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

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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/Dynamic 3D object

2D Image Reconstruction

Volume (3D) Image Reconstruction

Static 3D Reconstruction

Volume-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

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

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.

$$S_{ij} = \frac{C_{ij} - C_{ij}^l}{C_{ij}^h - C_{ij}^l}$$
<table>
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<th>Reconstruction</th>
<th>Methodology</th>
<th>Characteristics</th>
<th>Example</th>
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<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 ( C = SG, ) ( G = S^T C )</td>
</tr>
<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 Back Projection</td>
<td>Landweber ILBP ( G^{K+1} = S^T C - \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>
</tr>
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Shape & Edge Detection

Experimental Results

Location Inside Sensor

ECVT Imaging

3D Concentration map

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
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

Gas: 0.454
Liquid: 21.7

Region of interest, mainly pulsing flow

From Guray Tosun’s paper
Videos for pulsing flow

(G: 0.454 kg/m²s, L:21.7 kg/m²s)

Original video in normal speed

ECVT reconstructed video in normal speed (50fps)

CVT Sensor location

3D Concentration map

Axial Cross-sectional maps
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 increases linearly with air flow rate.
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

Cyclone
- Gas outlet
- ECVT sensor II

Downer
- Gas

Riser
- ECVT sensor I

Distributor
- Gas

*Courtesy of: The Ohio State University*
3-D gas-solid flow patterns in the exit region of a gas-solid CFB riser

\[ U_g = 1.16 \text{ m/s} \quad U_g = 1.36 \text{ m/s} \quad U_g = 1.55 \text{ m/s} \]

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

\[ G_s = 21.2 \text{ kg/m}^2\text{s} \]
Resolution & Number of Channels
Sensors & Number of Channels

12 channel Sensor

24 channel Sensor
Two Static Objects

12 Channels

24 Channels
Complex Shaped Object

3 in

2 in

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