Electrical Capacitance Volume Tomography: An Imaging Tool for Multiphase Flow Systems

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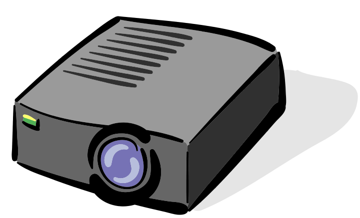
[2]The Ohio State University
Department of Chemical and Biomolecular Engineering



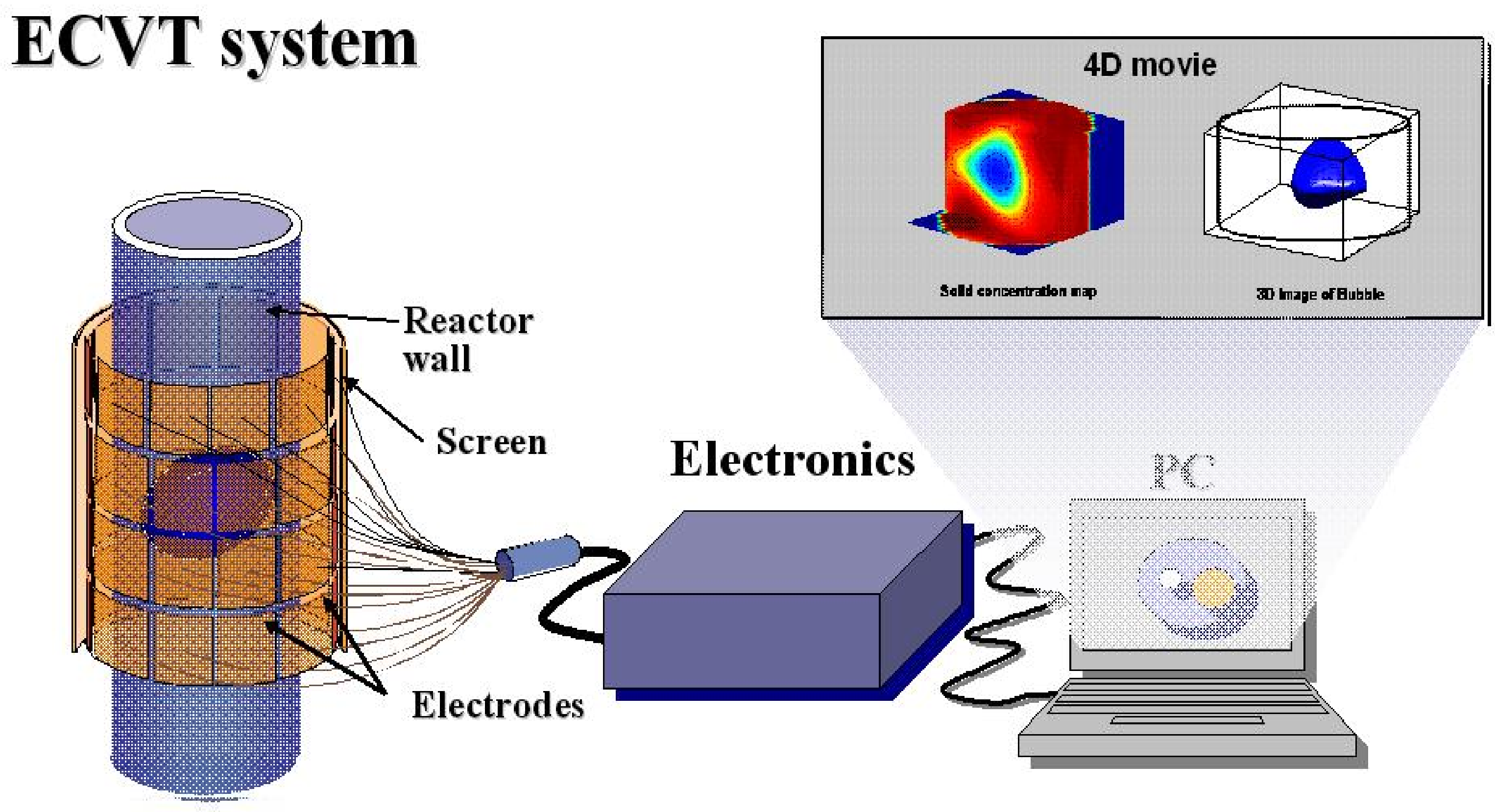
Introduction

- Electrical Capacitance Volume Tomography (ECVT) is a 3D imaging technique for viewing cold flow processes. It can potentially be applied to hot units too.
- ECVT is among few know non-invasive imaging tool that can be used for commercial applications (low cost, suitable for scale-up, fast, and safe)
- Tech4Imaging LLC is a spin-off company from The Ohio State University to develop and commercialize imaging technologies, including ECVT.
- Tech4Imaging, with DOE support, is developing a complete system of acquisition hardware, sensors, and reconstruction software for.

Preface

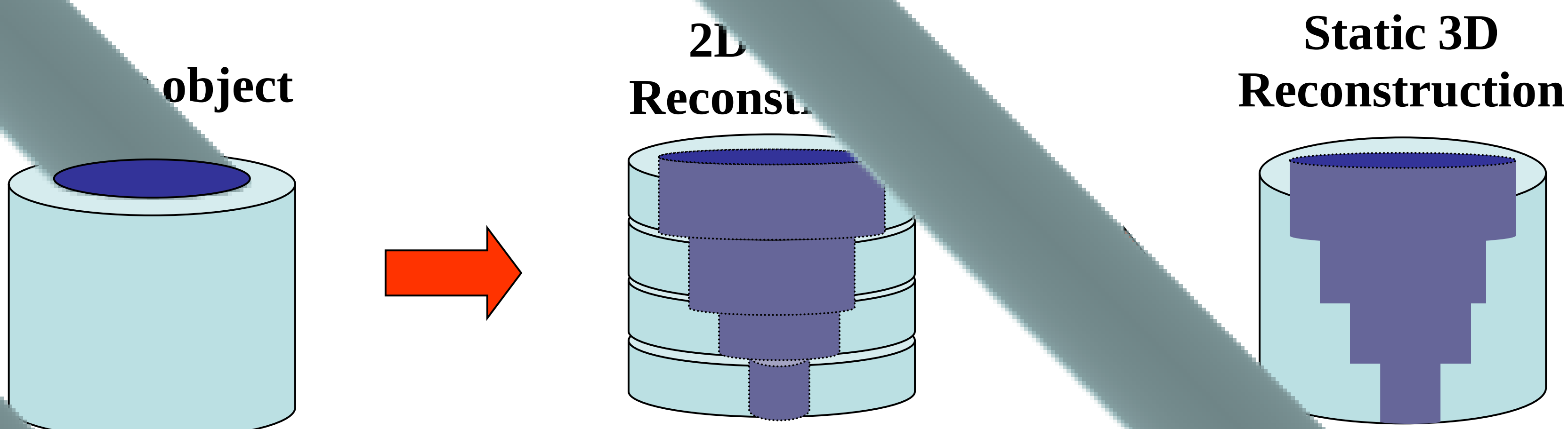
1. ECVT Technology
2. Verification
3. Jet Example
4. Velocimetry
5. Sensors and Scale up Application
6. Complex geometries

ECVT System

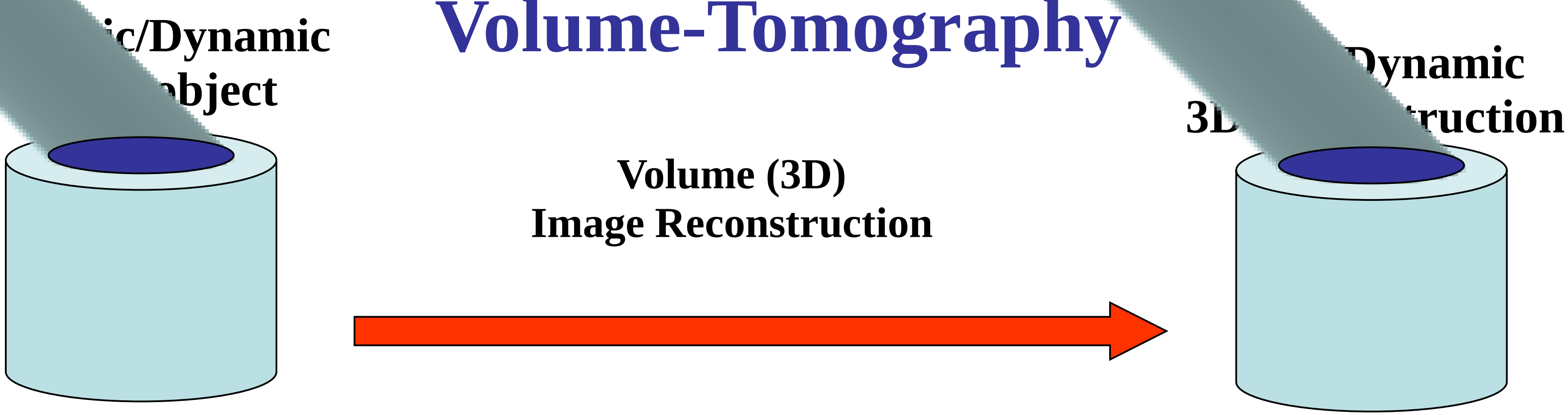

ECVT system
Reactor wall
Screen
Electrodes
Electronics
PC
4D movie
Solid concentration map
3D image of Bubble

Volume Tomography Concept

Conventi[illegible] Tomography



Volume-Tomography



ECVT technique

Reconstruction	Methodology	Characteristics	Example
Single Step Linear Back Projection	The sensor system is linearized (usually by constructing a sensitivity matrix). The image is obtained by back projecting the capacitance vector using the sensitivity matrix.	Fast, low image resolution, and introducing image artifacts	LBP
Iterative Linear Back Projection	The mean square error between the capacitance data and forward solution of the final image is minimized by iterative linear projections using the sensitivity matrix.	Slower than Single Step Linear. Providing better images than Single Step	Landweber ILBP
Optimization	A set of objective functions are minimized iteratively to provide the most likely image. Different optimization algorithms and objective functions can be used.	Slower than Iterative Linear Back Projection. Providing better images than Iterative Linear Back Projection	3D-NNMOIRT

3D-NNMOIRT

Objective functions

Negative entropy function $$f_1(\mathbf{G}) = \gamma_1 \sum_{j=1}^{N} G_j \ln G_j$$

Error function $$f_2(\mathbf{G}) = \frac{1}{2}\gamma_2 \left\| \mathbf{SG} - \mathbf{C} \right\|^2 = \gamma_2 \sum_{i=1}^{M} \left(\sum_{j=1}^{N} S_{ij} G_j - C_i \right)^2$$

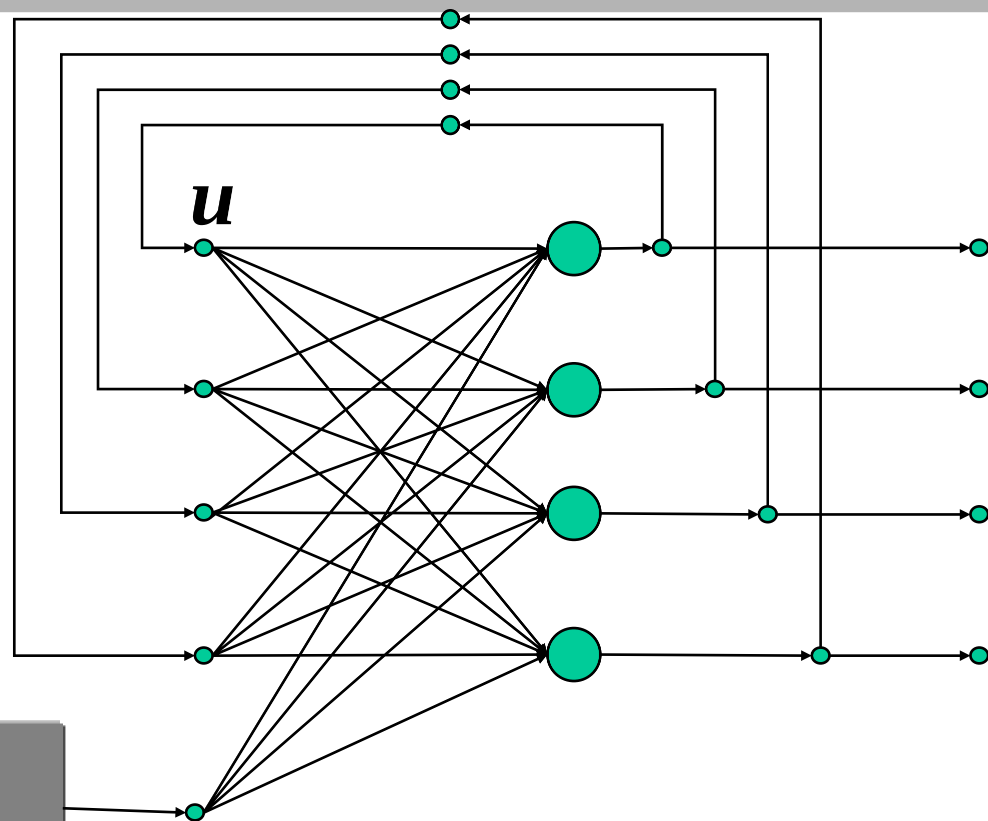
3-D Smoothness function $$f_3(\mathbf{G}) = \frac{1}{2}\gamma_3 \left(\mathbf{G}^T \mathbf{X} \mathbf{G} + \mathbf{G}^T \mathbf{G} \right)$$

