BUBBLE EXTRACTION AND ANALYSIS OF GROUP-A GAS-SOLID FLUIDIZED BEDS – A COMPARISON BETWEEN TWO-FLUID SIMULATIONS AND EXPERIMENTS

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Bubbling Fluidized Bed Reactors are Critical for Many Chemical Processes

Fluidized bed technology is a critical reactor technology for multiple-billion-dollar businesses across multiple sectors at Dow

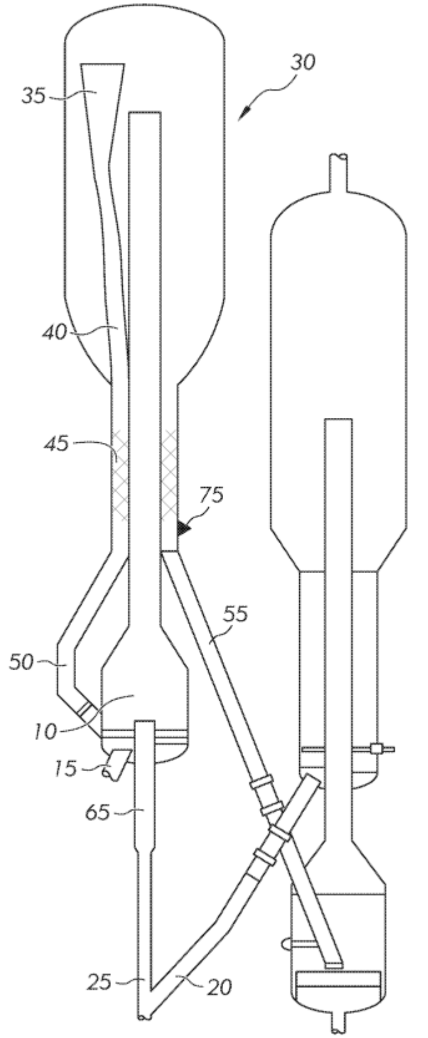
An example of bubbling fluidized bed

- **Fluidization**
  → Under appropriate conditions, a solid/fluid mixture behaves as fluid
- **Advantages of fluidized beds over packed bed reactors**
  → Superior heat transfer: 5X to 10X better

  → Moves solid like a fluid: easy to add/remove particles w/o shutdown

  → Able to handle materials with a wide particle size distribution
- **Applications of fluidized beds**
  → Dow's patented fluidized catalytic dehydrogenation (FCDh) technology (patent number: EP3455196B1)

  → Fluid catalytic cracking (FCC), coal combustion, biomass pyrolysis, polyolefin production & **a lot more**



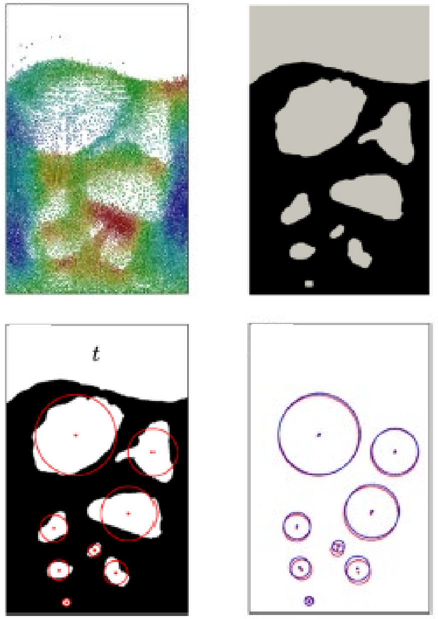
Dow's patented FCDh configuration

Bubbling Dynamics Controls Heat and Mass Transfer of Bubbling Fluidized Bed

***Goal of this work:** develop an efficient bubble extraction algorithm for 3D fluidized bed simulations*

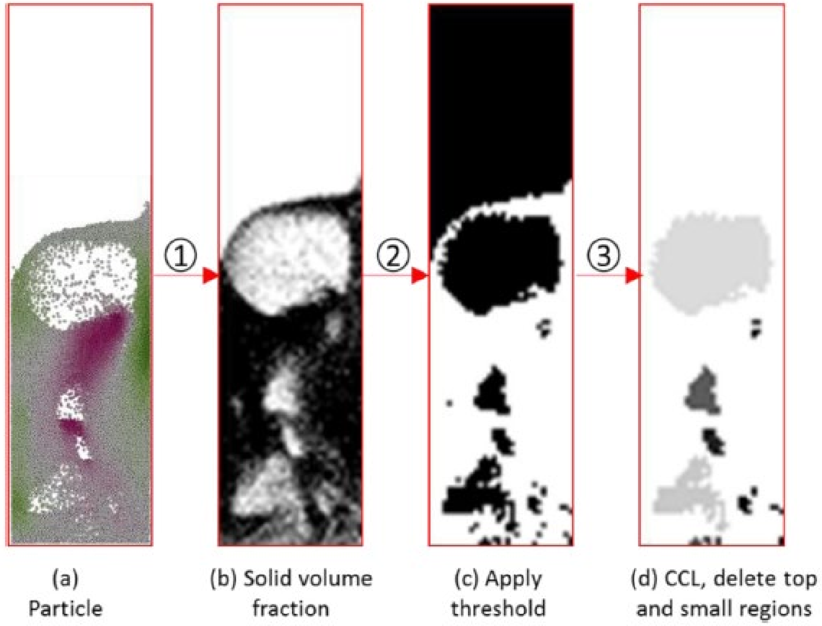
- Experimental measurement techniques
  - Non-invasive: ECVT, MRI, X-ray tomography; Invasive: PSRI optical fiber bubble probes, FBRM, EasyViewer
- Bubble information is not readily available in CFD simulations
  - Some recent literature still focused on bubble detection in 2D simulations
  - **Existing methods are not capable of 3D bubble detection / reconstruction**

(1)



Approximate Image Processing Method (AIPM)
(Li et al. 2019 CES)

(2)



Linear-time Connected-Component Labeling (Lu et al. 2017 CEJ)

