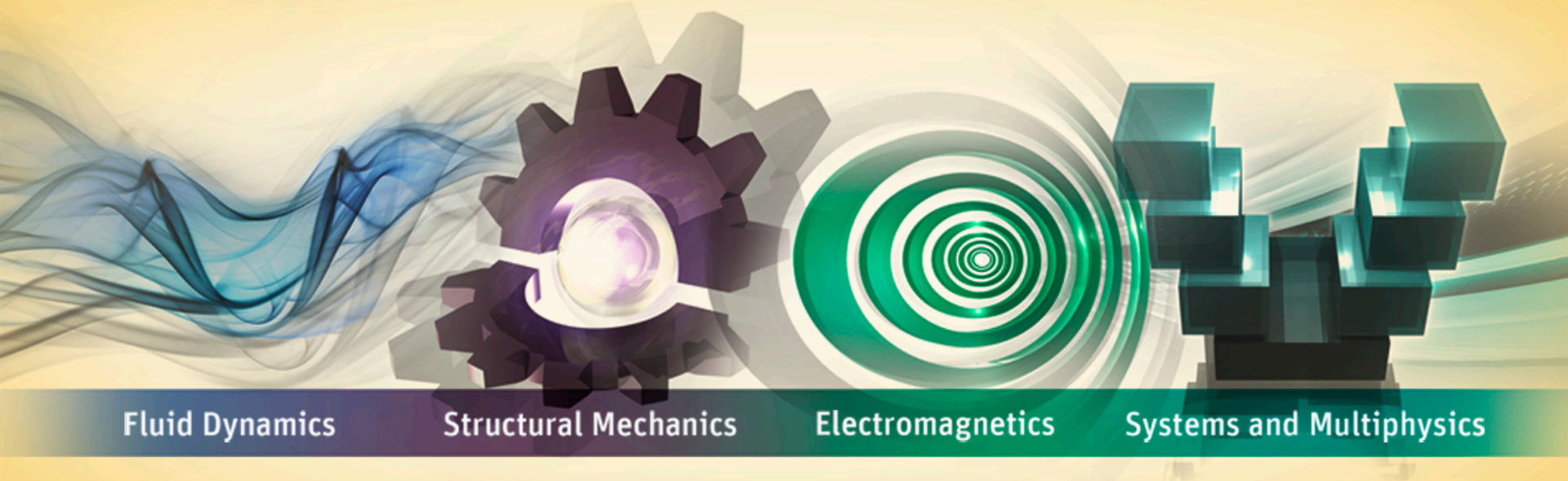
Validation of filtered two-fluid models for gas-particle flows in bubbling fluidized beds



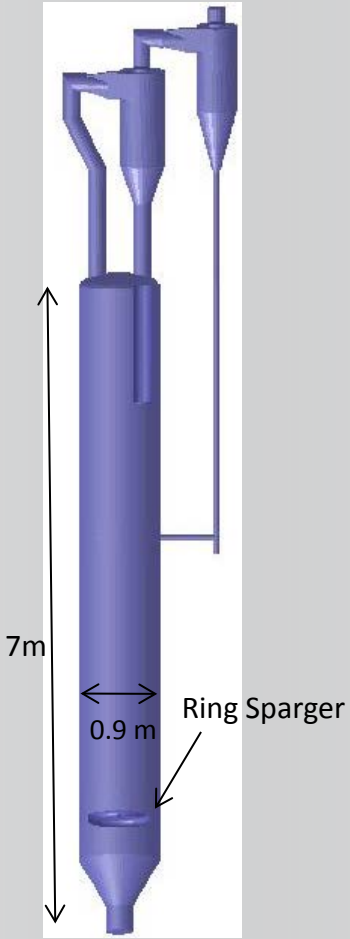
Shailesh Ozarkar, Xiaokang Yan, Shuyan Wang, Chris Milioli, Fernando Milioli, Sankaran Sundaresan

Filtered Two-Fluid Models validation studies

- **Circulating Fluidized Bed (CFB) Challenge Problem**
- **Bubbling Fluidized Bed (BFB) Challenge Problem**

  - Shuyan Wang, Xiaokang Yan, Chris Milioli, Fernando Milioli, Sankaran Sundaresan – Princeton University
  - Shailesh Ozarkar - ANSYS

Bubbling Fluidized Bed (BFB) challenge problem



BFB Geometry

- **Gas and Particle properties**

  Gas: Air at 25 ^{o}C

  Particles:

  -- FCC Catalyst Particles

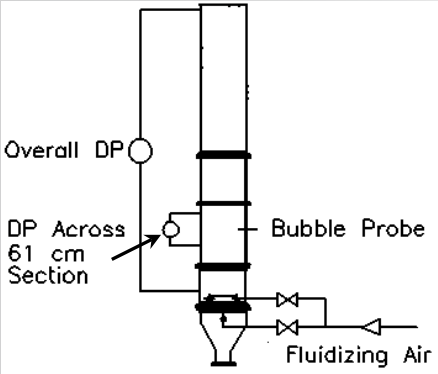
  -- 3% or 12 % fines content (d_{32} = 78E-06 or 68E-06 m)