3-to-2D and 3-to-1D matching function for 3-D imaging

$$f_4(\mathbf{G}) = \frac{1}{2}\gamma_4 \left\{ \left\| \mathbf{H}^1 \mathbf{G} - \mathbf{G}^1_{2D} \right\|^2 + \left\| \mathbf{H}^2 \mathbf{G} - \mathbf{G}^2_{2D} \right\|^2 \right\}$$

$$= \frac{1}{2}\gamma_4 \left\{ \sum_{j=1}^{N_{1D}} \left(\sum_{k=1}^{N} H^1_{jk} G_k - G_{1D,j} \right)^2 + \sum_{j=1}^{N_{2D}} \left(\sum_{k=1}^{N} H^2_{jk} G_k - G_{2D,j} \right)^2 \right\}$$

Hopfield Network



INPUTS
(Initial conditions)

OUTPUTS v

$$v_j = f_\Sigma(u_j)$$

$$\frac{dE(\mathbf{v})}{dt} = \sum_{j=1}^{N} \frac{\partial E(\mathbf{v})}{\partial v_j}\frac{dv_j}{dt} = -\sum_{j=1}^{N} C_{0j}\frac{du_j}{dt}\frac{dv_j}{dt}$$

$$\boxed{C_{0j}\frac{du_j}{dt} = -\frac{\partial E(\mathbf{v})}{\partial v_j}}$$

$$= -\sum_{j=1}^{N} C_{0j}\left[\frac{\partial f_\Sigma(u_j)}{\partial u_j}\right]\left(\frac{du_j}{dt}\right)^2 = -\sum_{j=1}^{N} C_{0j}\left[\frac{\partial f_\Sigma^{-1}(v_j)}{\partial v_j}\right]\left(\frac{dv_j}{dt}\right)^2$$

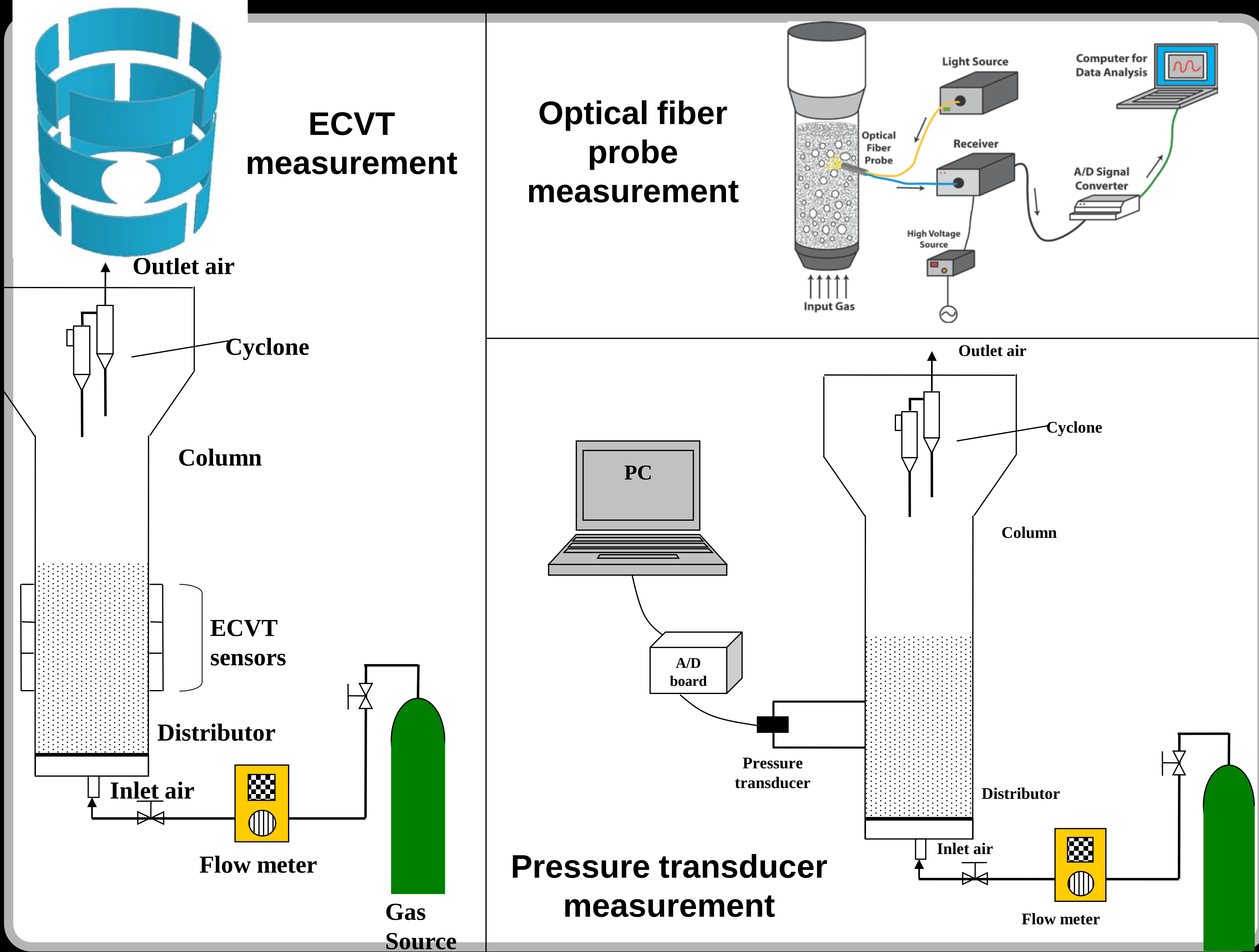
$$\boxed{\frac{dE}{dt} \le 0; \frac{du_j}{dt} = \frac{dv_j}{dt} = 0, t \to \infty}$$

2. ECVT Verification

1) Comparison of the local time-averaged solids concentrations by ***ECVT***, ***ECT***, and ***optical fiber probe***

2) Comparison of the time-averaged cross-sectional solids concentrations by ***ECT*** and ***optical fiber probe*** and the time-averaged volume solids concentration obtained by ***ECVT*** and ***pressure transducer***

3) Comparison of **ECVT** and **MRI**


ECVT
measurement
Outlet air
Cyclone
Column
ECVT
sensors
Distributor
Inlet air
Flow meter
Gas
Source
Optical fiber
probe
measurement
Light Source
Computer for
Data Analysis
Optical
Fiber
Probe
Receiver
A/D Signal
Converter
High Voltage
Source
Input Gas
Outlet air
PC
Cyclone
Column
A/D
board
Pressure
transducer
Distributor
Inlet air
Flow meter
Pressure transducer
measurement

Experimental Conditions

1

FCC particle:

Particle size: 60 μm
Particle density: 1400 kg/m^3

Fluidized bed:

ID: 4 inch
Total height: 2.5 m
Two-stage cyclone

Distributor:

Porous plate with a pore size of 20 μm
Fractional free area: 60%

Gas:

Air density:1.225 kg/m^3
Air viscosity: 1.8x10^{-5} Ns/m^2

2

FCC particle:

Particle size: 60 μm
Particle density: 1400 kg/m^3

Fluidized bed:

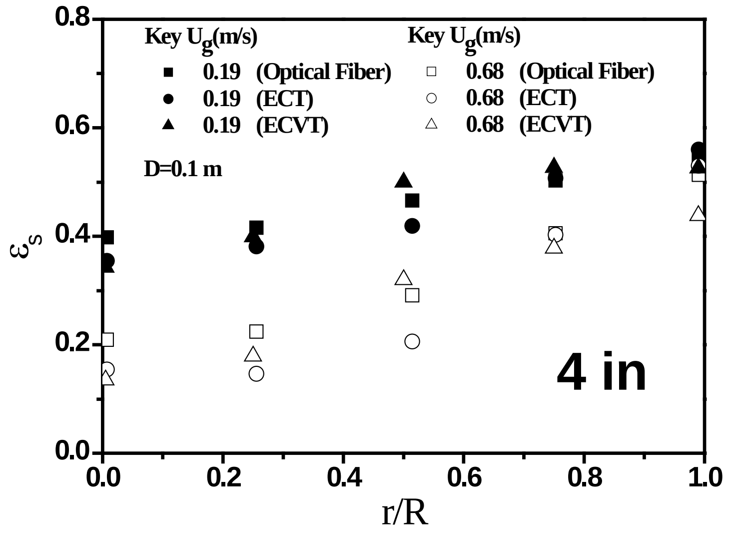
ID: 12 inch
Disengagement section: 0.5 m
Total height: 2.3 m
Two-stage cyclone

Distributor:

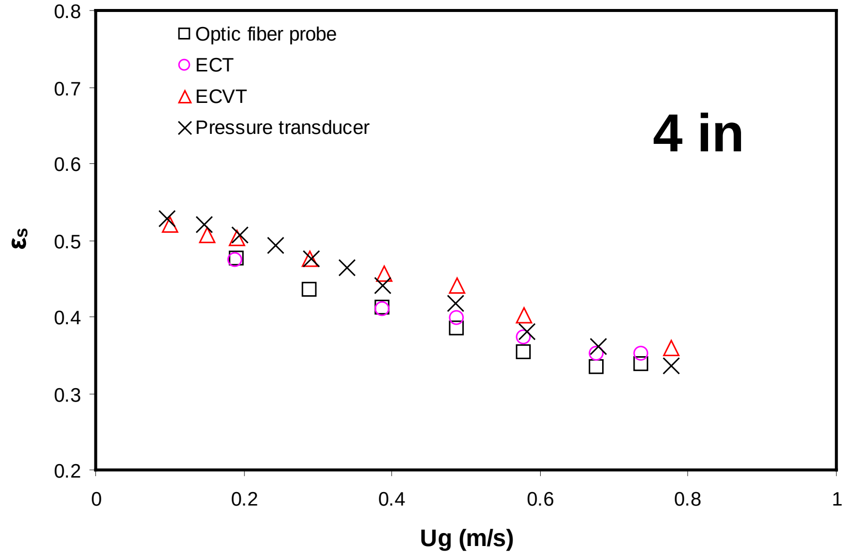
Porous plate with a pore size of 20 μm
Fractional free area: 60%

Gas:

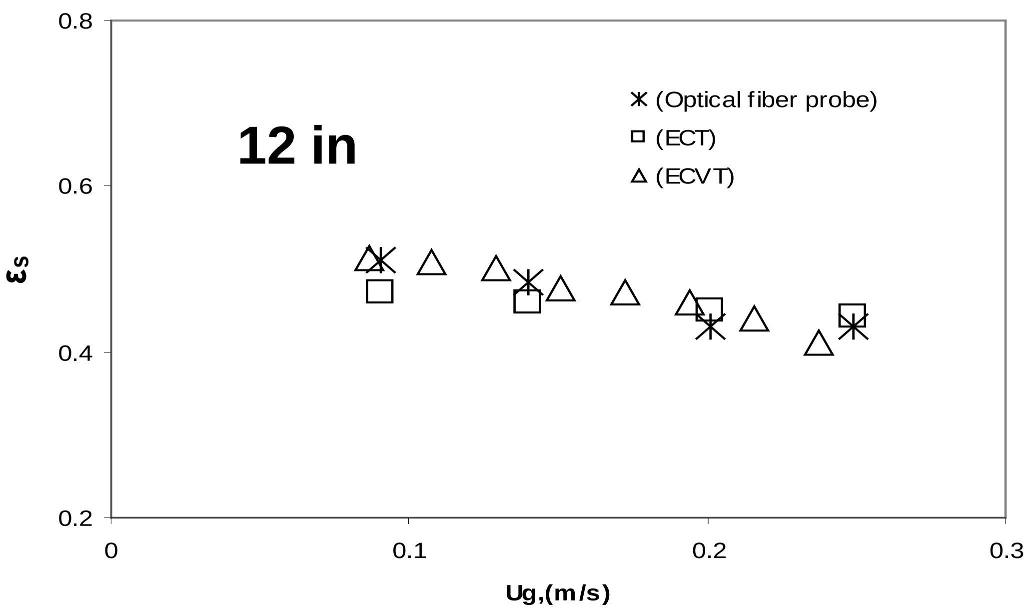
Air density:1.225 kg/m^3
Air viscosity: 1.8x10^{-5} Ns/m^2