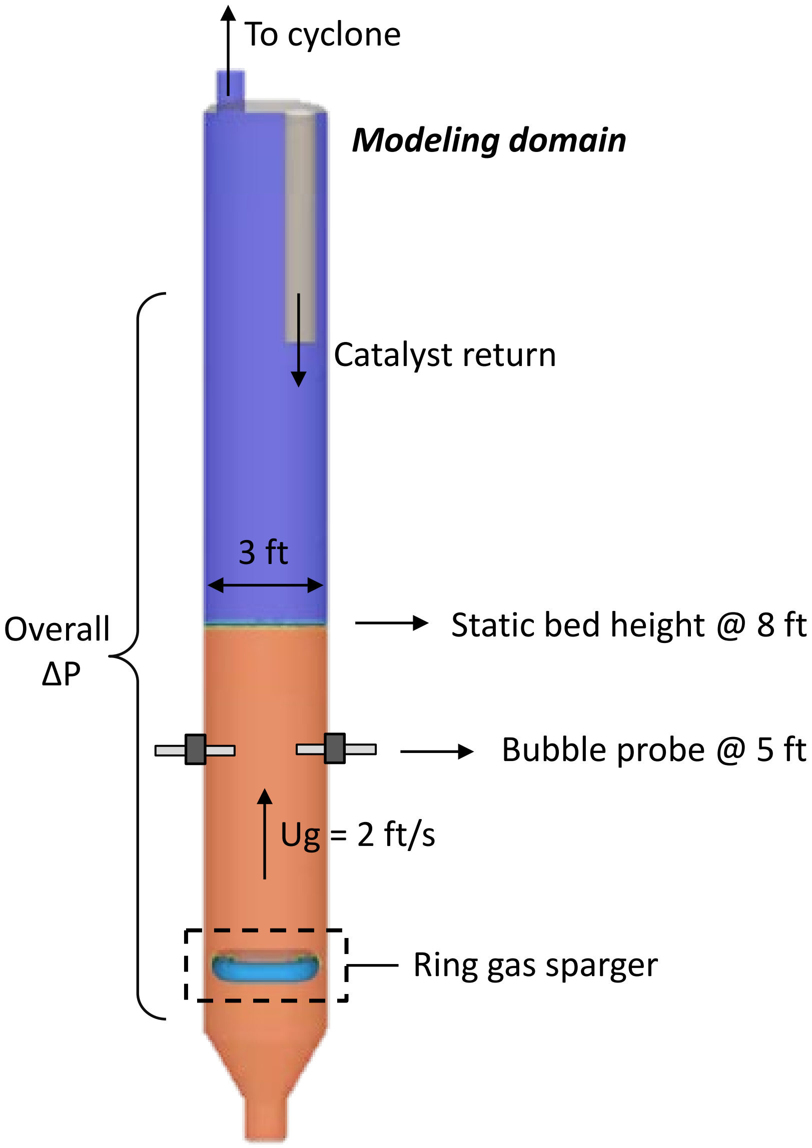
Test cases:

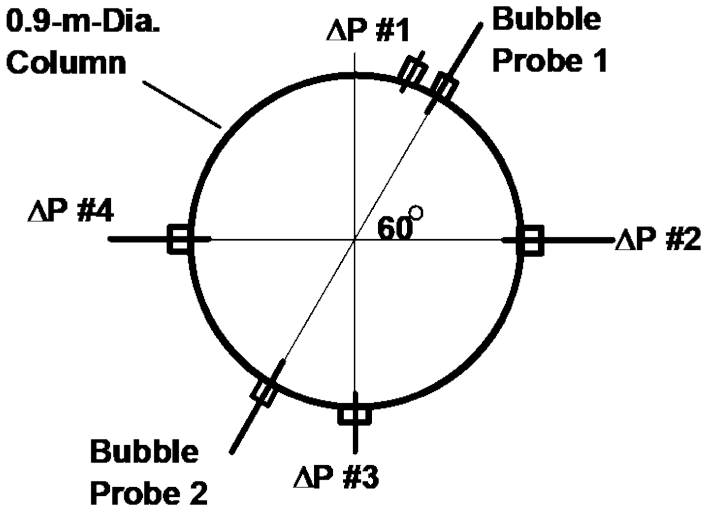
- Case A: NETL BFB Challenge Problem (2010)
- Case B: 18.4-cm BFB at UC Boulder with glass beads

Comparison:

- Bubble size vs. radial position
- Bubble void fraction

CASE A: 3-FT NETL BUBBLING BED CHALLENGE PROBLEM (2010)[1]





Probe circumferential locations (top view)

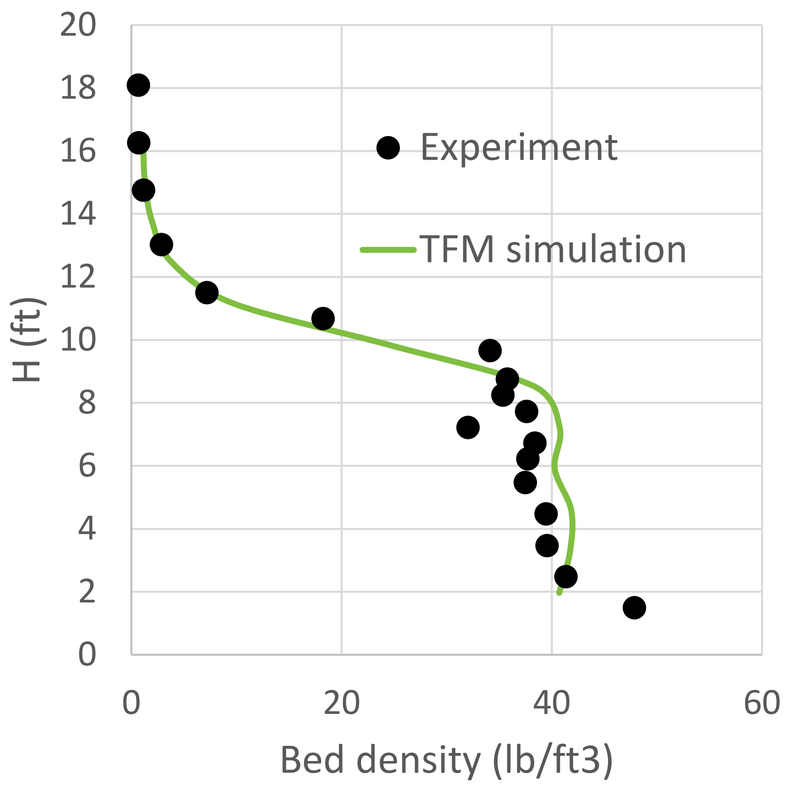
Experimental setup:

