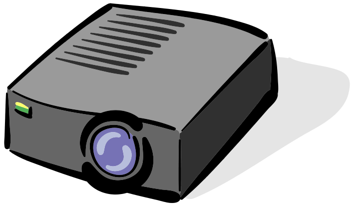
TECH 4 IMAGING

Development and Implementation of 3D High Speed Tomography for Imaging Large-Scale, Cold-Flow Circulated Fluidized Bed

Qussai Marashdeh

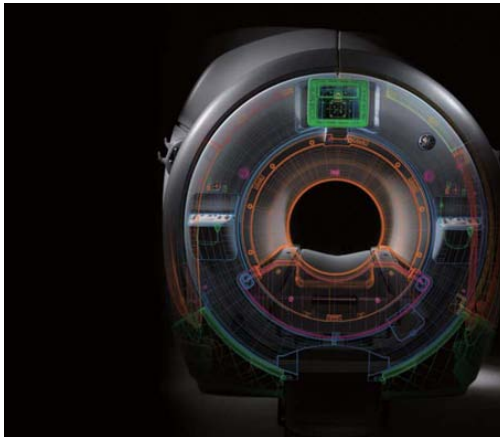
Tech4Imaging LLC
4171 Fairfax Dr.
Columbus, OH 43220



Introduction

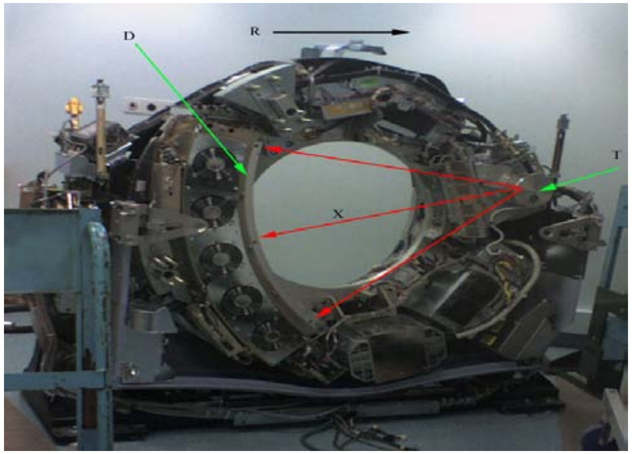
- Electrical Capacitance Volume Tomography (ECVT) is a 3D imaging technique for viewing cold flow processes. It can be applied to hot units too.
- ECVT is among few know non-invasive imaging tools that can be used for commercial applications (low cost, suitable for scale-up, fast, and safe)
- Tech4Imaging 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.

Process Tomography



MRI

PET



X-ray

Electrical Capacitance
Volume tomography
System

Selection of Imaging Technology

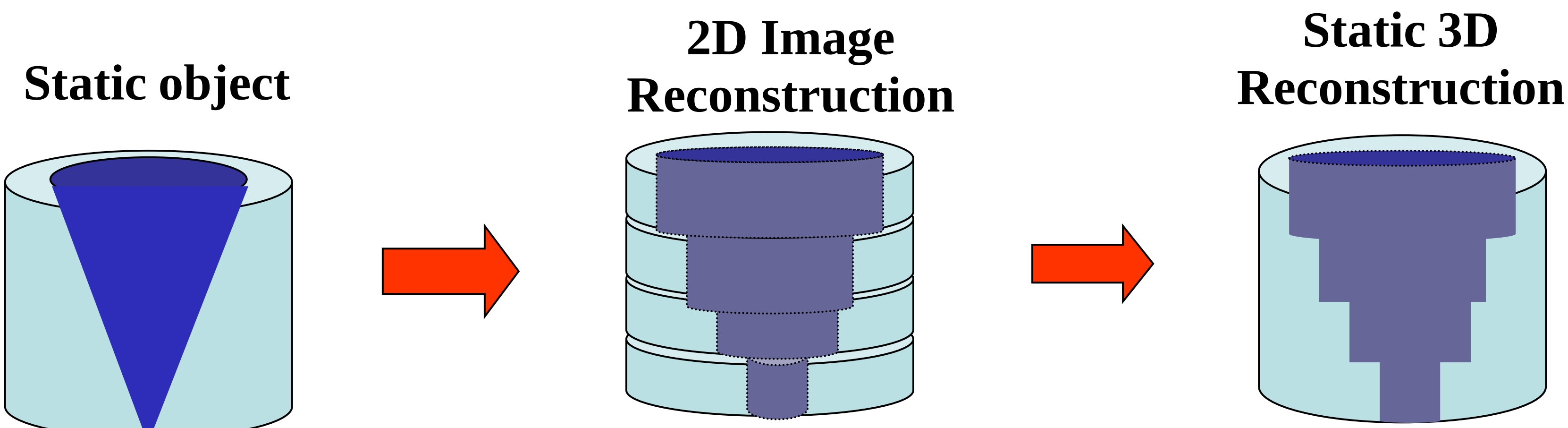
- Safety: To user and to process
- Cost: fixed and variable
- Complexity: implementation and operation
- Speed: rate of capture
- Flexibility: to different vessel sizes and shapes
- Resolution: as a percentage of imaged volume

Preface

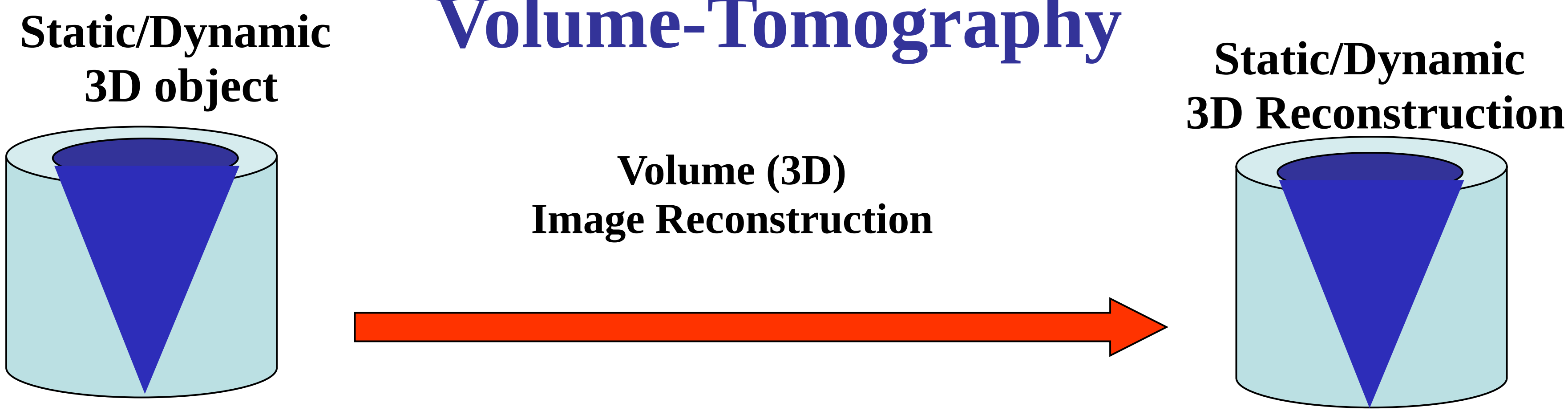
1. ECVT Technology
2. Verification
3. Jet Example
4. Sensors and Scale up Application
5. Complex geometries
6. Combustion Imaging

Volume Tomography Concept

Conventional Tomography

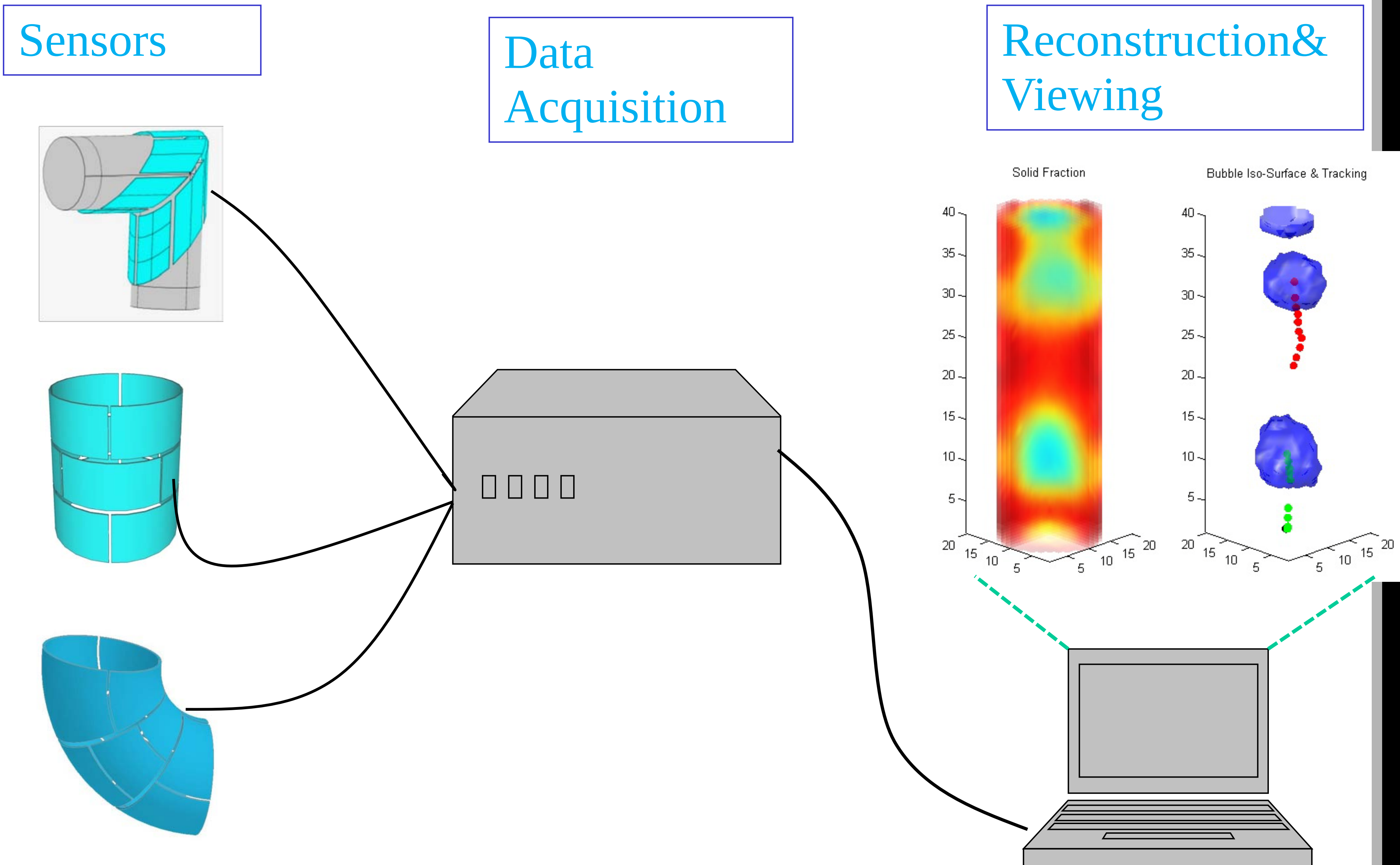


Volume-Tomography



W. Warsito, Qussai Marashdeh, and Liang-Shih Fan **“Electrical Capacitance Volume Tomography”** *IEEE Sensors Journal* 7 (2007) 525–535

Complete ECVT System

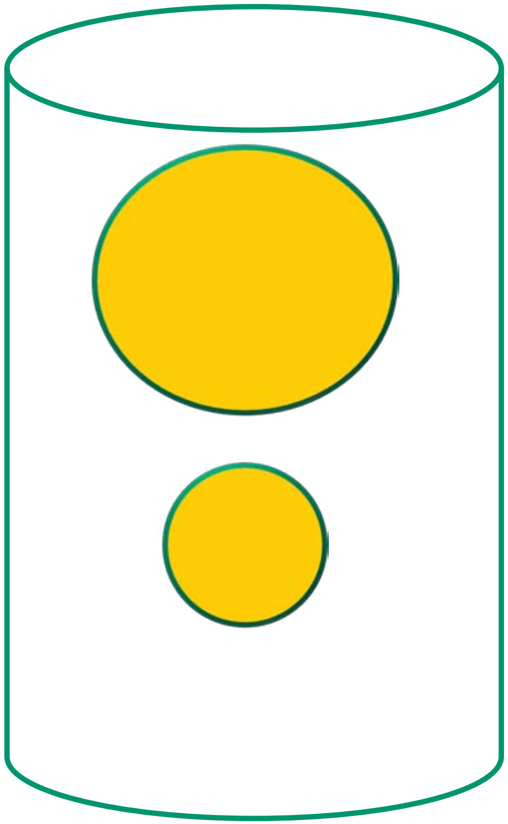


ECVT Reconstruction

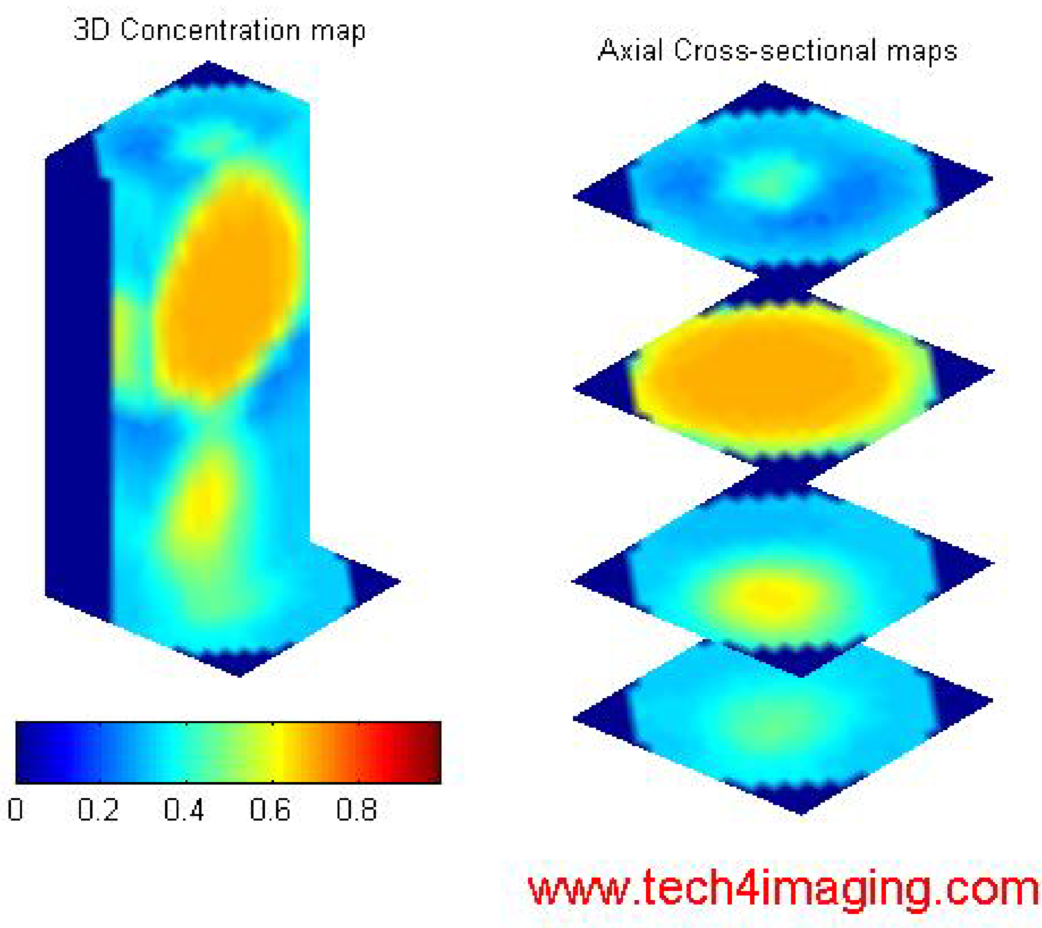
Reconstruction	**Methodology**	**Characteristics**	**Example**
Single Step Linear Back Projection	The sensor system is linearized (usually by constructing a sensitivity matrix). The image is obtained by back projecting the capacitance vector using the sensitivity matrix.	Fast, low image resolution, and 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

