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Contents

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Modeling of Potential Distribution of Electrical Capacitance Tomography Sensor for Multiphase Flow Image

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Abstract: Electrical Capacitance Tomography (ECT) was used to develop image of various multi phase flow of gas-liquid-solid in a closed pipe. The principal difficulties to obtained real time image from ECT sensor are permittivity distribution across the plate and capacitance is nonlinear; the electric field is distorted by the material present and is also sensitive to measurement errors and noise. This work present a detailed description is given on method employed for image reconstruction from the capacitance measurements. The discretization and iterative algorithm is developed for improving the predictions with minimum error. The author analyzed eight electrodes square sensor ECT system with two-phase water-gas and solid-gas. *Copyright © 2007 IFSA.*

Keywords: Electrical capacitance tomography, Finite difference method, Discretization, Image reconstruction, Multi phase flow

1. Introduction

An electrical capacitance tomography (ECT) sensor [1] consists of multiple electrodes, usually mounted outside an insulating pipe, the capacitance data measured from the multiple electrode sensors. The changes in capacitance, due to the presence of permittivity of the material, are processed to represent the permittivity distribution, which in turn maps the material distribution in the process. ECT is one of the imaging techniques most likely to provide quantitative flow visualization flow rate information in industrial flows. It has particularly used in two-phase gas/liquid and gas/solids flows typical of petroleum and process industry. The most commonly used data predicted from ECT system are microprocessor or micro controller based system. But the response time for a single measurement is approximately 10.4-μ sec. the time to reconstruct one image was measured to be approximately 8.48msec.

The most popular image reconstruction algorithms are called the linear back-projection [3, 4] (LPB). It is based on first obtaining the sensitivity distributions for all electrode pairs, and then linearly superimposing the normalized capacitances using the sensitivity maps as the weighting factors to obtain images. It is simple and fast, but image quality is not good, especially for a complex permittivity distribution.

2. Sensors Structure and Signal Conditioning

The Fig.1 shows the schematic diagram of multiple measurement electrodes mounted equally around the cross-section of the pipe, with an earthed screen outside the electrode to reject external noise. For a static system, sensor with N-measurement electrodes, there are N (N-1)/2 electrode pairs and thus N (N-1)/2 independent capacitances are measured. In dynamic system N (N-1) independent capacitances are measured.

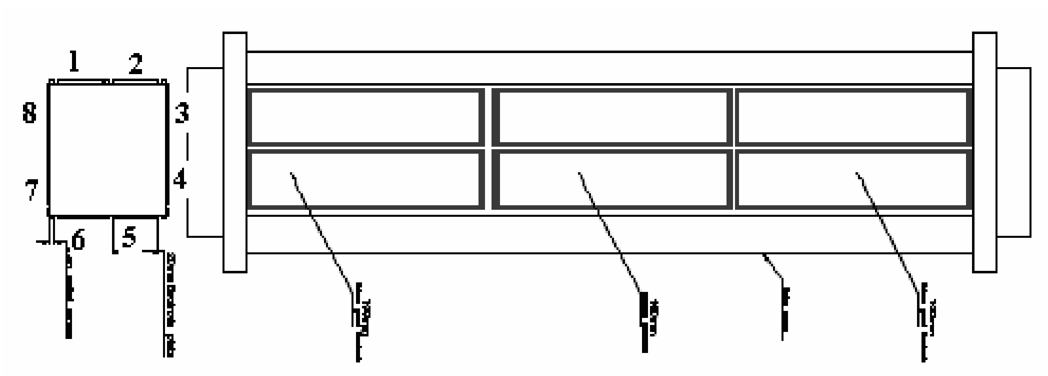


Fig. 1. Schematic diagram of ECT sensor.

There are some specific requirements for the measuring circuit of capacitance: large dynamic range, high resolution, good linearity, and good stray capacitance immunity. After C/V conversion and certain signal process by sensor electronics, these data fed in to the computer. The capacitance measurements are realized by measuring the induced charges on the detection electrode and used to recognize pipe flow patterns (i.e. the permittivity distribution). The high-speed pulse input capacitance measurement principle [2] is used to detect capacitance between the electrodes. In this method to determine the charging voltage on detector electrode when an impulse voltage signals of constant magnitude is applied to the source electrode.