- **Experiments conducted at four different flow conditions**

Case	Fines Content, % Less Than 44 micron % < 44 micron	Static Bed Height Hstatic, ft (m)	Superficial Gas Velocity at Bed Bottom Ug, ft/s (m/s)	Air Distributor Type
1	3	12 (3.66)	1 (0.3)	Pipe Manifold
2	3	4 (1.22)	1 (0.3)	Pipe Manifold
3	3	8 (2.44)	2 (0.6)	Ring Sparger
4	12	8 (2.44)	2 (0.6)	Ring Sparger

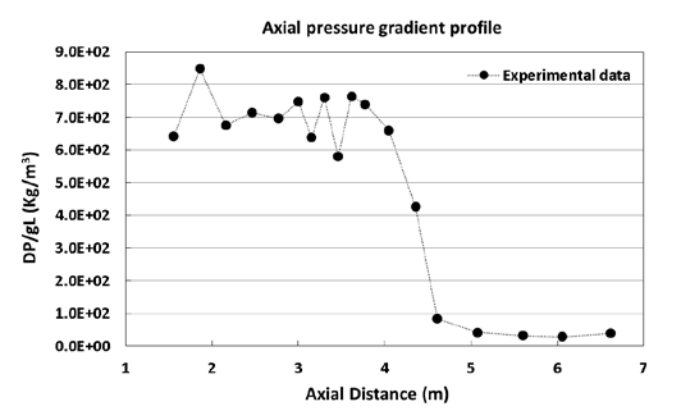
- Initially Case 3 considered for validation of filtered models. Subsequently all other cases were also studied.

Experimental Measurements



- Axial profiles of Pressure
- Differential Pressure (DP) fluctuations across entire bed and 24 inch section
  -- Mean and Std. Dev.
- Radial profile of bubble void fraction

➢ Case 3 : Axial Pressure gradient profile



- Missing data
  - Total inventory of particles not provided.
  - Only initial static bed height data available but not the voidage of static bed. We estimated inventory and revised it slightly later.

Filtered Two-Fluid Models

- Simulations were based on filtered two-fluid model with constitutive models for filtered drag and particle phase stress.

  *Y. Igci, S. Sundaresan, "Constitutive models for filtered two-fluid models of fluidized gas-particle flows," Ind. Eng. Chem. Res., **50**, 13190–13201 (2011).*

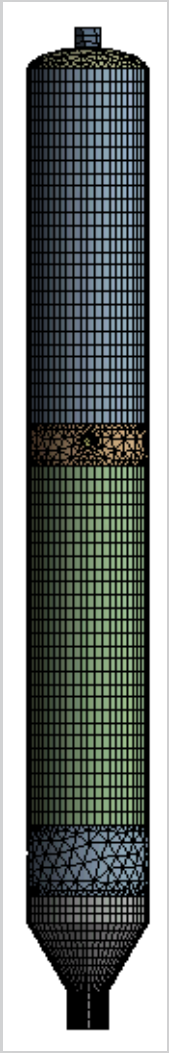
- Some simulations were augmented with wall correction

  *Y. Igci, S. Sundaresan, "Verification of filtered two-fluid models for gas-particle flows in risers," AIChE J., **57**, 2691-2707 (2011)*

- Further refined sub-filter scale models recently proposed by Milioli et al. were also tested.

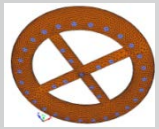
  C. Milioli et al., "Filtered two-fluid models of gas-particle flows: New constitutive relations," *AICHE J.,* doi: 10.1002/aic.14130 *(2013).*

Grid and Initial Conditions



Hybrid grid on truncated BFB geometry

Air distributor



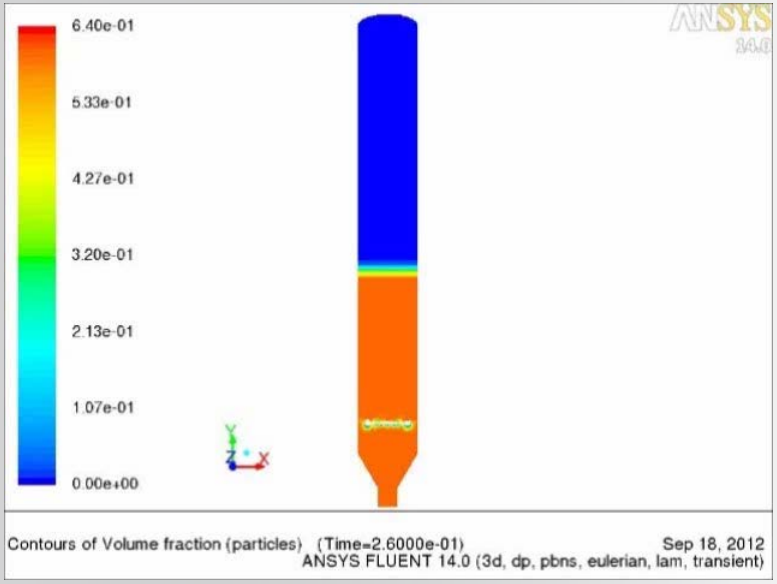
- Hybrid grid (tets, hex and prisms) generated on BFB geometry without cyclones
- To avoid excessively fine grid near air distributor, each orifice size is taken as twice its actual size
- Grid resolutions examined:
  - 20000 cells grid
  - 40000
  - 75000
  - 198000
- All cases initialized with initial static bed height and 0.4 void fraction