Shape & Edge Detection

Experimental Results



Location Inside Sensor



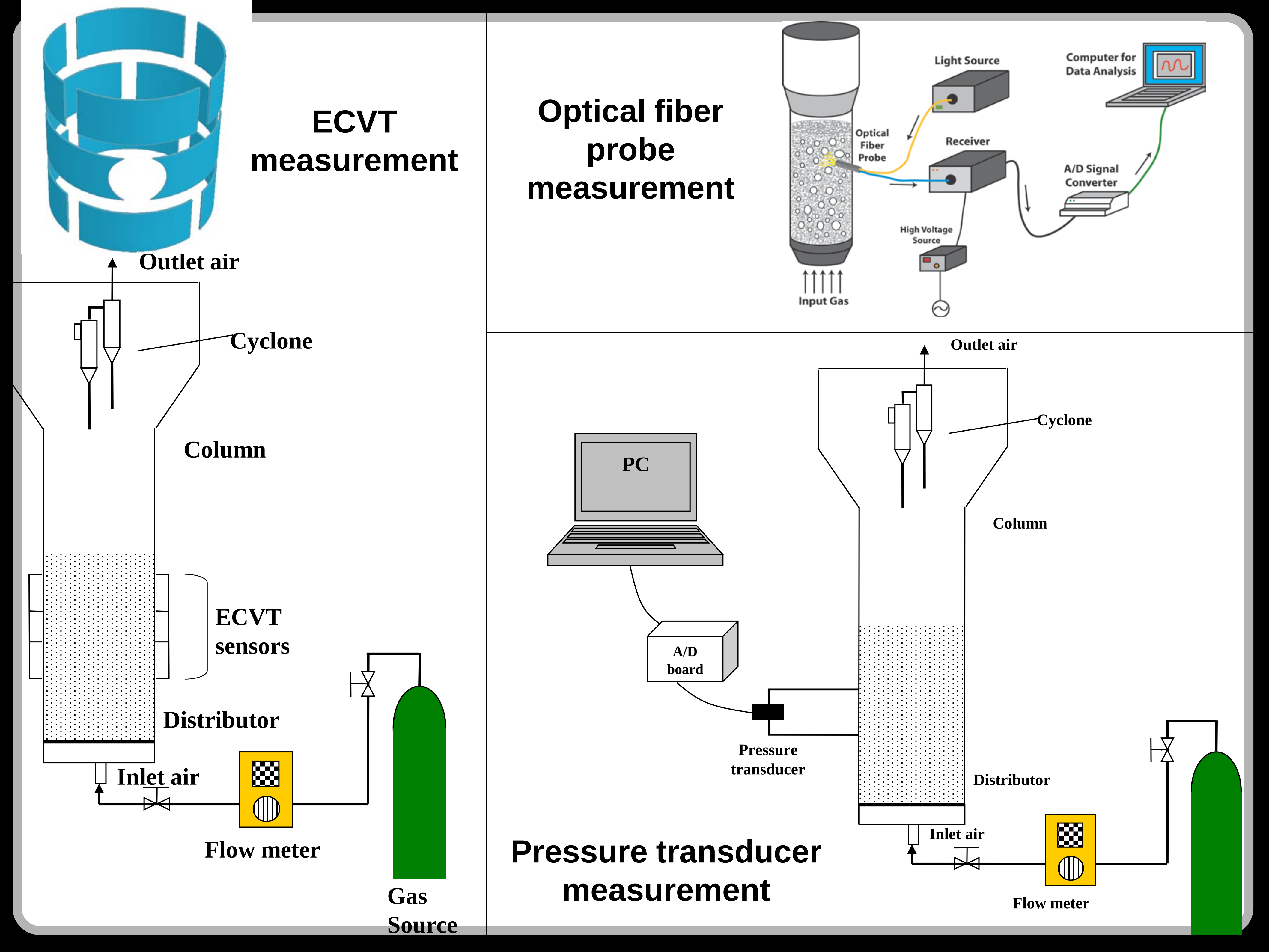
ECVT Imaging

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
Cyclone
PC
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:

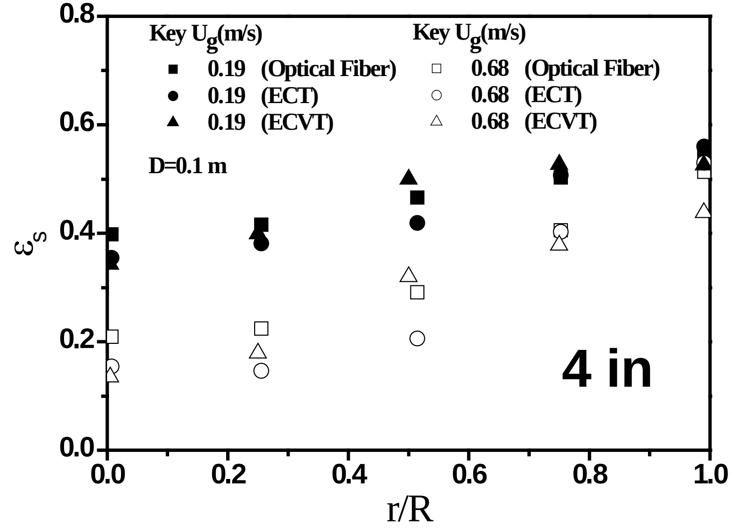
Porous plate with a pore size of 20 μm

Fractional free area: 60%

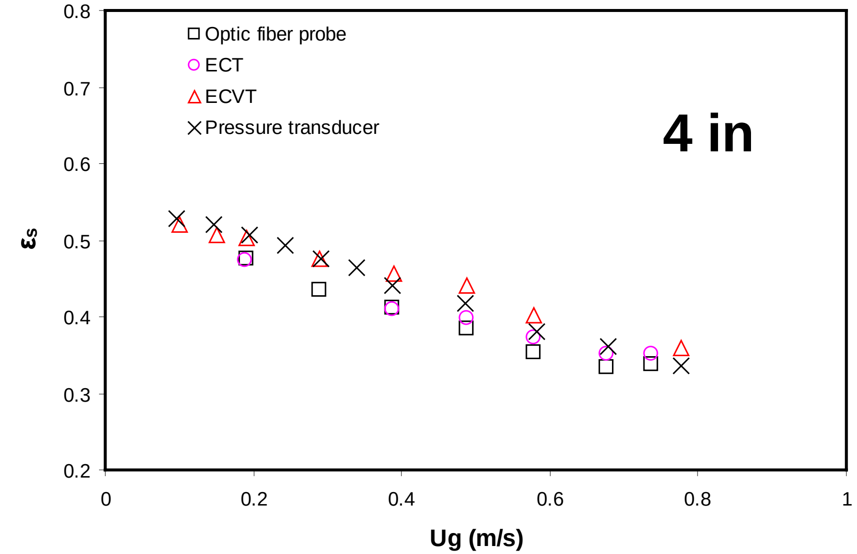
Gas:

Air density:1.225 kg/m^3

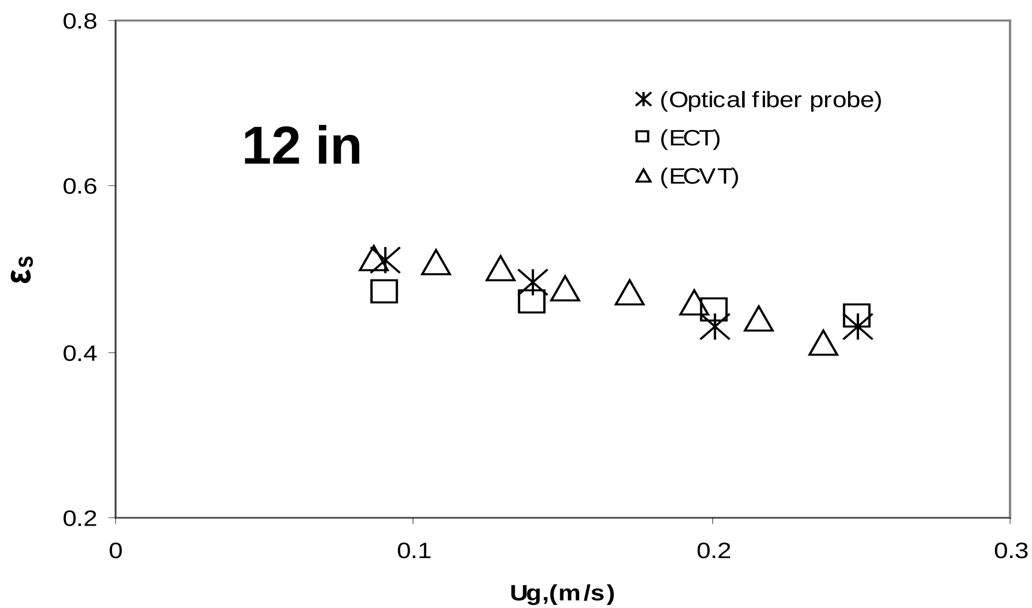
Air viscosity: 1.8x10^{-5} Ns/m^2



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*



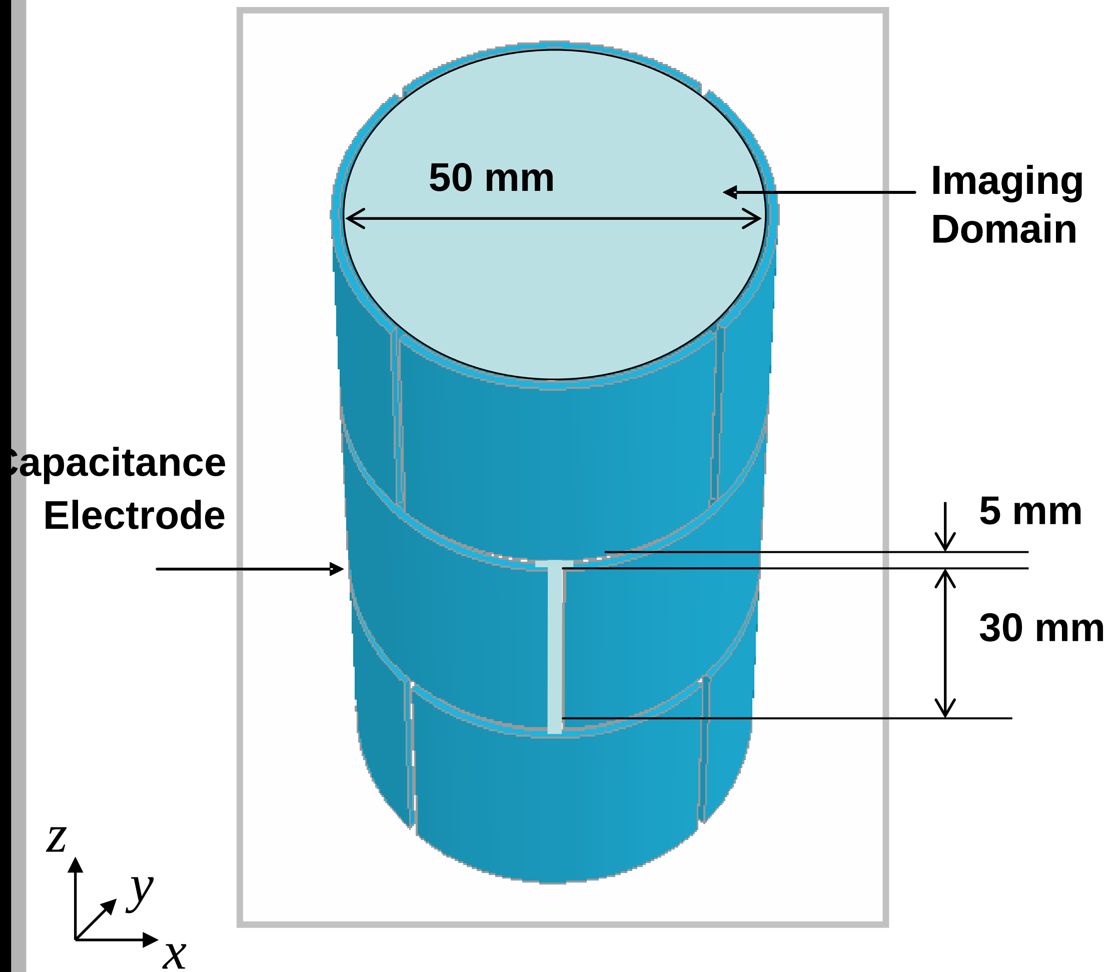
Comparison of the time-averaged cross-sectional solids concentrations obtained by *ECT* and *optical fiber probe* and the time-averaged volume solids concentration obtained by *ECVT* and *pressure transducer* for a 4-in gas-solid fluidized bed with FCC particles (d_p = 60 μm; ρ_p = 1400 kg/m^3)

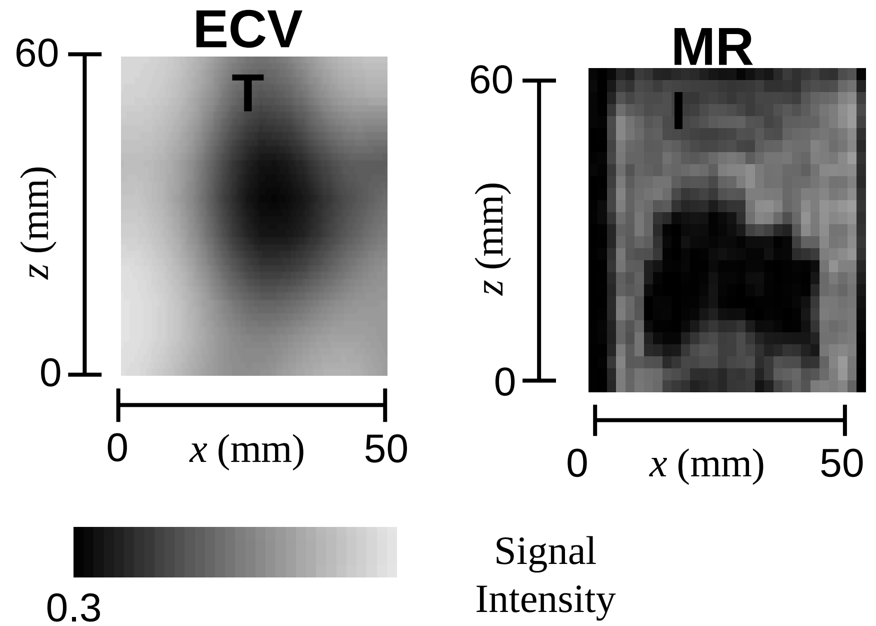


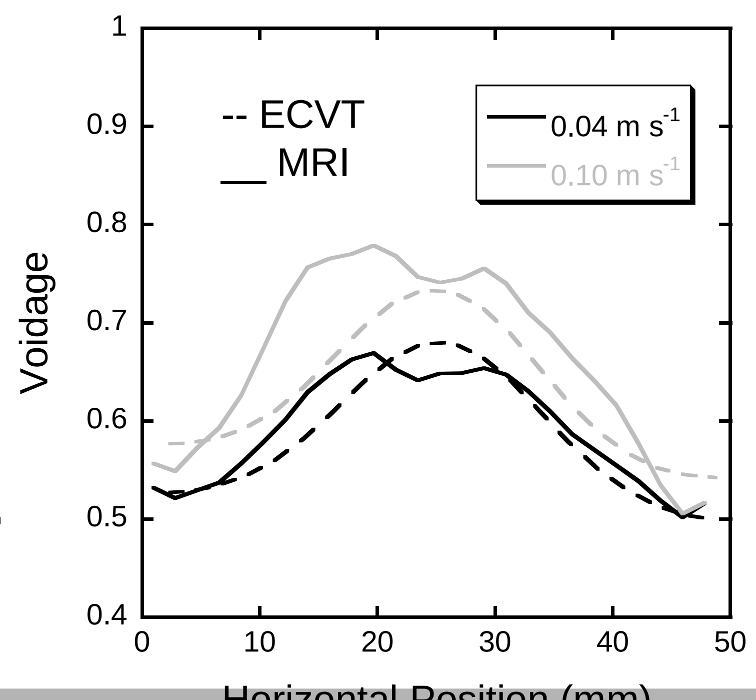
Comparison of the time-averaged cross-sectional solids concentrations obtained by the *ECT* and the *optical fiber probe* and the time-averaged volume solids concentration obtained by the *ECVT* for a 12-in gas-solid fluidized bed with FCC particles (d_p = 60 μm; ρ_p = 1400 kg/m^3)