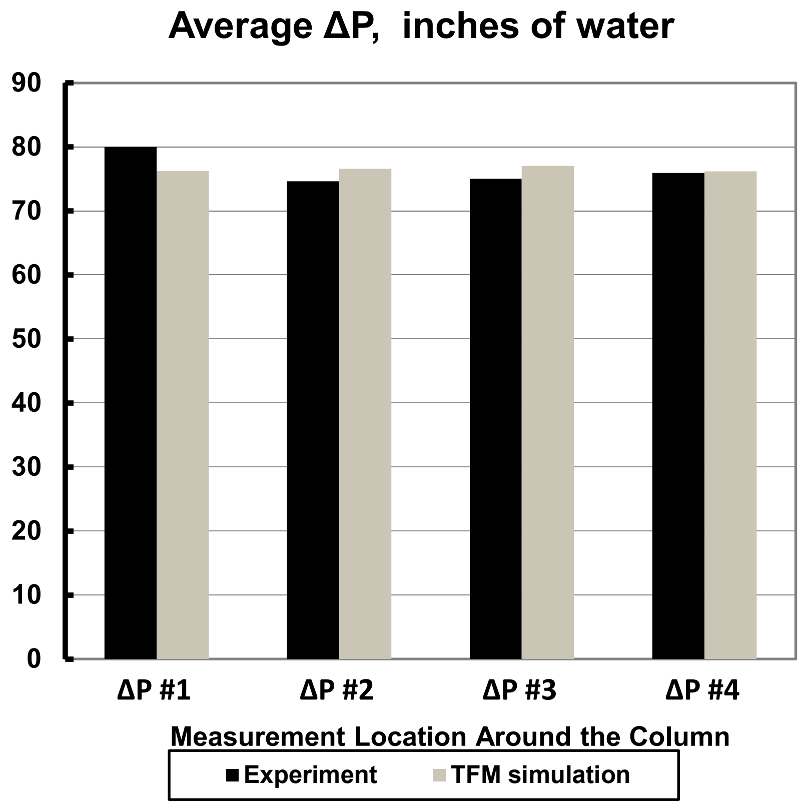
- Four ΔP transmitters
- Two PSRI optical fiber bubble probes
- FCC particles: SMD = 60 µm, ρ_p = 1490 kg/m^3

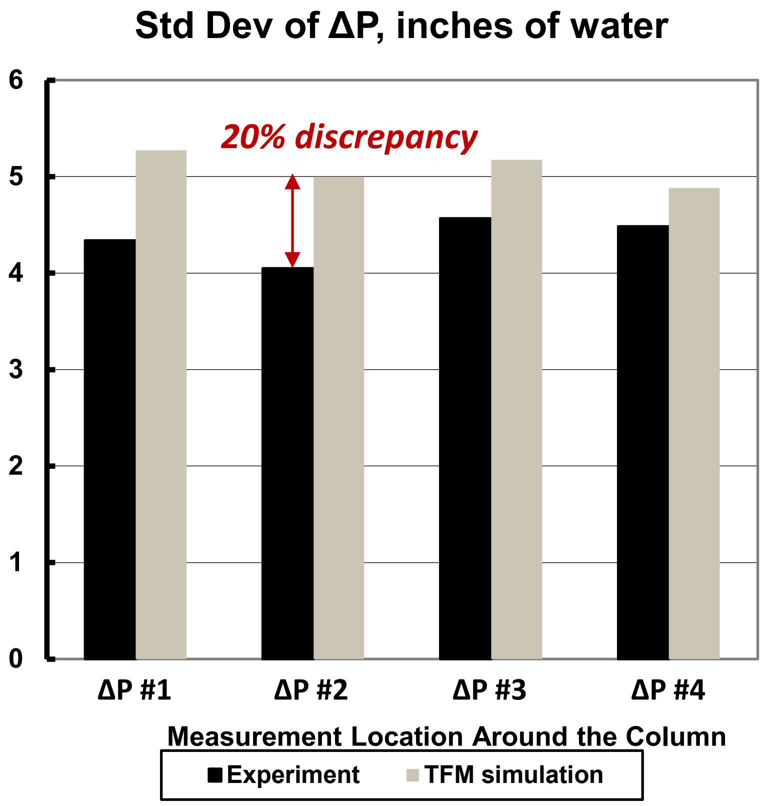
[1]https://mfix.netl.doe.gov/research/laboratory-studies/challenge-problems

CASE A: COMPARISON OF BED DENSITY PROFILES & PRESSURE FLUCTUATIONS

- The averaged bed density profile and overall ΔP match with experiments
- The standard deviation of ΔP fluctuations exhibits up to 20% discrepancies
  - Indicative of discrepancies in **bubble statistics** (size, velocity, frequency)!