Radial profiles of time-averaged solids concentration in a 4-in gas-solid fluidized bed with FCC particles (d_p = 60 μm; ρ_p = 1400 kg/m^3) *obtained by ECVT, ECT and optical fiber probe*

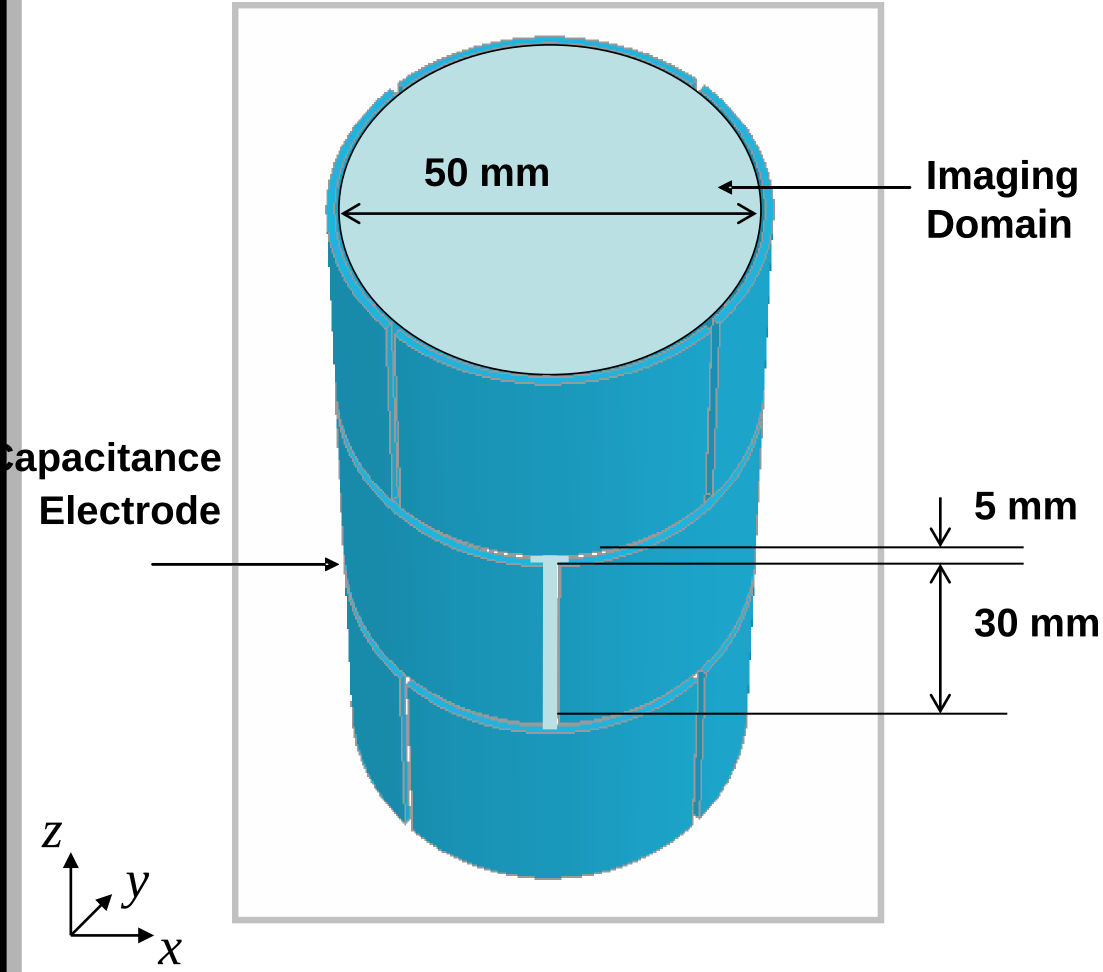


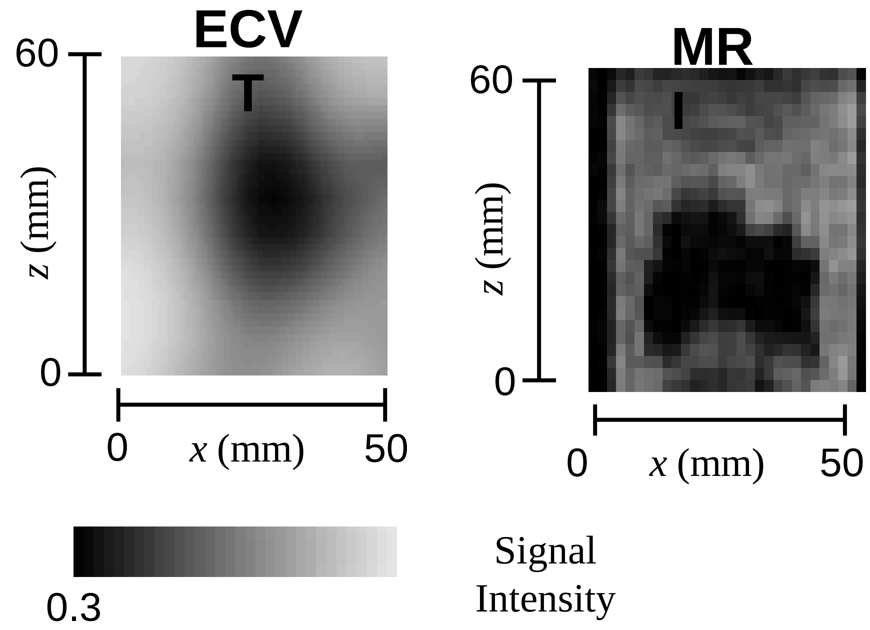
Comparison of the time-averaged cross-sectional solids concentrations obtained by *ECT* and *optical fiber probe* and the time-averaged volume solids concentration obtained by *ECVT* and *pressure transducer* for a 4-in gas-solid fluidized bed with FCC particles (d_p = 60 μm; ρ_p = 1400 kg/m^3)

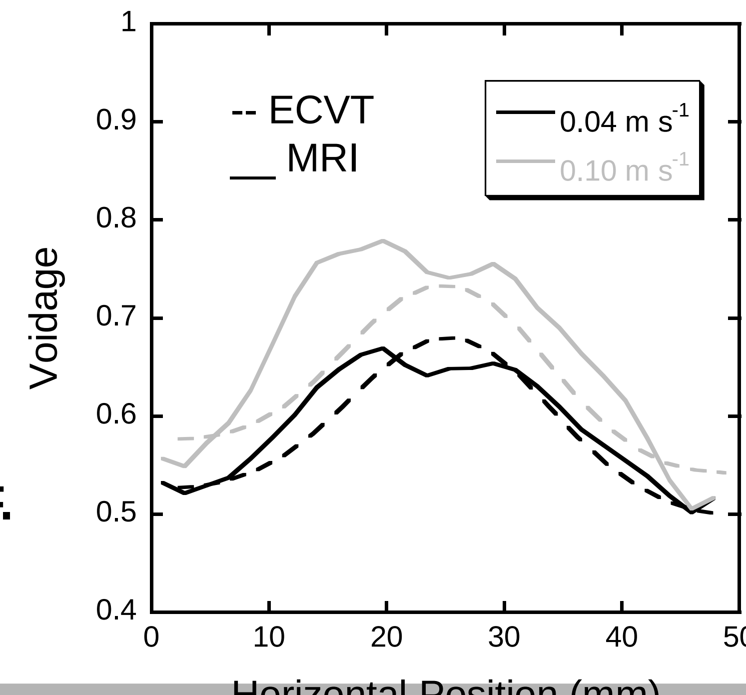


Comparison of the time-averaged cross-sectional solids concentrations obtained by the *ECT* and the *optical fiber probe* and the time-averaged volume solids concentration obtained by the *ECVT* for a 12-in gas-solid fluidized bed with FCC particles (d_p = 60 μm; ρ_p = 1400 kg/m^3)

Electrical Capacitance Volume Tomography – Comparison with MRI

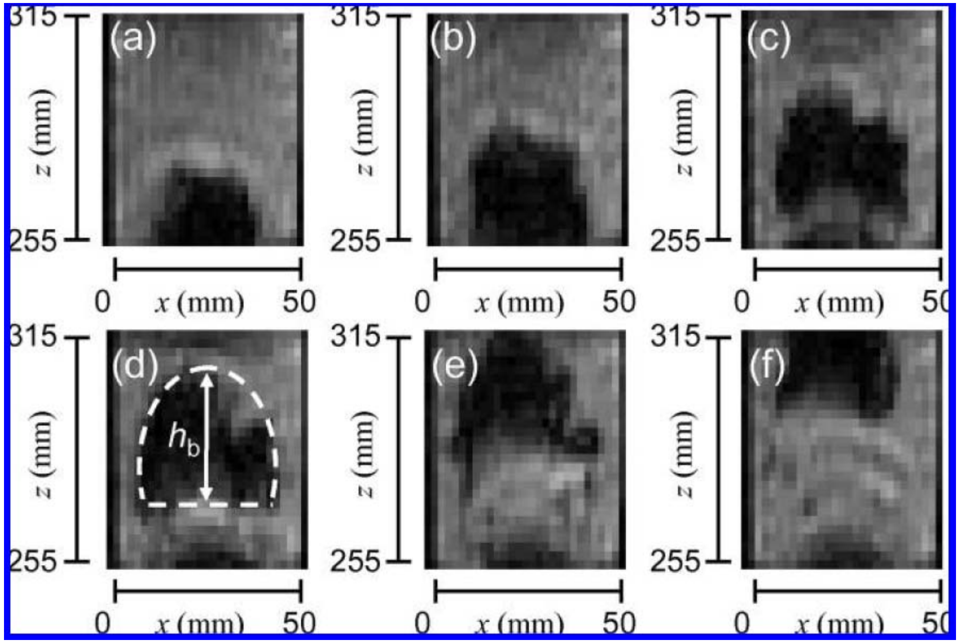


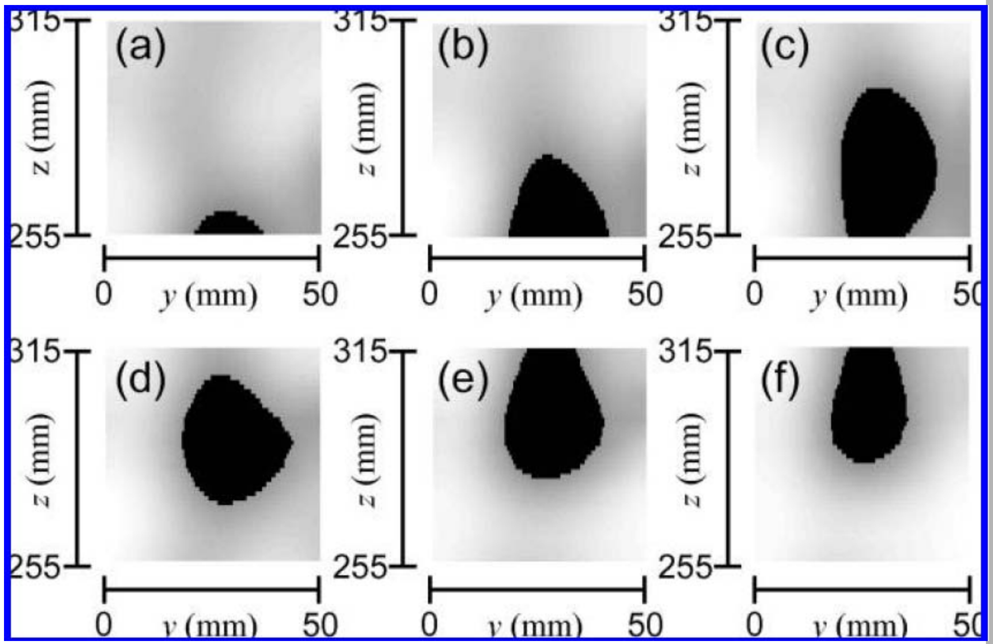




Work of **D.J. Holland[1], Q. Marashdeh[2], C.R. Müller[1], F. Wang[2], J.S. Dennis[1], L.-S. Fan[2], L.F. Gladden[1]**
[1]Cambridge University, [2]The Ohio State University

Electrical Capacitance Volume Tomography – Comparison with MRI





Superficial Gas Velocity: 0.04 m/s;
MRI: every frame (26 ms)
ECVT: every 2nd frame (25 ms)

Work of **D.J. Holland[1], Q. Marashdeh[2], C.R. Müller[1], F. Wang[2], J.S. Dennis[1], L.-S. Fan[2], L.F. Gladden[1]**