Case 3 simulations

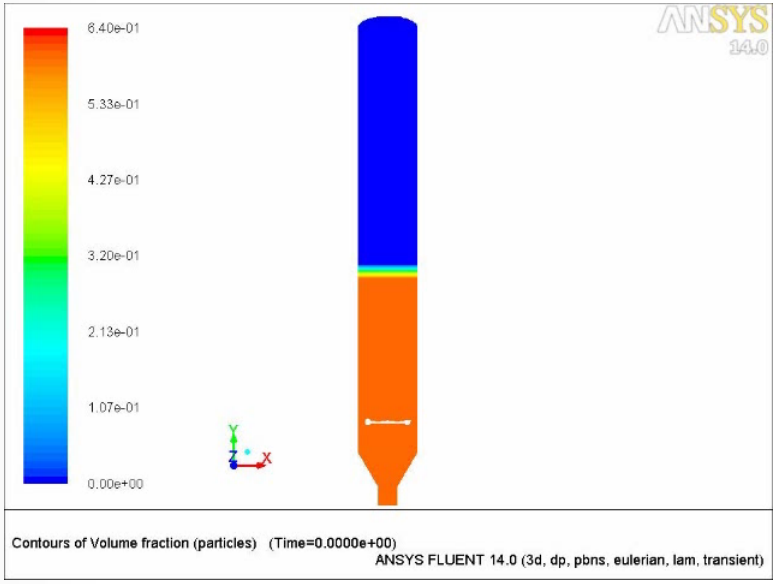
Kinetic Theory based TFM and Igci et al. filtered TFM

Animations: Contours of volume fraction of particles

Kinetic Theory based TFM
Intermediate grid (40000)



Igci et al. filtered model
Intermediate grid (40000)

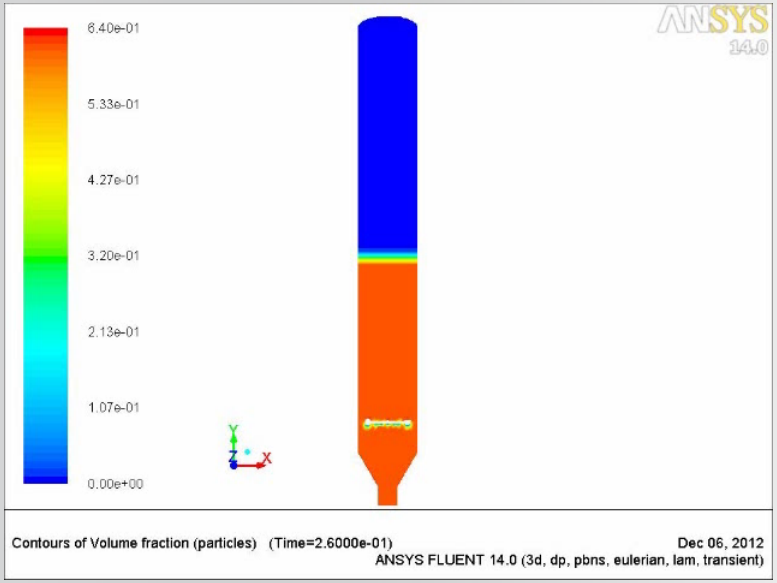


- Unphysical bed expansion is observed with both models even with refined grids.
- No improvement with
  - Wall corrections with Igci et al. filtered TFM
  - Solids recirculating boundary condition to maintain inventory.