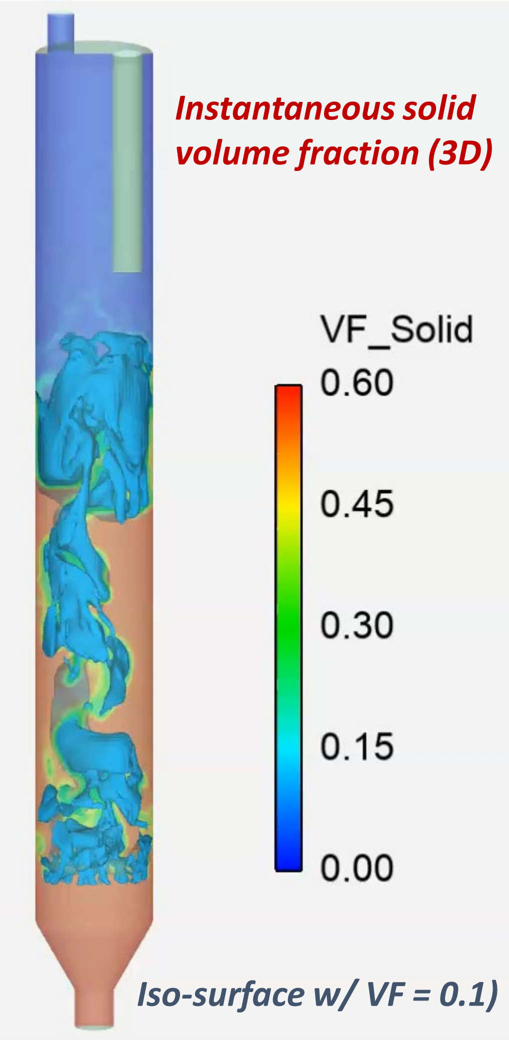


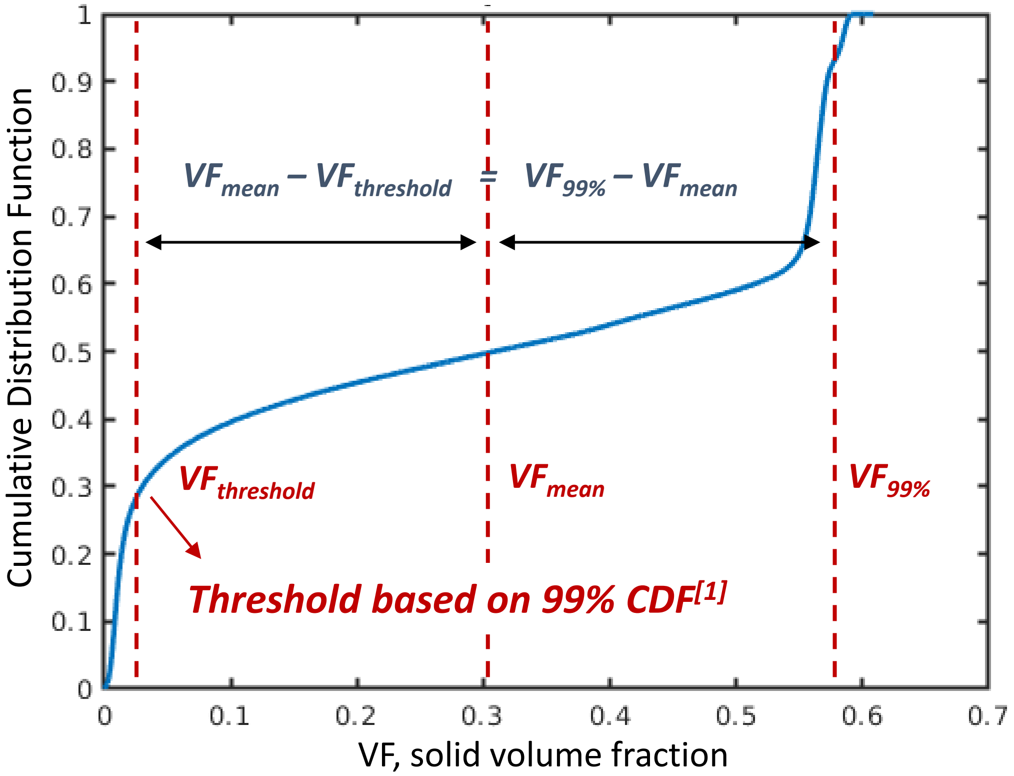


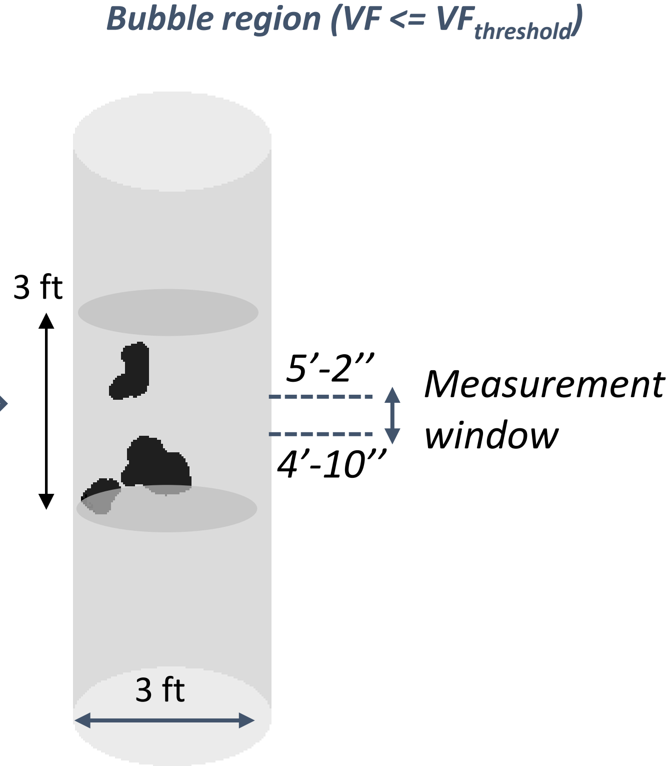
A Two-step Bubble Extraction Algorithm Based on DBSCAN

Case A (12% Fines FCC, H = 8 ft, Ug = 2 ft/s)

Step 1: detect bubble region based on solid volume fraction distribution







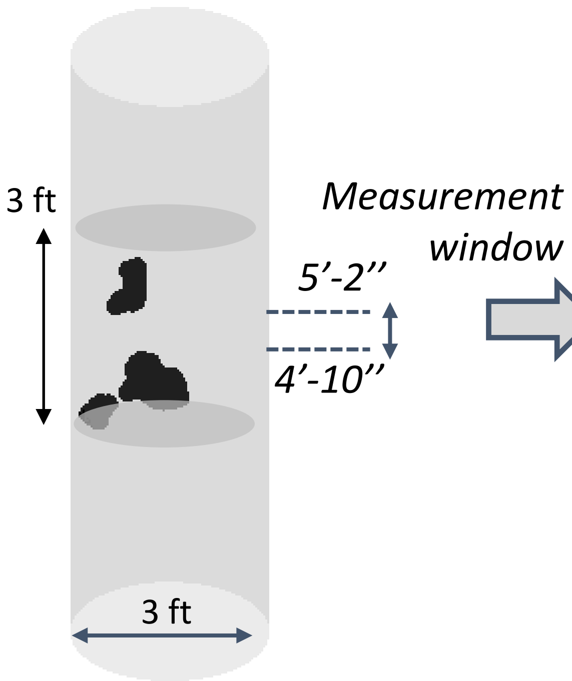
Bubble size enlarged for visualization

[1] Chew, J., Hrenya, C.M., AICHE Journal *(2011)*

A Two-step Bubble Extraction Algorithm Based on DBSCAN

Step 2: Individual bubble extraction using DBSCAN[1] clustering algorithm

Bubble region ($VF \le VF_{threshold}$)