Courtesy of: The Ohio State University

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

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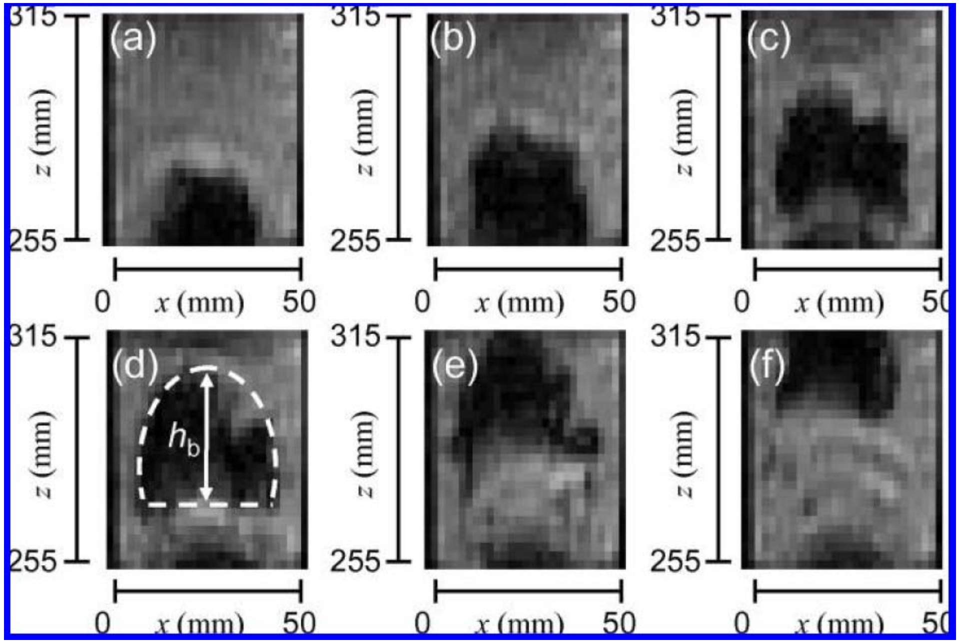

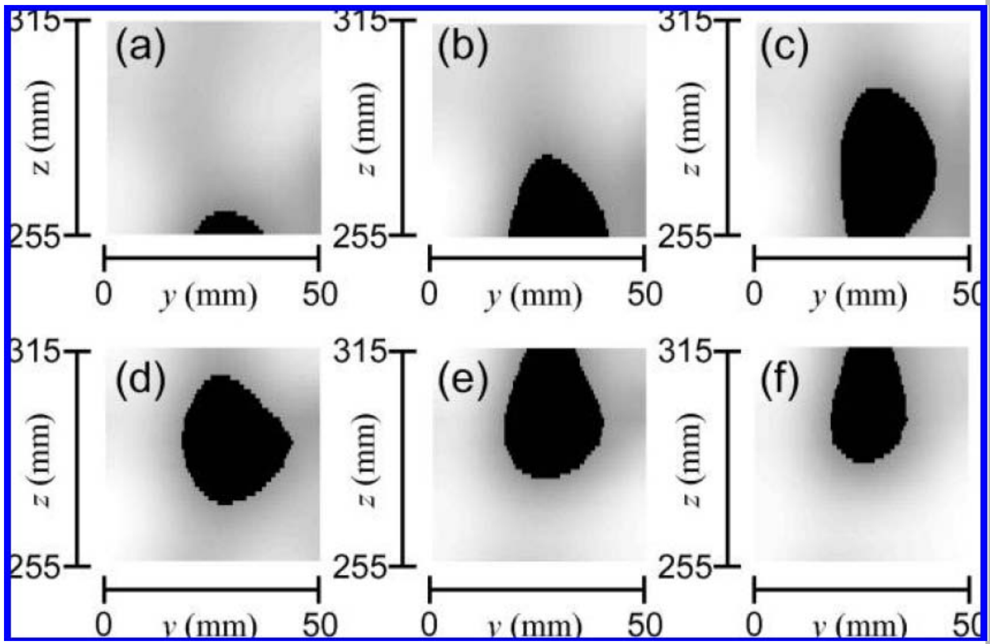

Superficial Gas Velocity: 0.04 m/s;
MRI: every frame (26 ms)
ECVT: every 2nd frame (25 ms)

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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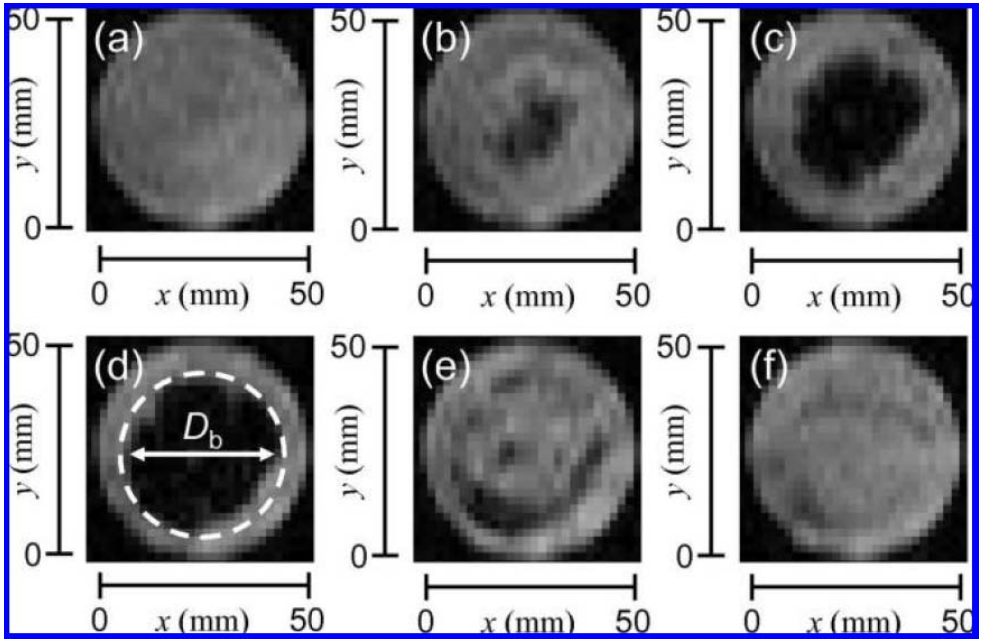

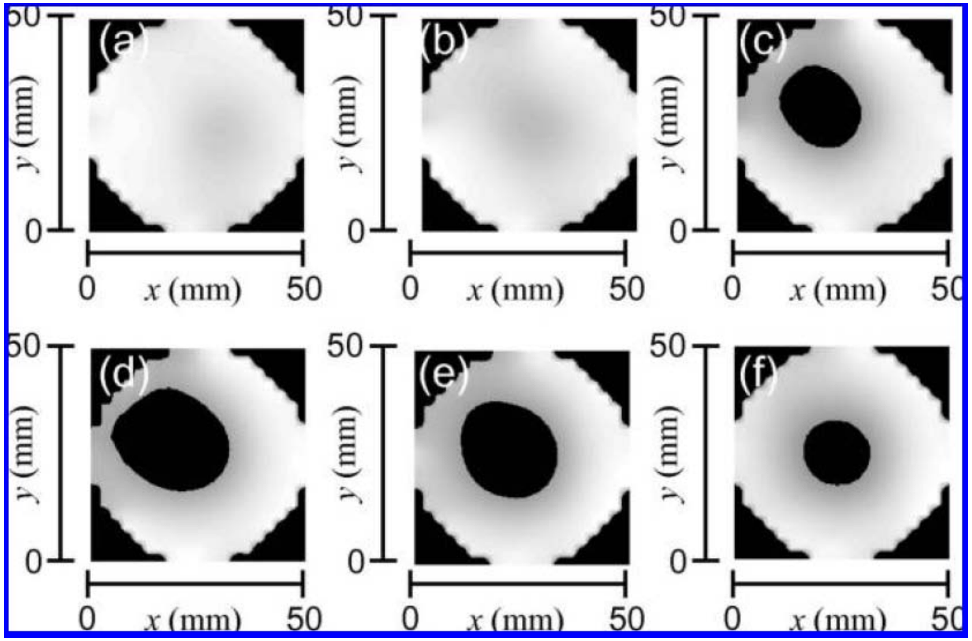

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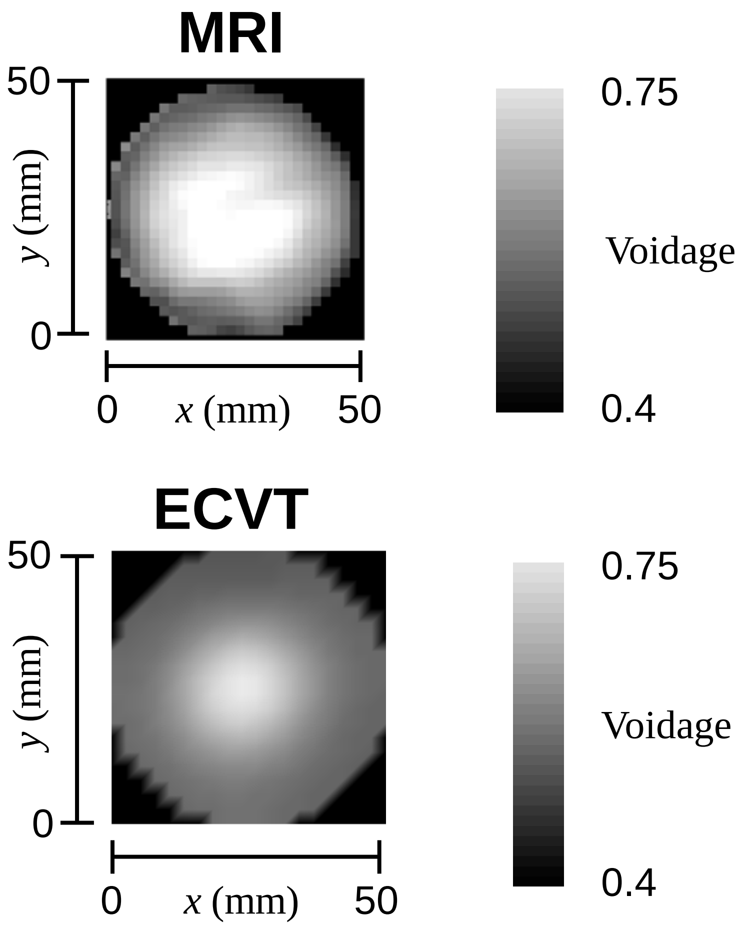
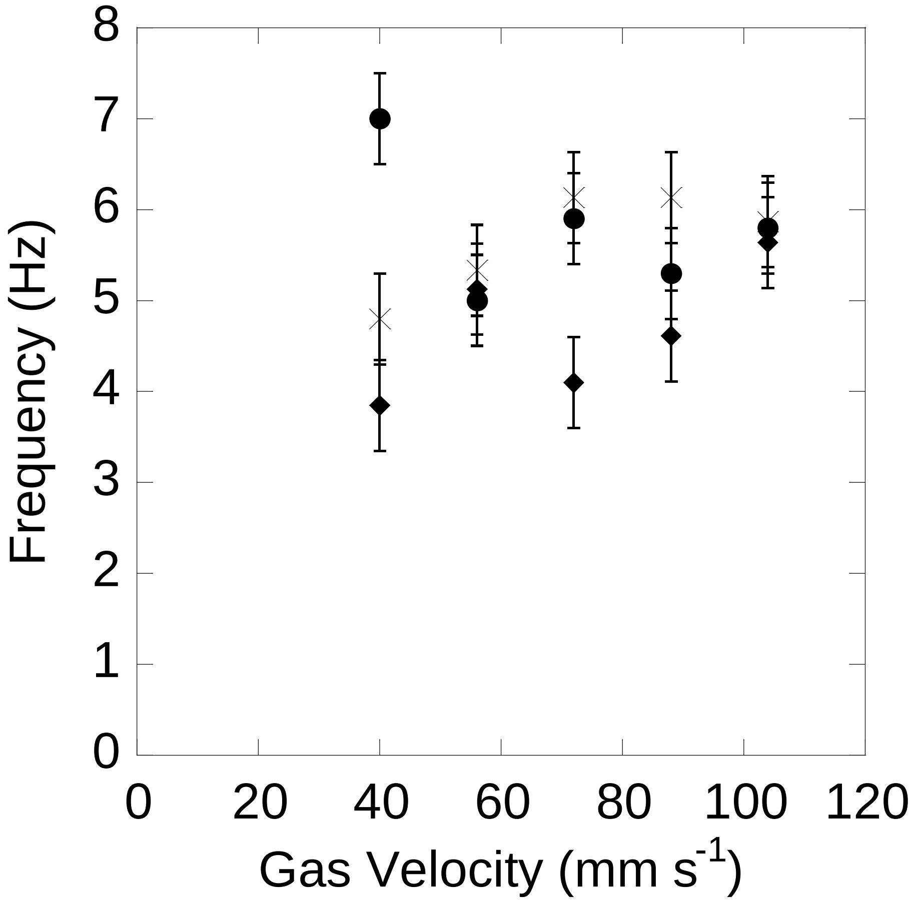


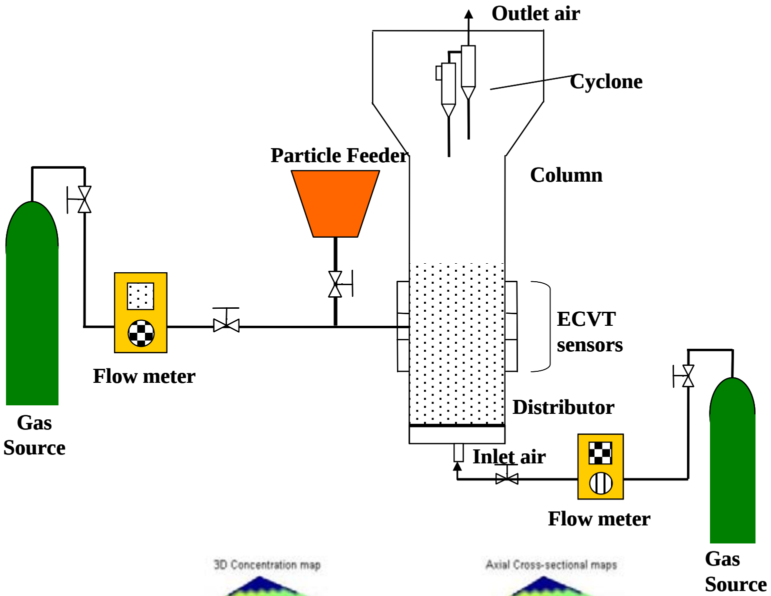
Superficial Gas Velocity: 0.104 m s-1

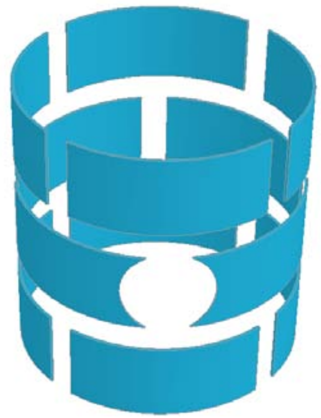


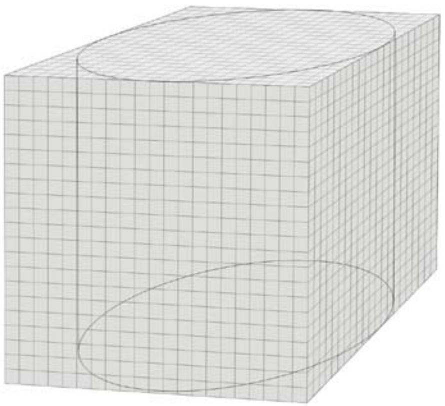
Bubble frequency calculated from the ECVT (×), 2D MR data (♦) and 1D MR data (●).