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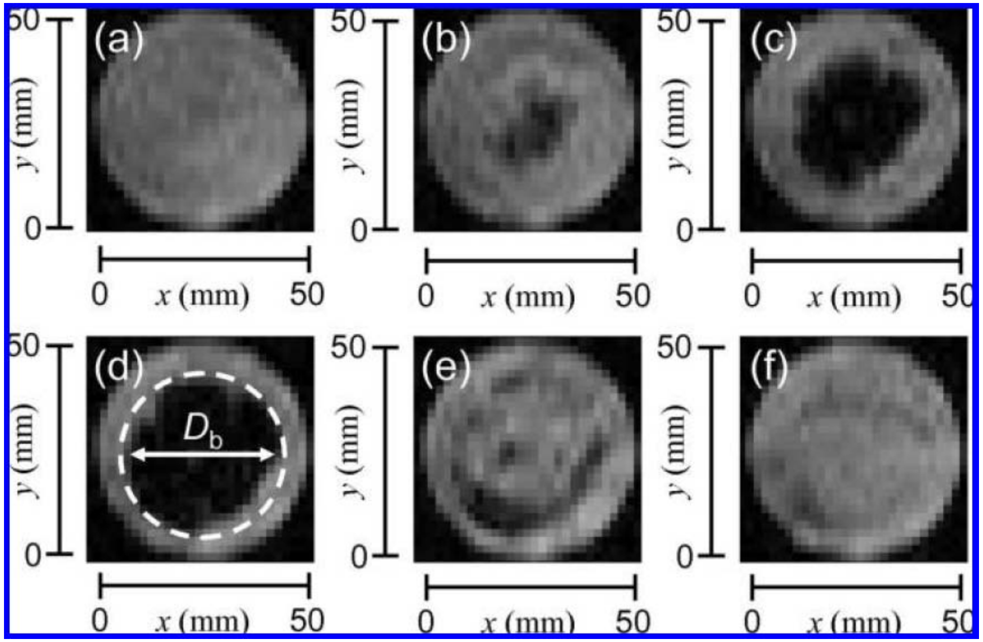
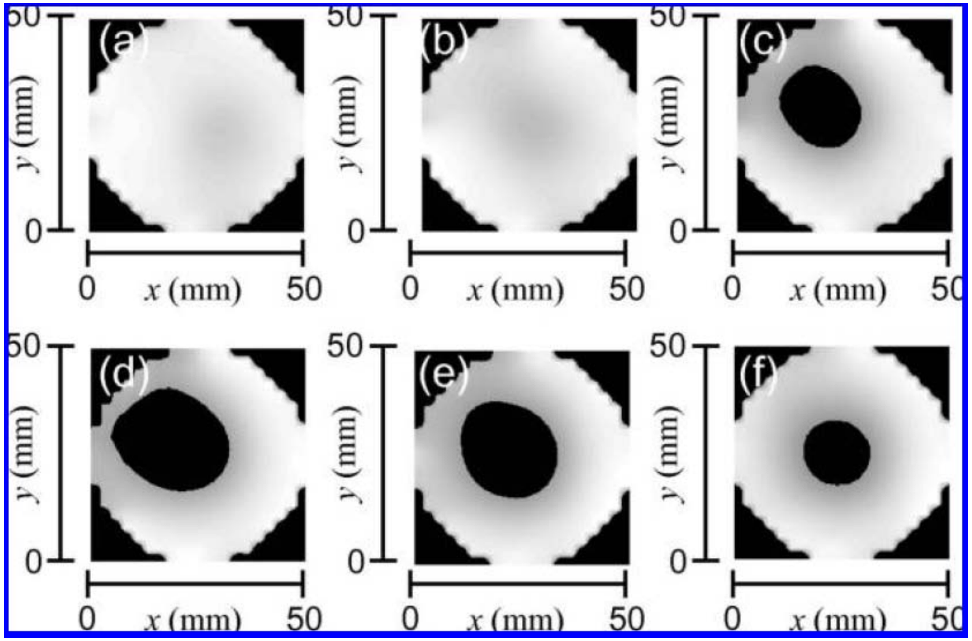
Electrical Capacitance Volume Tomography – Comparison with MRI





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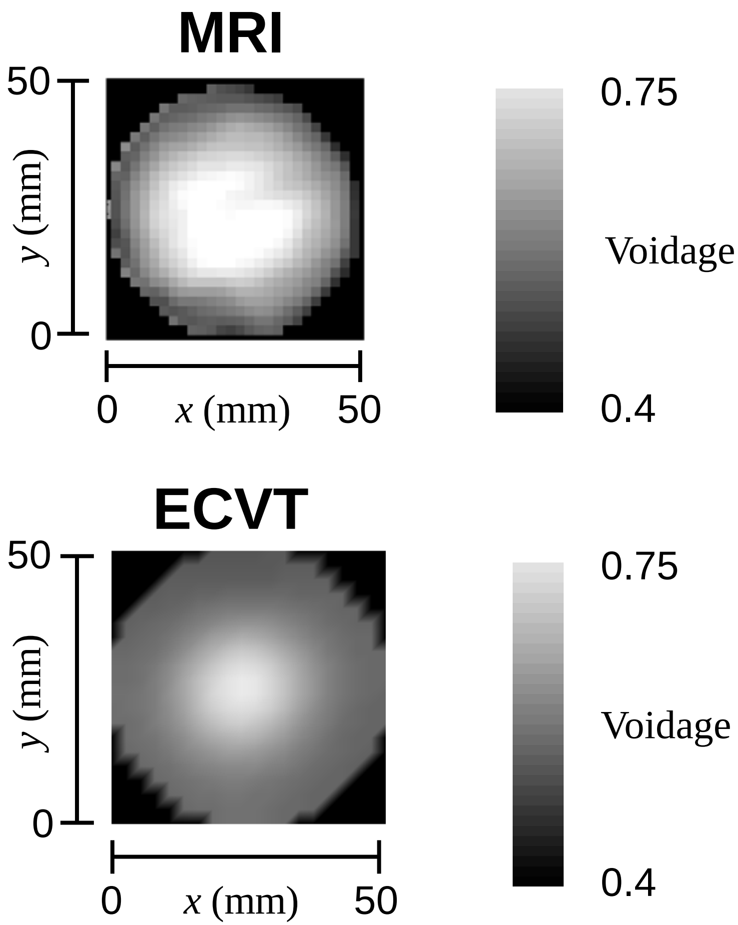
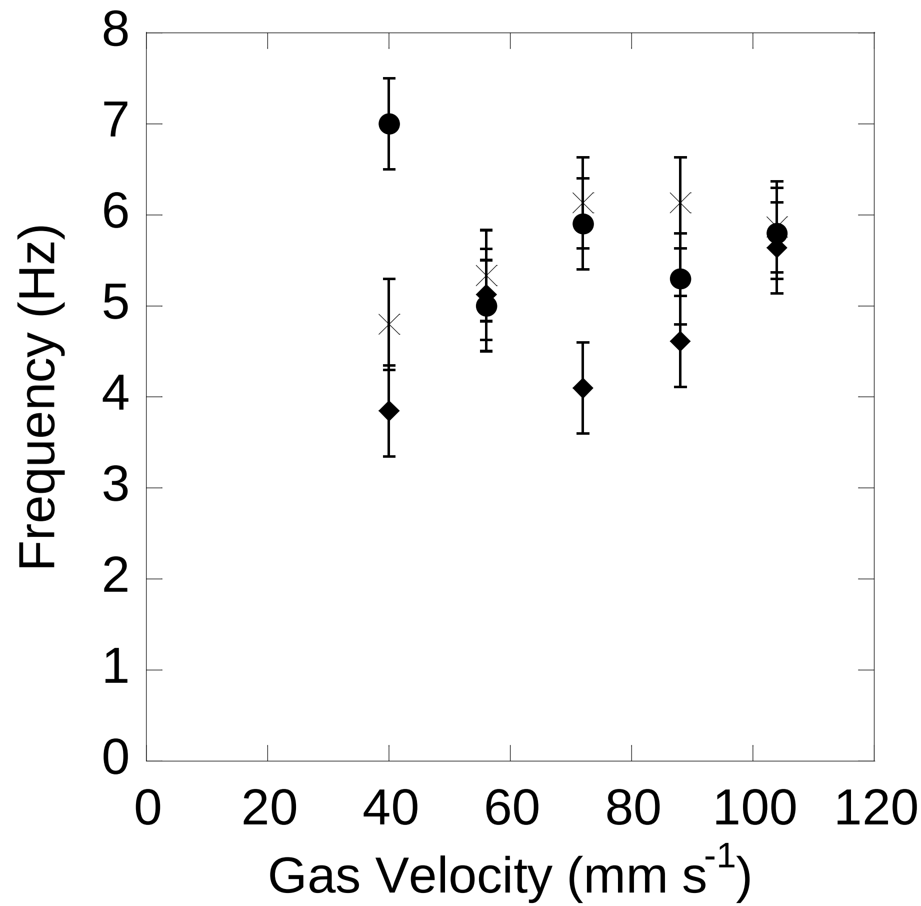
Electrical Capacitance Volume Tomography – Comparison with MRI



Superficial Gas Velocity: 0.104 m s-1



Bubble frequency calculated from the ECVT (×), 2D MR data (♦) and 1D MR data (●).

Work of **D.J. Holland[1], Q. Marashdeh[2], C.R. Müller[1], F. Wang[2], J.S. Dennis[1], L.-S. Fan[2], L.F. Gladden[1]**

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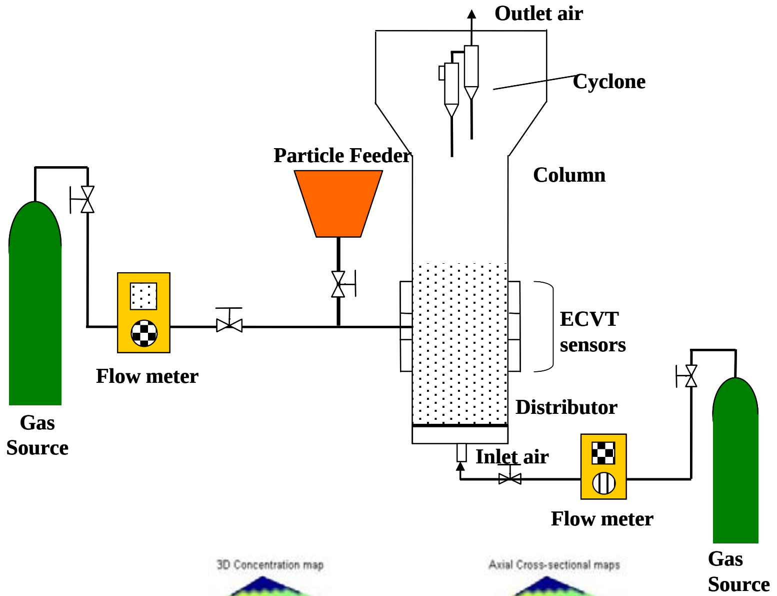
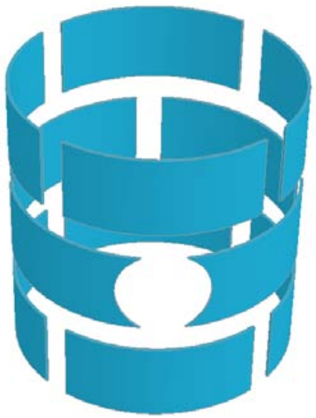
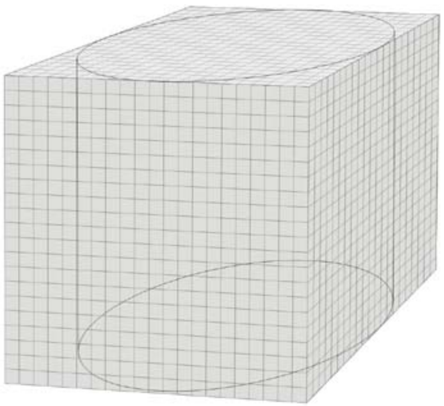
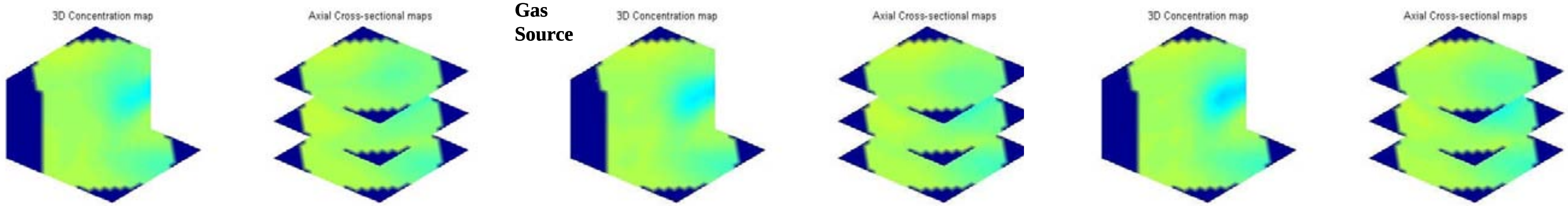
3. Horizontal gas jet penetration in a gas-solid fluidized bed

