Electrical Capacitance Volume Tomography for the Packed Bed Reactor ISS Flight Experiment

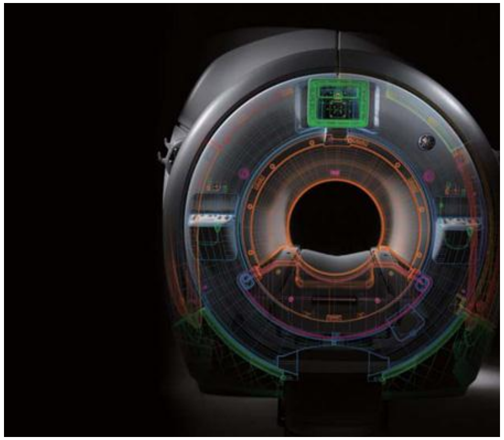
[1]Qussai Marashdeh, [2]Brian Motil, [3]Aining Wang, and [3]Liang-Shih Fan

[1]Tech4Imaging LLC,
[2]NASA Glenn Research Center
[3]The Ohio State University

Introduction

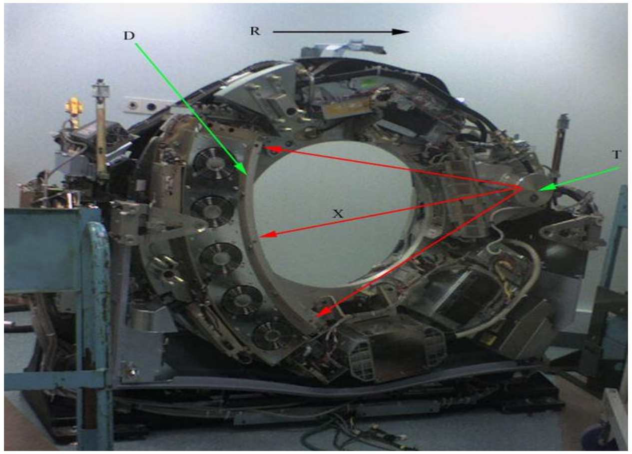
- Electrical Capacitance Volume Tomography (ECVT) is a 3D imaging technique for viewing cold flow processes. It can be applied to hot units too.
- ECVT is among the few known non-invasive fluid imaging tools that can be used for Space applications (Features: low cost, suitable for different applications, fast, and safe)
- Tech4Imaging LLC is a technology company acclaimed for the development and commercialization of ECVT.
- Tech4Imaging has a complete system of acquisition hardware, sensors, and reconstruction software for imaging multiphase flow systems (fluidized beds, trickle beds, slurry columns, flow through porous media, etc.).

Process Tomography

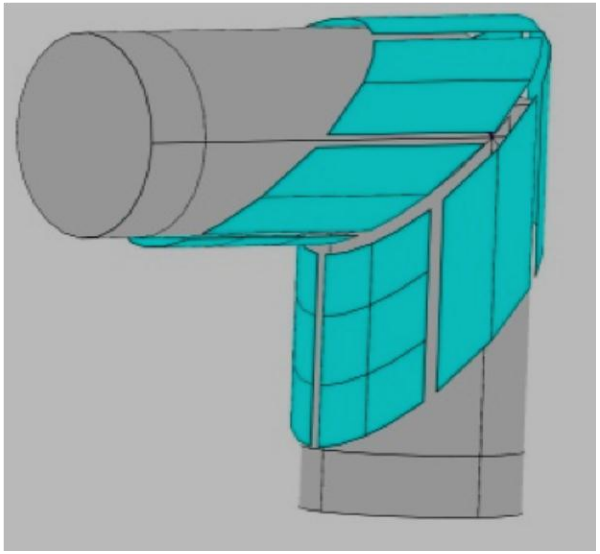


MRI

PET



X-ray



Electrical Capacitance
Volume tomography
System

Advantages of ECVT for Space Applications

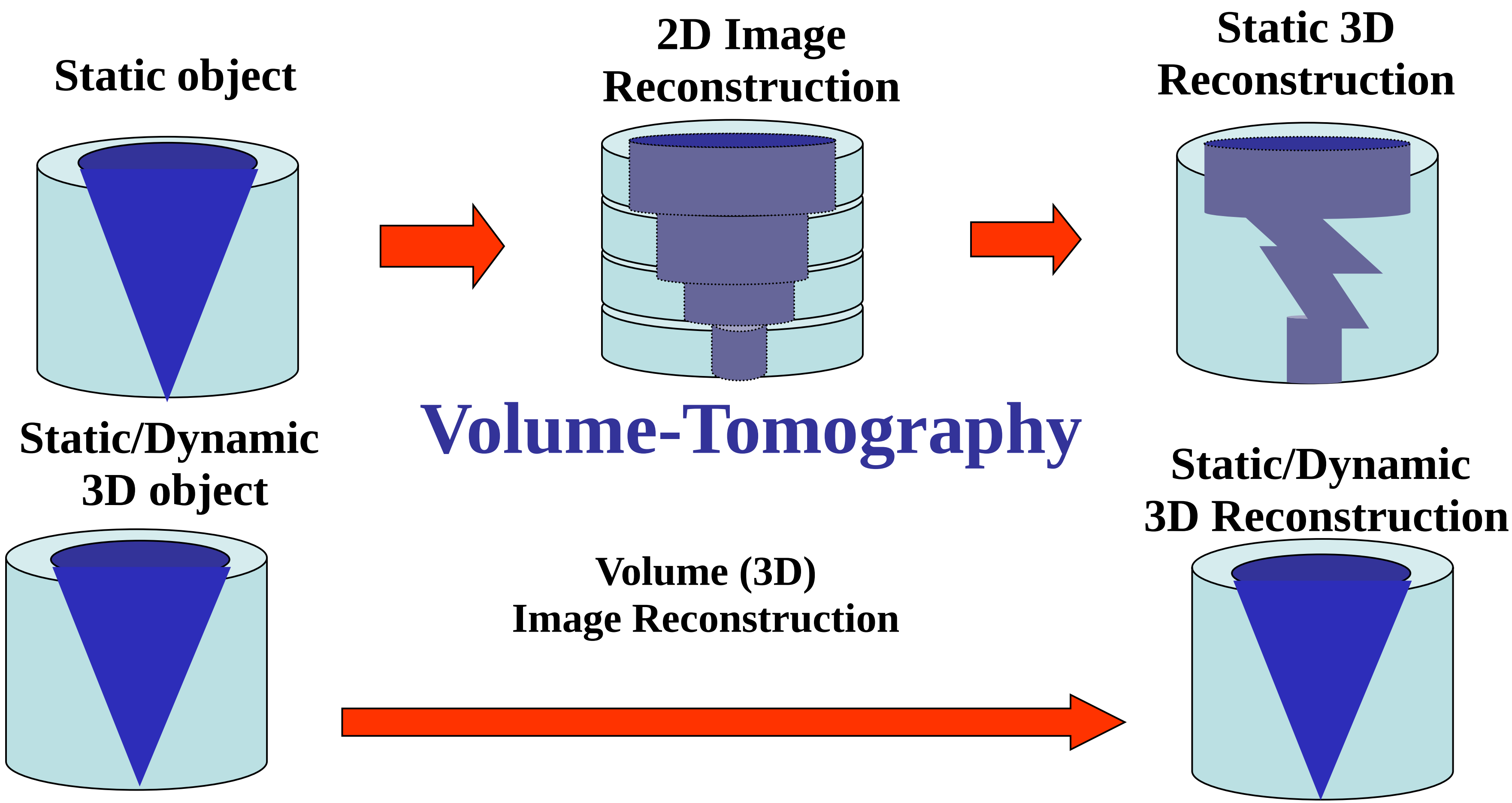
- **Safety**: To user and to process (no radiation)
- **Cost**: Low fixed and variable cost
- **Complexity**: Easy to operate
- **Speed**: Up to 800 frames (images) per second
- **Flexibility**: Applicable to vessel with various sizes and shapes
- **Resolution**: ECVT resolution is a percentage of imaged volume (i.e. sensors are scalable)
- **Size**: The whole system is portable!
- **Low power**: Requires less than 50W to operate (can be as low as 10 w)