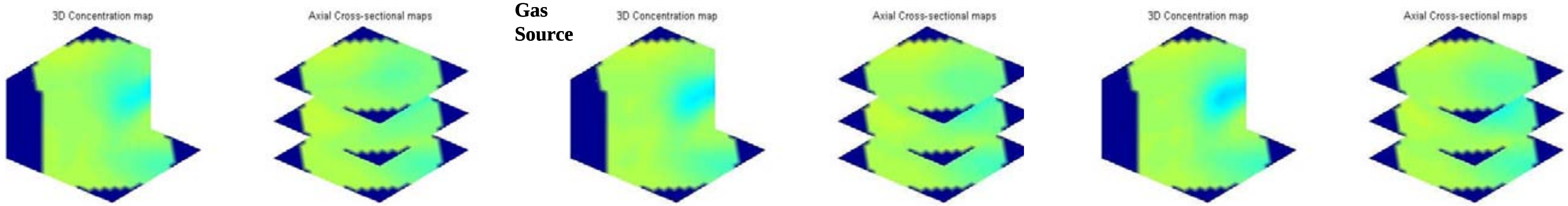
Work of **D.J. Holland[1], Q. Marashdeh[2], C.R. Müller[1], F. Wang[2], J.S. Dennis[1], L.-S. Fan[2], L.F. Gladden[1]**
[1]Cambridge University, [2]The Ohio State University

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

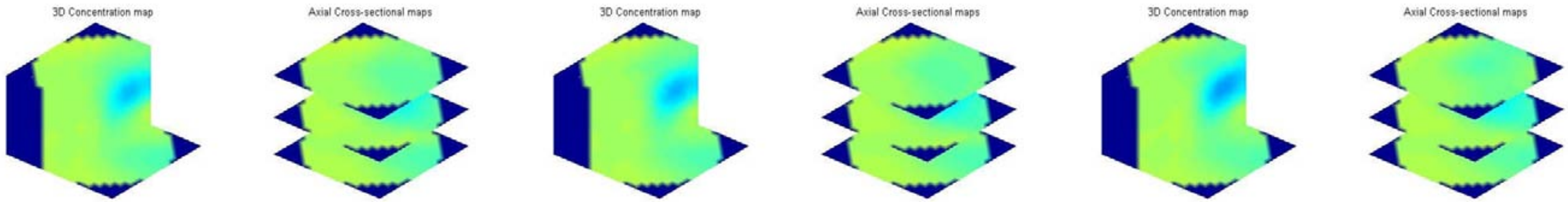








(a) t=0; (b) t=12.5 ms; (c) t=25.0 ms; (d) t=37.5; (e) t=50.0 ms; (f) t=62.5 ms. Ug=0.064 m/s, U0=15 m/s



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:

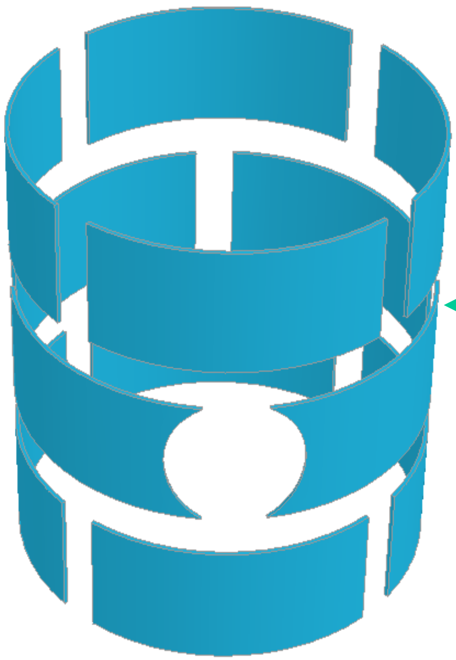
Air density:1.225 kg/m^3

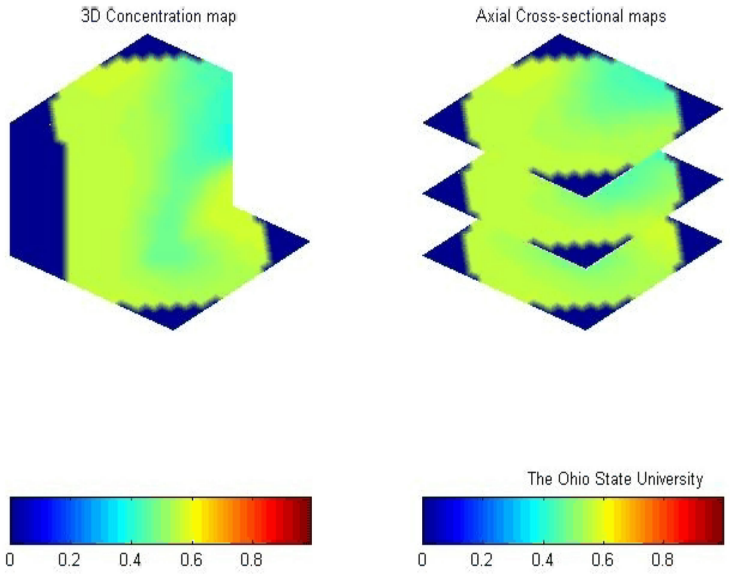
Air viscosity: 1.8×10^{-5} Ns/m^2

Sensors and Experimental Setup

Courtesy of: The Ohio State University

Side Injection



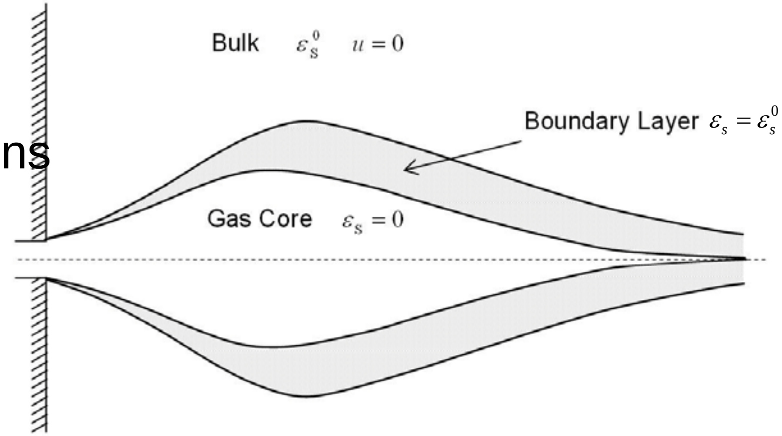


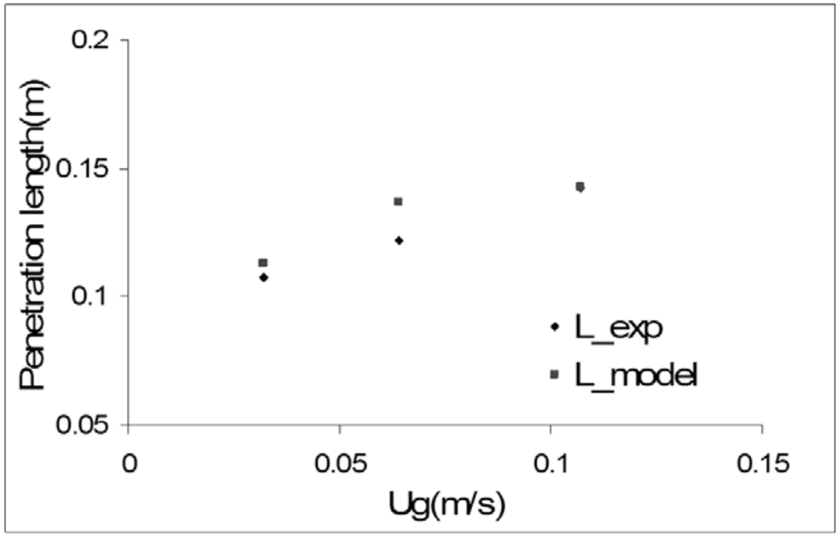
Courtesy of: The Ohio State University

Horizontal gas jet penetration in a gas-solid fluidized bed

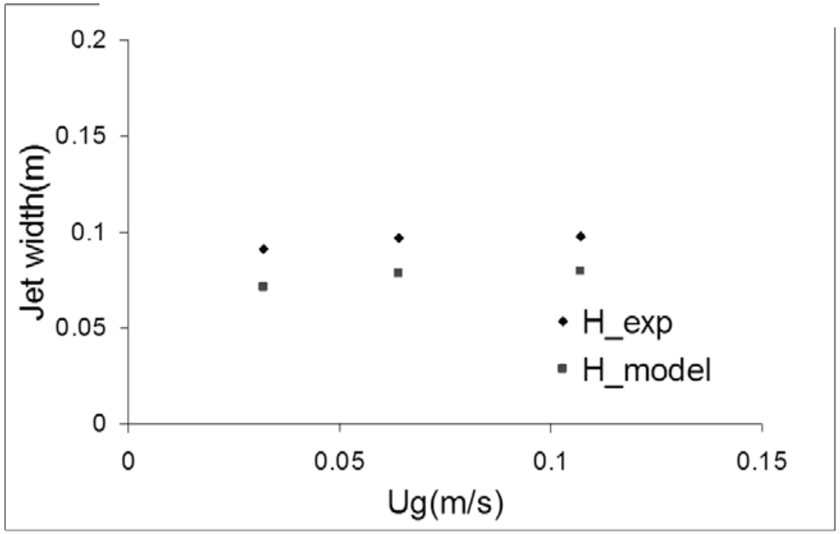
Horizontal jet in a gas-solid fluidized bed:

- 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



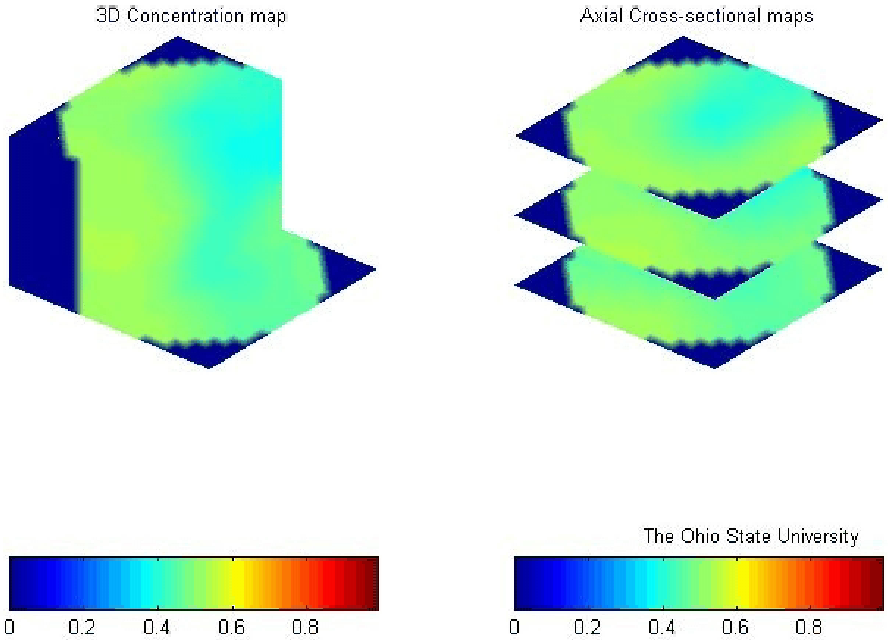


Comparison of the maximum penetration lengths of the horizontal gas jet obtained by ECVT experiments and model prediction for the 0.3 m gas-solid fluidized bed

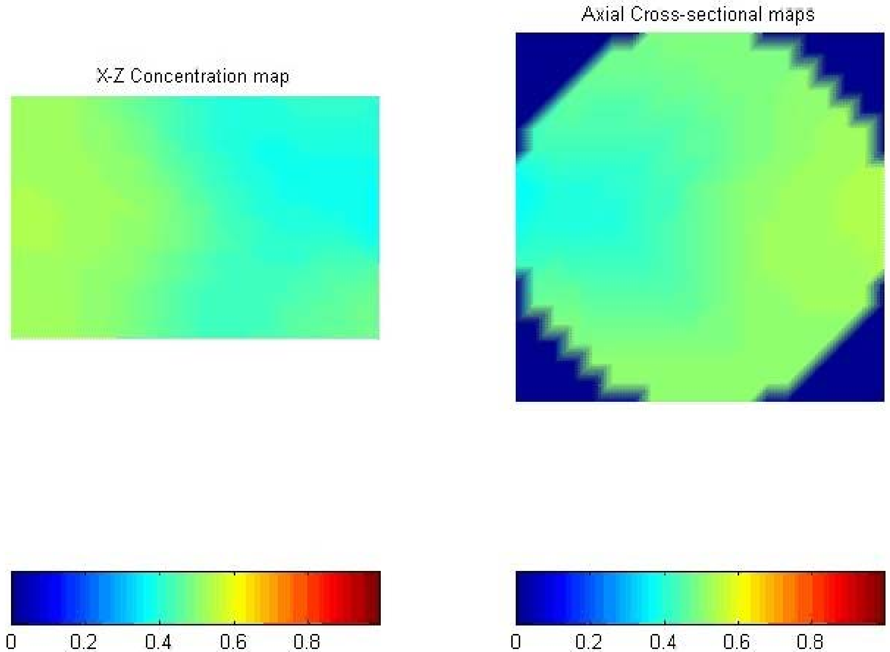


Comparison of the maximum width of the horizontal gas jet obtained by ECVT experiments and model prediction for the 0.3 m gas-solid fluidized bed

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



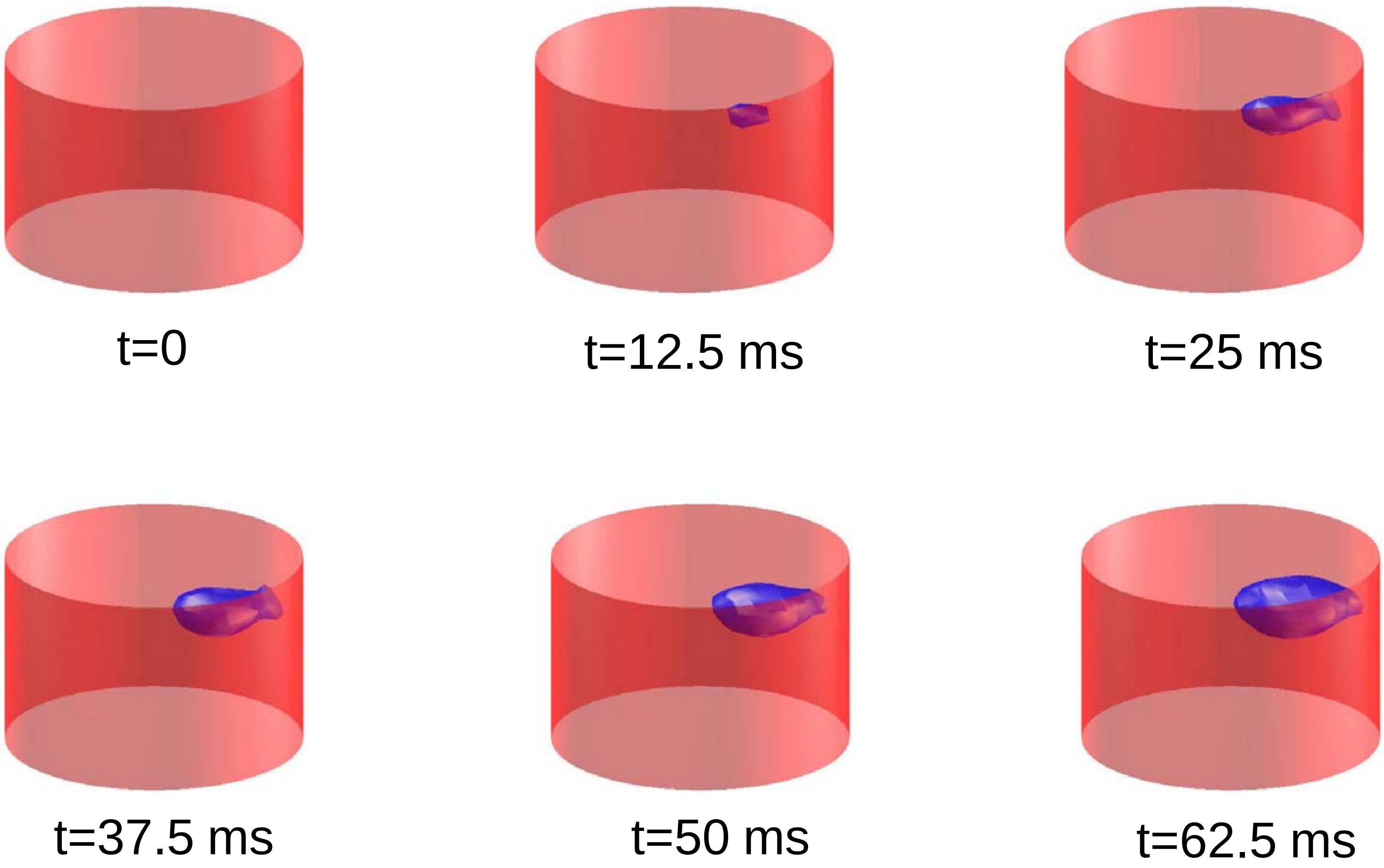
Superficial gas velocity: Ug=0.108 m/s
Side gas velocity: Ug_side=15.5 m/s
Side solids velocity: Us_side=0



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

Jet shape from ECVT images

(Maximum jet penetration)