2.1. Mathematical Model of the ECT Sensor.

The capacitance between two measurement electrodes is the internal capacitance [1, 5], which is solely related to the relative permittivity of the material and spatial potential distribution across the plate.

$$C_x=\varepsilon_o/V_c\int_{(x,\,y)\,\in\Gamma} \varepsilon r(x, y)\ \Delta\Phi(x, y)\ d\Gamma, \qquad (1)$$

where ε_0 is the permittivity of free space, ε_r (x, y) is the relative permittivity distribution in the sensor, V_c is the potential difference between the two electrodes. Φ (x, y) is potential distribution in the sensor and **Γ** is the spatial location

If the sensor is completely filled with a material of the relative permittivity ε_r the equation (1) becomes.

$$C_x = \varepsilon_r \, \varepsilon_o / V_c \int_{(x,y) \in \Gamma} \Delta\Phi \, (x, y) \, d\Gamma = \varepsilon r \, C_{o,} \quad (2)$$

where

$$C_o = \varepsilon_o / V_c \int_{(x,y) \in \Gamma \, \Delta\Phi} (x, y) \, d\Gamma \quad (3)$$

C_0 is the internal capacitance when the sensor is empty i.e. filled with air, $\boldsymbol{\varepsilon_r}$=1.0.or filled with water $\boldsymbol{\varepsilon_r}$=80.

3. ECT Image Reconstruction

In ECT system, the forward problem is to determine the capacitance values for known Permittivity distribution conversely; the inverse problem is to obtain the material distribution (permittivity distribution) from the capacitance measurements is a process known as image reconstruction. The first step, forward problem, consists of modeling the capacitance as an explicit function of the permittivity. The second step, inverse problem, consists of inverting the relation of the forward problem in order to retrieve the permittivity.

3.1. Image Reconstruction Based on Linear Back Projection (LBP) Method

In yang's method based on landowner's iteration, a simple linear approximation forward problem is used. In matrix form

$$C=SG, \quad (4)$$

where, C is an m x 1 vector of the normalized measured capacitance. G is an n x 1 vector of the image of the permittivity distribution, which is often called the grey level, S is m x n normalized sensitivity matrix, m is the number of unique electrode pair combinations, n is the number of pixel in image region. Sensitivity matrix is usually calculated by finite element method. The sensitivity value of electrode pair i –j of pixel k in pipe is defined as:

$$S_{i,j}(k)=\mu\,(k)(C^m_{i,j}\,(k) - C^l_{i,j}\,(k))/(C^h_{i,j}-C^l_{i,j})$$
$$k=1,2\ldots n,\ i=1,2\ldots N-1,\ j=I+1\ldots N,\ m=N\,(N-1)/2, \quad (5)$$

where, μ (k) is the correction factor related to the area of (2D FEM analysis) or volume (3D FEM analysis) of the k^{th} in pipe element. $C^m_{i,j}$ is the measured capacitance of electrode pair i-j, $C^l_{i,j}$ and $C^h_{i,j}$ are capacitance when the pipe is filled with low and high dielectric material respectively.

4. Discretization and Iterative Algorithm

Consider the square sensor filled with two phases with different dielectric constants and fitted with eight sensors and guard electrodes. The wall permittivity is constant. Fig. 2 depicts the model basis for formulating the equations.

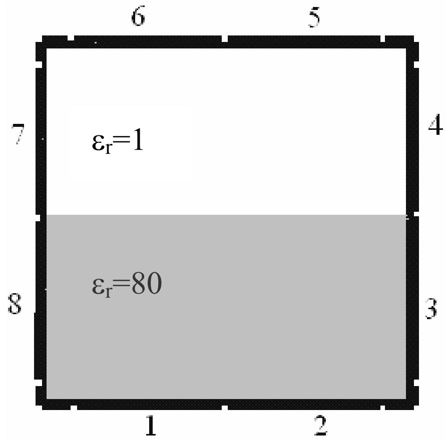


Fig. 2. Cross section of eight electrodes ECT sensor.

Thus, the domain of model is the unit square Ω on the x-y plane, representing the cross section of the scaled sensor area. The electrodes are placed on the unit square $x^2=1$, where the x is the length of the side, the boundary of Ω. Suppose the relative radial thickness of the wall is t_0 ($0<t_0<1$), and denotes the interior cavity by

$$\Omega_0 = \{(x, y): x^2 < (1-t_0)^2\}. \tag{6}$$

The electric potential u (x, y) on Ω is governed by Poisson's Equation derived for static electric field and is given by the equation.

$$\nabla. (\varepsilon\nabla u) = 0 \quad \Omega, \tag{7}$$

where $\varepsilon = \varepsilon(x, y) > 0$ is the (relative) permittivity distribution in Ω. A finite difference scheme is employed for descritizing the differential equation for the numerical solution using rectangular coordinates.