Preface

1. ECVT Technology
2. PBRE & ECVT
3. Gas-Liquid Example
4. Complex Geometries
5. Resolution & Number of Channels

Volume Tomography Concept

Conventional Tomography

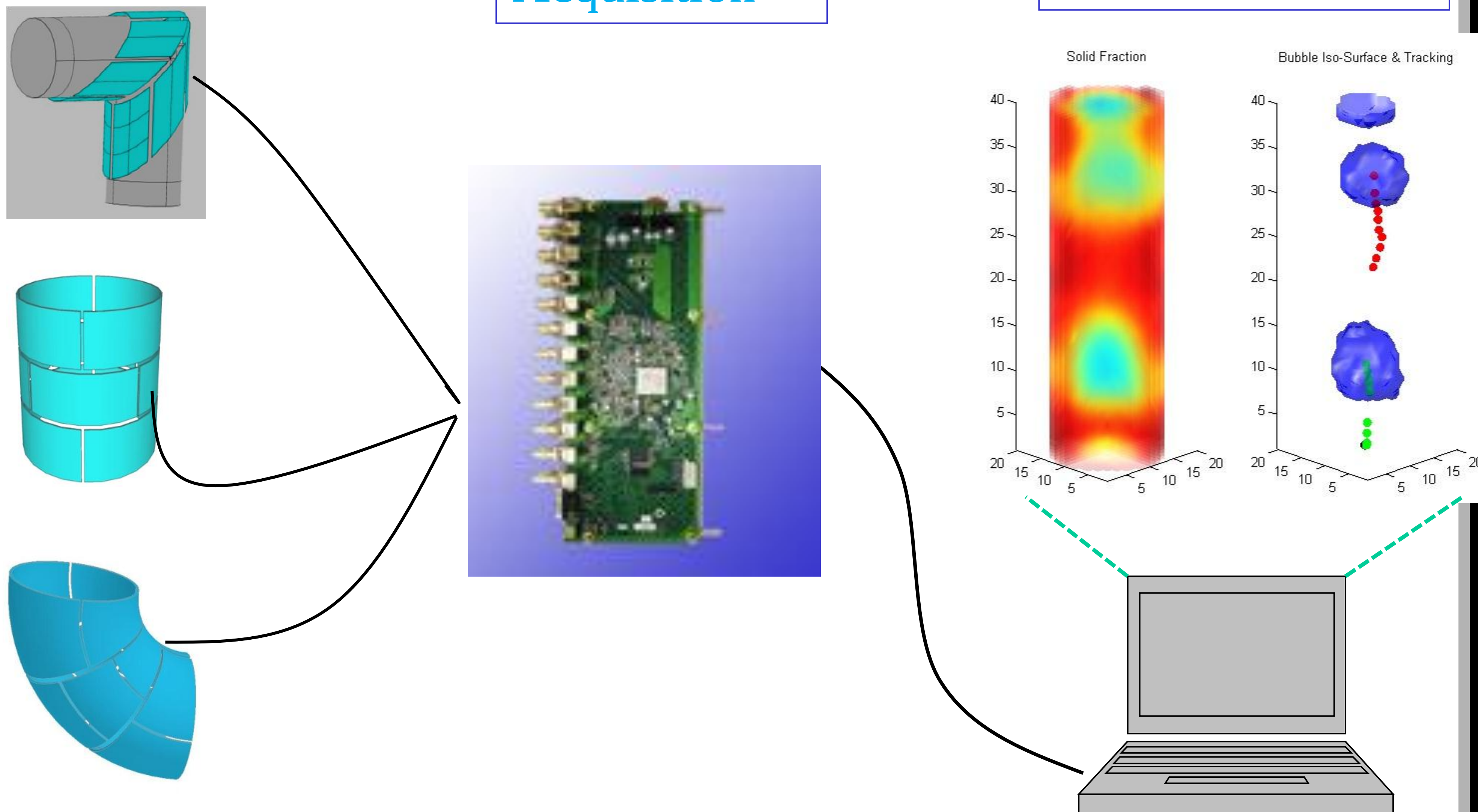


Complete ECVT System

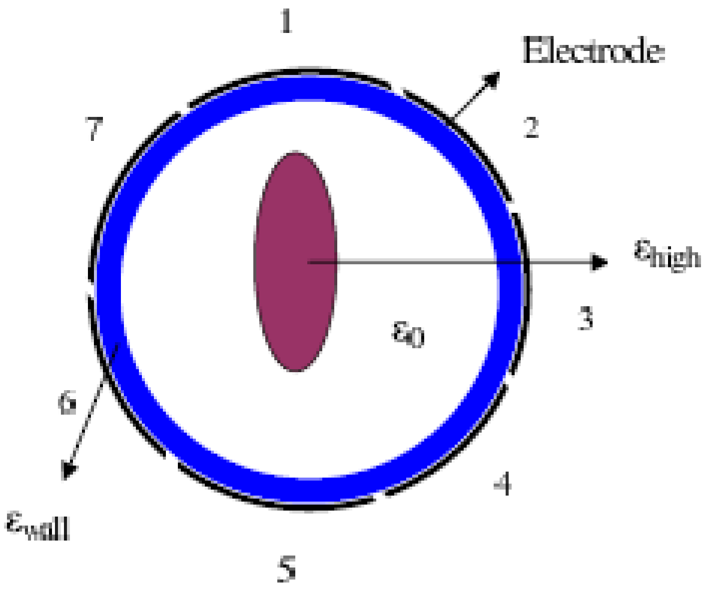
Sensors

Data Acquisition

Reconstruction& Viewing



Capacitance Tomography Problem & Basic Equations



Electric Field Distribution is a function of Dielectric media distribution and boundary conditions

$$\nabla \cdot (\varepsilon(x,y)\nabla\phi(x,y)) = -\rho(x,y),$$

Measured capacitance is related to charge on sensor plates

$$C_{ij} = \frac{Q_j}{\triangle V_{ij}},$$

Charge is an integration of electric field and Dielectric media distributions

$$Q_j = \oint_{\Gamma_j} \epsilon(x,y)\nabla\phi(x,y) \cdot \hat{n} dl,$$

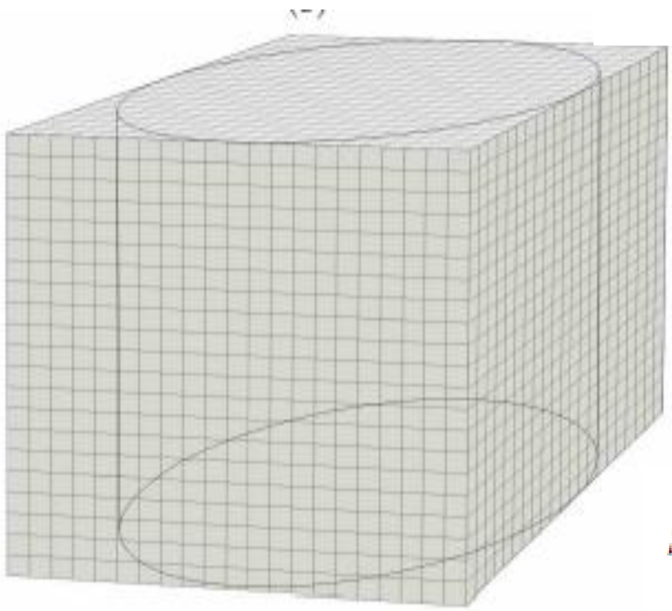
Capacitance is also an integration of electric field and Dielectric media distributions

$$C_{ij} = \frac{1}{\triangle V_{ij}} \oint_{\Gamma j} \epsilon(x,y)\nabla\phi(x,y) \cdot \hat{n} dl,$$

Capacitance Tomography Inverse Problem

In ECT, the main equation to be solved is Poisson equation

$$\nabla \cdot (\varepsilon(x,y,z)\nabla V(x,y,z)) = -\rho(x,y,z),$$



(c)

To solve for Dielectric media distribution, a map (Sensitivity Matrix) for capacitance change as a function of perturbations in

$$S_{ij}(x_k,y_k,z_k) = \int_{V_0} \frac{E_i(x,y,z)E_j(x,y,z)}{V_iV_j} dxdydz \nabla\phi(x,y,z)dA,$$

Sensitivity Matrix is a linearization of capacitance sensor response to simplify inverse solutions .

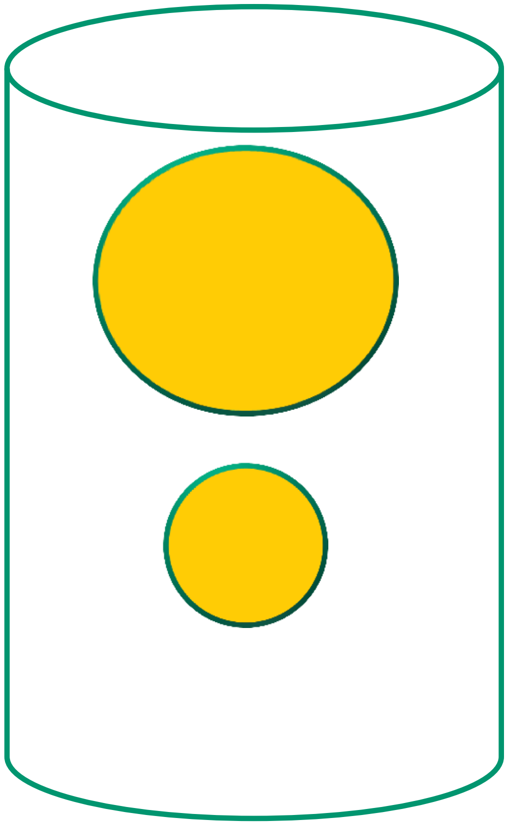
$$S_{ij} = \frac{C_{ij} - C_{ij}^l}{C_{ij}^h - C_{ij}^l}$$

ECVT Reconstruction

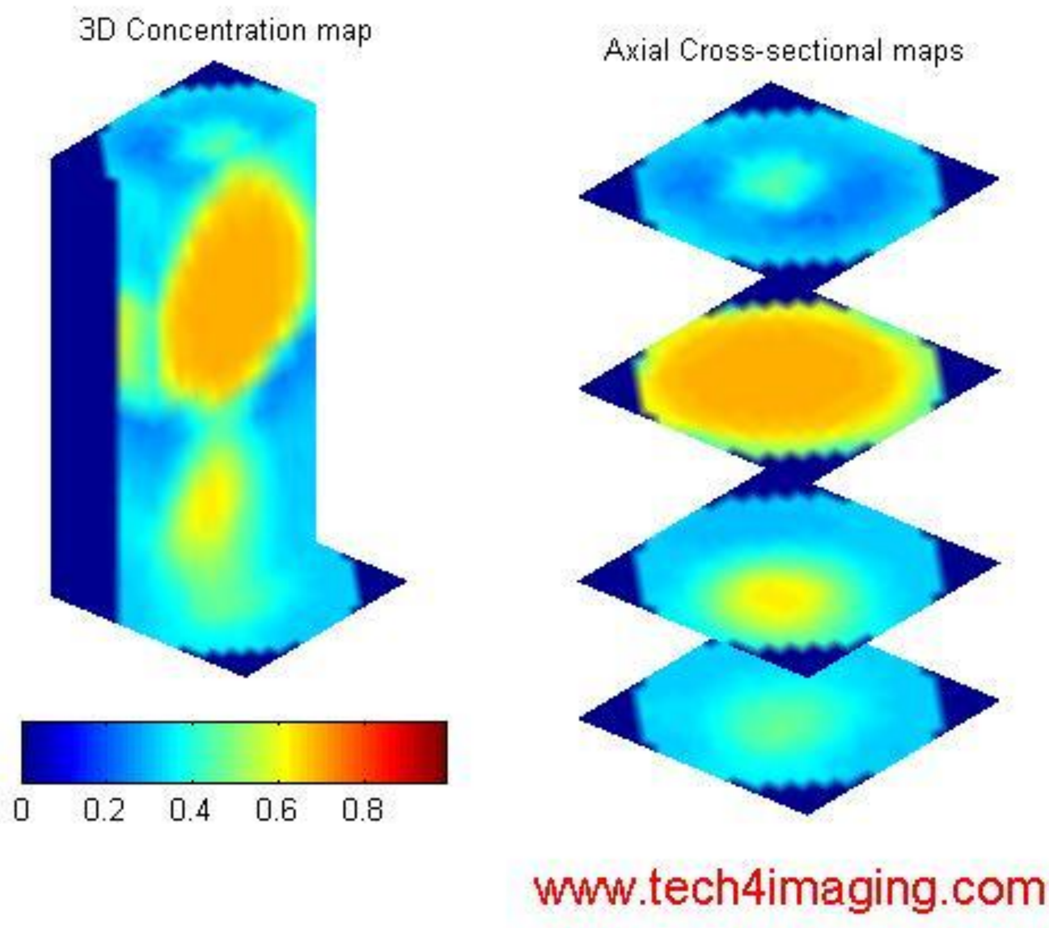
Reconstruction	Methodology	Characteristics	Example
Single Step Linear Back Projection	The sensor system is linearized (usually by constructing a sensitivity matrix). The image is obtained by back projecting the capacitance vector using the sensitivity matrix.	Fast, low image resolution, and introducing image artifacts	LBP $C=SG$, $G=S^{T}C$
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 $G^{K+1}=S^{T}C-\alpha(SG^{K} - C)$
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



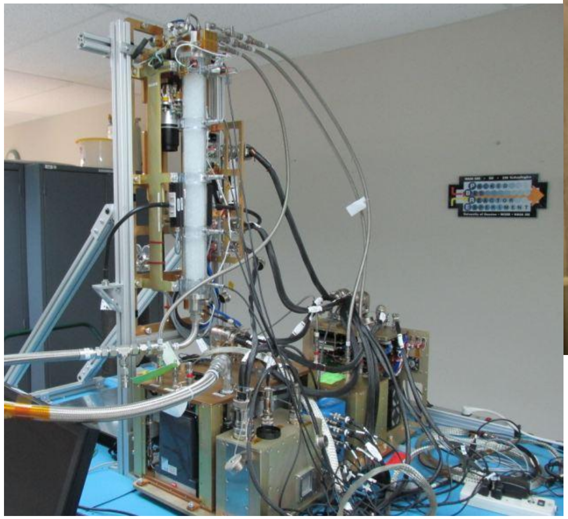
ECVT Imaging

PBRE & ECVT

Packed Bed Reactor Experiment (PBRE) – launching on SPACEX-8 (6/2015)

- Will investigate the role and effects of gravity on gas-liquid flow through porous media - a critical component in life-support; thermal control devices; and fuel cells.
- Will validate and improve design and operational guidelines for gas-liquid reactors in partial and microgravity conditions.
- Preliminary models predict significantly improved reaction rates in 0-g.
- Testing spans two orders of magnitude of Liquid and Gas Re.
- Includes identification of min. liquid flows to expel gas and hysteresis studies.
- 3 mm packing – 2 types of packing (wetting and non-wetting).