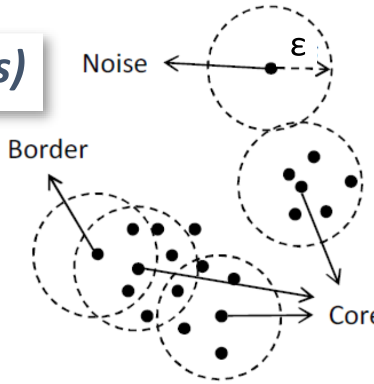


Bubble size enlarged for visualization

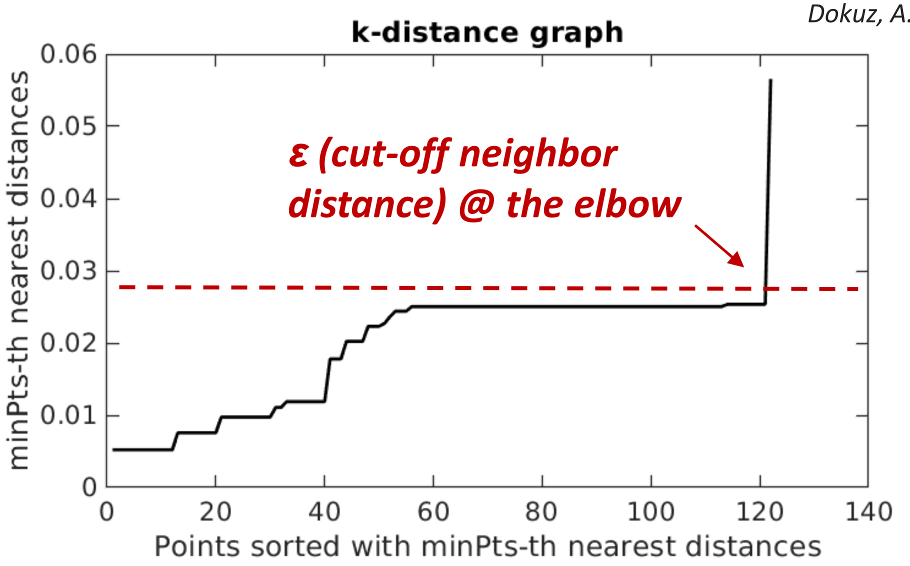
labels = DBSCAN($[x_{bbl}\ y_{bbl}\ z_{bbl}]$,ε,minPts)

(1) minPts = 2
(bubble should span at least 2 cells)

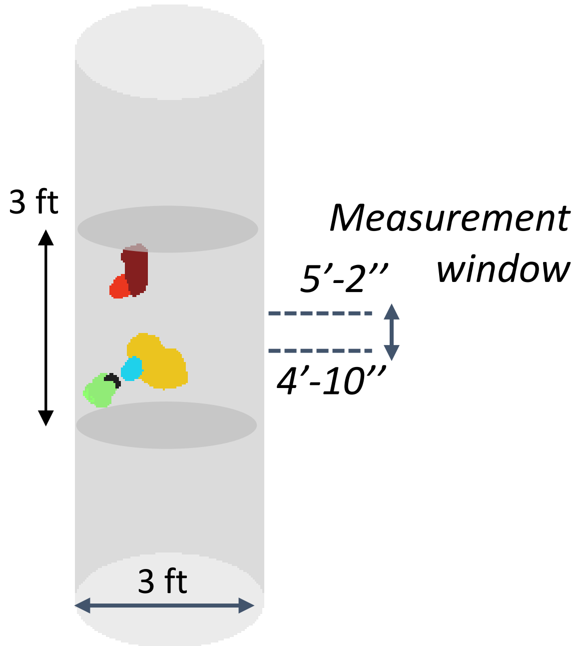
(2) ε = 0.028
(cut-off neighbor distance)



Dokuz, A. S. (2019). JES



Colors used to distinguish different bubbles

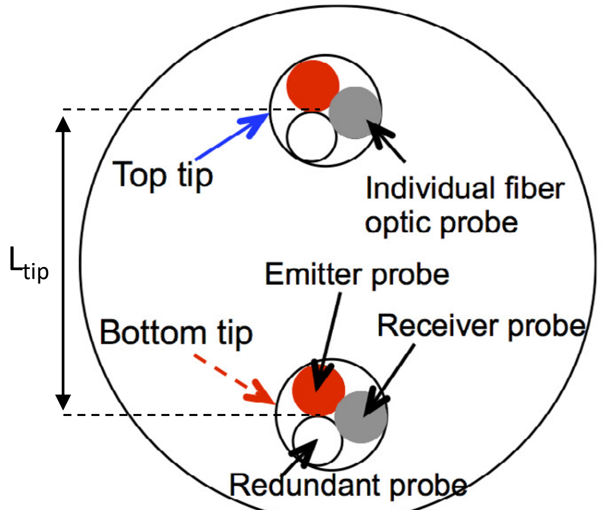


- ***Bubble size enlarged for visualization***
- *Black (-1): bubble that spans less than 2 cells → neglected*

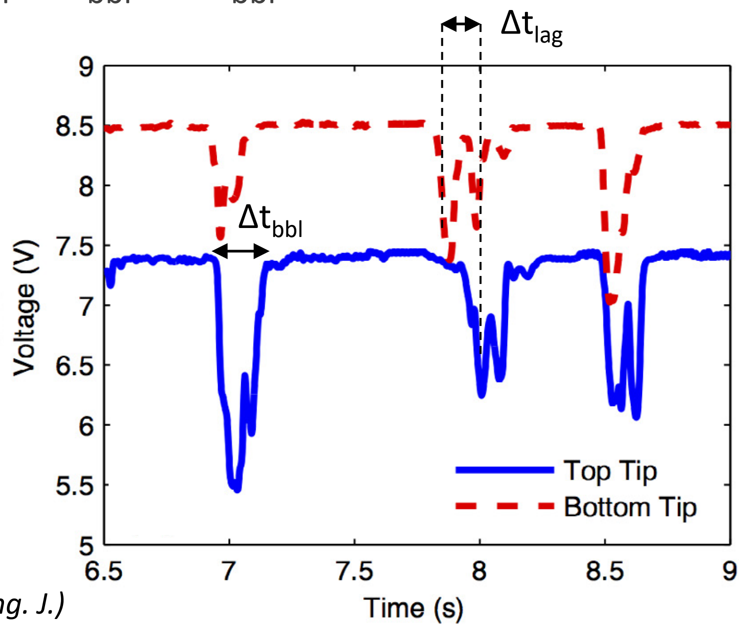
[1] Ester, Kriegel, Sander, Xu (1996). *A density-based algorithm for discovering clusters in large spatial databases with noise*. Proceedings of the Second International Conference on Knowledge Discovery and Data Mining