In rectangular coordinates (x, y), the boundary value problem (6) takes the following form

$$\frac{\partial}{\partial x}(\varepsilon_{xy}\frac{\partial u}{\partial x}) + \frac{\partial}{\partial y}(\varepsilon_{xy}\frac{\partial u}{\partial y}) = 0 \tag{8}$$

$$\frac{\partial u}{\partial x} \rightarrow \frac{(u_{ij} - u_{i-1,j})}{\Delta x} \tag{9}$$

$$\frac{1}{\Delta x}[\varepsilon_{xy}\frac{\partial u}{\partial x}\mathrm{I}_{i,j} - \varepsilon_{xy}\frac{\partial u}{\partial x}\mathrm{I}_{i-1,j}] + \frac{1}{\Delta y}[\varepsilon_{xy}\frac{\partial u}{\partial y}\mathrm{I}_{i,j} - \varepsilon_{xy}\frac{\partial u}{\partial y}\mathrm{I}_{i,j-1}] \tag{10}$$

$$\frac{(\varepsilon_{i+1,j}u_{i+1,j}-\varepsilon_{i,j}u_{i,j})}{\Delta x^2}-\frac{(\varepsilon_{i,}u_{i,j}-\varepsilon_{i-1,j}u_{i-1,j})}{\Delta x^2}$$
$$+\frac{(\varepsilon_{i,j+1}u_{i,j+1}-\varepsilon_{i,j}u_{ij})}{\Delta y^2}-\frac{(\varepsilon_{i,j}u_{i,j}-\varepsilon_{i,j-1}u_{i,j-1})}{\Delta y^2}=0$$

$$\frac{\partial y}{\partial x}\mathrm{I}_b=\frac{-u_{i+2,j}+4u_{i+1,j}-3u_{i,j}}{2\Delta x}, \tag{11}$$

when $0 < x < 1$, $0 < y \le 1$,
$u = V_k$ when $x = 1$, $y \in I_k$ ($k=1, 2\ldots.n$),

$$\varepsilon\frac{\partial u}{\partial x}=0, \tag{12}$$

when $x=1$, $y \in (0, 1) \setminus U_{k=1}^{\ell} I_{n,}$

where I_k denotes the spatial interval for the k^{th} electrode.

A standard five –point finite difference scheme is used for the numerical solution. Given integer's N and M, we set up a uniform discretization grid

$$(x_i, y_j) = (i\Delta x, j\Delta y) \ \ with\ \Delta x = \frac{1}{N},\quad \Delta y = \frac{1}{M}.$$

For i=0, 1…N and j =0, 1…M. on each rectangular pixel we assume that the permittivity ε is a constant:

$$\varepsilon(x,y)=\varepsilon_{i+1/2,\ j+1/2} \quad \text{On } [x_i, x_{i+1}] \text{ x } [y_j, y_{j+1}], \tag{13}$$

for $0 \le i \le N-1$ and $0 \le j \le M-1$.

The central difference approximation of equation at nodal point (i, j) for $U_{ij}=u(x, y_j)$ is given by

$$\begin{aligned}&\frac{1}{(x_i\Delta x)^2}\Big((x\varepsilon)_{i-1/2,j}U_{i-1,j}-\big((x\varepsilon)_{i-1/2,j}+U_{i+1/2,j}\big)U_{ij}+(x\varepsilon)_{i+1/2,j}+U_{i+1/2,j}\Big)+\\&\frac{1}{x_i^2(\Delta y)^2}\Big(\varepsilon_{i,\ j-1/2,}U_{i,\ j-1,}-\big(\varepsilon_{i,\ j-1/2,}+\varepsilon_{i,\ j+1/2,}\big)U_{ij}+\varepsilon_{i,\ j+1/2,}U_{i,\ j+1}\Big)=0\end{aligned} \tag{14}$$

for $1 \le i \le n-1$ and $1 \le j \le m$. Quantities with non-integer indices in the equations are approximated by the averages of the corresponding pixel values; The permittivity data, the array $\{\varepsilon_{i+1/2,\ j=1/2}\}$, may be arranged in to a vector ε, and denote the vector that consists of only the interior pixel values in Ω_0 by the N_0 Vector ε_0.

4.1. Evaluation of Algorithms

The image reconstruction algorithms are to be evaluated by comparing with the experimental measurements [6, 7]. Three evaluation criteria are used:

- Relative image error
- Relative capacitance residual and
- Correlation coefficient between the test object and the image.

The image and capacitance are treated as vector; their norms are used to calculate the error and the residual.