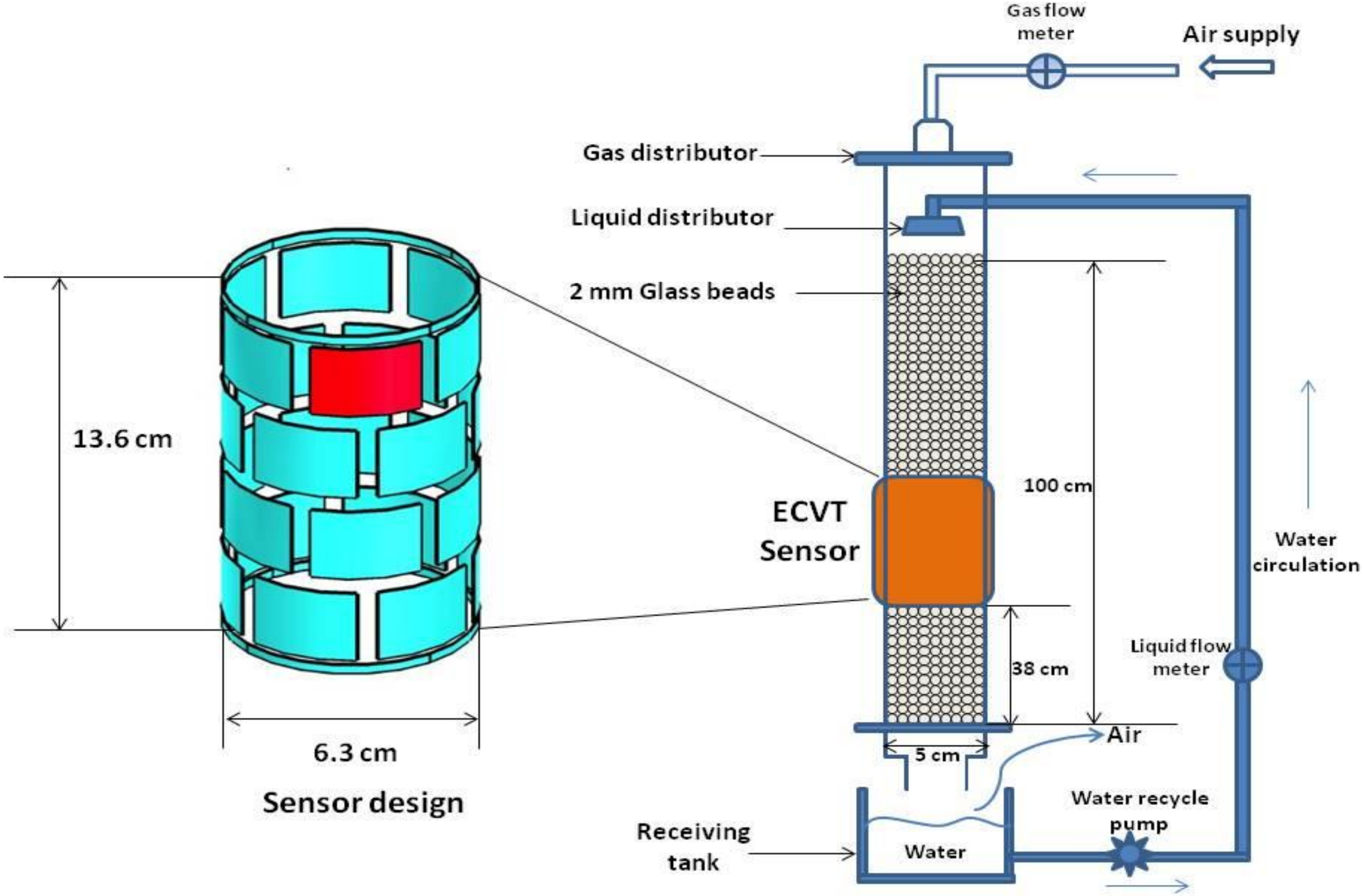
Volatile Reactor Assembly (VRA) on STS 89