Case 3 Simulations

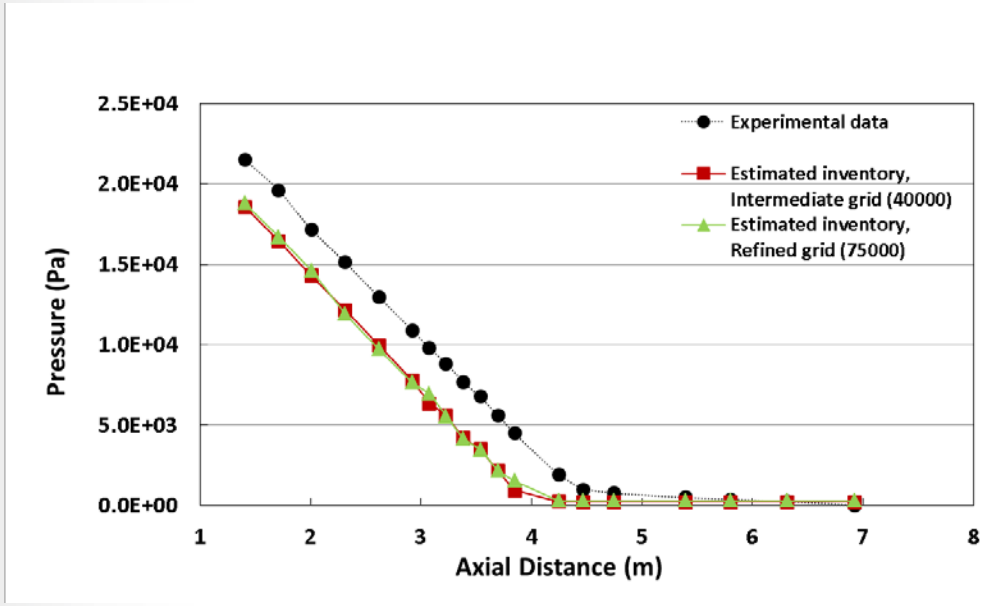
Milioli et al. filtered TFM

Animation: Contours of volume fraction of particles



Estimated Inventory

Fluid Static Pressure



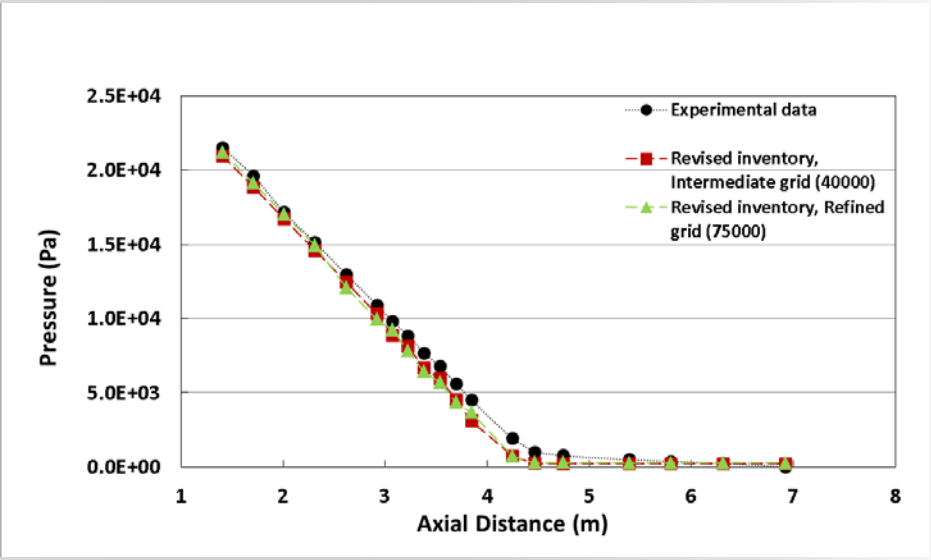
- Lower fluid static pressure values in simulations
  - -- Solids inventory experimental data is missing.
  - -- It appears that specified solids mass in simulation is lower than experiment.
  - -- Estimated difference is about 2407Pa or 160 Kg.

Case 3 Simulations

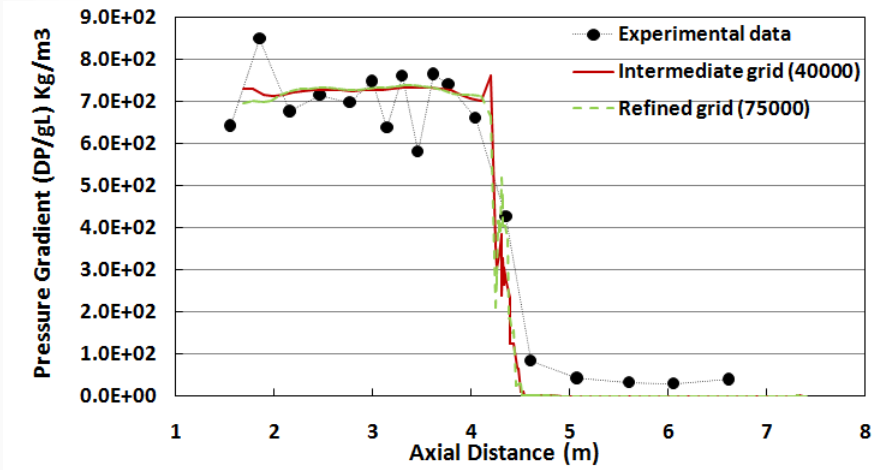
Milioli et al. filtered TFM

Revised Inventory

Fluid Static Pressure



Axial Pressure Gradient



- Total wall clock time to simulate 1 sec of flow time on 8 compute nodes

Total wall-clock time (min)	20000	40000	75000
	9	210	322

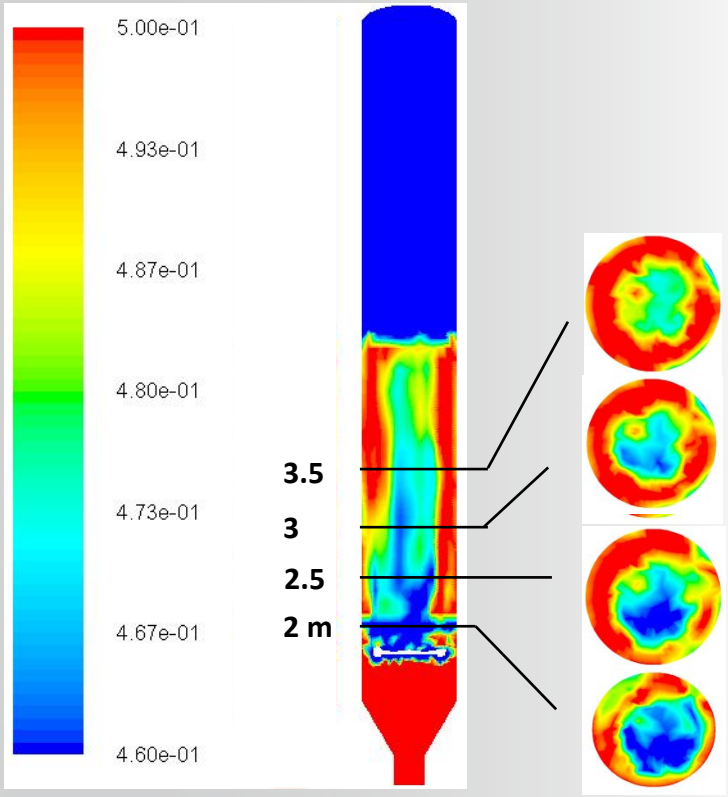
- Unphysical bed expansion in 20000 cells grid case. Predicted bed expansion with intermediate and refined grids compared well with experiment.