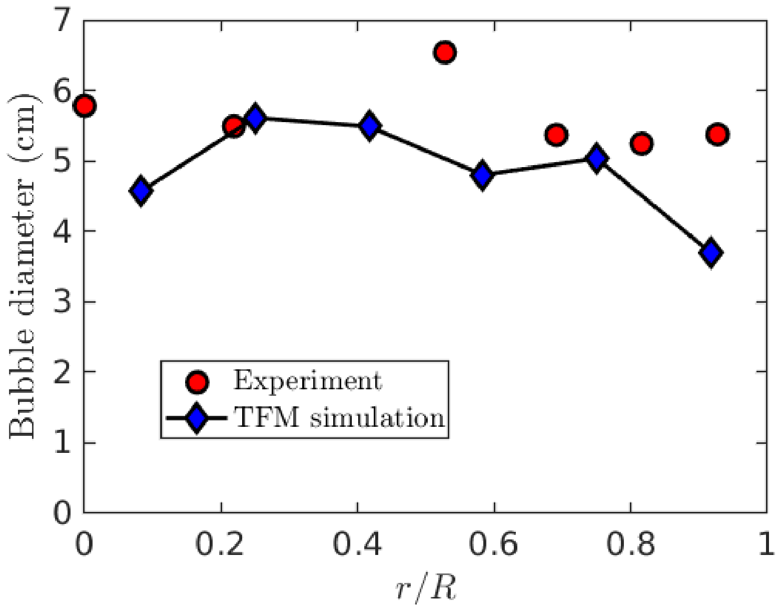
Case A: Comparison of Bubble Size

- Simulation: Δt = 1ms for 30s, data analysis: every 0.05s × 600 frames
  - Bubbles reconstructed using *alphaShape* function in MATLAB
  - Sauter mean diameter computed from reconstructed geometry
- Experiment: bubble probe voltage signal converted to bubble size (Chew & Hrenya)[1]
  - Voltage dip below threshold → bubble
  - $V_{bbl} = L_{tip} / \Delta t_{lag} \rightarrow D_{bbl} = V_{bbl} \times \Delta t_{bbl}$



PSRI bubble probe (LaMarche 2016 Chem. Eng. J.)



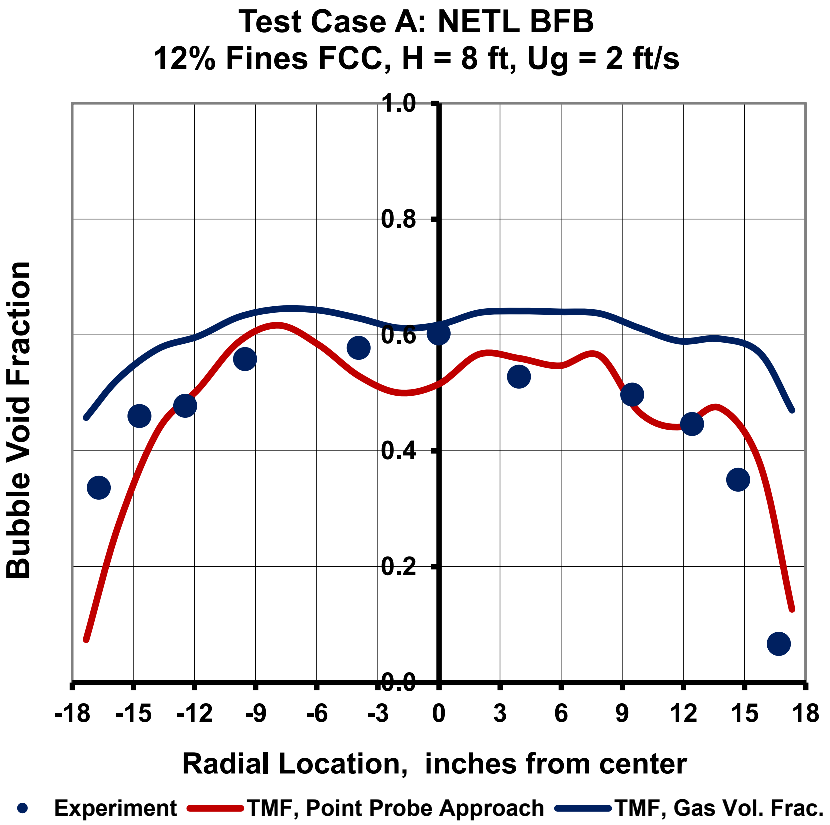


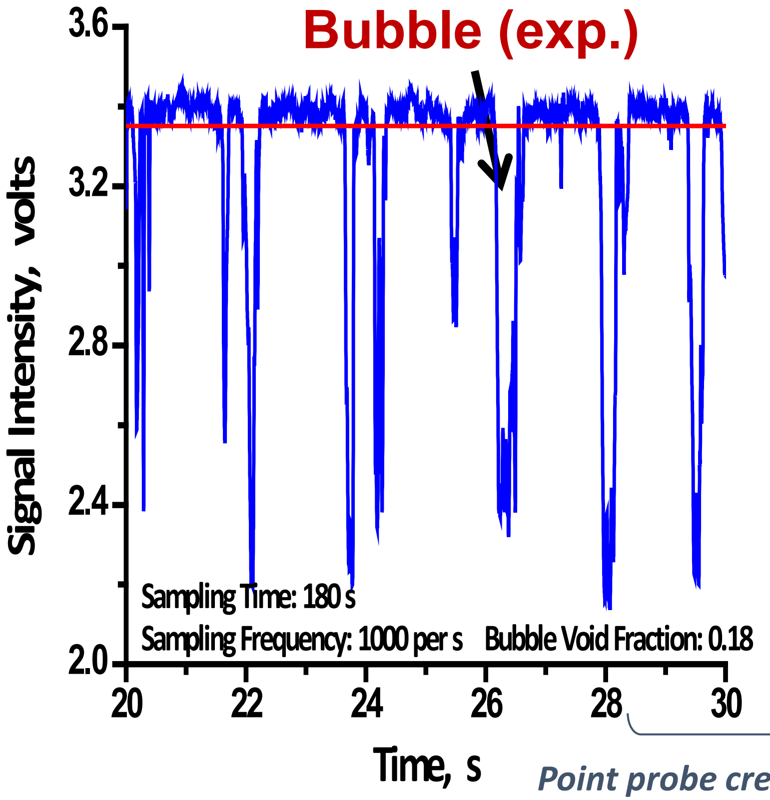
[1] Chew, J., Hrenya, C.M., AICHE Journal *(2011)*