PBRE Engineering Unit

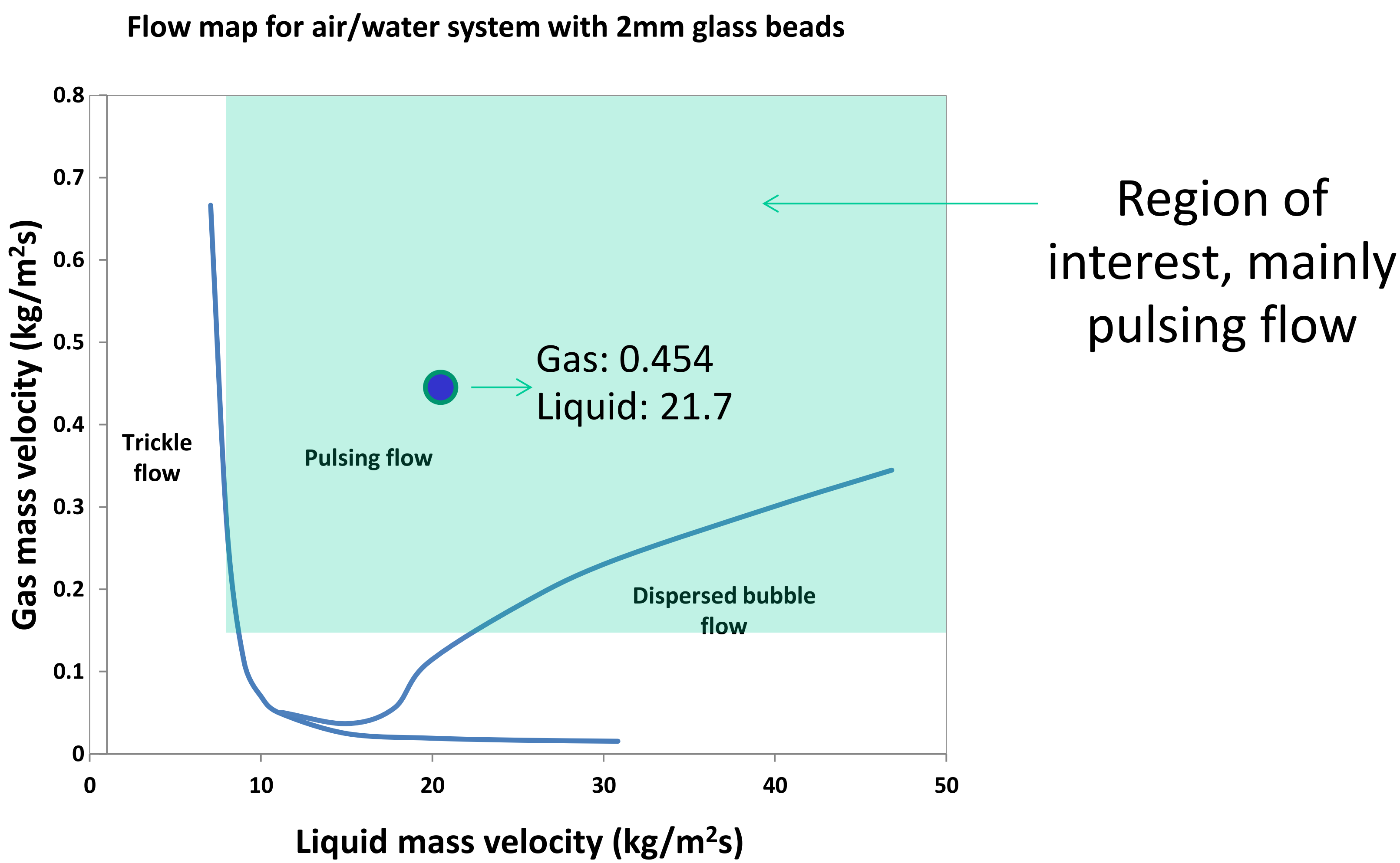
Biological Reactors

ECVT PBRE Experimental setup



Liquid: water
Gas: air
Particles: 2 mm diameter glass beads

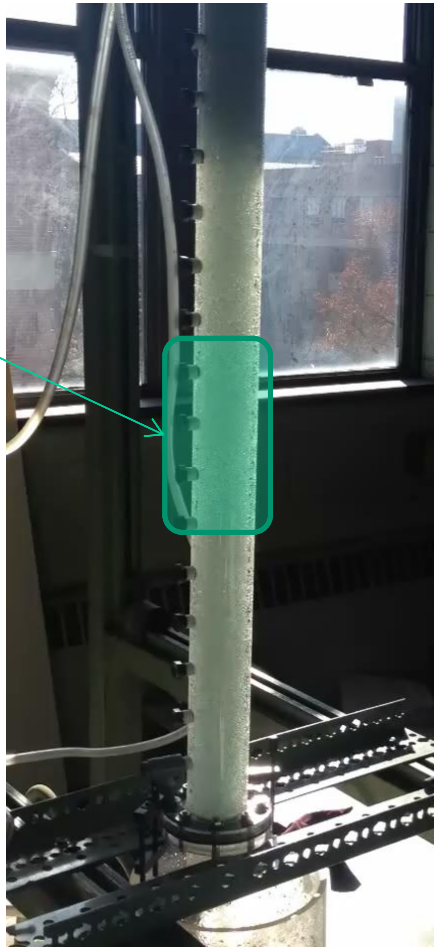
Flow regime map

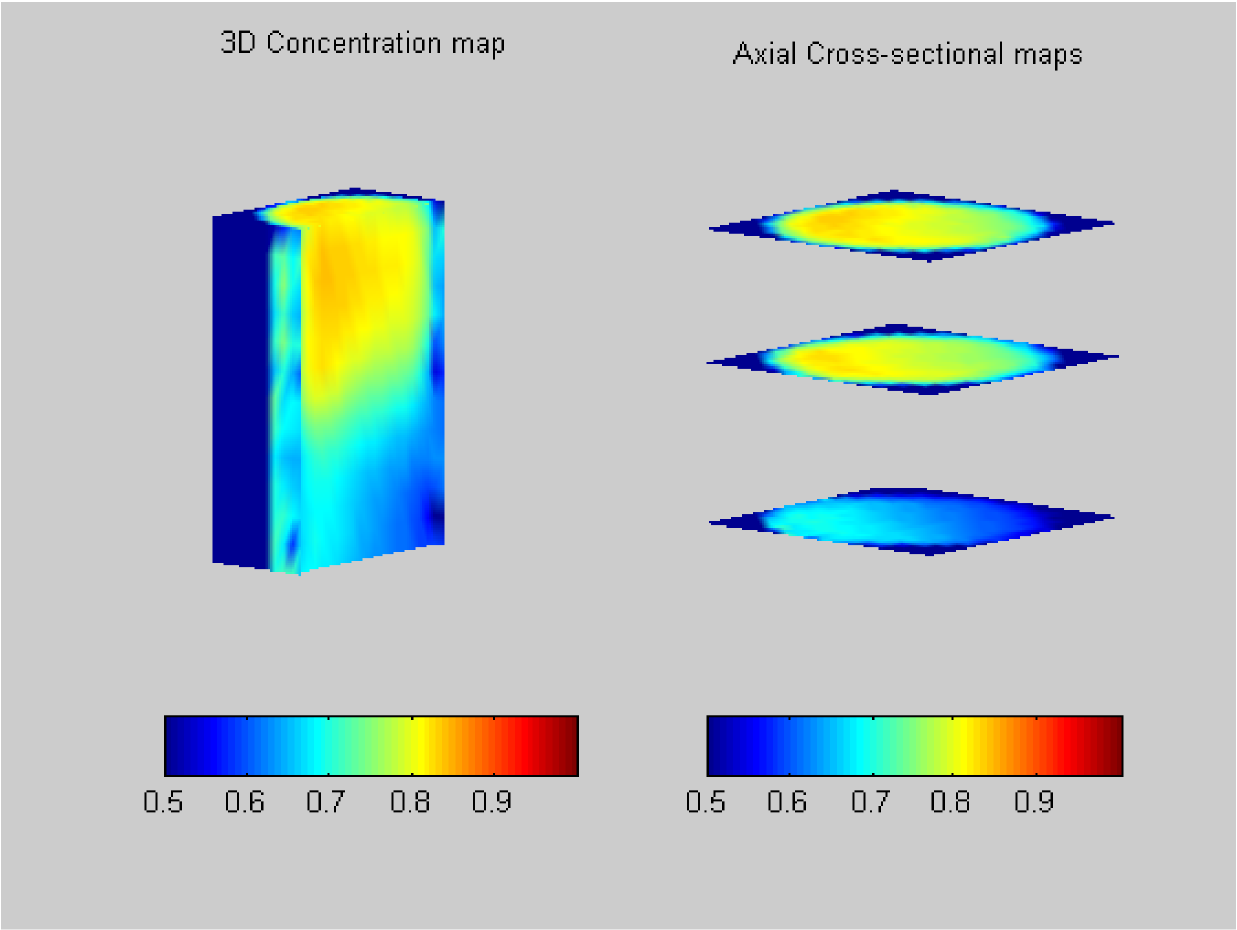


From Guray Tosun's paper

Videos for pulsing flow
(G: 0.454 kg/m^{2}s, L:21.7 kg/m^{2}s)

CVT Sensor location

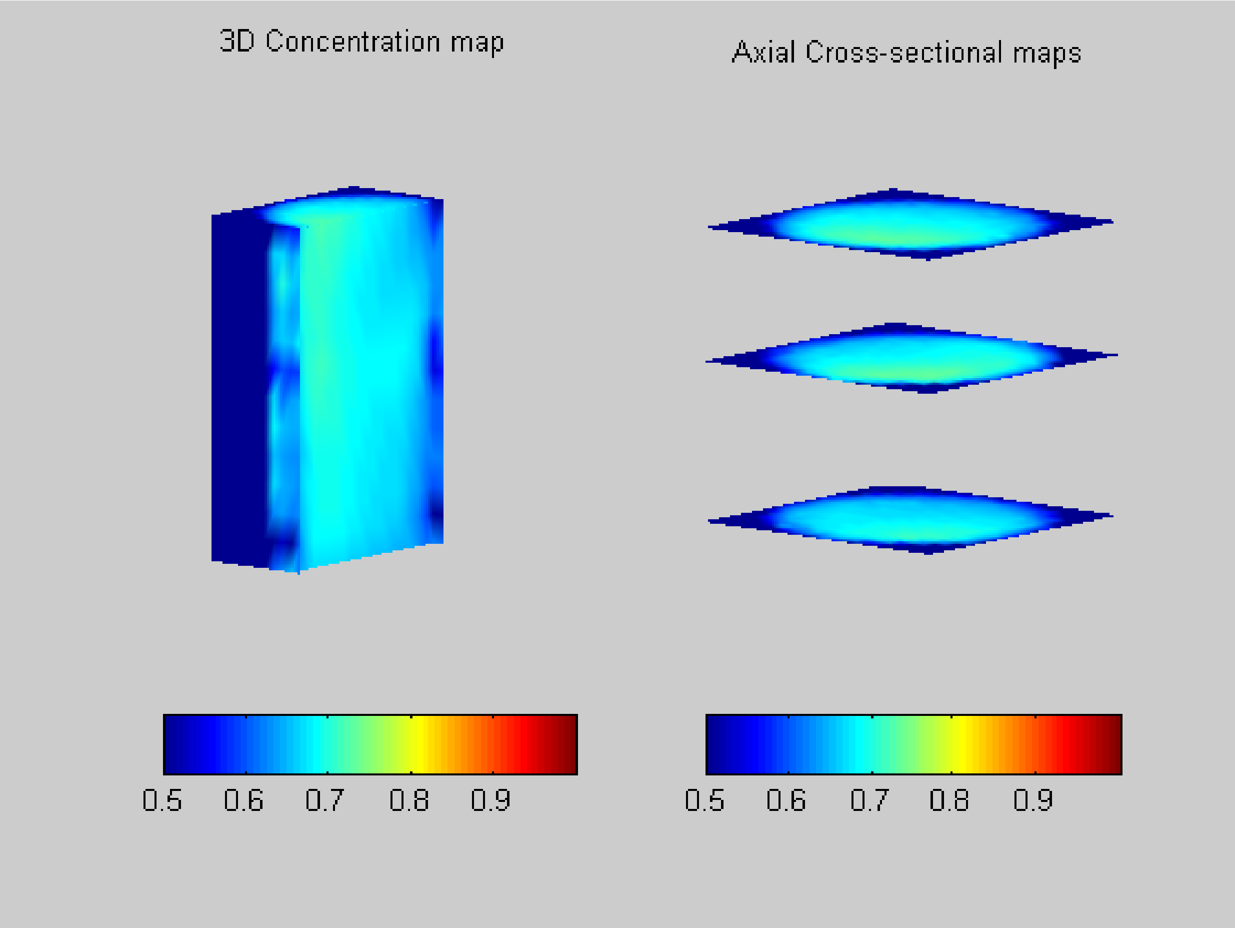




Original video in normal speed

ECVT reconstructed video in normal speed (50fps)

Slow motion (0.1X of original speed, 5fps)
(G: 0.454 kg/m^{2}s, L:21.7 kg/m^{2}s)



Observations:

1.

The pulse & interval lengths are not the same, not in a stable status.

2.

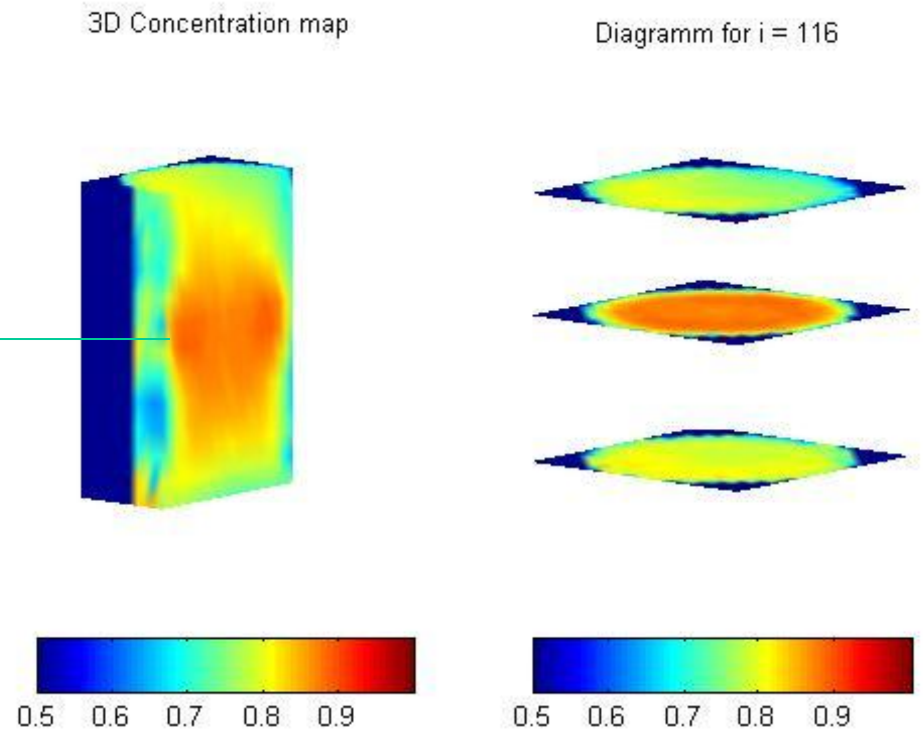
Pulse: Liquid rich region with some gas

Interval: Liquid scare region with lot of gas

Pulse shape

Under mild flow rate, the pulse is basically symmetric along the length, and does not change too much among the cross-section.