Case 3 simulations

Milioli et al. filtered TFM, Intermediate grid (40000)

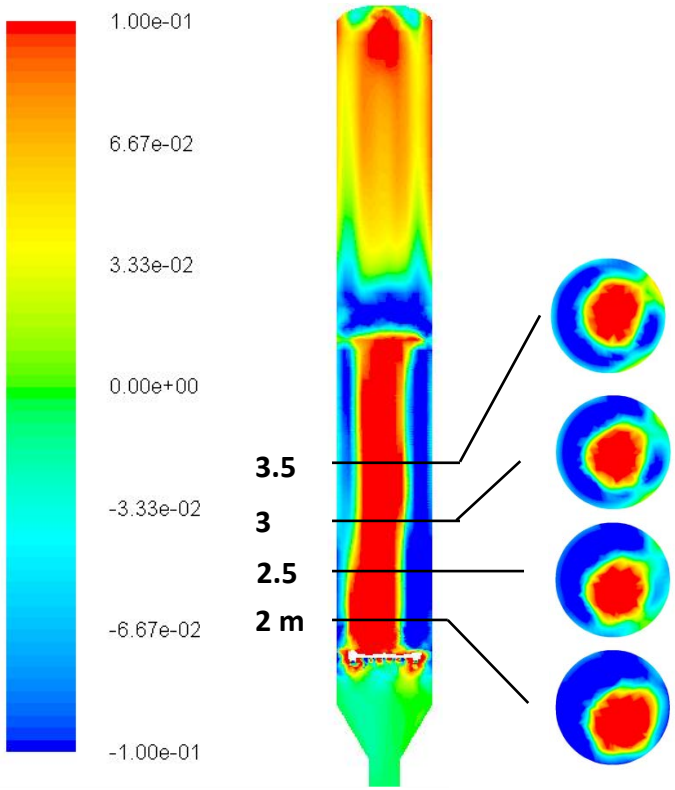
Time-averaged results

Volume fraction of particles



Axial velocity of particles

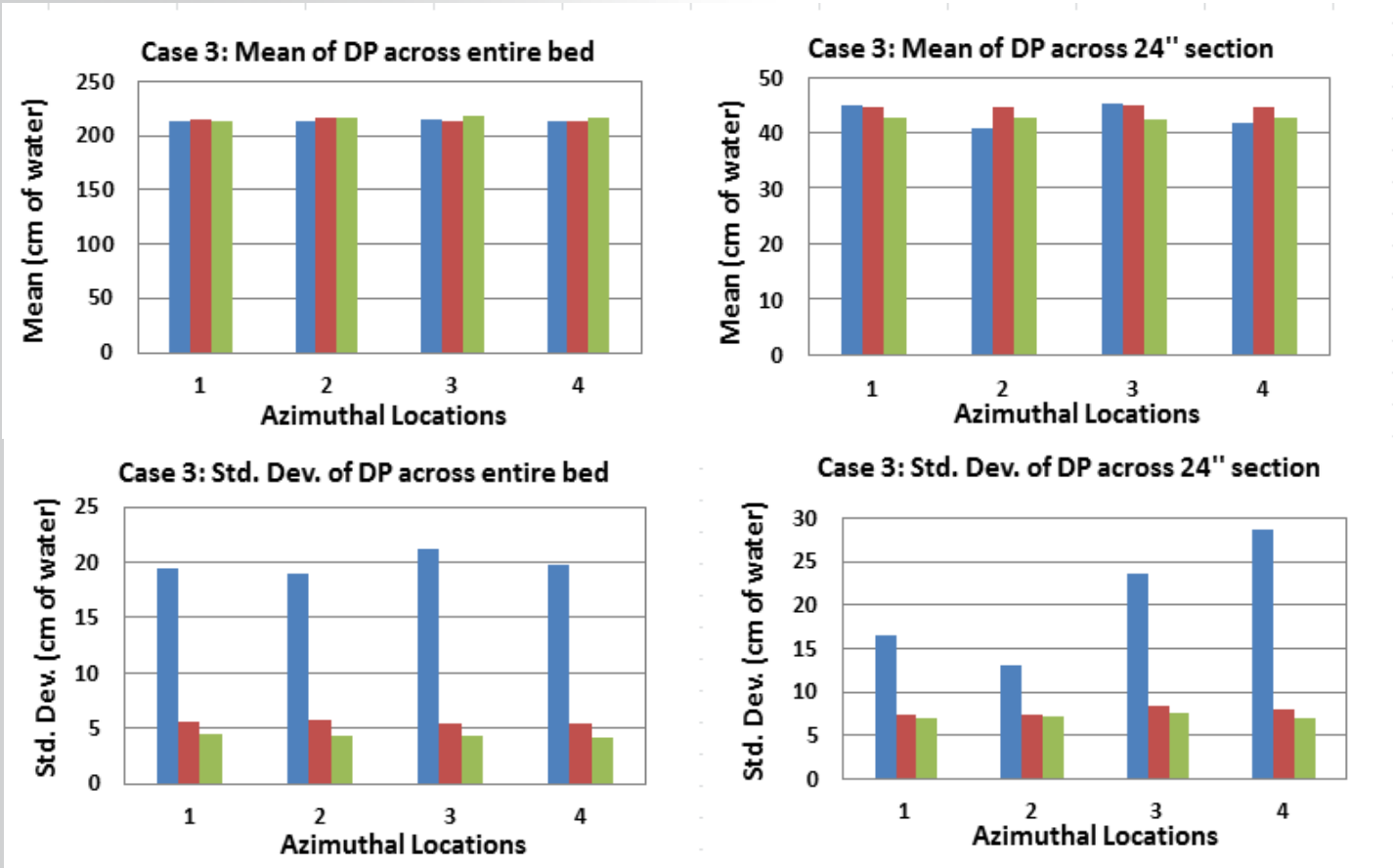
Units: m/s



BFB Case 3

Milioli et al. filtered TFM