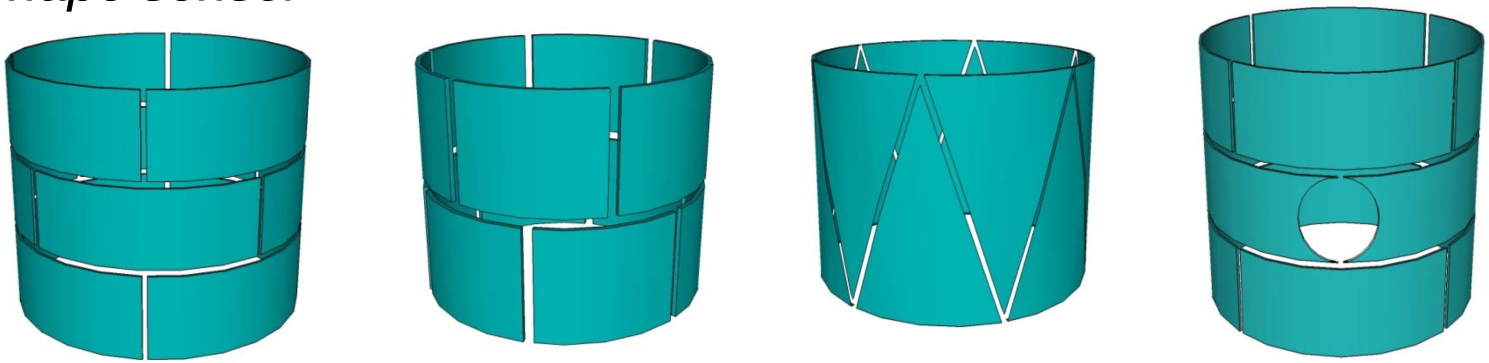


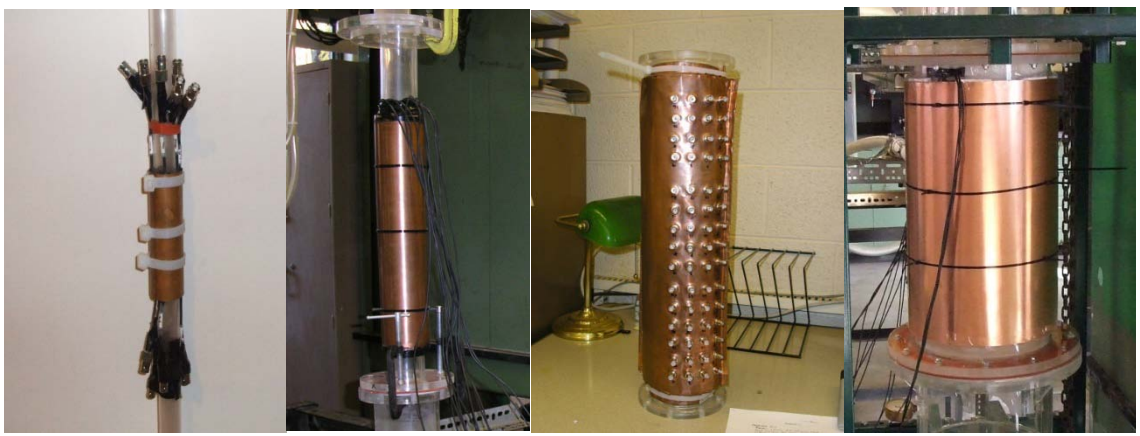
U_g=0.064 m/s, U_0=15 m/s

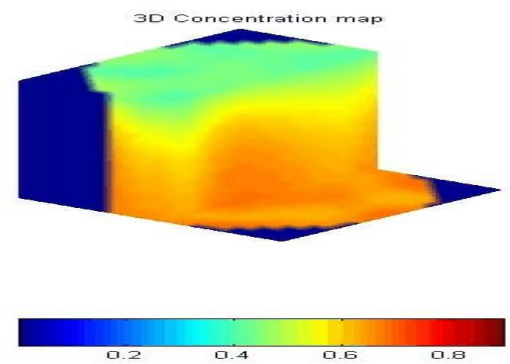
Fei Wang, Zhao Yu, Qussai Marashdeh, Liang-Shih Fan * "Horizontal gas and gas/solid jet penetration in a gas–solid fluidized bed " *Chemical Engineering Science* 65 (2010) 3394–3408

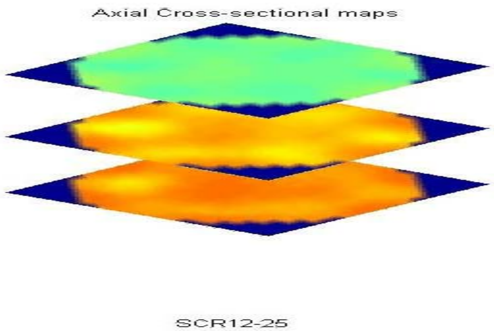
4. ECVT Sensor Applications

Cylindrical shape sensor



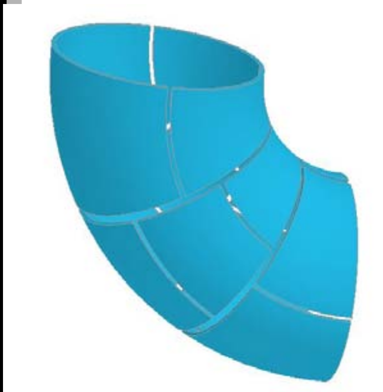


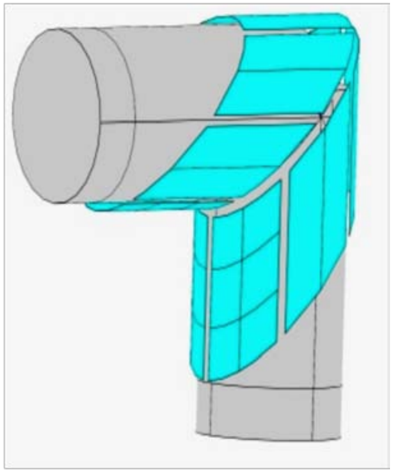


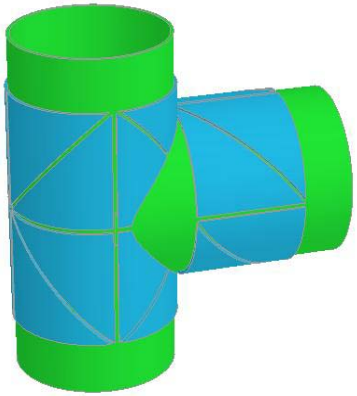


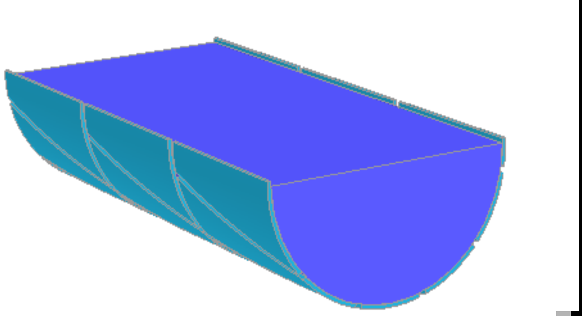
ECVT sensor design

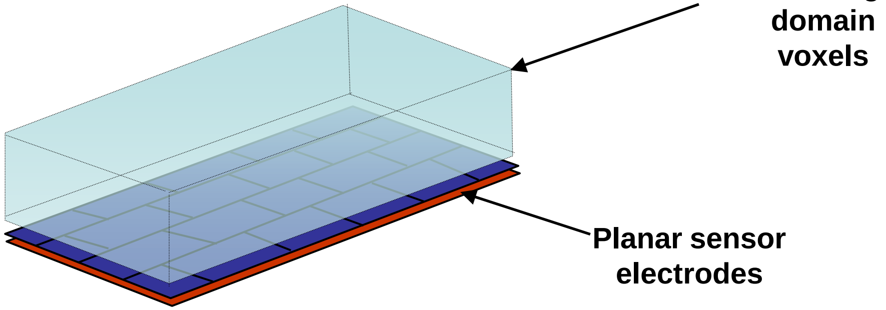
Sensors with complex geometries

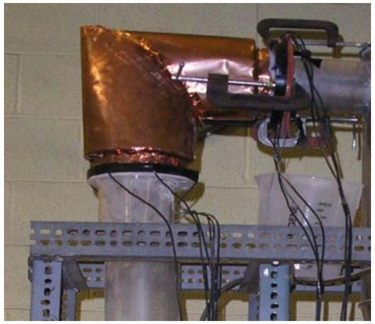


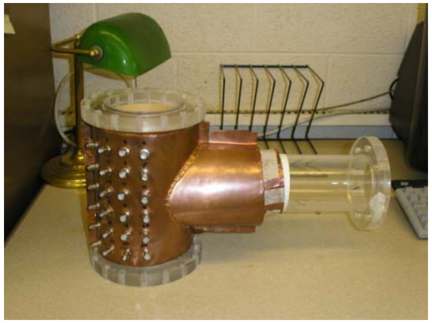


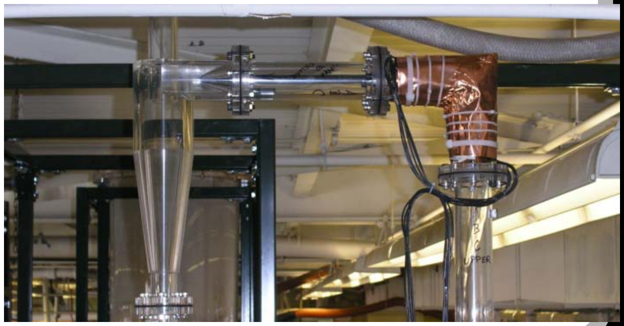




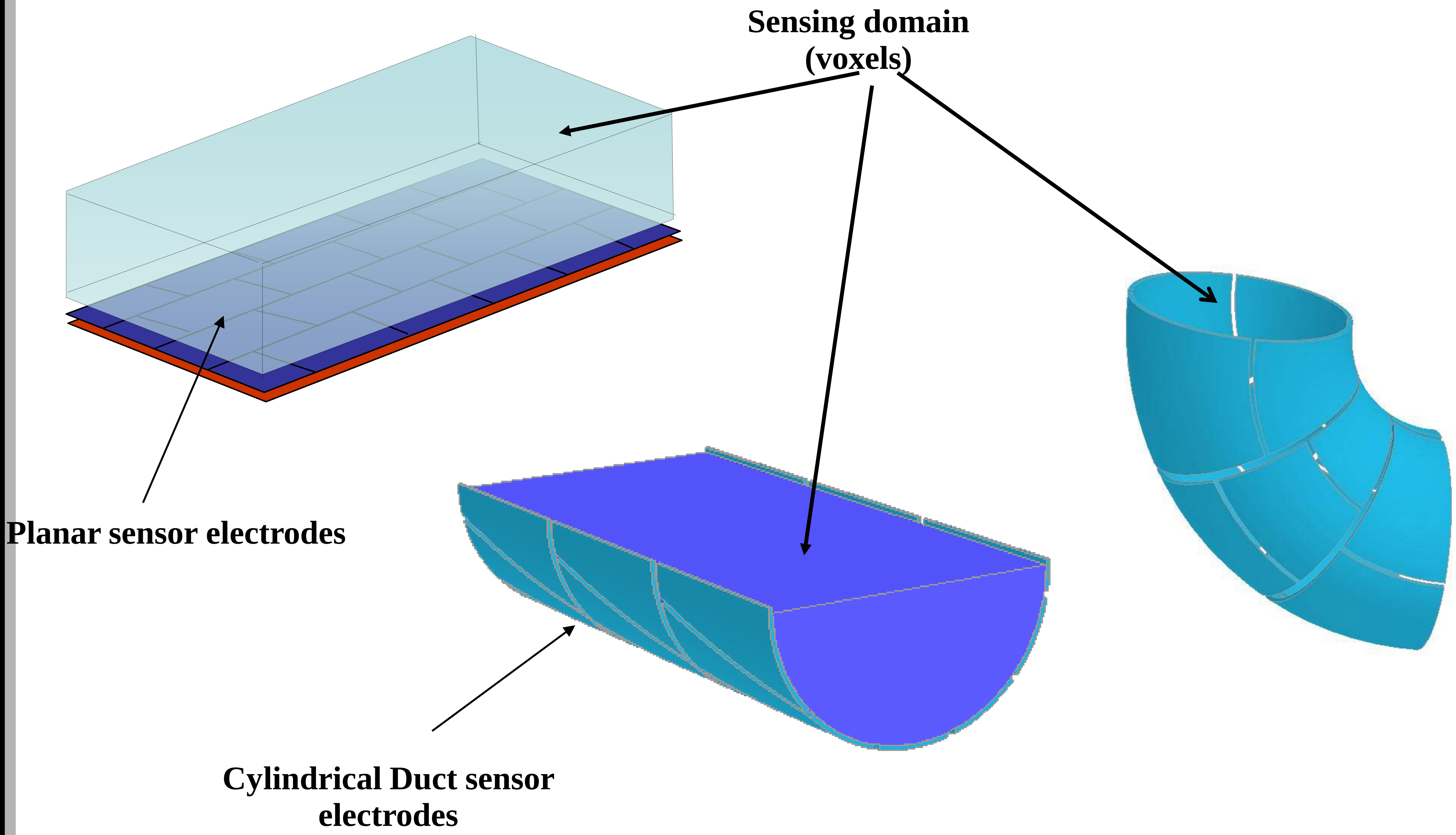








Designs for Various Geometries



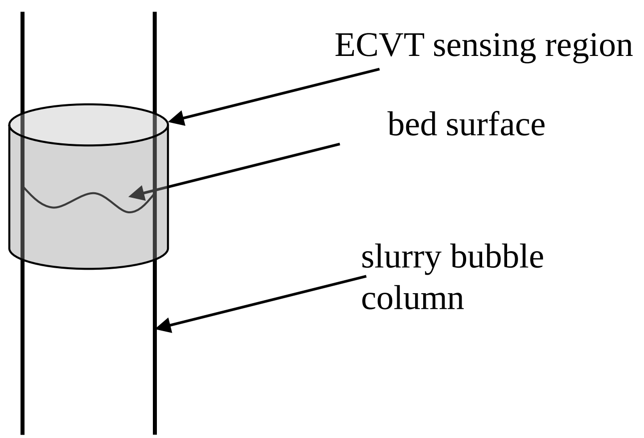
ECVT sensor design

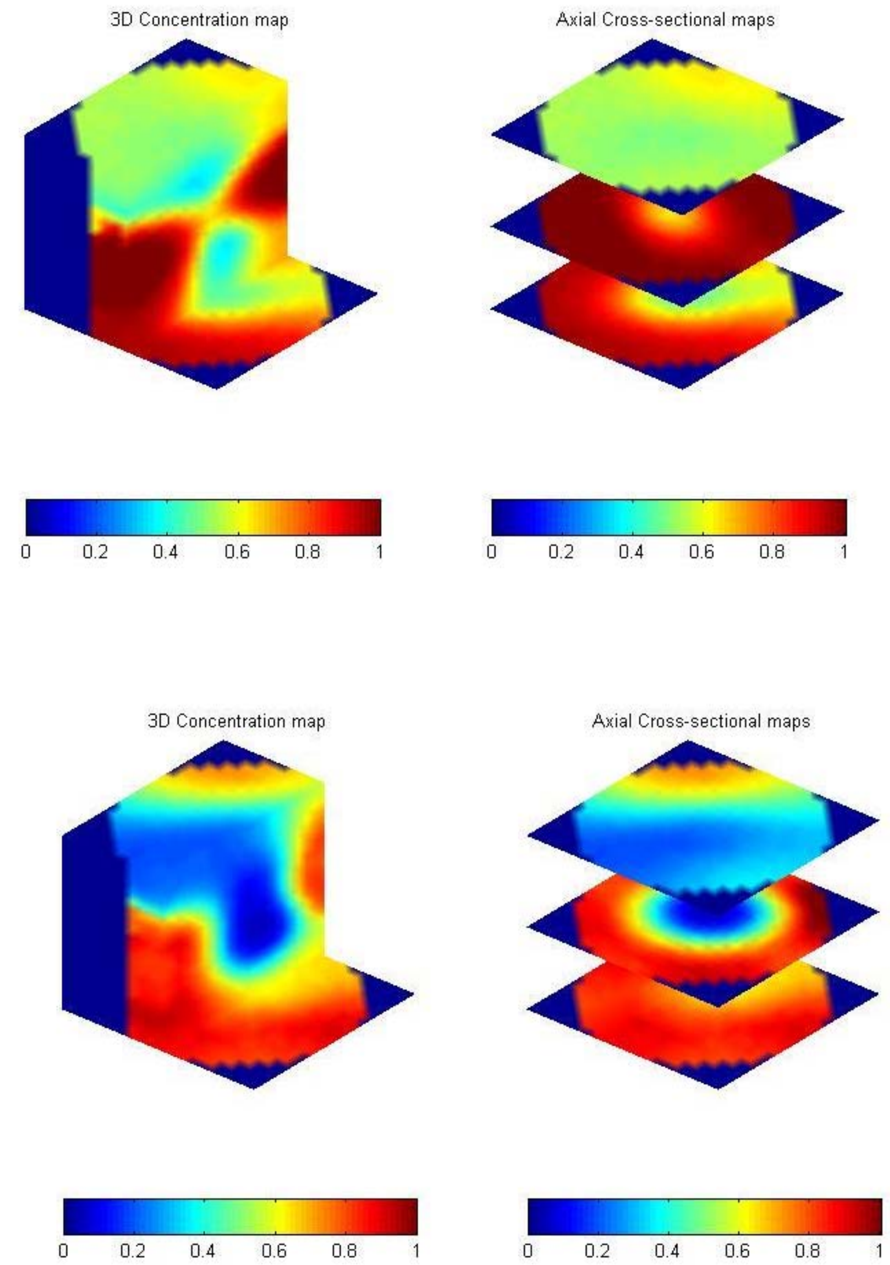
Comparison of different sensor geometries in terms of symmetry, axial resolution and radial resolution