Lengthily Symmetric

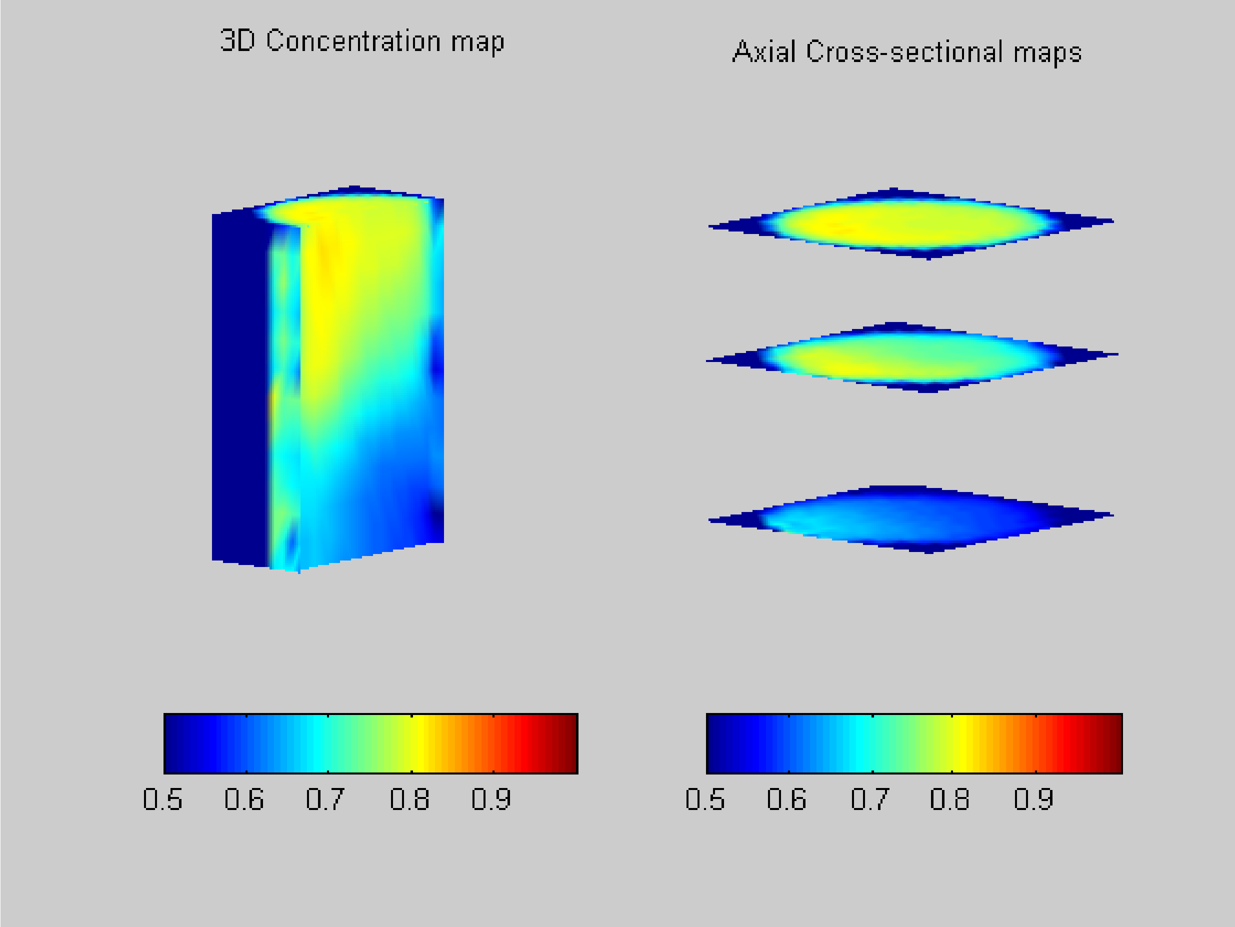


Horizontally uniform

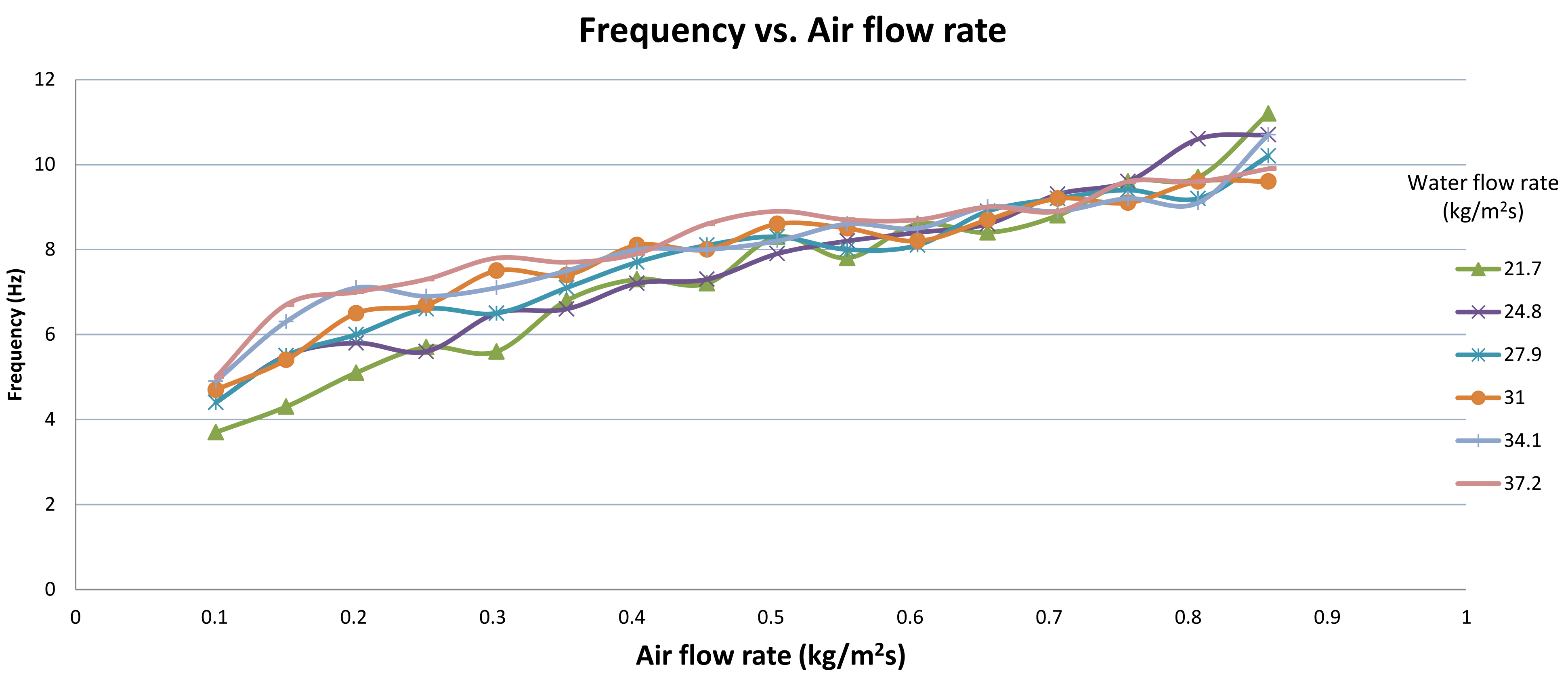
Snap shot of a mild pulse (G: 0.252 kg/m^{2}s, L:24.8 kg/m^{2}s)

Pulse shape

Under high flow rate, the pulse is no longer symmetric along the length, has a 'tail' with gradual holdup reduction.

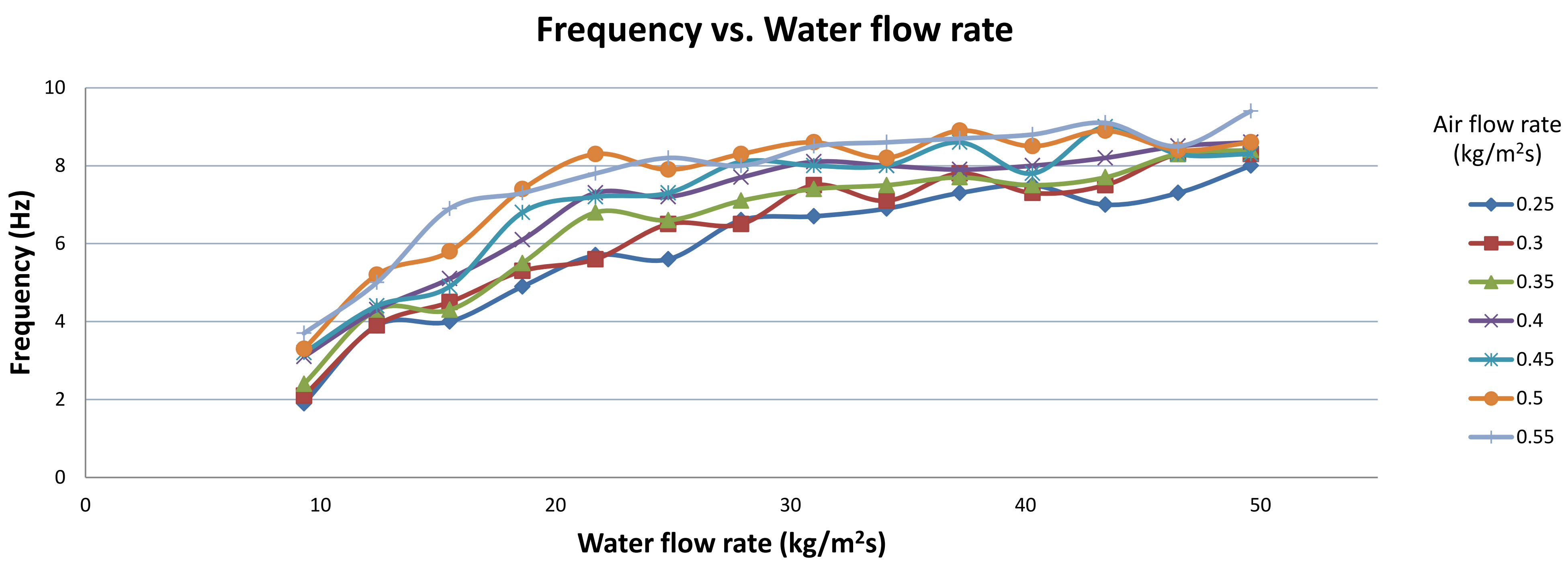


Pulse frequency



Pulse frequency increases linearly with air flow rate.

Pulse frequency



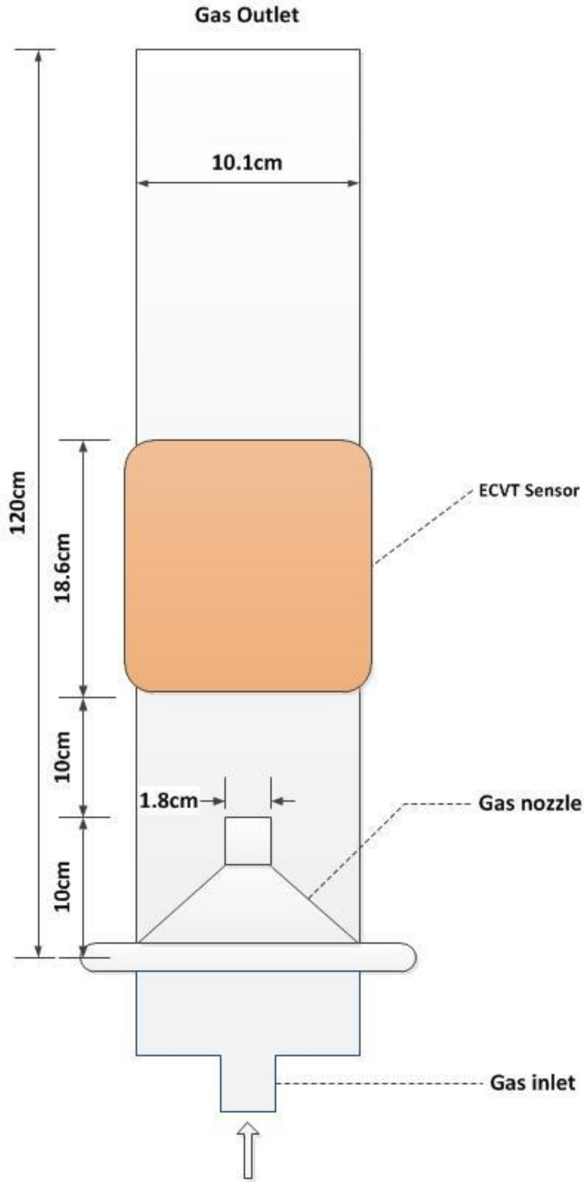
Frequency increases with liquid flow rate initially , and then keeps stable.