Differential Pressure (DP) across entire bed and 24 inch section

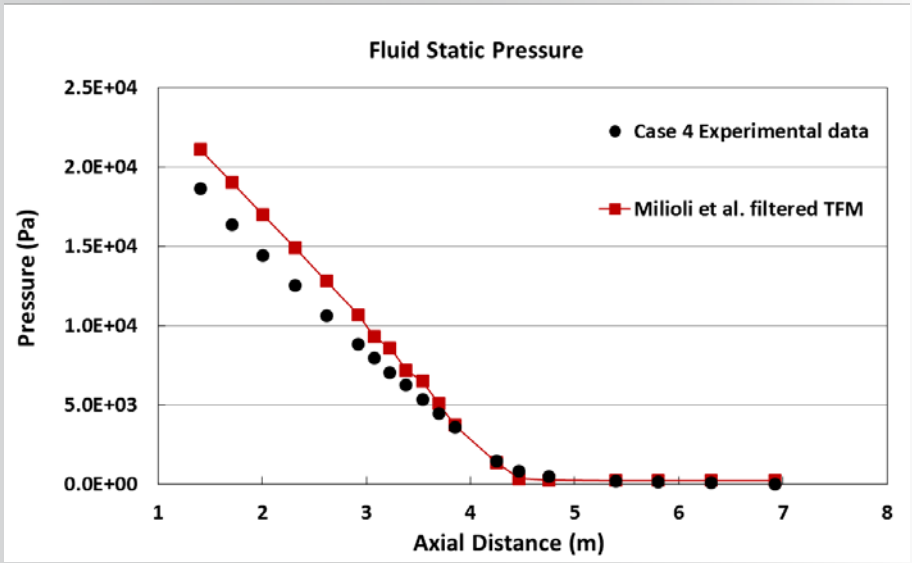


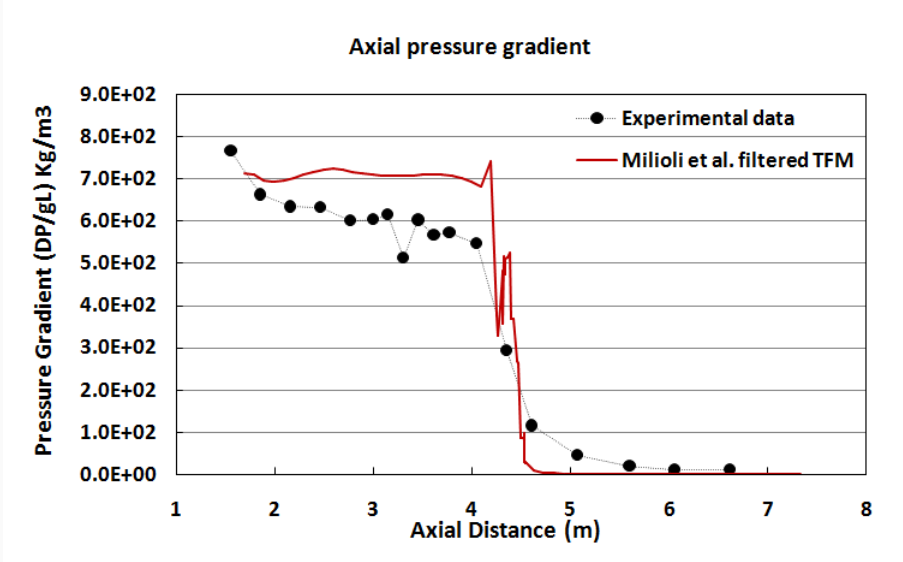
BFB Case 4

Case attributes

- 12% fines content (d_{32} = 68 E-06 m)
- Moderate bed height (2.44 m)
- Air distributor: Ring sparger

Orifice diameter is taken as twice the actual size.