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

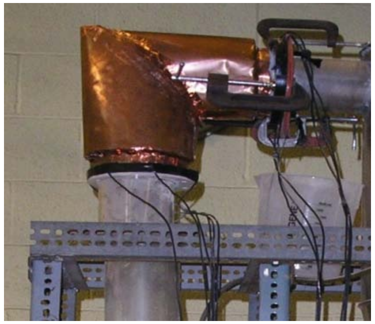


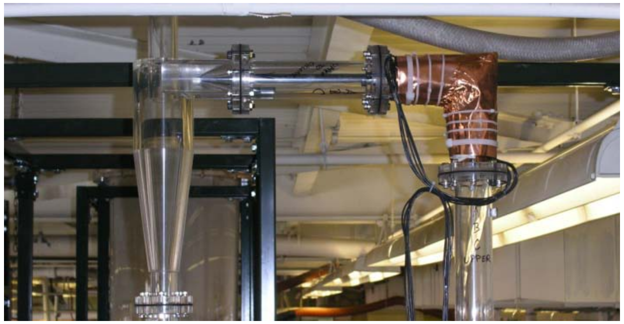


Snapshots of bubble bursting at the surface of a slurry bubble column by ECVT: (a) 3D image before bubble bursting; (b) 3D image after bubble bursting

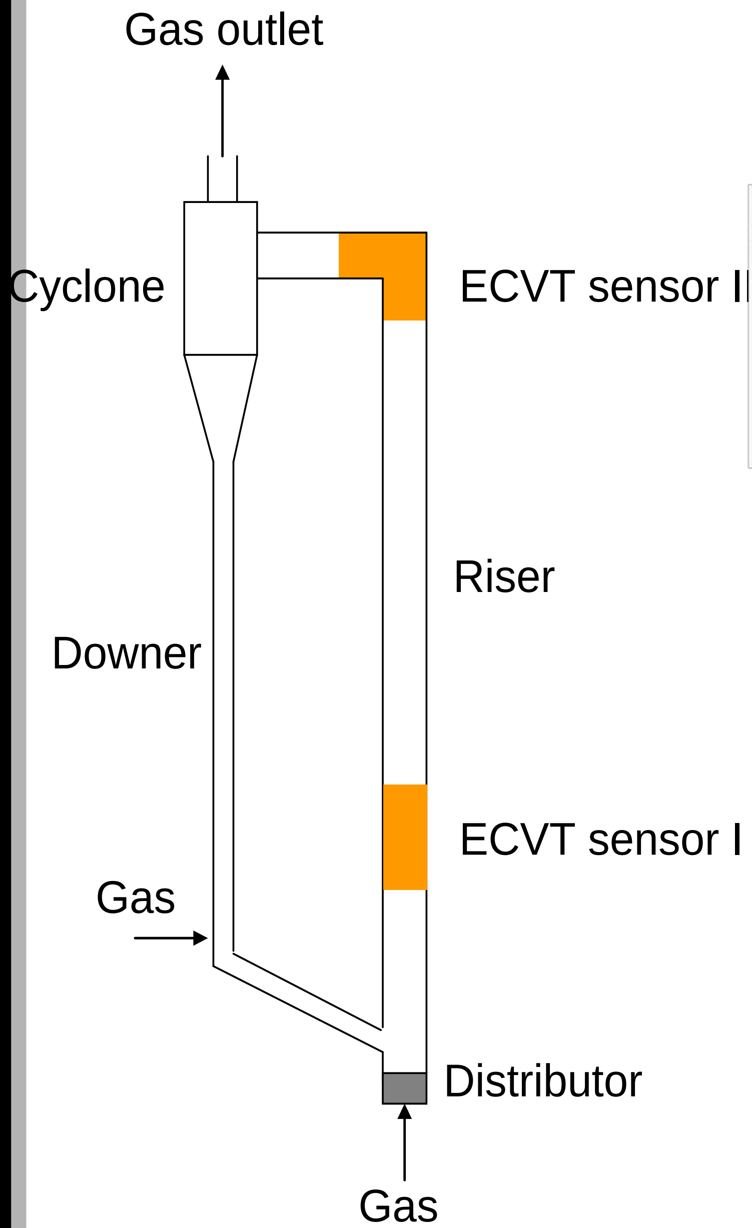
Courtesy of: The Ohio State University

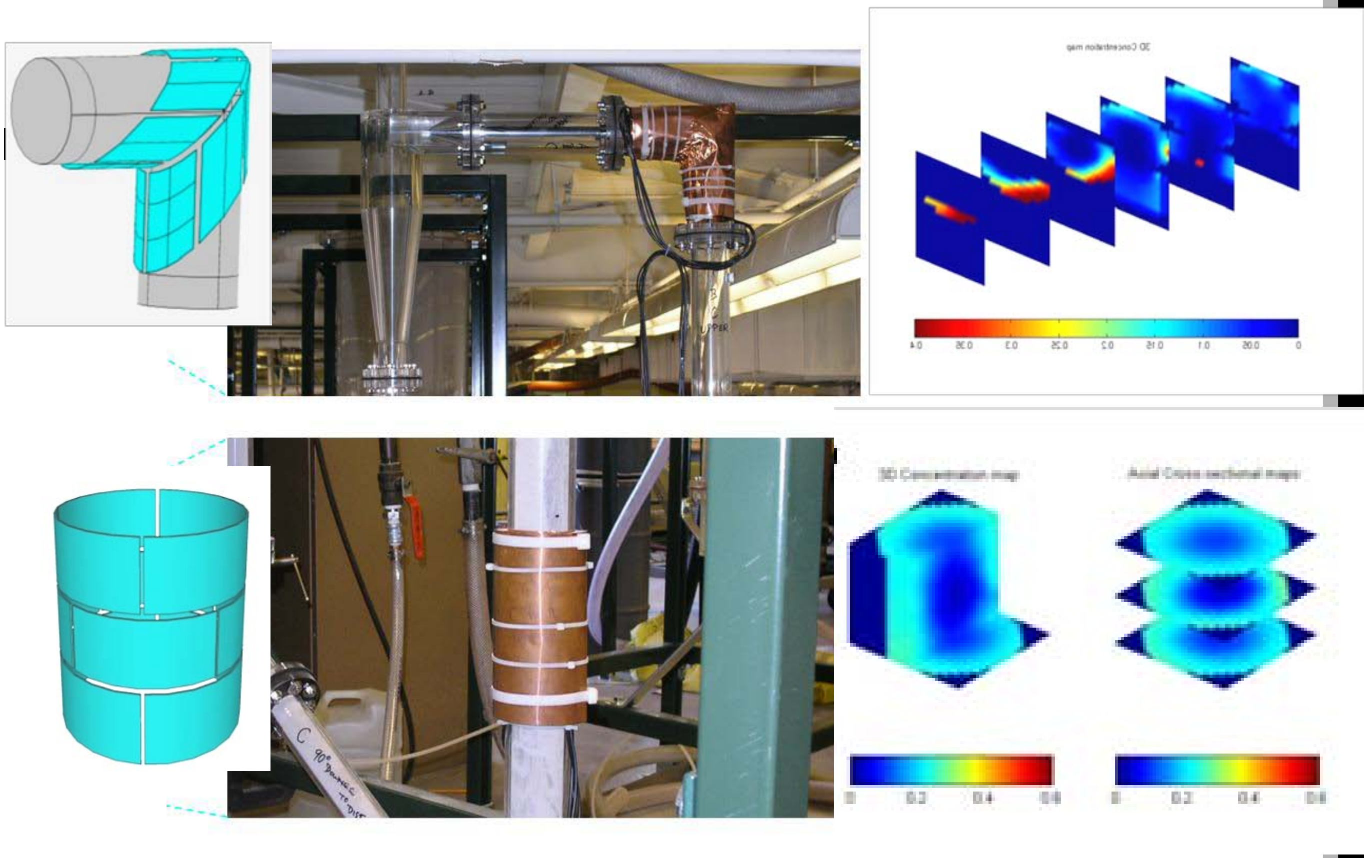
6. Complex Geometries Examples





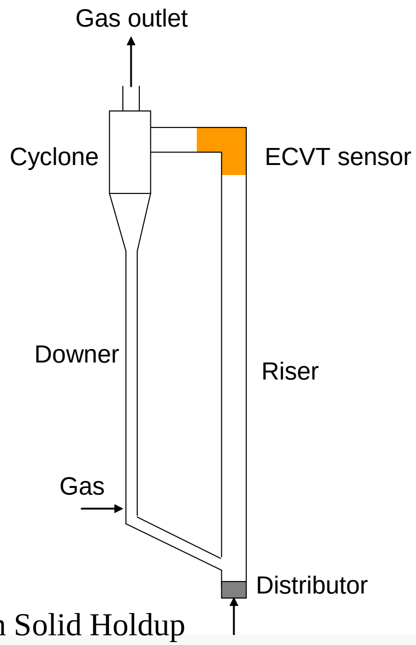
90 Degrees Bend & Riser

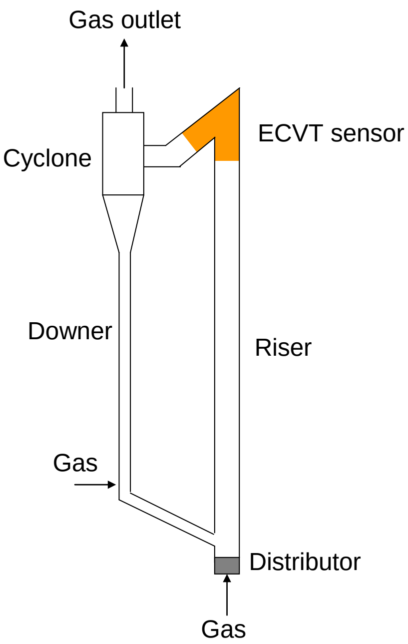


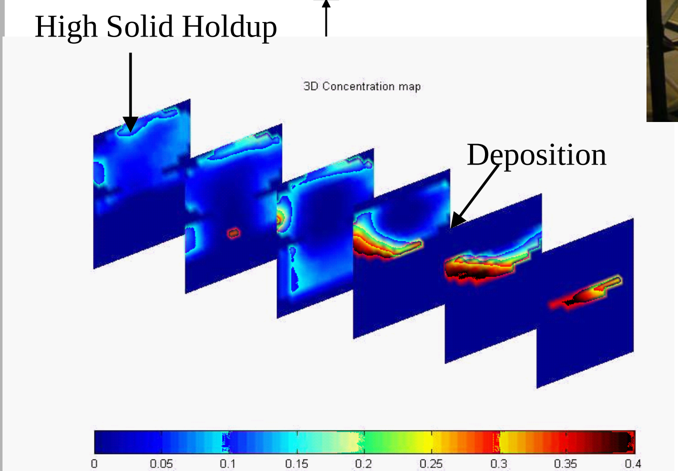


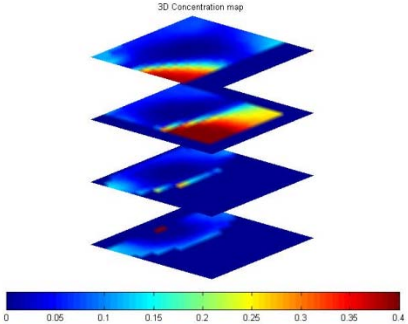
Courtesy of: The Ohio State University

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

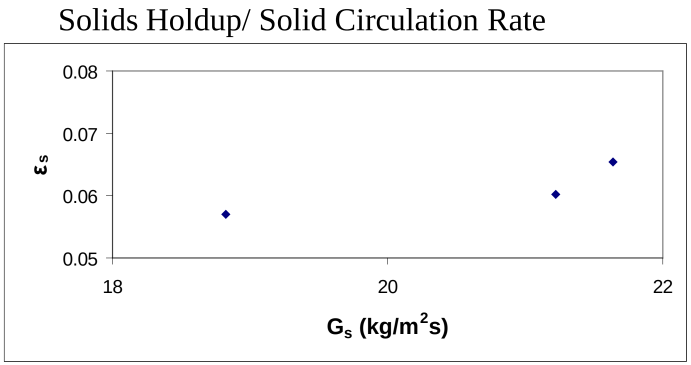








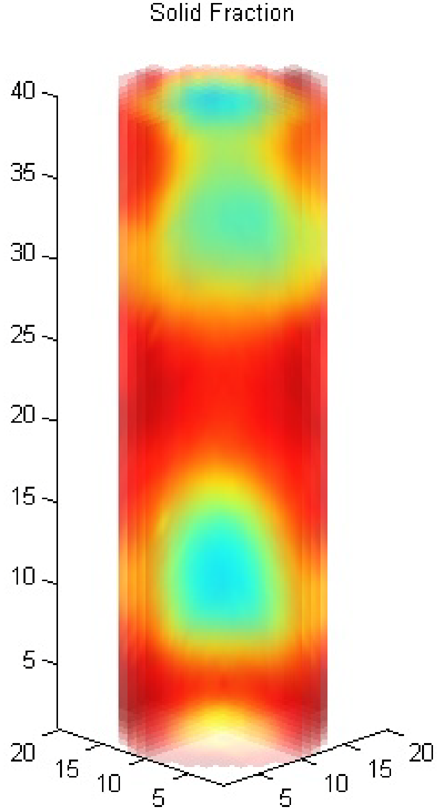
Solids holdup distribution in the bend of the CFB riser at Ug=1.36 m/s and Gs=21.2 kg/m^{2}s:vertical slices and horizontal slices

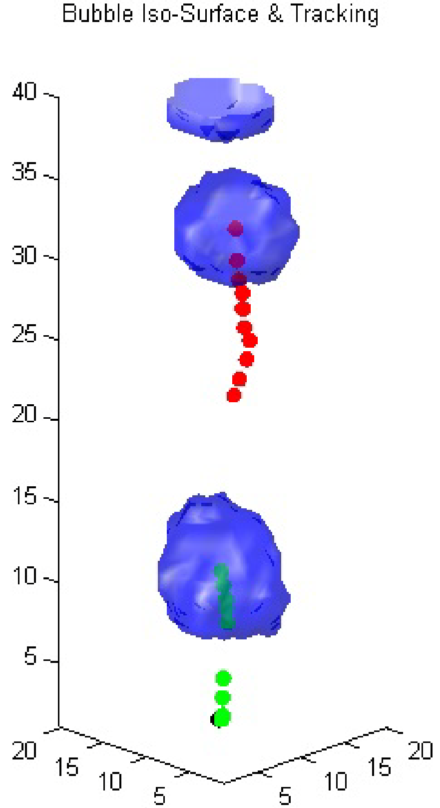


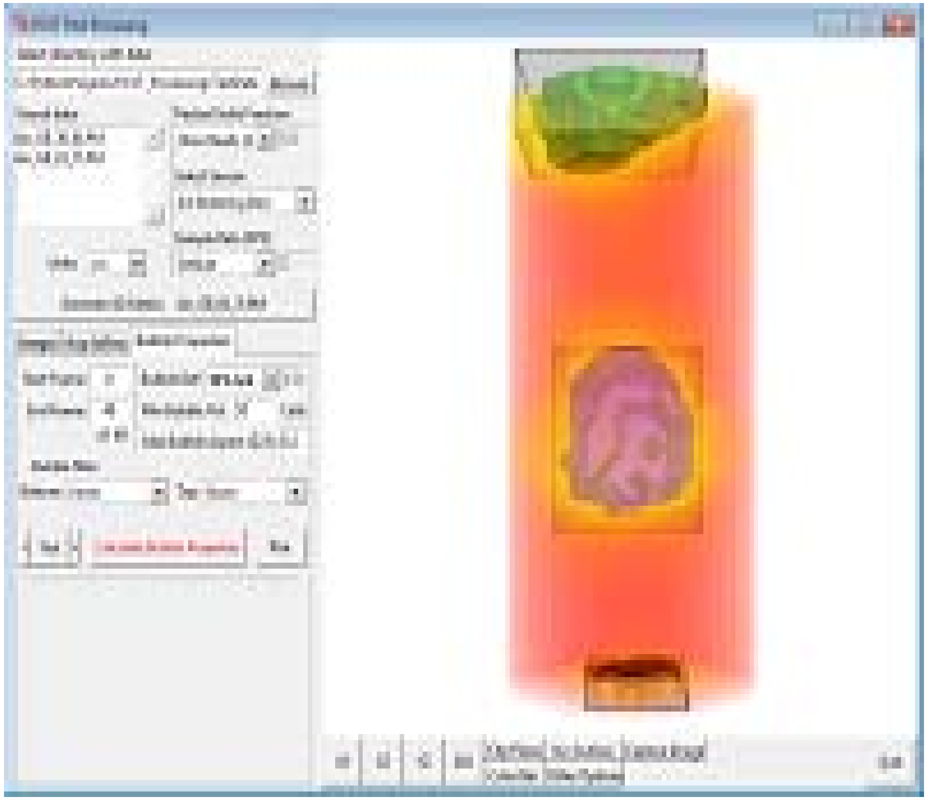
Time-averaged volume solids holdup at the top wall region at the start of the horizontal duct of the bend at Ug=1.16 m/s