Gas-Liquid System

Example : Spiral motion in bubble column

- A bubble column reactor is characterized by its simple construction and a complex flow structure.
- It is widely known that there is a spiral flow regime under moderately high gas flow rate using orifice/nozzle distributor.
- In this regime, bubble clusters can form the central bubble stream moving in a spiral manner.

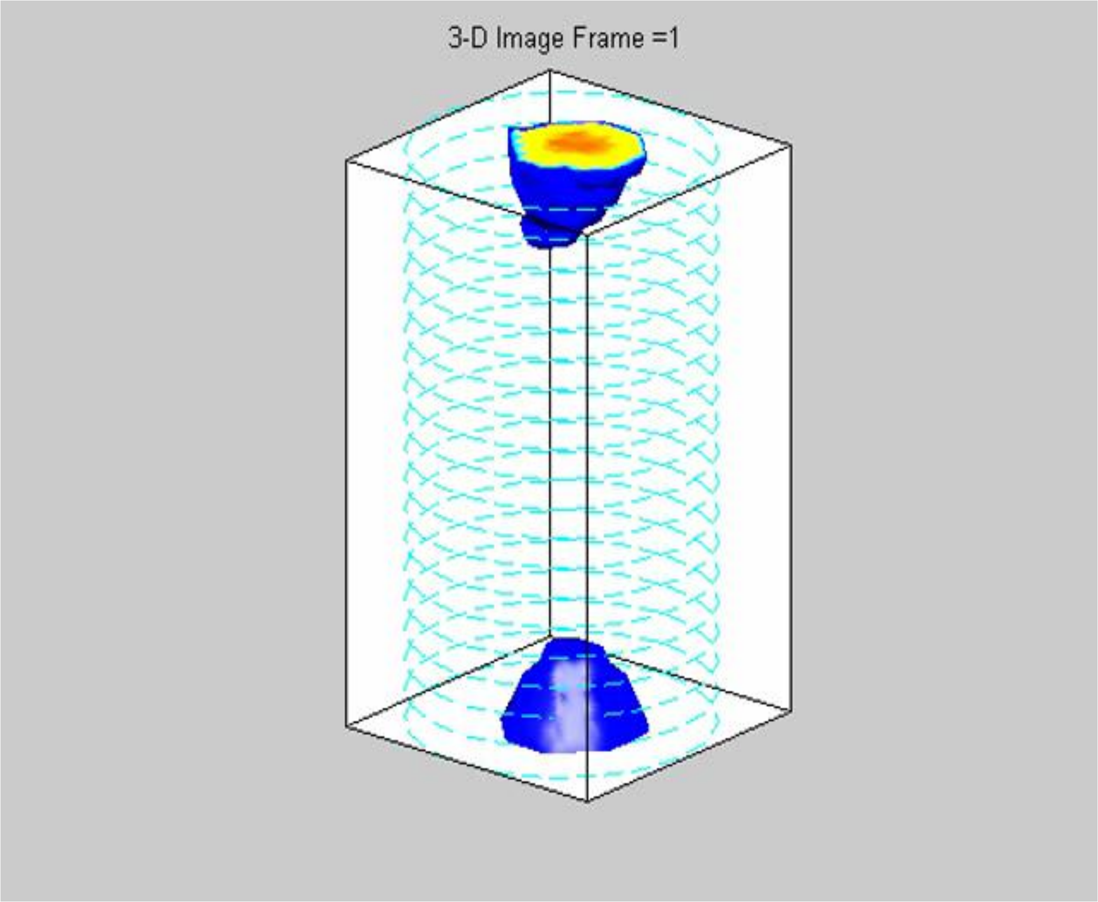
Experimental setup



Gas: Air
Liquid: Mineral spirits

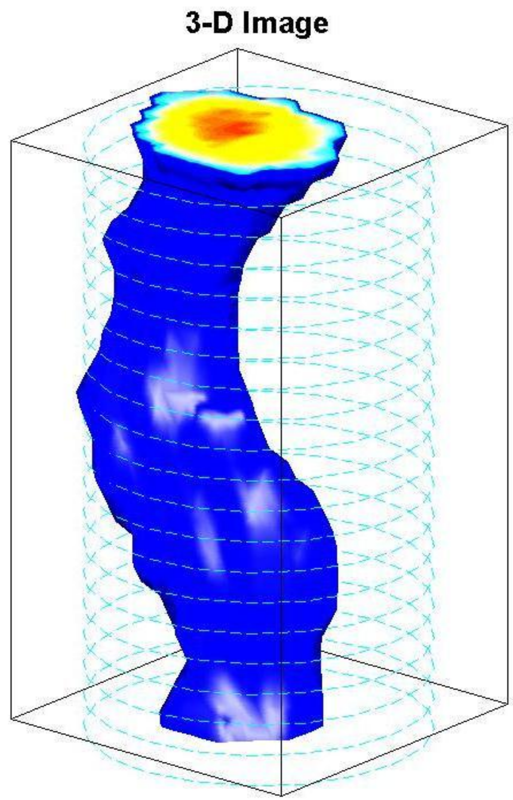
Mineral spirits:
1.Non-conductive
2.Good fluidity
3.Lower relative dielectric constant
compared to water
4. Safe to human and the environment

Movies from camera and ECVT

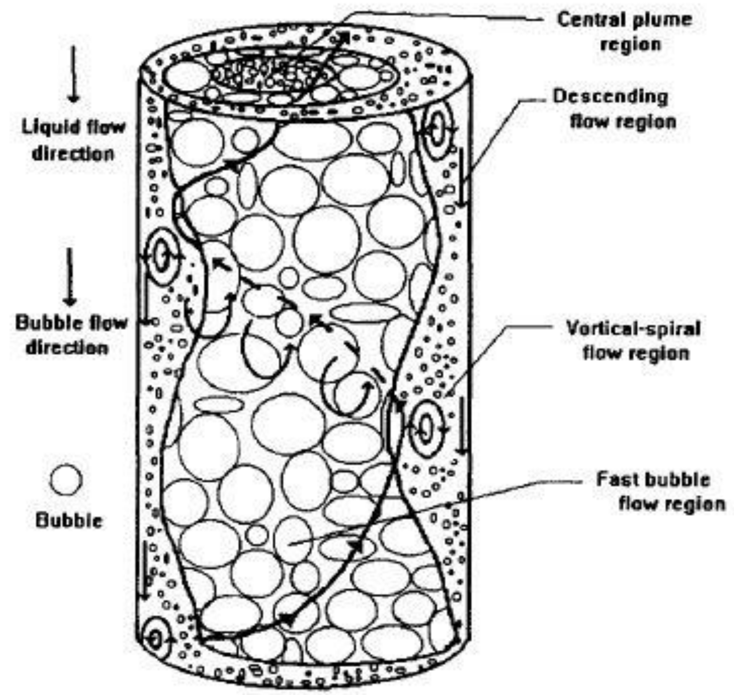


Superficial gas velocity : 0.07 m/s

Spiral motion

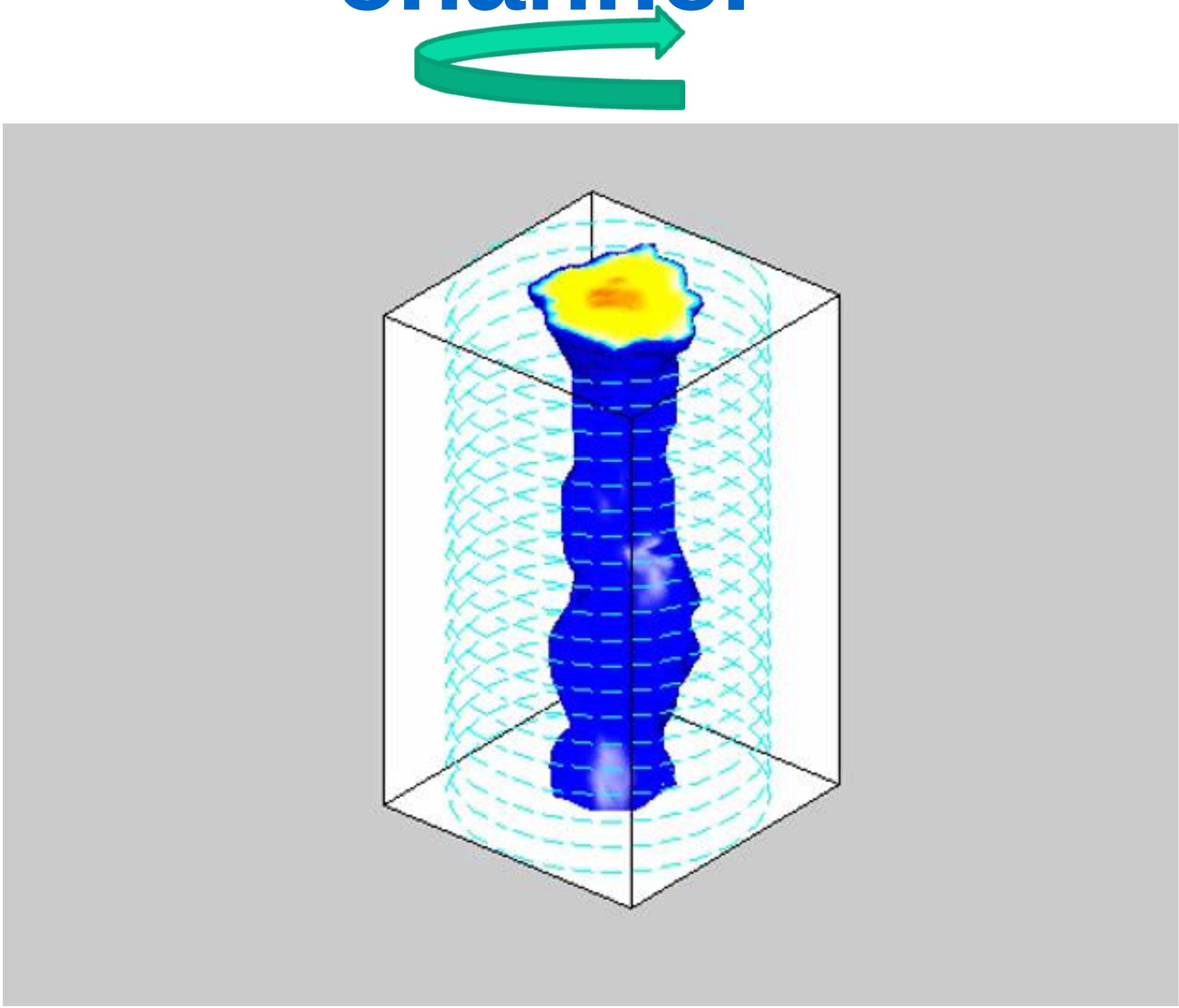


ECVT Experiment: A typical spiral locus for a bubble cluster (gas: 0.06m/s)