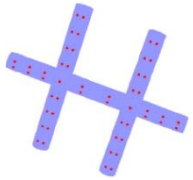




BFB Case 1 and Case 2

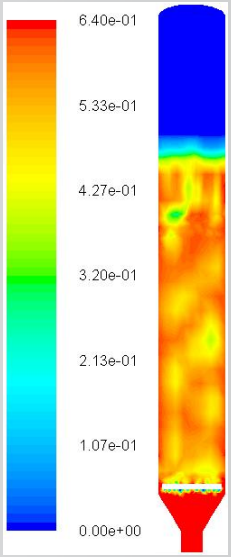
Case attributes

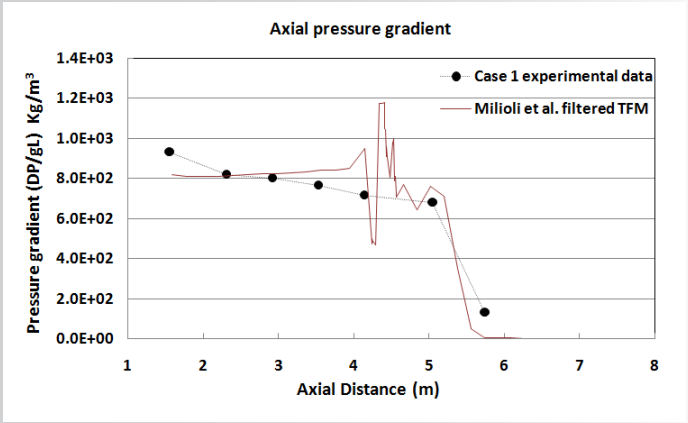
- 3% fines content
- Case 1: Deep bed (3.66 m)
  Case 2: Shallow bed (1.22 m)
- Air distributor:
  Pipe manifold



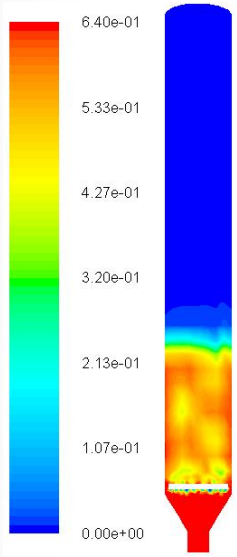
Orifice diameter is taken as twice the actual size.