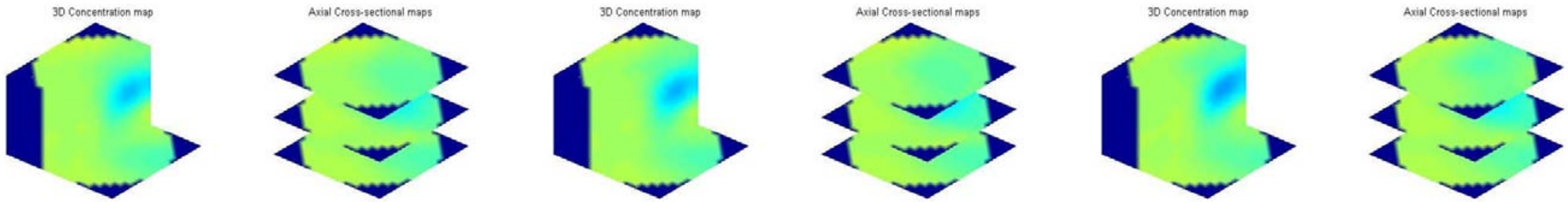








(a) t=0; (b) t=12.5 ms; (c) t=25.0 ms; (d) t=37.5; (e) t=50.0 ms; (f) t=62.5 ms. Ug=0.064 m/s, U0=15 m/s



Dynamic Of Jet Penetration

Fei Wang, Zhao Yu, Qussai Marashdeh, Liang-Shih Fan * "Horizontal gas and gas/solid jet penetration in a gas–solid fluidized bed " *Chemical Engineering Science* 65 (2010) 3394–3408

Experimental Conditions

FCC particle:

Particle size: 60 μm

Particle density: 1400 kg/m^3

Fluidized bed:

ID: 12 inch

Disengagement section: 0.5 m

Total height: 2.3 m

Two-stage cyclone

Distributor:

Porous plate with a pore size of 20 μm

Fractional free area: 60%

Gas:

Air density:1.225 kg/m^3

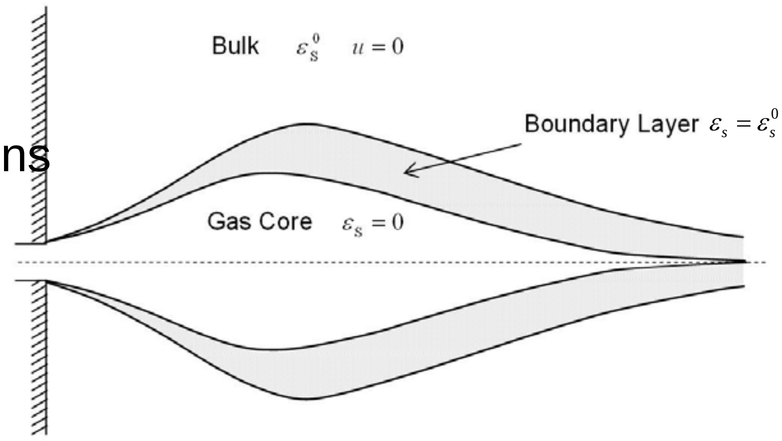
Air viscosity: 1.8×10^{-5} Ns/m^2

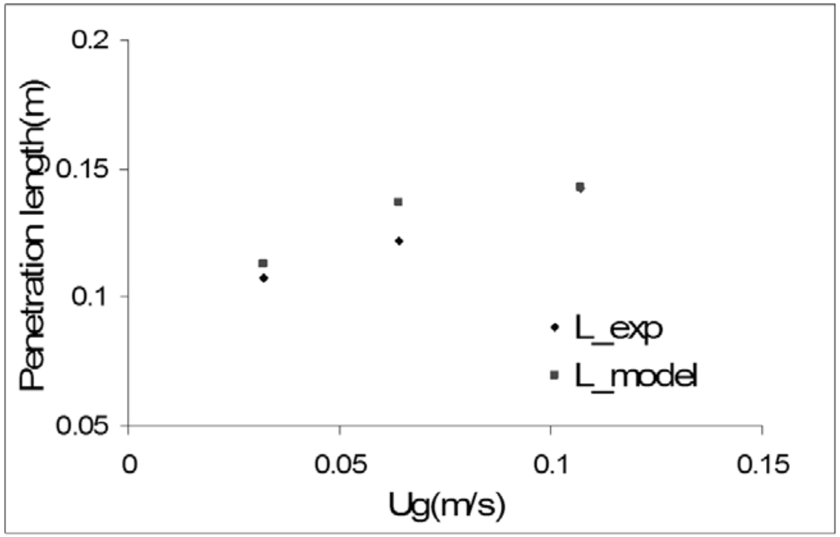
Sensors and Experimental Setup

Horizontal gas jet penetration in a gas-solid fluidized bed

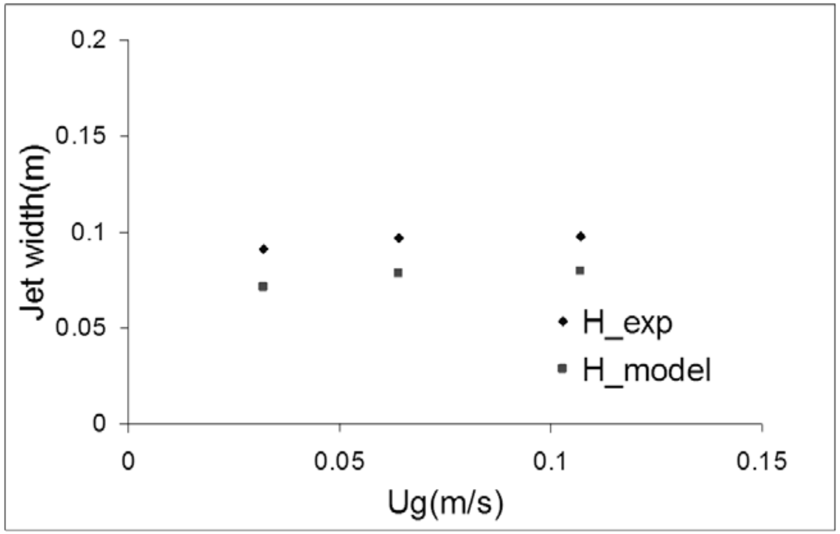
Horizontal jet in a gas-solid fluidized bed:

- solid particle holdup varies in the radial and axial directions
- particles entrain into the jet
- momentum is transferred from the jet to the solid particle
- the closure of the jet is due to the momentum loss

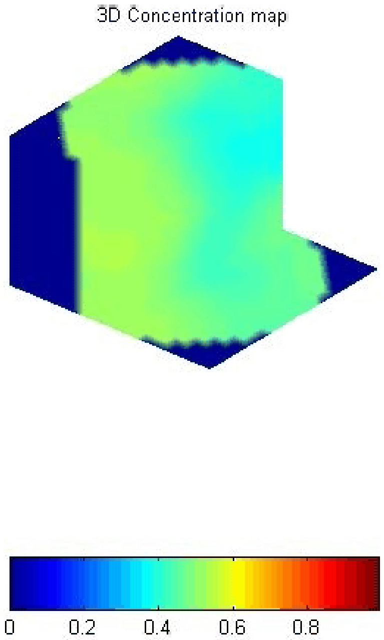


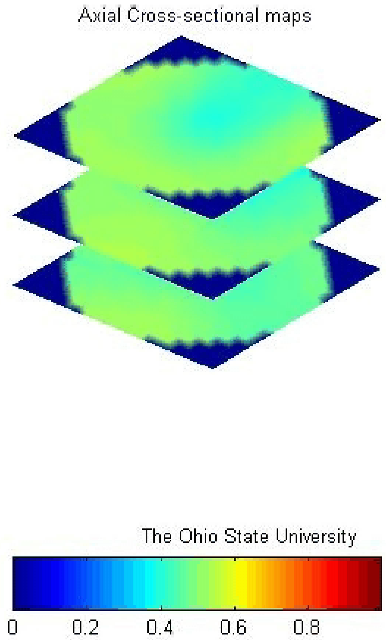


Comparison of the maximum penetration lengths of the horizontal gas jet obtained by ECVT experiments and model prediction for the 0.3 m gas-solid fluidized bed

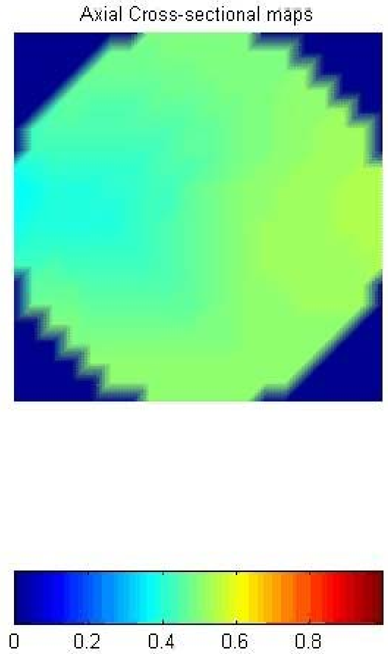


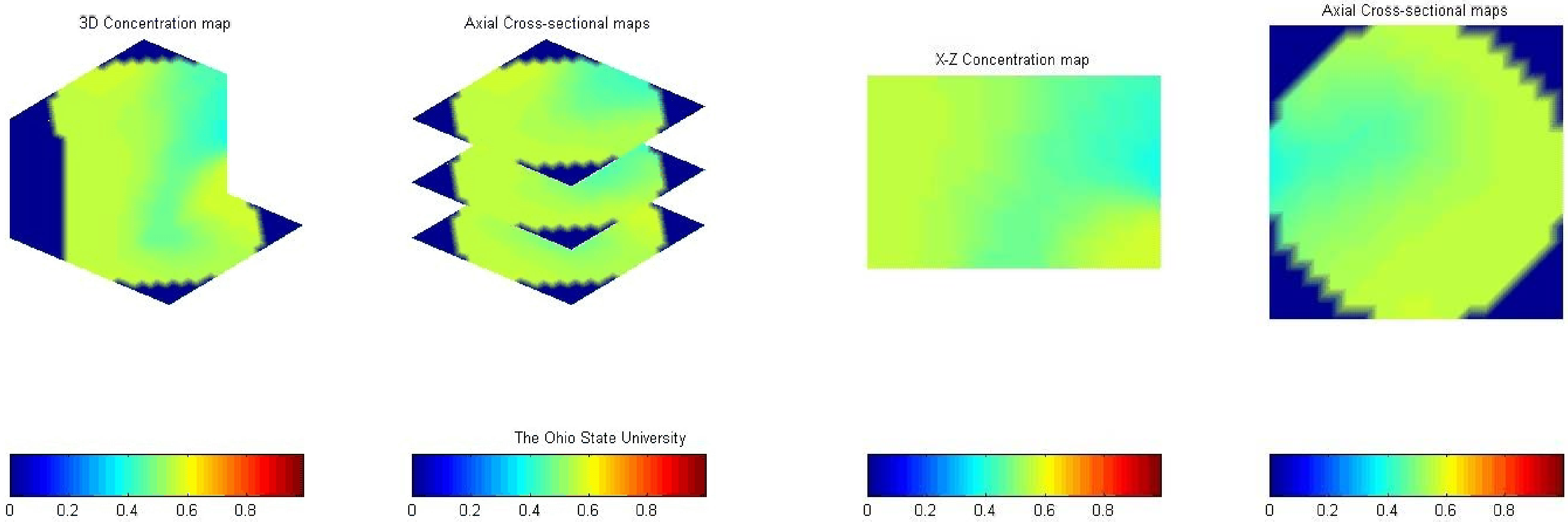
Comparison of the maximum width of the horizontal gas jet obtained by ECVT experiments and model prediction for the 0.3 m gas-solid fluidized bed