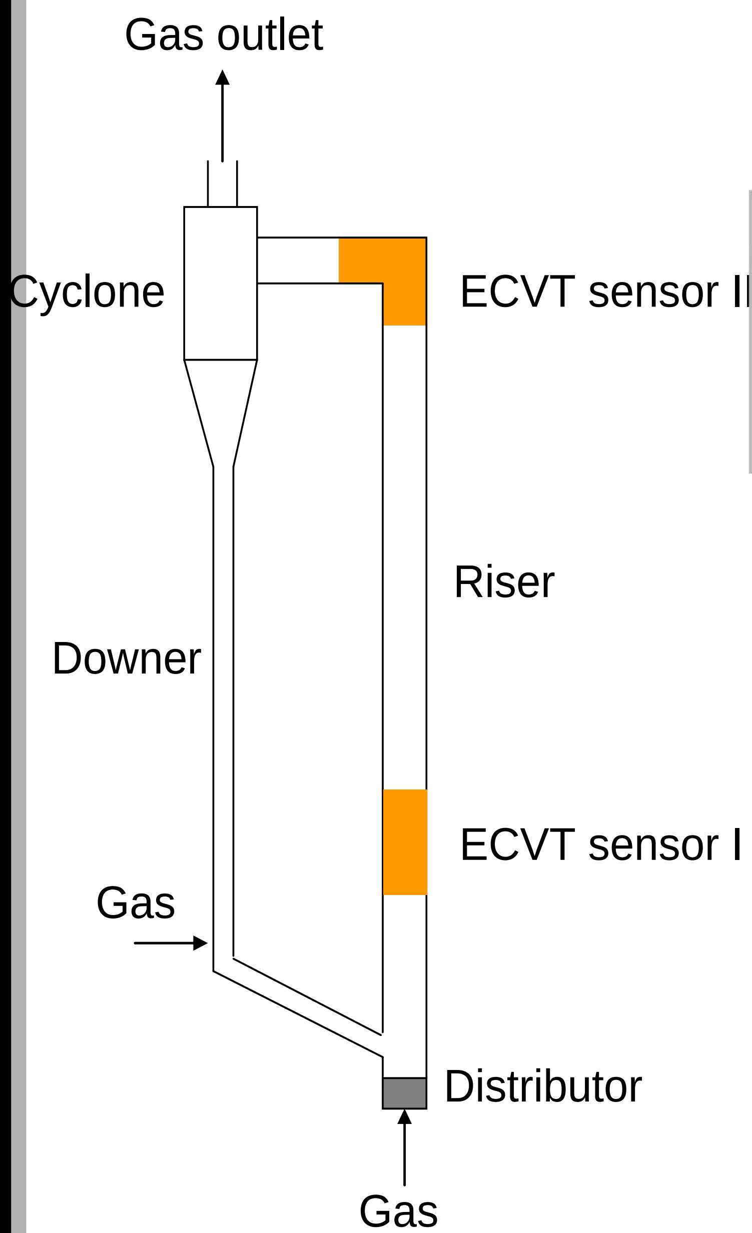
Model: Flow structure in a 3-D gas-liquid bubble column (Chen RC, 1994)

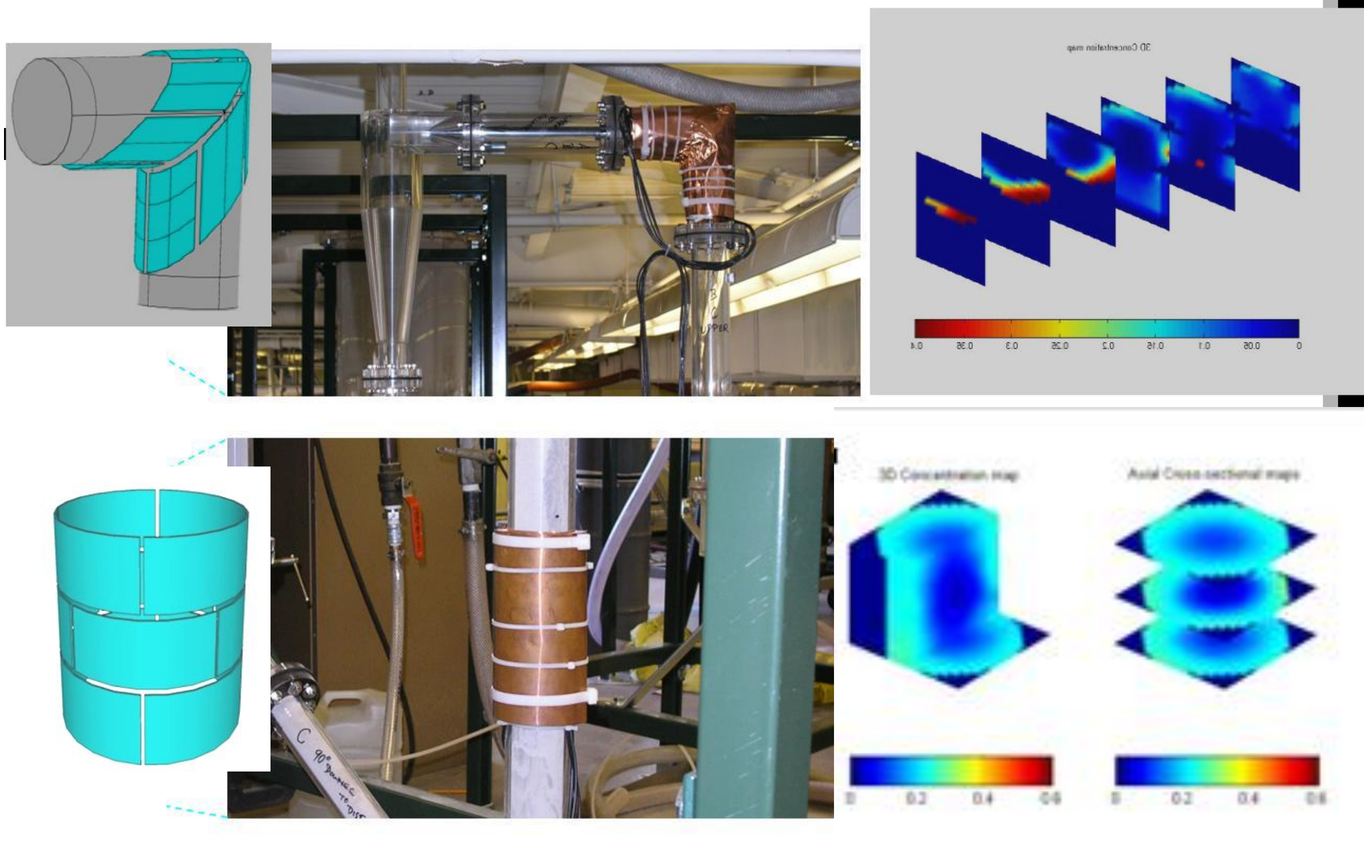
Rotation of the bubble rising channel



Complex Geometries

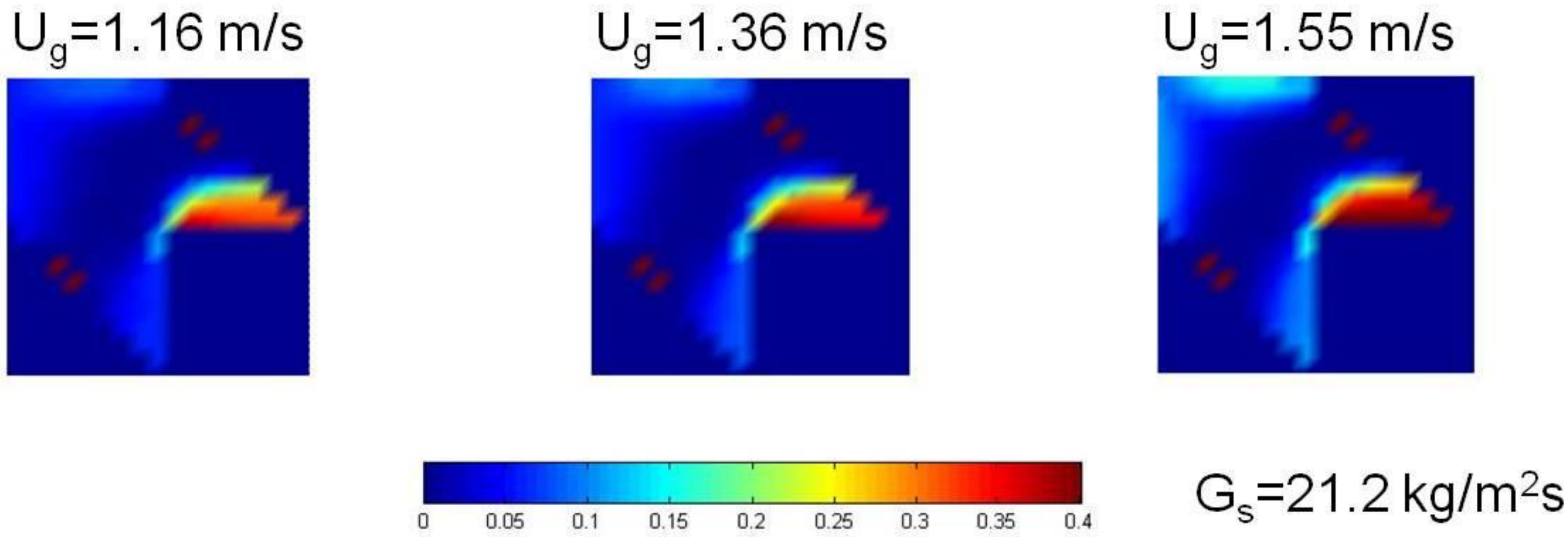
90 Degrees Bend & Riser



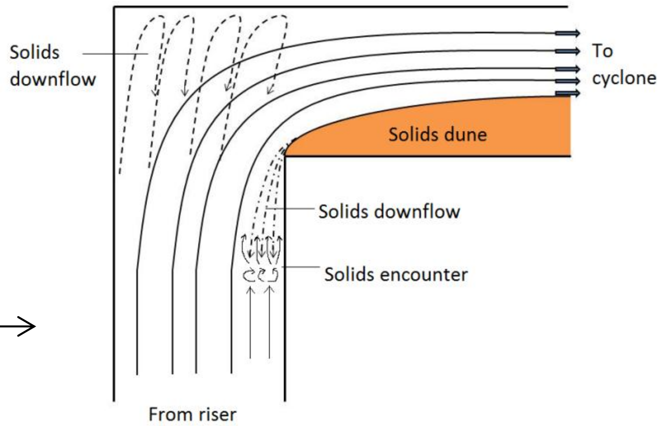


Courtesy of: The Ohio State University

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

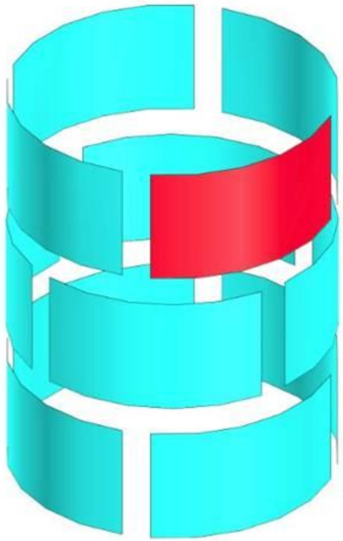


Gas and solids flows in a 90-degree bend (from Harris et al., 2003).