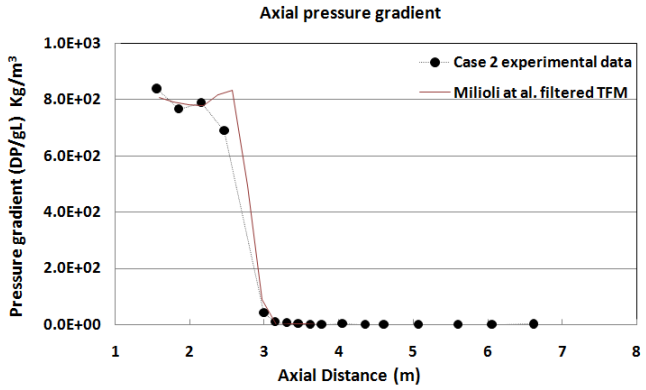
Case 1





Case 2



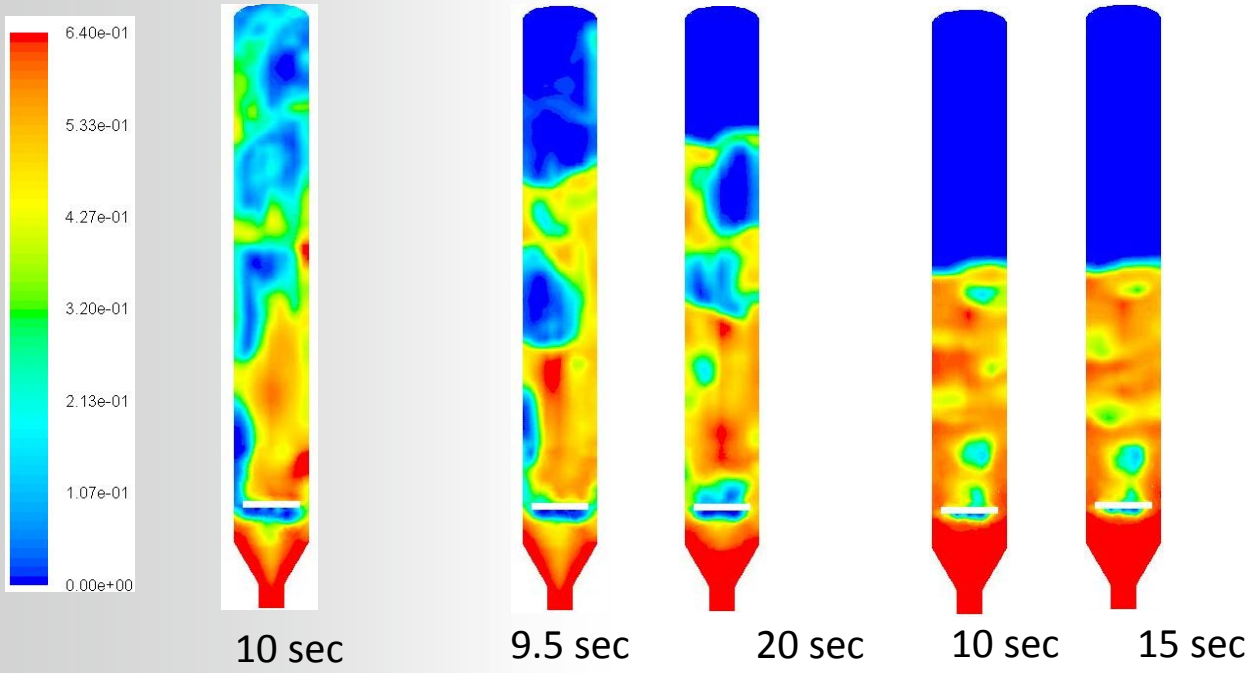


Case 3 simulations

Euler-Lagrange approach with DEM to account parcel collisions

Preliminary results

Contours of volume fraction of particles

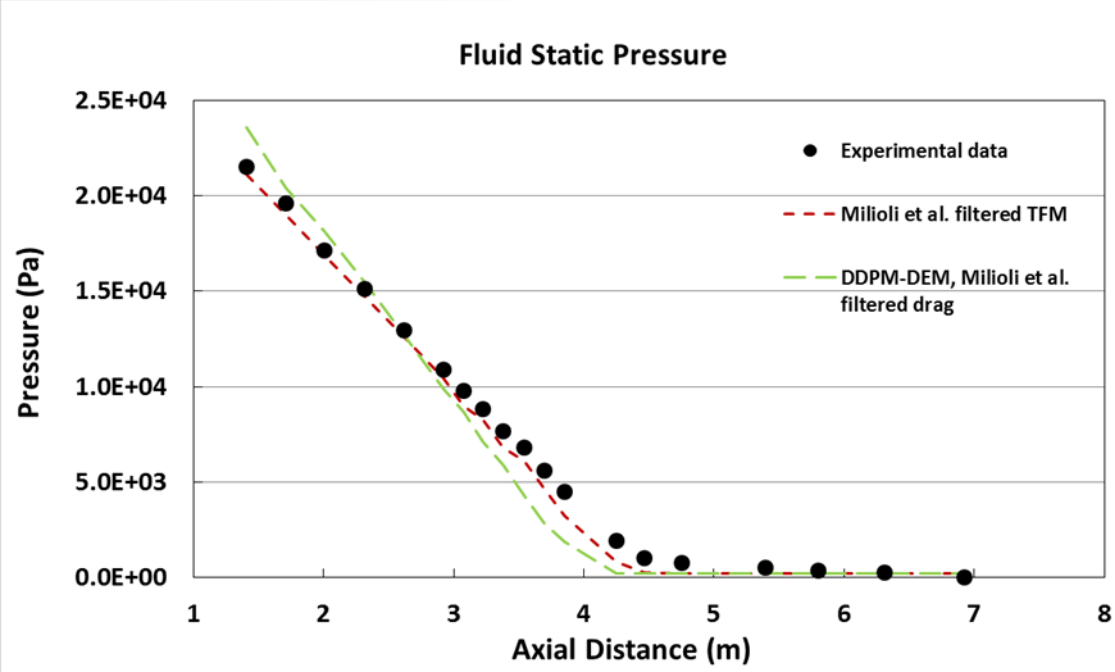


- Unphysical bed expansion with Wen & Yu drag model. Bed expansion is relatively less pronounced with Igci et al. filtered drag model while it appears reasonable with Milioli et al. filtered drag model.

Case 3 simulations

Euler-Lagrange approach with DEM to account parcel collisions

Preliminary results



- Use of effective filtered drag for Euler-Euler (EE) framework in Euler-Lagrange (EL) approach is a reasonable first approximation.

Summary

- Kinetic theory based TFM and Igci et al. filtered TFM yielded unphysical bed expansion.

- Further refined filtered TFM by Milioli et al. is more promising.
  - Bed expansion and mean of differential pressure captured reasonably well.
  - Under prediction of Std. Dev. Of differential pressure.
    - Need further investigation
      - -- Refinement of stress model ??
      - -- Defluidization ??

- Results from EL approach with effective filtered drag developed for EE framework are encouraging.

Extra slides….

Case 3 DDPM-DEM simulation

In all three DDPM-DEM simulations (Wen & Yu, Igci and Milioli)

- Grid resolution:
  - 40000

- Total number of parcels : 830,000

- Particle diameter is kept constant (78.66 micron, same as in TFM study)

- Number of particles per parcel: 6E+06

- Recirculating boundary condition on particles to maintain inventory if in case particles leave from outlet.

  See next slide for specified DEM parameters ….

Case 3 DDPM-DEM simulation

- **DEM parameters**

- Normal spring constant	400 or 1000 N/m
- Coefficient of normal restitution	0.9
- Friction coefficient	0.2
- Contact time (tc) (based on parcel mass)	~ 5e-3 s
- Particle time step (dt_p = tc/5)	~1e-3 s