Relative capacitance residual : $\dfrac{\left\| c(\varepsilon) - c^* \right\|}{c^*}$

Relative image error: $\dfrac{\left\| \varepsilon_0 - \varepsilon_0^* \right\|_r}{\left\| \varepsilon_0^* \right\|_r}$

Correlation coefficient: $\dfrac{\left\langle \varepsilon_0 - \overline{\varepsilon_0}, \varepsilon_0^* - \overline{\varepsilon_0} \right\rangle_r}{\left\| \varepsilon_0 - \overline{\varepsilon_0} \right\|_r \left\| \varepsilon_0^* - \overline{\varepsilon_0^*} \right\|_r}$.

5. Results and Discussions

Image reconstruction is carried out by the discretization and iterative algorithm for different test profiles such as the sensor filled with 25% of water, the sensor filled with 50% of water, the sensor filled with 75% of water like a stratified flow, single component at corner of the sensor, single component at middle of the sensor, and two component at opposite corner of the sensor. The algorithm is written in MATLAB and use to reconstruct the images from the capacitance measurements for stratified flow, single and two object flows. The model parameters are given below:

Number of electrode n=8

$$\in_r^{(0)} = 2.56, \qquad \in_r = 80 \qquad \Delta x = \frac{1}{N} = \frac{1}{50}, \qquad \Delta y = \frac{1}{M} = \frac{1}{50}$$

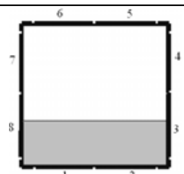
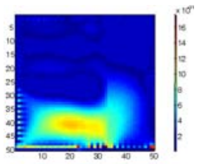
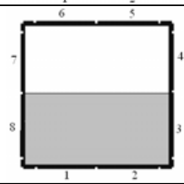
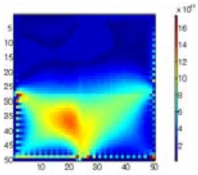
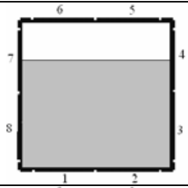
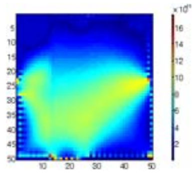
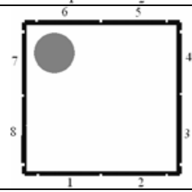
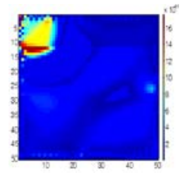
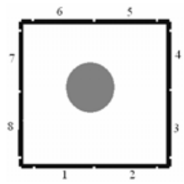
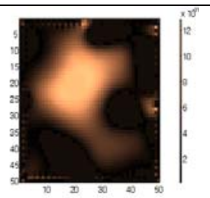
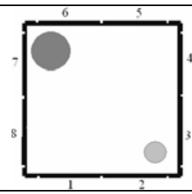
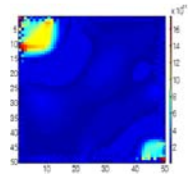
Thus, the discrete system for each boundary value problem is of size N x N with N = 2500 and the interior permittivity vector $\in_0$ has length N_o=2500. The capacitance vector C consists of n_0 = 28 components. All the computations were performed using MATLAB on a personal computer with a Pentium 4 processor. The results are given in the Table 1.

The results show that the quality of image reconstruction is not adequate in case of stratified-flow; however, a good approximation is obtained in other cases. The overall correlation coefficient is found to be 0.85. The acceptability of the quality of image is subjective. The capacitance data might be with large noise, thus giving rise to wide variation in the image quality. A suitable method should be used to filter this noise and to obtain good quality capacitance measurements.

6. Conclusions

The reconstructed images are compared with test conditions. The correlation coefficient is found to be 0.857.There is wide variation in the quality of images. This variation is expected from the quality of input capacitance data. The capacitance data might have corrupted with the noise associated with measurement. There is a need to adapt a suitable method to minimize the signal noise either using software techniques or incorporating the low pass hardware filters.

Table1. Image of different test profiles.

	Test profile	**Reconstructed image**	**Capacitance residual**	**Relative Image error**	**Correlation coefficient**
Sensor filled with 25% of water			0.582	0.215	0.83
Sensor filled with 50% of water			0.052	0.192	0.847
Sensor filled with 75% of water			0.064	0.204	0.079
Circular steel rod placed corner of the sensor			0.095	0.185	0.837
Circular steel rod placed center of the sensor			0.085	0.174	0.872
Different dielectric medium placed in the sensor			0.083	0.195	0.826

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Guide for Contributors

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