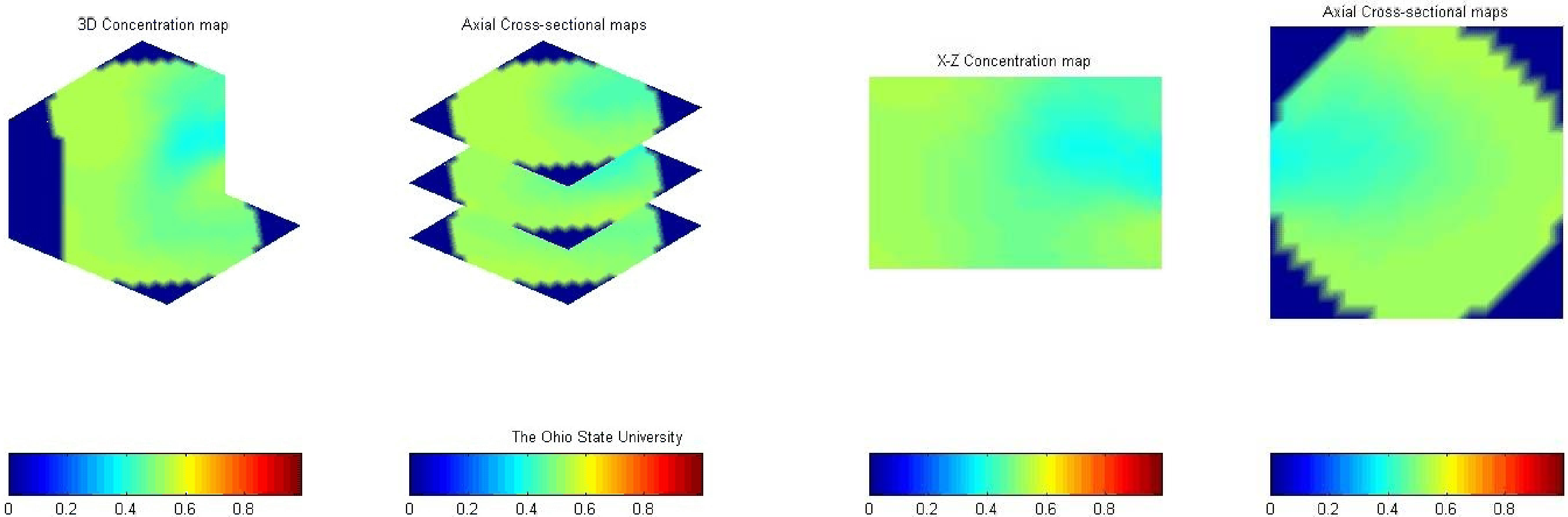
Superficial gas velocity: Ug=0.108 m/s
Side gas velocity: Ug_side=15.5 m/s
Side solids velocity: Us_side=0





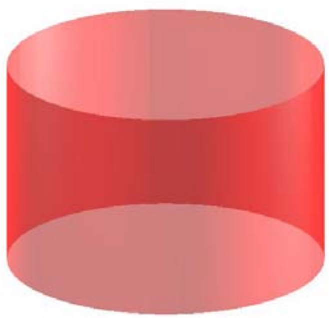
Superficial gas velocity: Ug=0.032 m/s; Side gas velocity: Ug_side=15.5 m/s; Side solids velocity: Us_side=0

Superficial gas velocity: Ug=0.032 m/s; Side gas velocity: Ug_side=16.3 m/s; Side solids velocity: Us_side=16.3 m/s

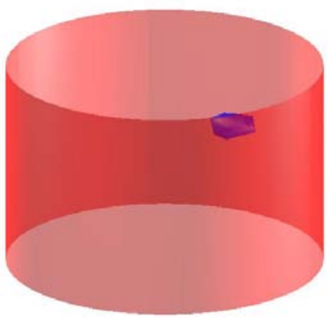


Jet shape from ECVT images

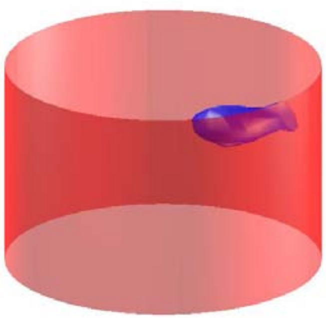
(Maximum jet penetration)



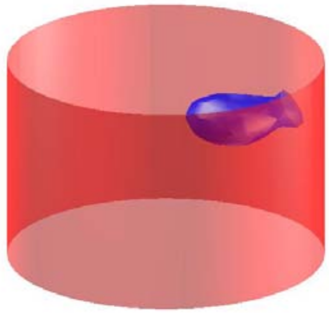
t=0



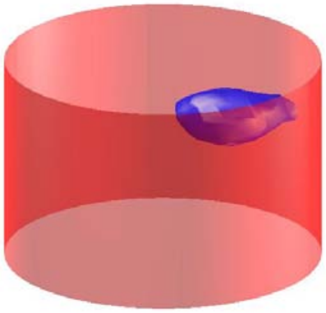
t=12.5 ms



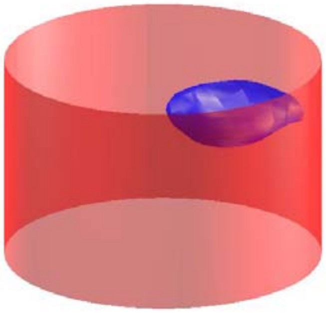
t=25 ms



t=37.5 ms



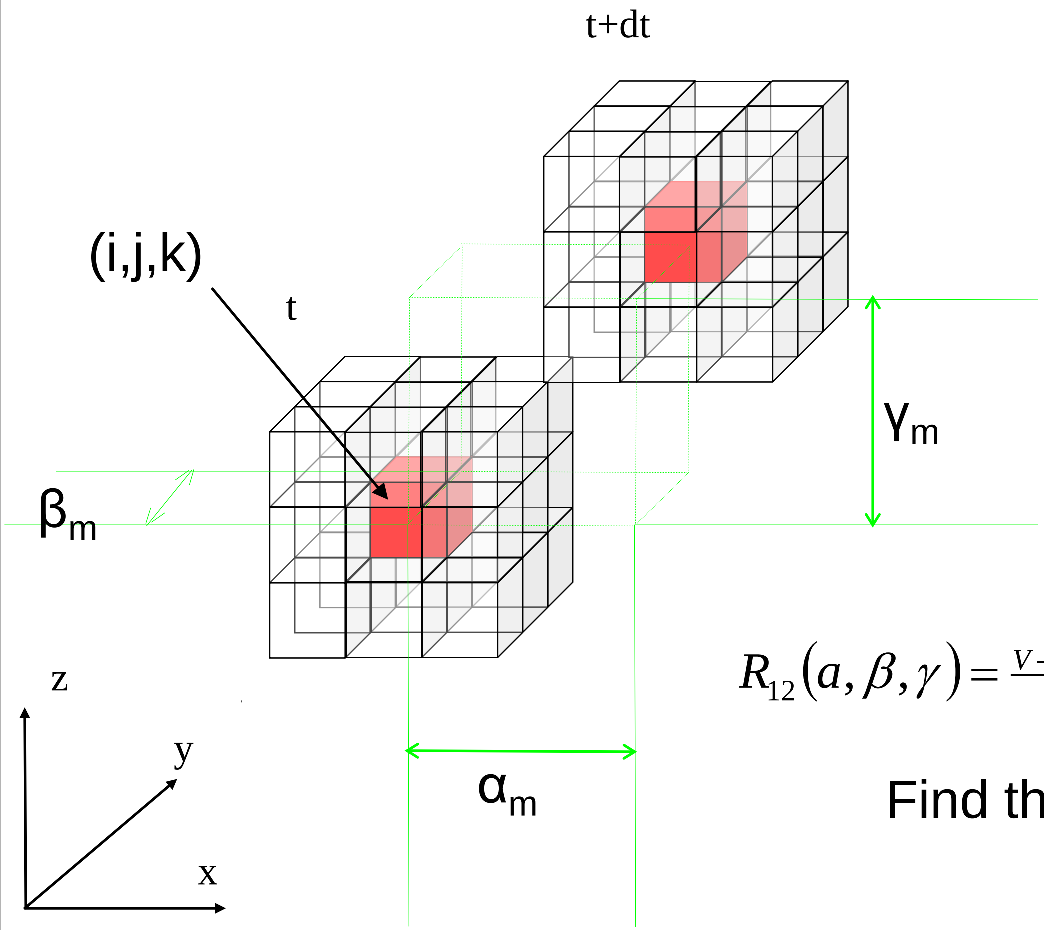
t=50 ms



t=62.5 ms

Ug=0.064 m/s, U_0=15 m/s

4. Velocimetry



Choose a window

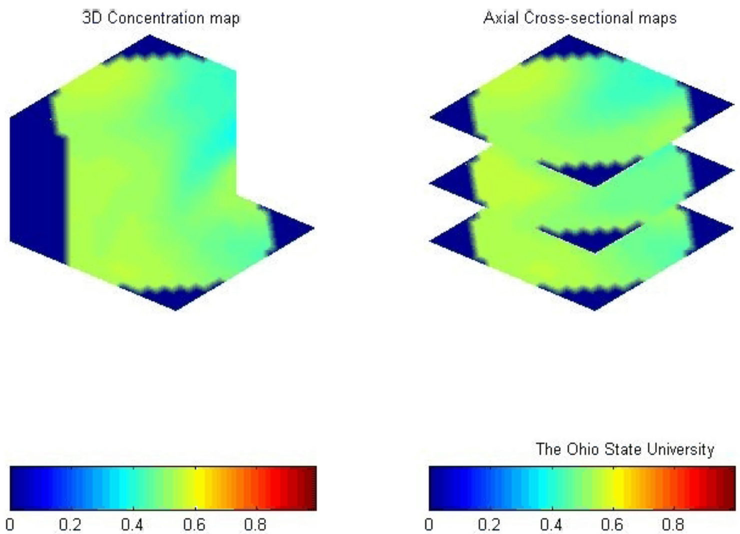
At Voxel (i,j,k):

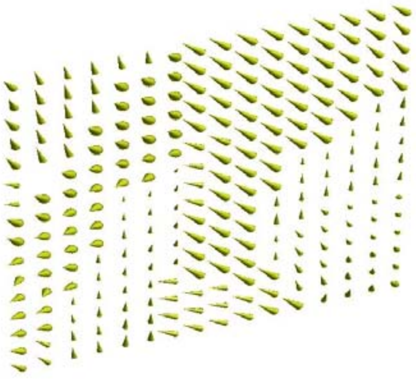
$$R_{12}(a,\beta,\gamma)=\frac{\int\limits_{V-Window} V_1(x,y,z,t)V_2(x+\alpha,y+\beta,z+\gamma,t+\Delta t)\,dxdydz}{|V_1|\cdot|V_2|}$$

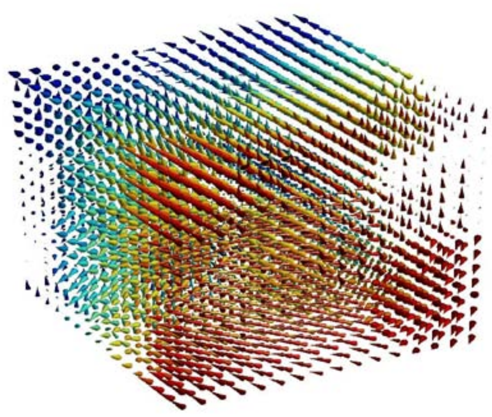
Find the maximum R_{12} at $(\alpha_m,\beta_m,\gamma_m)$

Voxel volume averaged phase velocity at Voxel (i,j,k):

$$v_x=\frac{\alpha_m-i}{\Delta t}\Delta x \qquad v_y=\frac{\beta_m-j}{\Delta t}\Delta y \qquad v_z=\frac{\gamma_m-k}{\Delta t}\Delta z$$