Courtesy of: The Ohio State University

Real-Time Imaging: Bubble Tracking



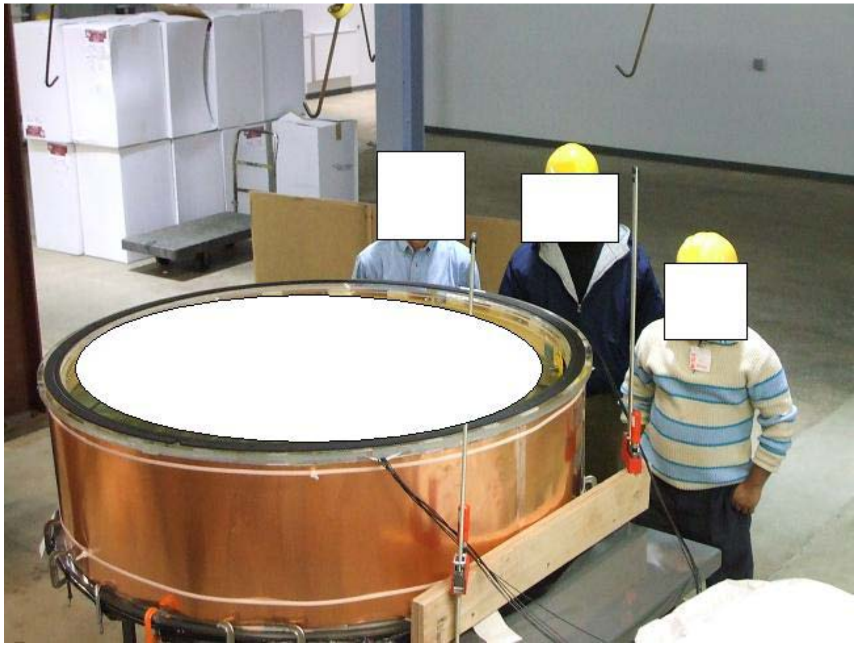




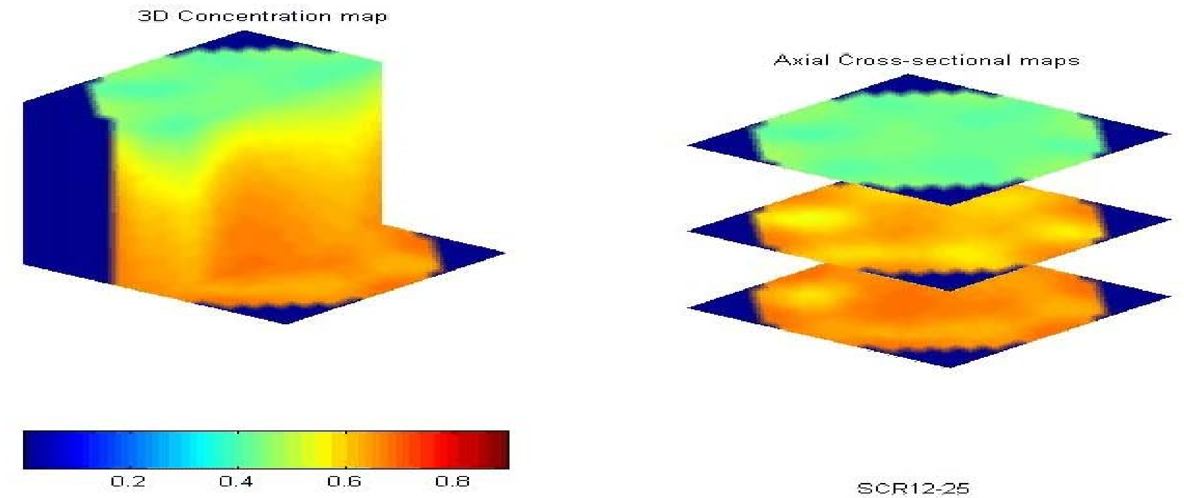
Courtesy of: NETL, U.S. Department of Energy

Scale-Up ECVT Sensors

60 inch ID

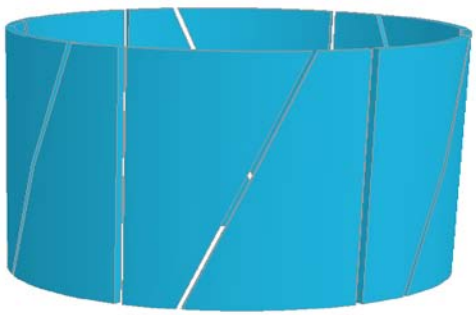


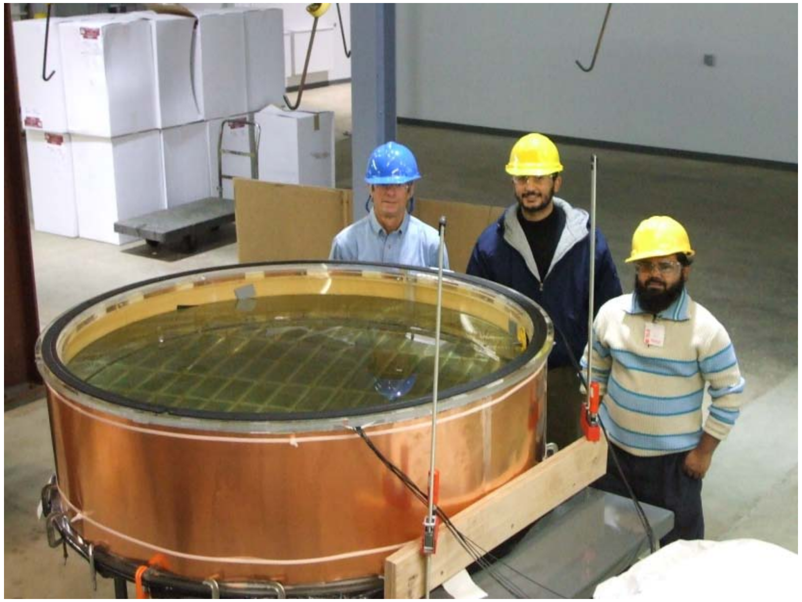
12 inch ID

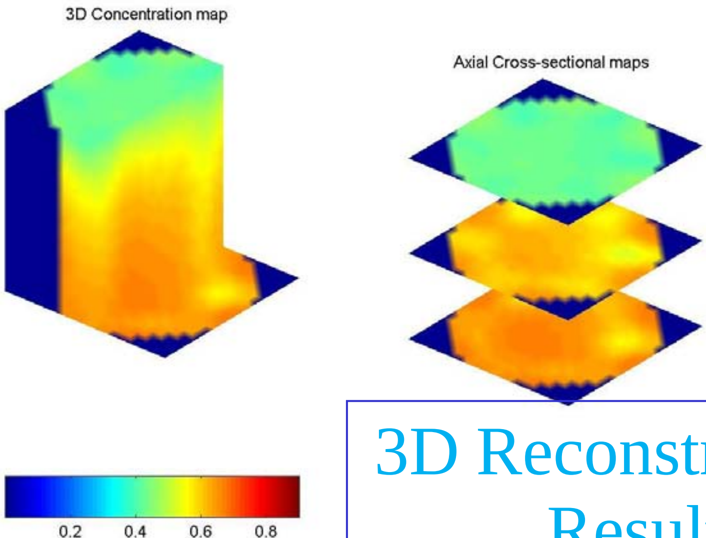


Scale-up Unit

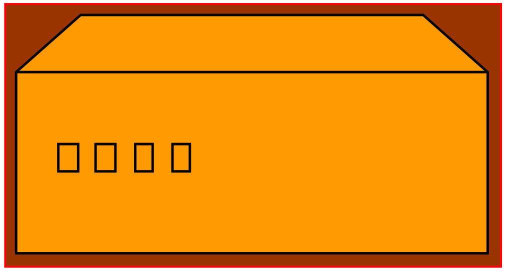
Sensor Design





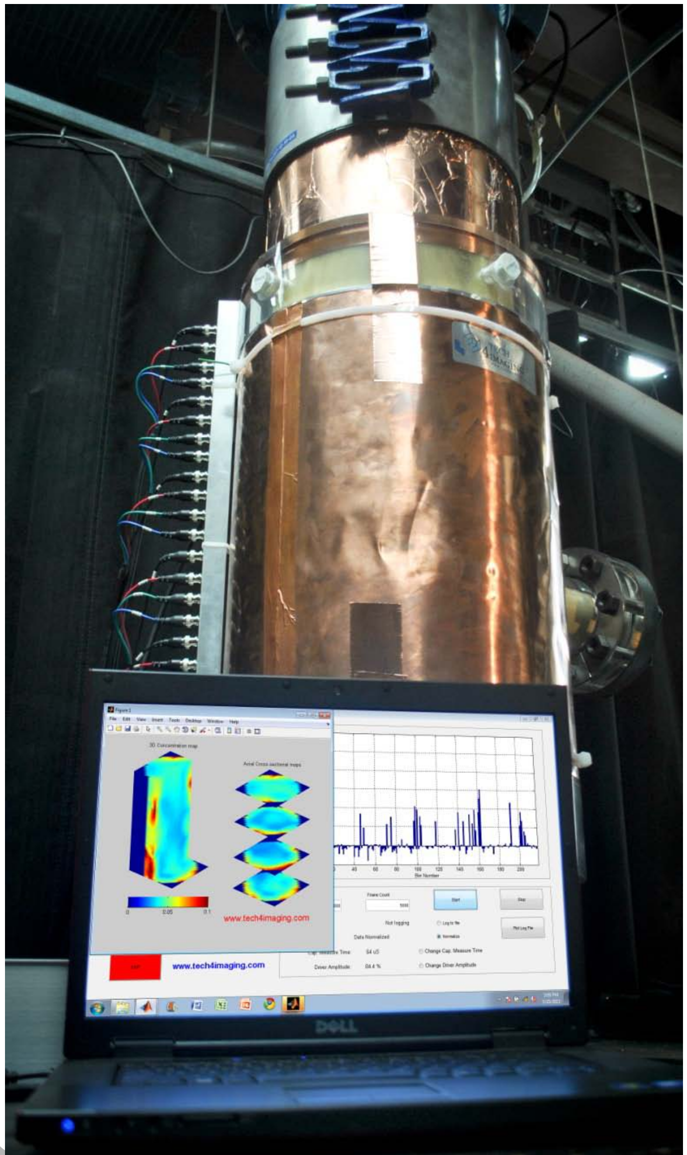


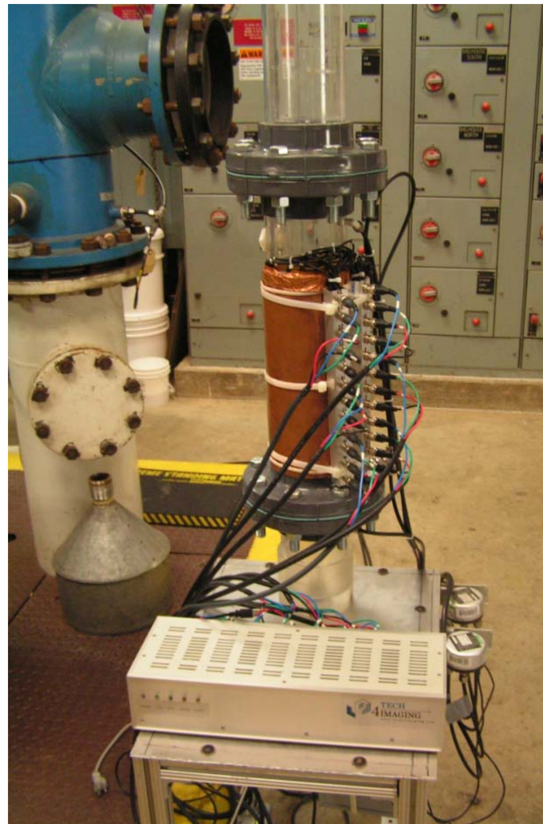
3D Reconstruction Result



Acquisition System

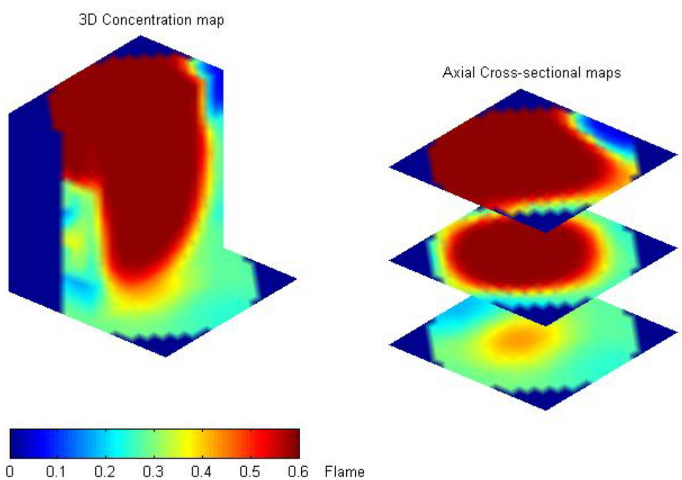
NETL Riser, Inlet, & Exit Sensors



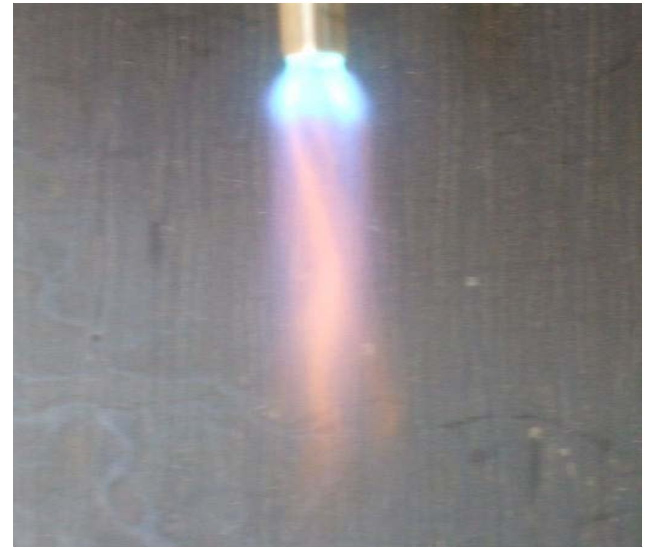


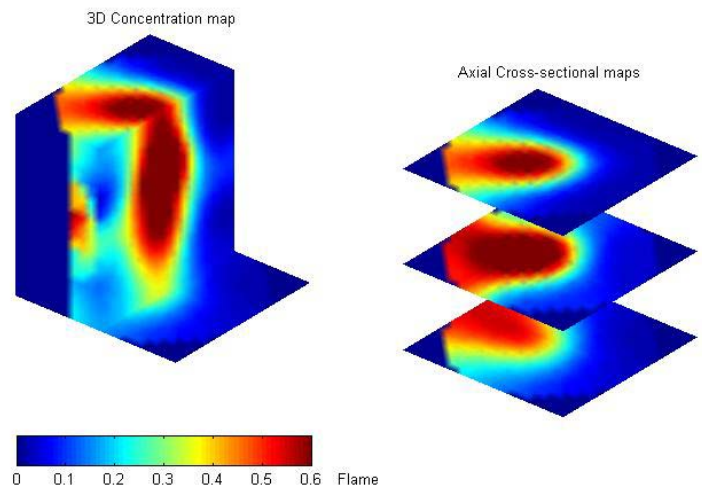
Courtesy of: NETL, U.S. Department of Energy

Combustion Imaging



Ignition





Stable Flame

Combustion

A change in heavy ion concentration has a remarkable effect on dielectric constant and conductivity of a medium containing free ionic species

dielectric constant: ε

and conductivity: σ

$$\epsilon = 1 - \sum_i \frac{\omega_c^2}{\omega^2 + \omega_i^2}, \quad \sigma = \frac{1}{4\pi} \sum_i \frac{\omega_c^2 \omega_i}{\omega^2 + \omega_i^2},$$

Smaller ions contribute less to changing dielectric constant.

