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

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

1Tech4Imaging LLC, 2NASA Glenn Research Center 3The 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

Static object

Static/Dynamic 3D object

2D Image Reconstruction

Volume (3D) Image Reconstruction

Static 3D Reconstruction
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

\[ C_{ij} = \frac{Q_j}{\Delta V_{ij}}, \]

Charge is an integration of electric field and Dielectric media distributions

\[ Q_j = \oint_{\Gamma_j} \varepsilon(x, y) \nabla \phi(x, y) \cdot \hat{n} dl, \]

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

\[ C_{ij} = \frac{1}{\Delta V_{ij}} \oint_{\Gamma_j} \varepsilon(x, y) \nabla \phi(x, y) \cdot \hat{n} dl, \]
Capacitance Tomography Inverse Problem

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

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

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

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

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

$$S_{ij} = \frac{C_{ij} - C^l_{ij}}{C^h_{ij} - C^l_{ij}}$$
<table>
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<th>Reconstruction</th>
<th>Methodology</th>
<th>Characteristics</th>
<th>Example</th>
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<tr>
<td>Single Step Linear Back Projection</td>
<td>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.</td>
<td>Fast, low image resolution, and introducing image artifacts</td>
<td>LBP</td>
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<td>C=SG, G=STC</td>
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<tr>
<td>Iterative Linear Back Projection</td>
<td>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.</td>
<td>Slower than Single Step Linear. Providing better images than Single Step Linear</td>
<td>Landweber ILBP</td>
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<td>G^{K+1} = STC - \alpha (SG^K - C)</td>
</tr>
<tr>
<td>Optimization</td>
<td>A set of objective functions are minimized iteratively to provide the most likely image. Different optimization algorithms and objective functions can be used.</td>
<td>Slower than Iterative Linear Back Projection. Providing better images than Iterative Linear Back Projection</td>
<td>3D-NNMOIRT</td>
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Shape & Edge Detection

Experimental Results

Location Inside Sensor

ECVT Imaging

www.tech4imaging.com
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

Flow map for air/water system with 2mm glass beads

Region of interest, mainly pulsing flow

From Guray Tosun’s paper
Videos for pulsing flow

\[(G: 0.454 \text{ kg/m}^2\text{s}, L:21.7 \text{ kg/m}^2\text{s})\]

Original video in normal speed

ECVT reconstructed video in normal speed (50fps)

3D Concentration map

Axial Cross-sectional maps
Slow motion (0.1X of original speed, 5fps)  
(G: 0.454 kg/m²s, L:21.7 kg/m²s)

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.

Snap shot of a mild pulse (G: 0.252 kg/m²s, L:24.8 kg/m²s)
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.

Frequency vs. Air flow rate

Water flow rate

Air flow rate (kg/m$^2$s)

Frequency (Hz)
Frequency increases with liquid flow rate initially, and then keeps stable.
Gas-Liquid System
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: 0.06 m/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

$U_g = 1.16 \text{ m/s}$  \hspace{2cm} $U_g = 1.36 \text{ m/s}$  \hspace{2cm} $U_g = 1.55 \text{ m/s}$

$G_s = 21.2 \text{ kg/m}^2\text{s}$

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

12 Channels

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