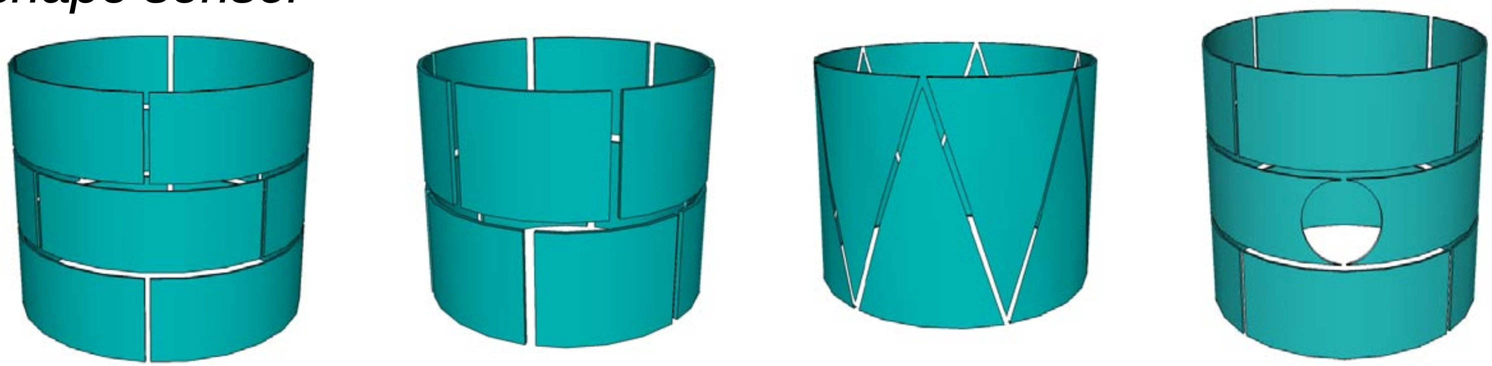


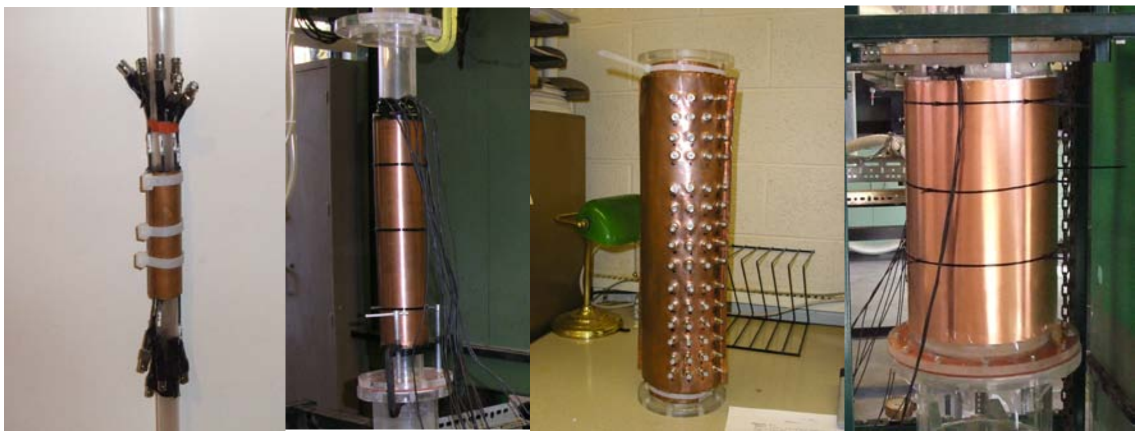


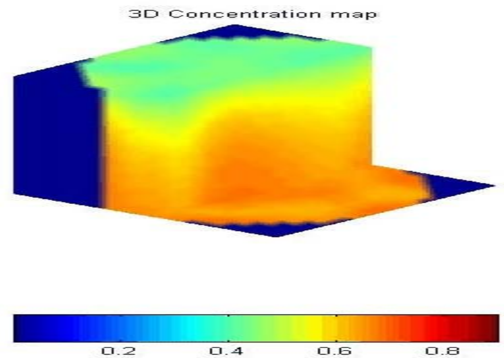
Ug=0.064 m/s, U_0=15 m/s

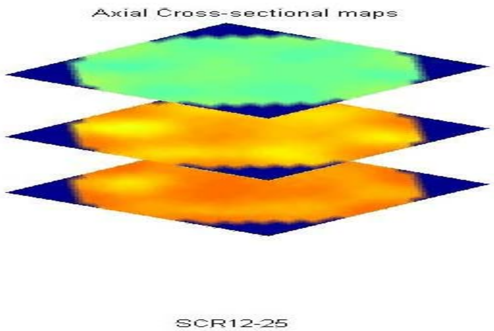
5. ECVT Sensor Applications

Cylindrical shape sensor



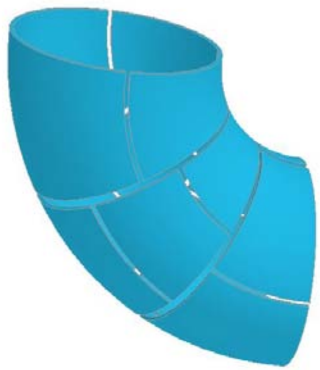


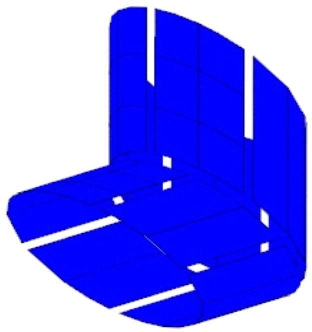


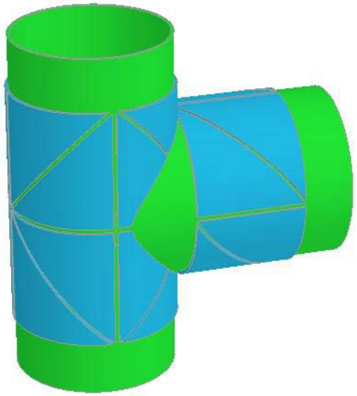


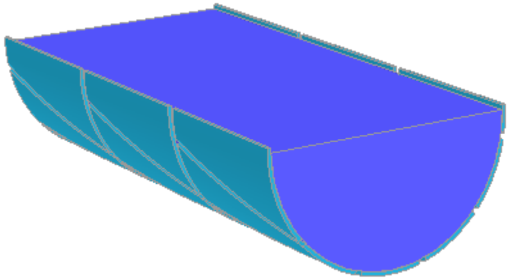
ECVT sensor design

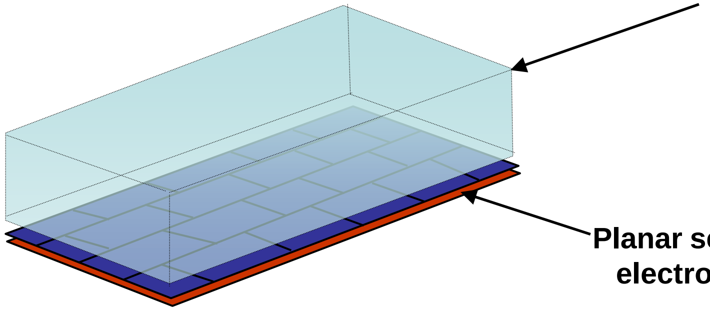
Sensors with complex geometries

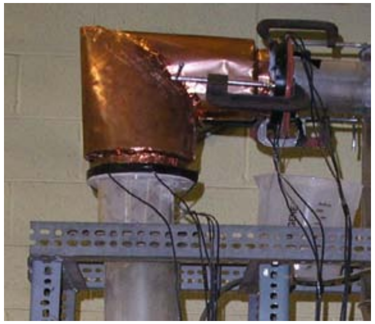


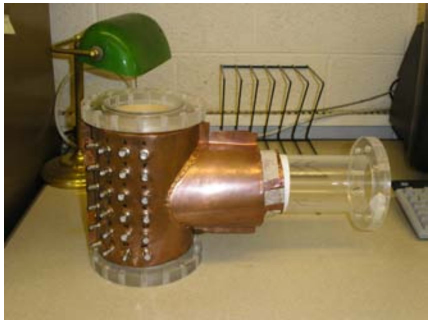


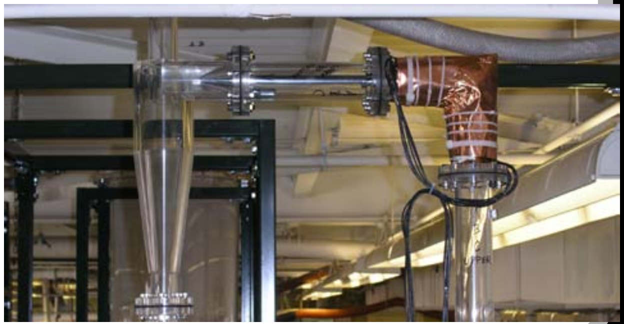












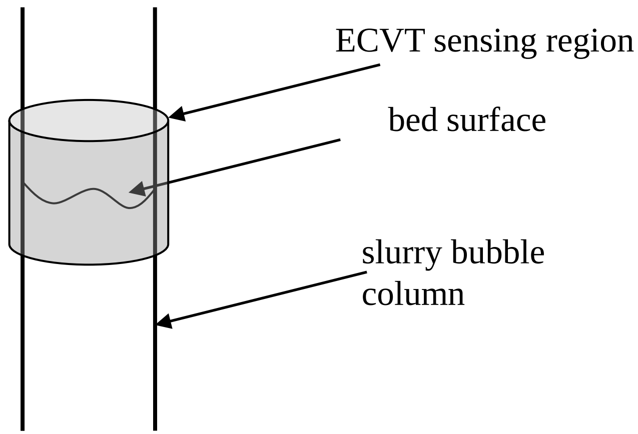
ECVT sensor design

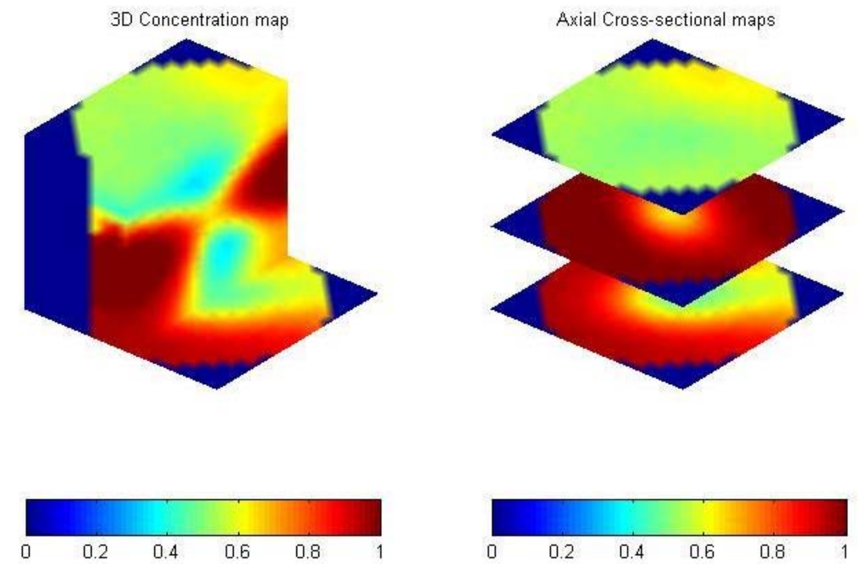
Comparison of different sensor geometries in terms of symmetry, axial resolution and radial resolution

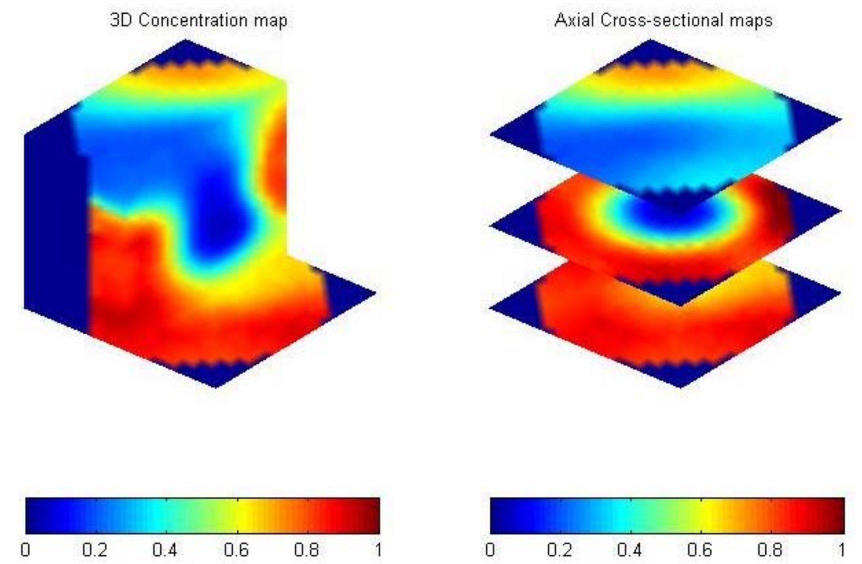
Sensor Type	Sensor Symmetry	Axial Resolution	Radial Resolution
Cylindrical sensor with 1 layer	High	Low, sensitivity decreases toward center.	High, sensitivity decreases toward center.
Cylindrical sensor with 2 shifted layers	Moderate	Moderate, sensitivity decreases toward center.	Moderate, sensitivity decreases toward center
Cylindrical sensor with 3 shifted layers	Moderate	High, sensitivity decreases toward center.	Moderate-High, sensitivity decreases toward center.
Planar sensor with shifted planes	Moderate	Low, sensitivity decreases away from sensor.	High, Sensitivity decreases away from sensor.
Bent sensor	Low	Depends on sensor plate arrangement	Depends on sensor plates arrangement

Fei Wang, Qussai Marashdeh, Liang-Shih Fan * and Warsito Warsito “**Electrical Capacitance Volume Tomography: Design and Applications**” *Sensors* **2010**, *10*, 1890-1917;