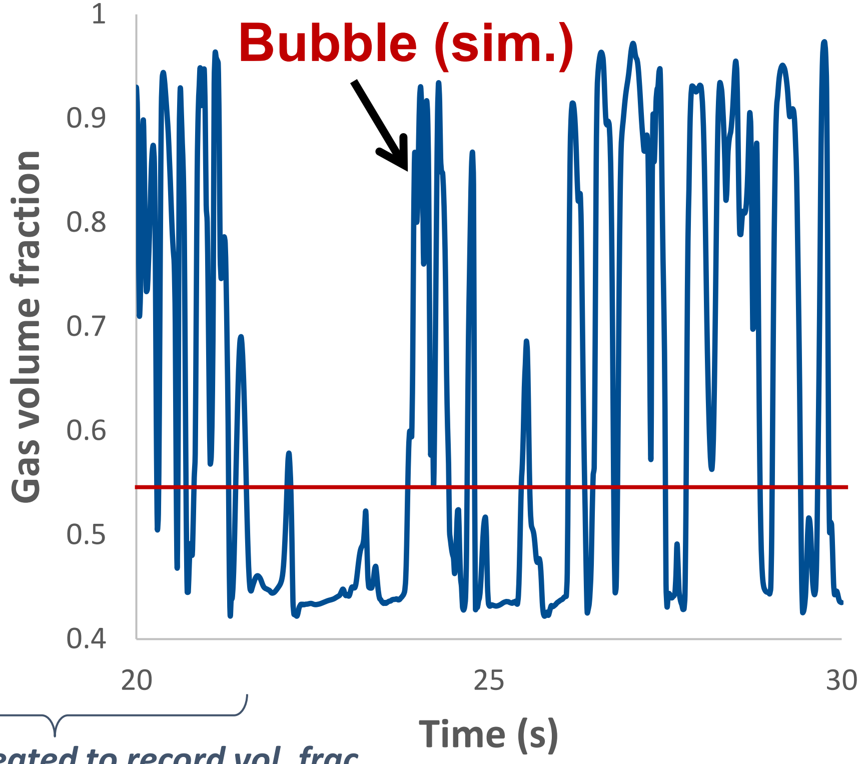
CASE A: COMPARISON OF BUBBLE VOID FRACTION

- Bubble void fraction in simulations estimated by mimicking experiments
  - Gas volume fraction ≠ bubble void fraction
  - Gas volume fraction can be treated as "voltage signals"

Bubble void fraction = fraction of time the probe is in contact with a bubble ($V<V_{threshold}$)



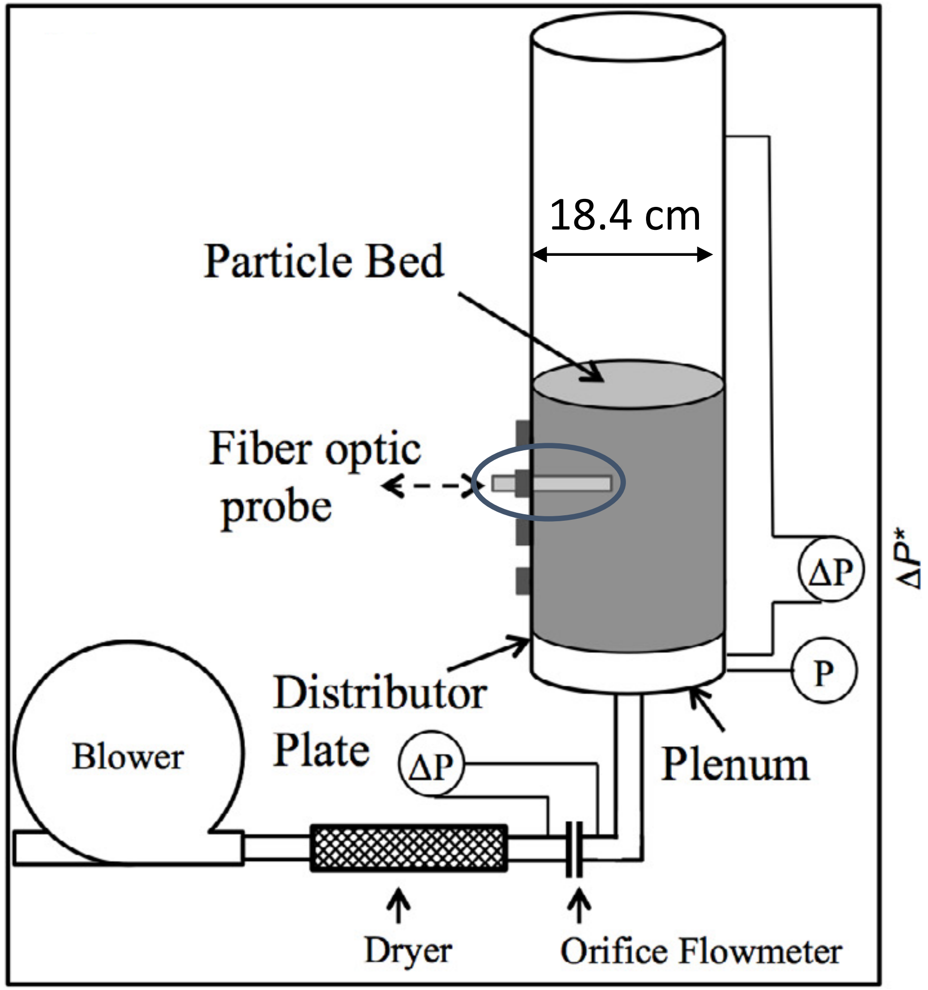


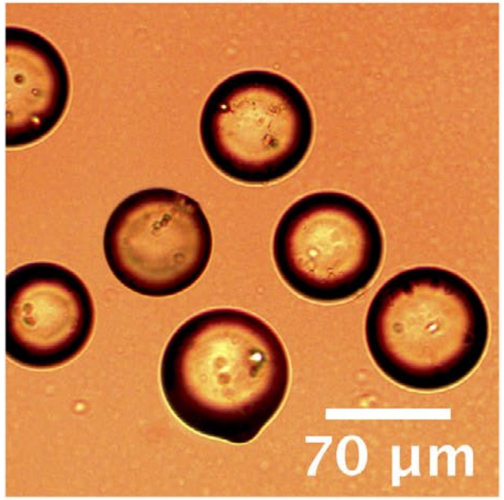


Point probe created to record vol. frac. in time (same location as bubble probe)