$\omega = 2\pi f$, angular frequency f , frequency of the electrical signal

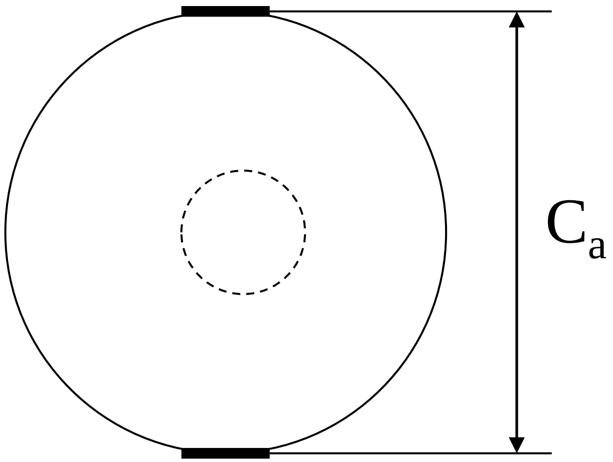
ω_i , collision frequency of the ith ionic species with other molecules

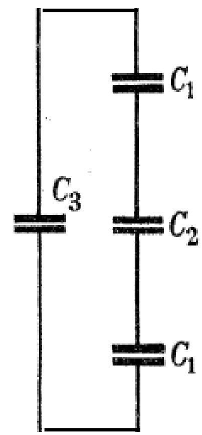
$\omega_c^2 = \dfrac{4\pi n_i e_i^2}{m_i}$ with n_i, e_i, m_i the no./cm^3, electrical charge, and mass of this ion respectively

H. Smith and T. M. Sugden, Studies on the Ionization Produced by Metallic Salts in Flames. III. Ionic Equilibria in Hydrogen/Air Flames Containing Alkali Metal Salts, Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, Vol. 211, No. 1104 (Feb. 7, 1952), pp. 31-58

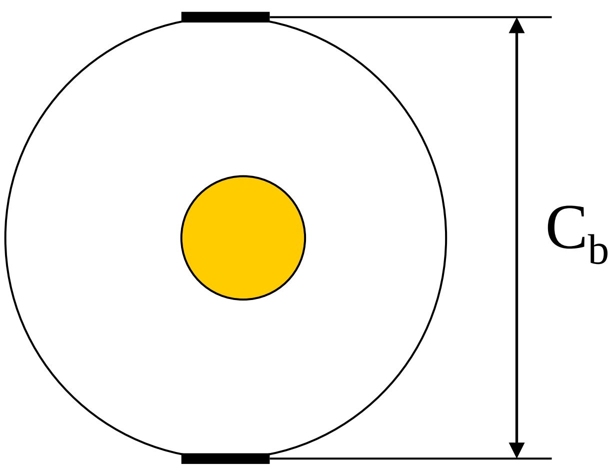
Ionization

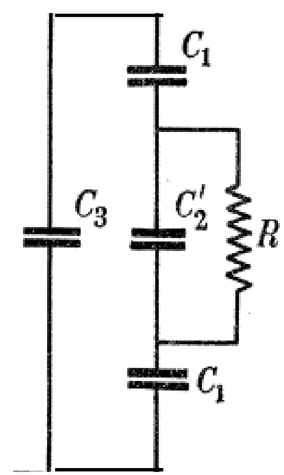
- Ionization occurs in flames during combustion
- The size and number of ions affect the conductivity of the flame more than it’s dielectric constant
- An electric capacitance response can be observed when introducing a flame between two plates.
- ECVT can be used to visualize combustion and flames based on variations in the capacitance signal





$$C_a = \frac{2C_3C_2 + C_1C_3 + C_1C_2}{C_1 + 2C_2}$$





$$C_b > C_a$$

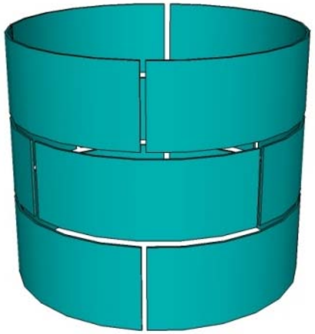
$$C_b = \frac{(2C_3 + C_1)^2 + \omega^2R^2(2C_3C_2' + C_1C_3 + C_1C_2')^2}{2(2C_3 + C_1) + \omega^2R^2(2C_2 + C_1)\ (2C_3C_2' + C_1C_3 + C_1C_2')}$$

H. Smith and T. M. Sugden, Studies on the Ionization Produced by Metallic Salts in Flames. III. Ionic Equilibria in Hydrogen/Air Flames Containing Alkali Metal Salts, Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, Vol. 211, No. 1104 (Feb. 7, 1952), pp. 31-58

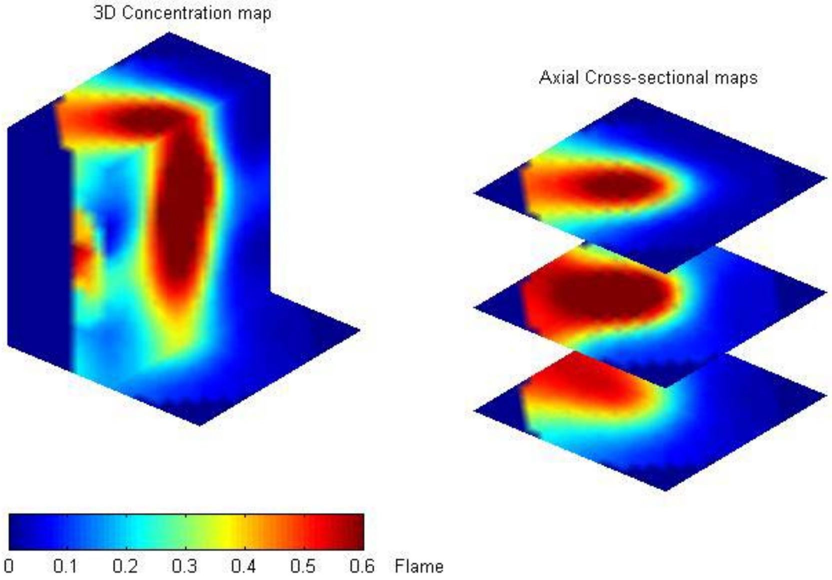
Experimental Condition

- Sensor: 4” ID, 3 layers, 12 channels
- Calibration material: Polyethylene
- Flame Source: Propylene (C_3H_6) Flame torch

$$\varepsilon_r \approx 2.3$$

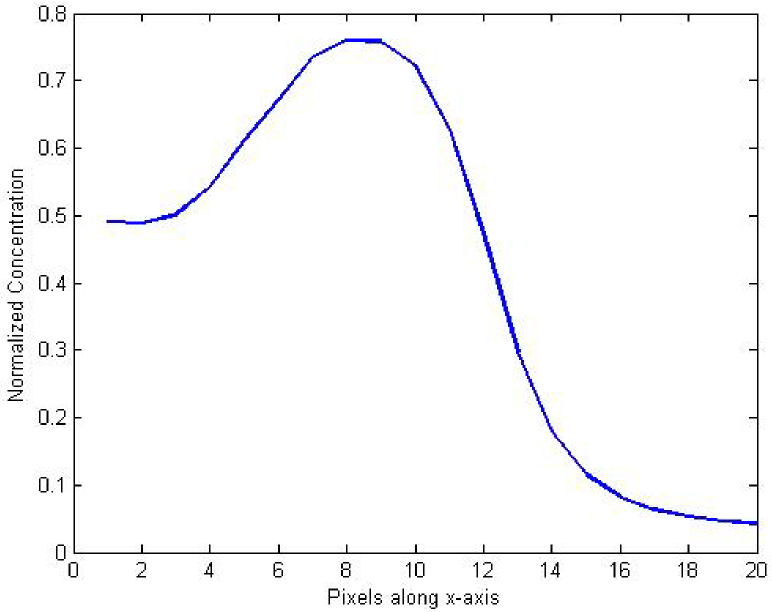


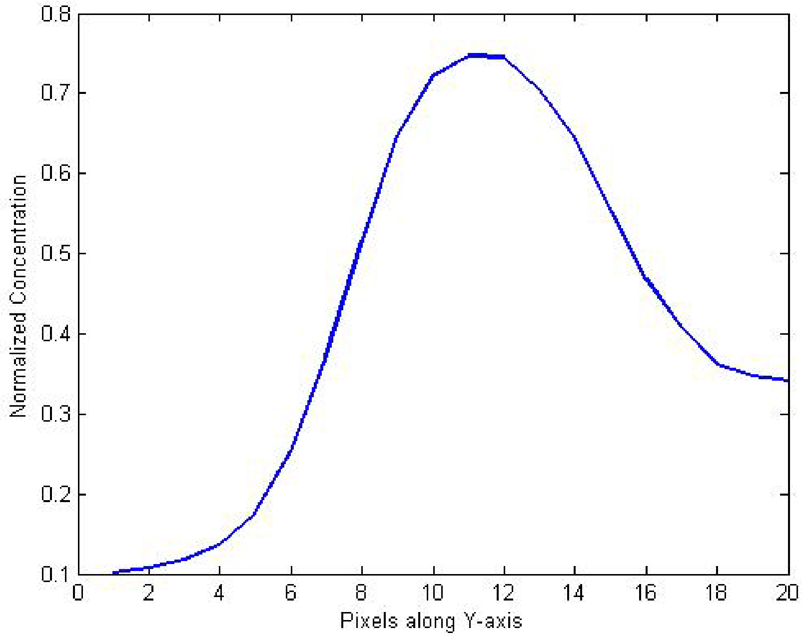
Combustion Imaging

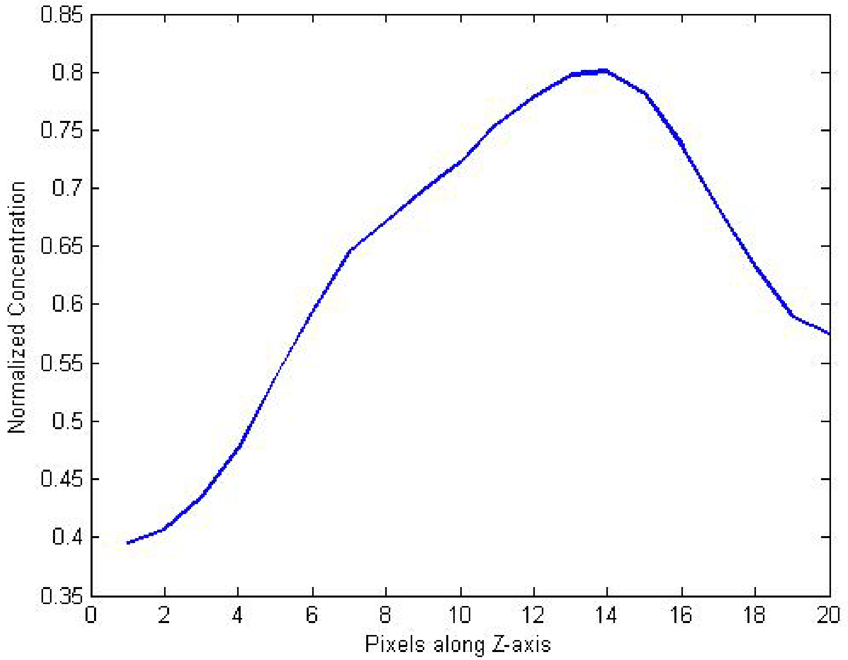


Stable Flame

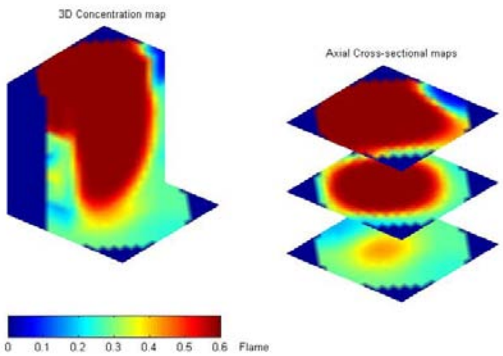
Capacitance Distribution



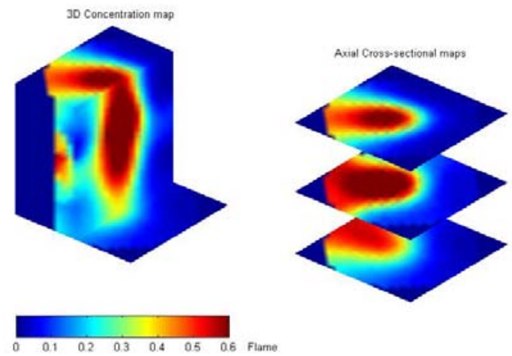




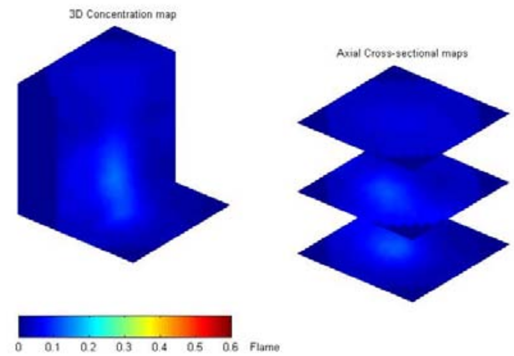
Combustion Imaging



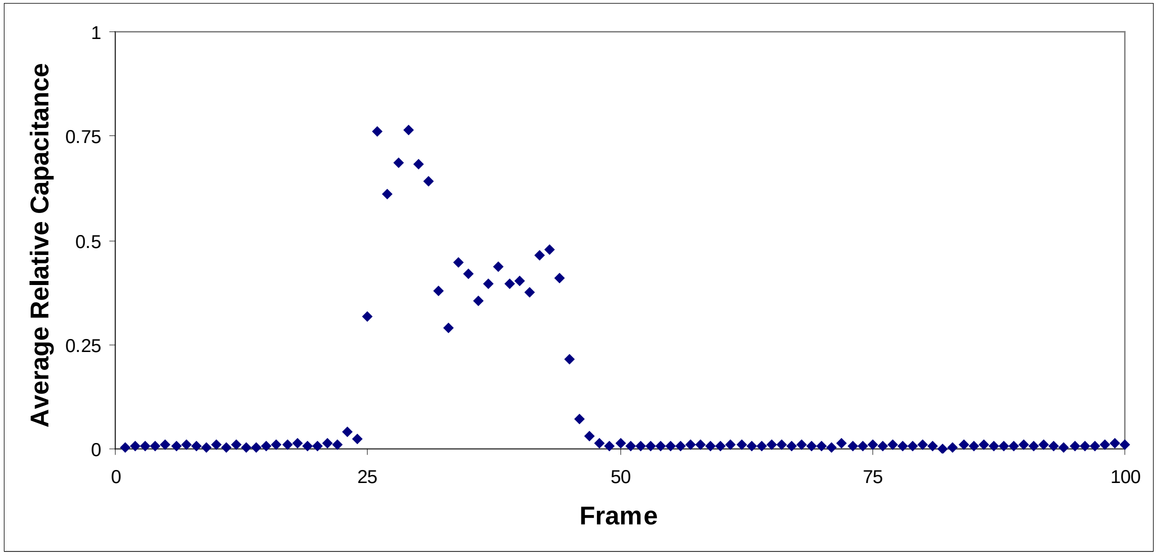
Ignition



Stable Flame



Shut Down



Concluding Remarks

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

- ECVT is a unique imaging technology with its potential for commercial scale-up, combustions imaging, and hot unit applications.

- Tech4Imaging LLC has developed a commercial ECVT system for imaging multi-phase flow systems in various conditions.

Acknowledgement

- The support of US. Department of Energy is gratefully acknowledged.
- The contribution of Professor L.S. Fan and his research group are also acknowledged.

Questions

4 TECH IMAGING