Surface of Slurry Bubble Columns

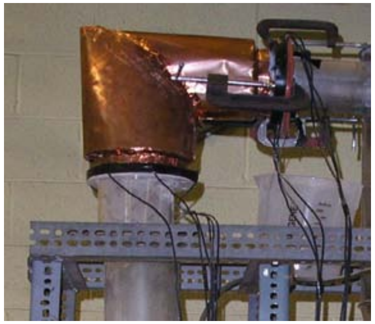




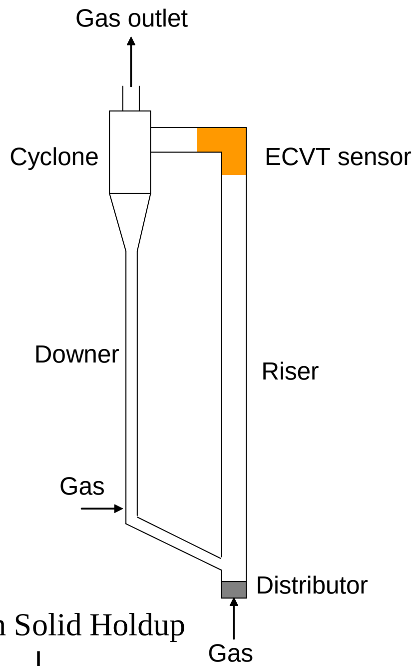


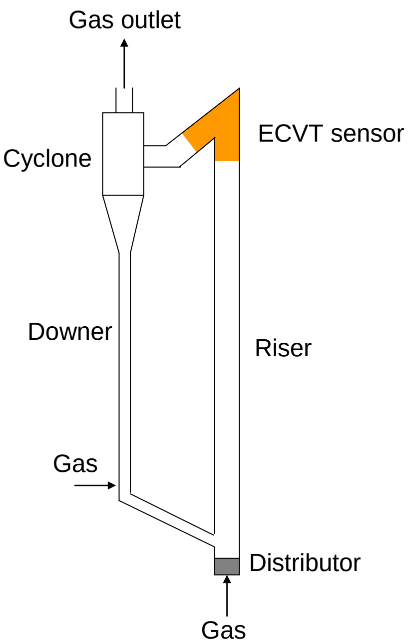
Snapshots of bubble bursting at the surface of a slurry bubble column by ECVT: (a) 3D image before bubble bursting; (b) 3D image after bubble bursting

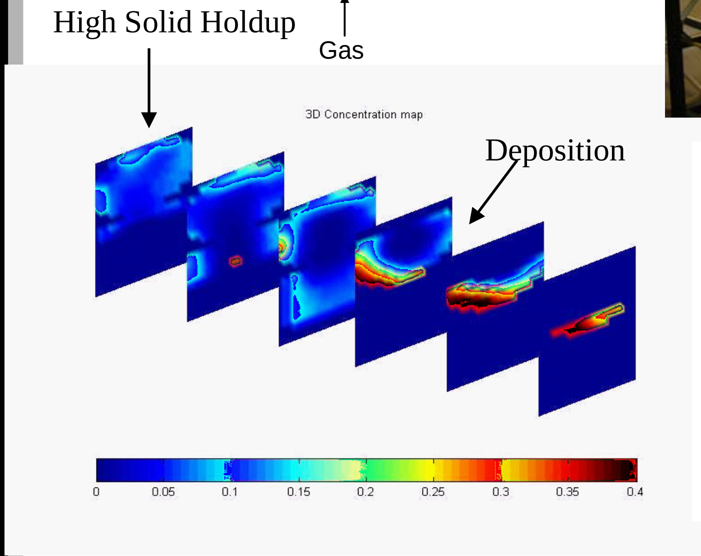
6. Complex Geometries Examples

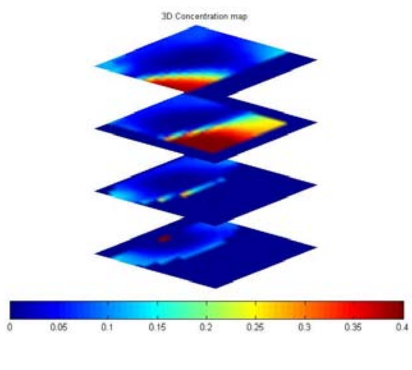


3-D gas-solid flow patterns in the exit region of a gas-solid CFB riser



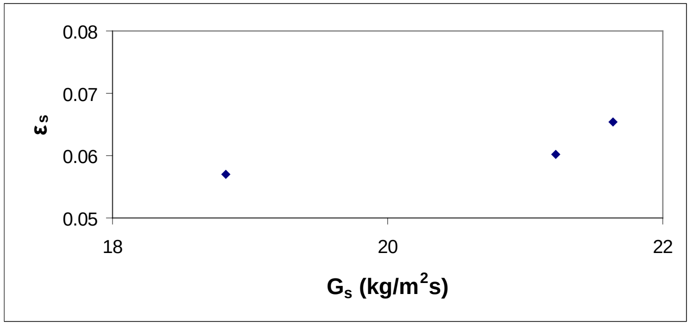




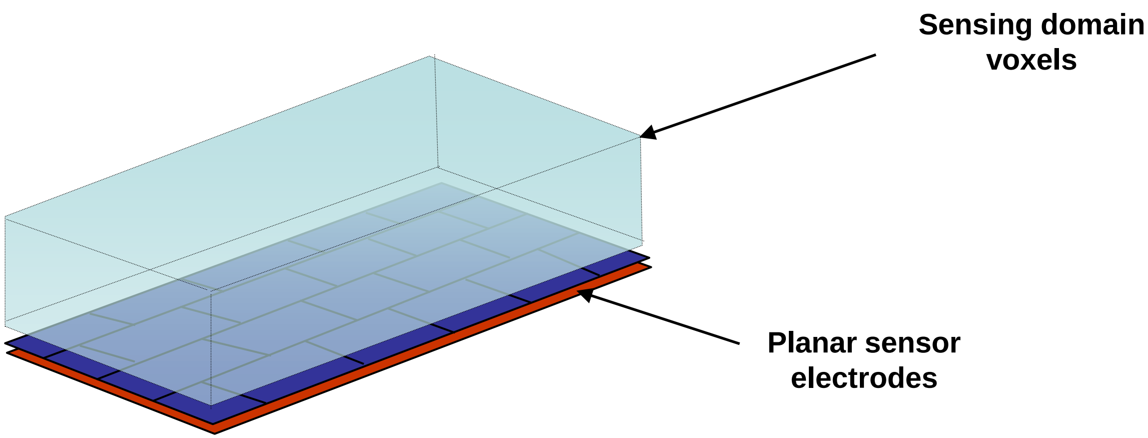


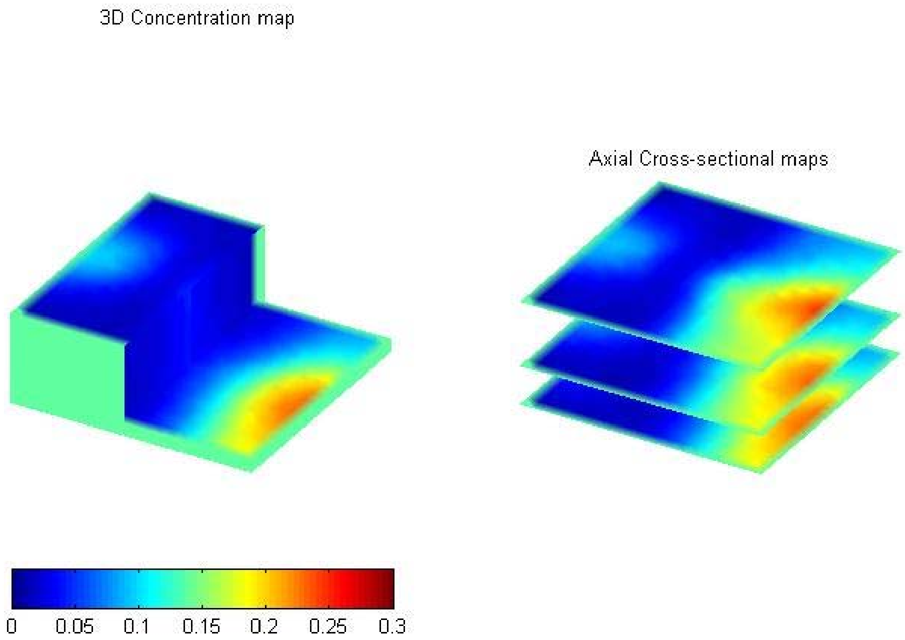
Solids holdup distribution in the bend of the CFB riser at Ug=1.36 m/s and Gs=21.2 kg/m^{2}s:vertical slices and horizontal slices

Solids Holdup/ Solid Circulation Rate



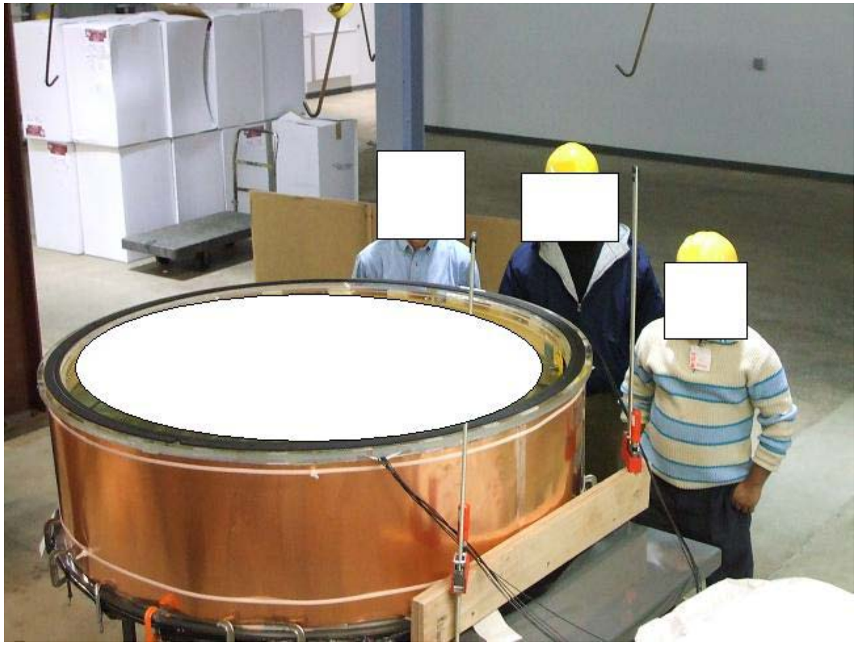
Time-averaged volume solids holdup at the top wall region at the start of the horizontal duct of the bend at Ug=1.16 m/s


Sensing domain
voxels
Planar sensor
electrodes

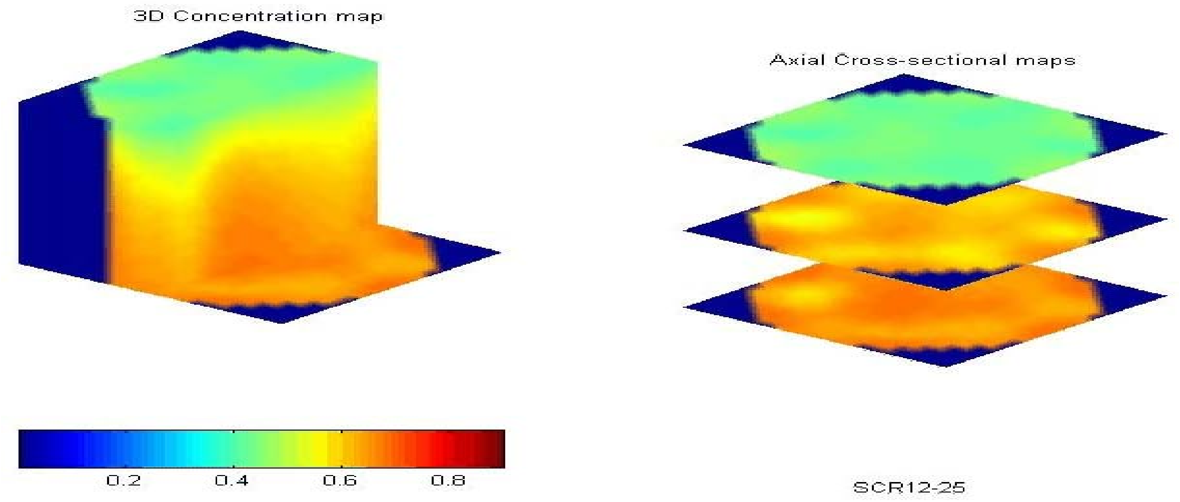

3D Concentration map
Axial Cross-sectional maps
0
0.05
0.1
0.15
0.2
0.25
0.3

Scale-Up ECVT Sensors

60 inch ID



12 inch ID



Concluding Remarks

- ECVT is a non-invasive imaging technology that can be applied to image processes vessels of various diameters.

- ECVT is a unique imaging technology with its potential for commercial scale-up

- Tech4Imaging LLC is developing a commercial ECVT system for imaging multi-phase flow systems.

Acknowledgement

- The support of US. Department of Energy under Grant # DE-NT0006564 is gratefully acknowledged
- Dr. W. Warsito, Dr. Bing Du, Dr. Zhao Yu, and all students who worked or are working on ECVT technology are also acknowledged.