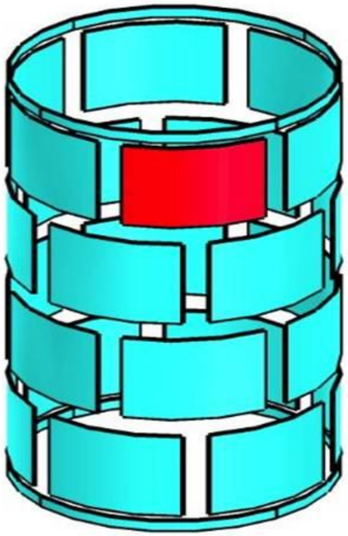


Resolution & Number of Channels

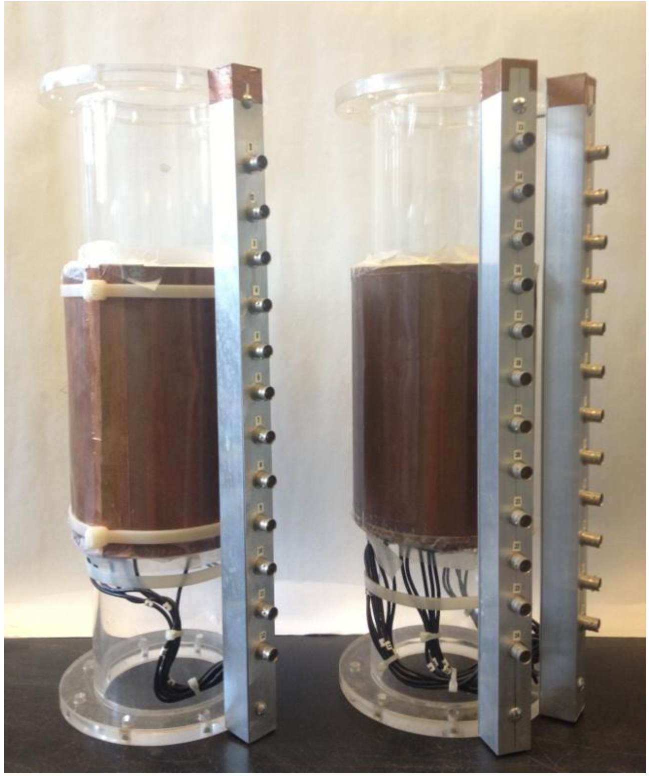
Sensors & Number of Channels



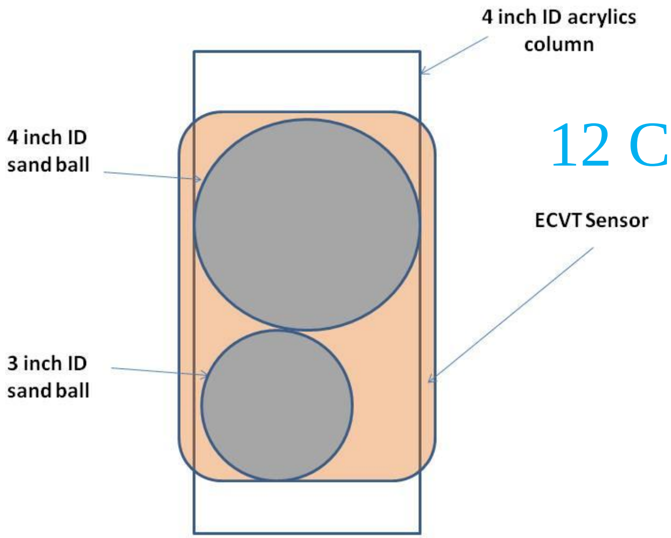
12 channel Sensor



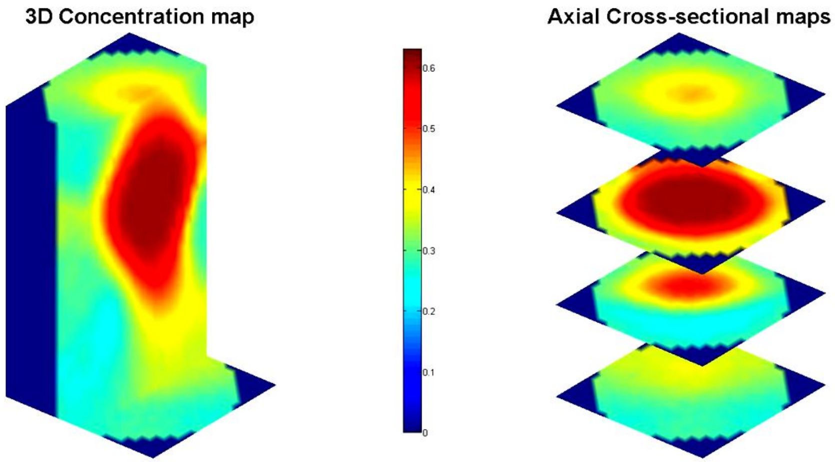
24 channel Sensor



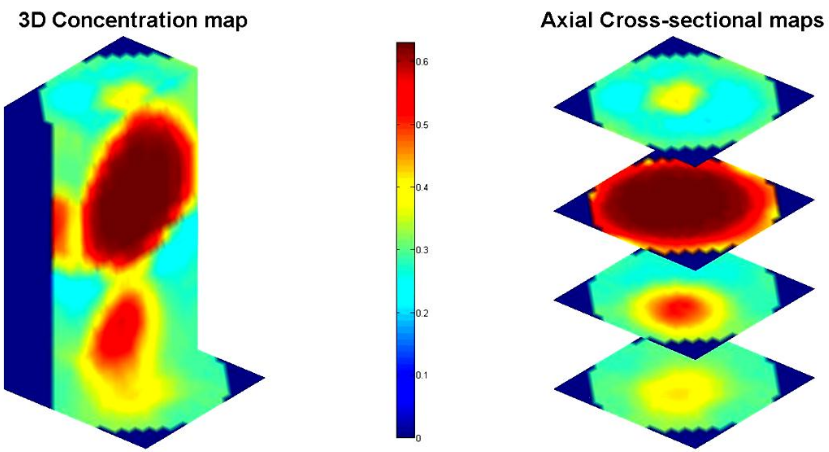
Two Static Objects



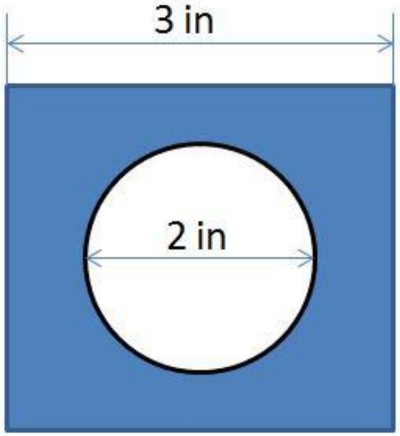
12 Channels

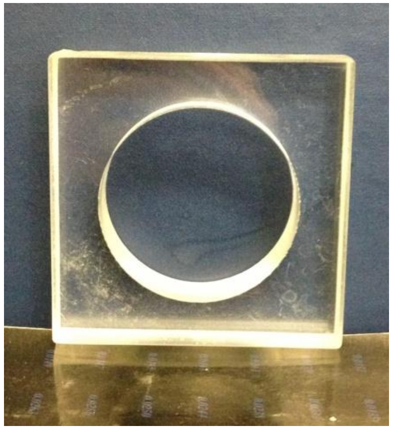


24 Channels



Complex Shaped Object





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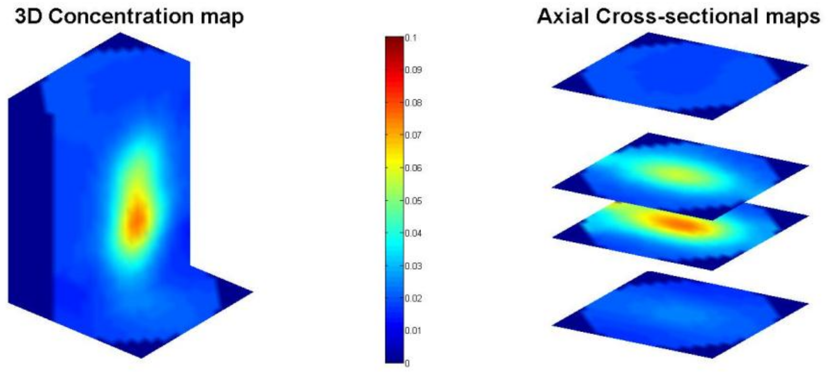
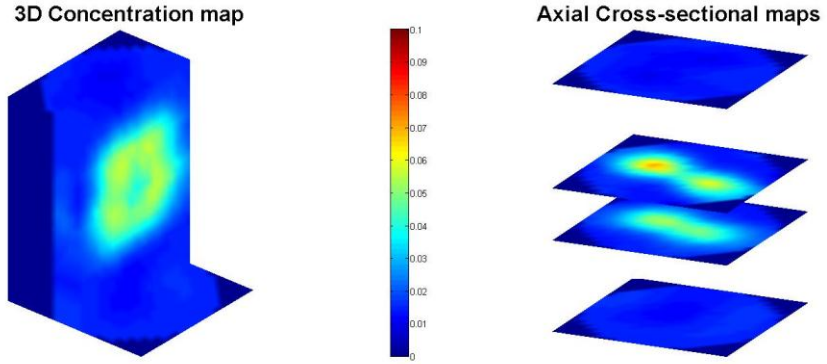


24 Channels



Concluding Remarks

- ECVT is a non-invasive imaging technology that can be applied to image Multiphase Flow systems (Fluidized Beds, Bubble Columns, Trickle Beds, etc) with vessels of various diameters and shapes.
- ECVT is a unique imaging technology with its potential for space applications.
- Tech4Imaging has developed a commercial ECVT system for imaging multi-phase flow systems at zero gravity conditions.

Questions

TECH 4 IMAGING

NASA GRC ⋆ ISS ⋆ ZIN Technologies

PACKED BED REACTOR EXPERIMENT

University of Houston ⋆ NCSER ⋆ NASA JSC