CASE B: 18.4-CM BUBBLING BED WITH GLASS BEADS (LAMARCHE 2016[1])

Experimental setup (LaMarche 2016[1]):





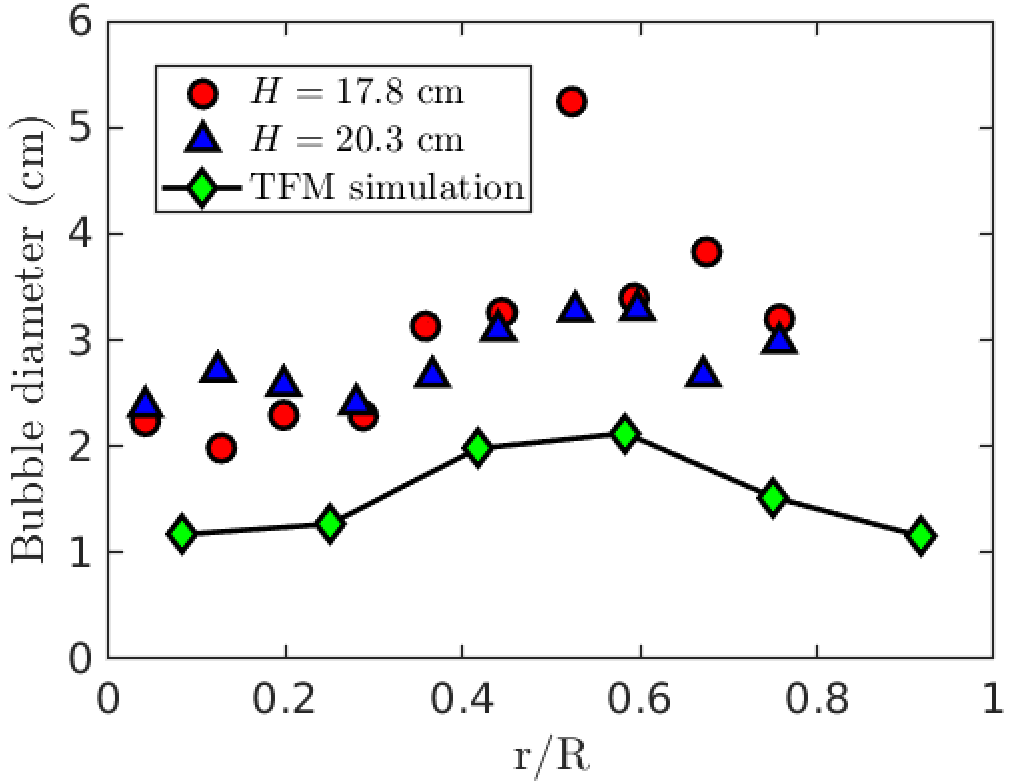
Microscopic image of glass beads

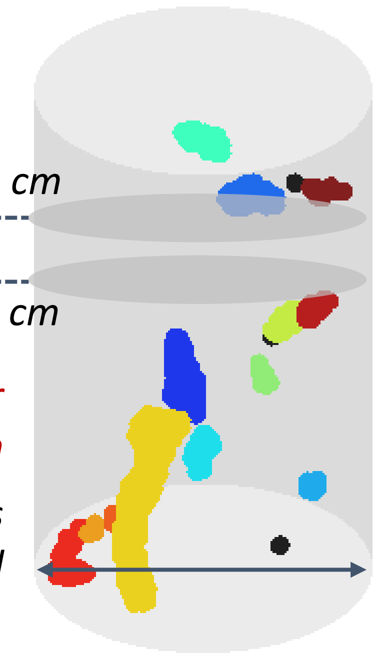
- *The same PSRI bubble probe was used in Case A and B.*
- *Voltage signals were recorded for 30s at two heights:*
  - *H = 17.8 cm and 20.3 cm*
- *Incipient fluidization:* $U_g \cong 3\ U_{mf}$

Particle size (µm)	Superficial velocity (cm/s)	Particle density (kg/m³)	Static bed height (cm)
69	1.86	2500	24

[1] LaMarche, C.Q., Liu, P., Kellogg, K.M., Hrenya, C.M. "Fluidized-bed measurements of carefully-characterized, mildly-cohesive (Group A) particles", Chemical Engineering Journal *(2016)*

CASE B: COMPARISON OF BUBBLE SIZE





Bubble size comparison:

- Bubbles are larger around r=0.5R, and smaller at the center and near wall in both TFM and experiments
- TFM predicts smaller bubbles
  - bubble size measured as **chord length** in experiments
  - but based on $\mathbf{D_{32}}$ in 3D simulations

***Gas streaming** observed experimentally in beds with:*

(1) large H/D
(2) less fine content
(3) low superficial velocity[1]

[1] Issangya, A., Knowlton, T., Karri, R., "Detection of Gas Bypassing due to Jet Streaming in Deep Fluidized Beds of Group A Particles", *THE 12TH INTERNATIONAL CONFERENCE ON FLUIDIZATION (2007)*

Summary and Conclusion

- Two-step bubble extraction / reconstruction algorithm for 3D CFD simulations
  - (1) **CDF-based** thresholding + (2) **DBSCAN-based** labeling of individual bubble
  - **Fully-reconstructed** actual bubble geometry provides better bubble statistics

- Algorithm was tested for two BFB cases and compared with experimental results
  - Smaller bubbles found **at the center** and **near wall** for both TFM and experiments
  - Bubble sizes match well for case A, but deviate for case B (**non-spherical bubbles** with **gas bypassing**)

- Future directions
  - Compute bubble **frequency** and **velocity** by matching two frames via **cross-correlation**
  - **Point probe approach** (mimicking voltage signal) to estimate frequency and velocity

- Acknowledgement

  - Yicheng Hu (Dow): discussion on image processing
  - Kevin Kellogg (Dow): providing details on Case B setup
  - Allan Issangya (PSRI): providing bubble data for Case A

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