Effect of pipeline thickness on electrical capacitance tomography

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Abstract. For the purpose of analyzing the effect of pipeline thickness on ECT system include sensor and image reconstruction, radius-electrode ratio is defined as the ratio of inner and outer radius of pipeline. The rules of 8-electrode sensor parameters such as capacitance, capacitance change, and change rate of capacitance and sensitivity map are discussed by ANSYS and Matlab, which are combined to simulate sensor characteristic. With the increase of radius-electrode ratio, capacitance sensitivity to inner media increases, and the effect of pipeline thickness on capacitances of four typical inter-electrode pairs is much different under the same inner radius. LBP algorithm is adopted to reconstruct the ECT images of stratified flow, core flow and annular flow with different radius-electrode ratios. Simulation results show that image error under high radius-electrode ratio is small, and the image reconstructed from stratified flow is better than the ones from core flow and annular flow, especially in the condition of low radius-electrode ratio. As a result, ECT with low radius-electrode ratio is benefit to image reconstruction.

1. INTRODUCTION

Two-phase (multi-phase) flow is a commix flow mode which is widely existed, and its parameter measurement technology takes a more and more important role in science research and industrial production. Thus process tomography (PT) comes out with this trend. Electrical capacitance tomography (ECT) is one of the most mature and promising methods, which measures the capacitance change of multi-electrode sensor due to the change of dielectric permittivity being imaged, and then reconstructs the cross-section images using the measured raw data with a suitable algorithm. It has the characteristics such as low cost, fast response, non-intrusive method, broad application, safety (Li Haiqing et al., 2000; Yang W Q et al., 1995a, 1995b).
ECT system includes sensor, capacitance measuring circuit and imaging computer. And ECT sensor consists of insulating pipeline, measurement electrode, radial screen and earthed screen (Yang W Q et al., 1999). The measurement electrode is mounted symmetrically around the circumference of pipeline. Radial screen is fitted between the electrodes to cut the electro line external to the sensor pipeline and reduce the inter-electrode capacitance. The earthed screen surrounds the measurement electrodes to shield external electromagnetic noise. ECT sensor converts the permittivity distribution of multi-phase flow to inter-electrode capacitance, which is the ECT forward problem. Capacitance measuring circuit takes the capacitance data and transfers to imaging computer. Imaging computer reconstructs the distribution image with a suitable algorithm, which is called ECT inverse problem.

Fig.1 Sketch of ECT system

In most application, ECT electrode is mounted outside the ECT pipeline which is called external electrode ECT sensor (Yang W Q et al., 1997), so pipeline thickness is a very important parameter in ECT sensor design. The external electrode ECT sensor can avoid polluting and eroding by inner media, and affecting from the inner media static, so that non-intrusive measurement is realized.

External electrode ECT sensor is easy to manufacture and use, but the pipeline isolates the measured media from measurement electrode, therefore it brings some difficult to capacitance measurement and image reconstruction. Sensor pipeline results in the electro line aberrance at the boundary of different media. There are three factors which have great effect on electro line, e.g. pipeline material, inner dielectric permittivity and the ratio of pipeline thickness and diameter (A J Jaworski et al., 2000).

Finite element method (FEM) has been widely used to numerically solve mathematical problems in many engineering fields (Xie et al., 1992). Hence characteristic of 8-electrode ECT sensor with different pipeline thickness is studied in the method of numerical simulation, in which ANSYS is combined with Matlab. At the same inner diameter, ECT sensor models of different pipeline thickness are built in gas-solid two phase flow, and inter-electrode capacitance is simulated so that the sensitivity maps used to reconstruct image is taken. Then the effect of pipeline thickness on the imaging fidelity is investigated. The influence of pipeline thickness on ECT system is analyzed from aspect of forward problem and inverse problem.

2. EFFECT OF PIPELINE_THICKNESS ON ECT SENSOR CHARACTERISTIC

2.1 Sensor Mathematical Model

For a sensor with N electrodes, there are N(N-1)/2 electrode pairs, hence N(N-1)/2 independent capacitance measurements. Fig. 2 is the cross section of 8-electrode ECT sensor, in which R₁ is inner
pipeline radius; $R_2$ is outer pipeline radius; $R_3$ is earthed screen radius; and radial screen is connected to outer pipeline. High electrode covering ratio can get high image fidelity (A Martinez Olmos et al., 2007), because it can enlarge the inter-electrode capacitance, especially for adjacent electrode pairs, so electrode stretch angle $\theta$ should be chosen as large as possible. The axial length of electrodes is related to inter-electrode capacitance, signal bandwidth and measurement uncertainty of measured media. Longer electrodes produce an average signal over a greater axial length, which results in bad dynamic performance. Shorter electrode may result in capacitance too small to be measured accurately. Normally, the electrode length is chose as 10 cm (Peng et al., 2003).

For the purpose of making the describe of pipeline thickness easier, the concept of radius-electrode ratio $\rho (\rho = R_1 / R_2)$ is put forward, which is the ratio of pipeline inner radius to electrode radius (i.e. pipeline outer radius). In ideal condition, pipeline thickness is zero, so $\rho$ is equal to 1. The smaller radius-electrode ratio is, the more serious the effect of pipeline thickness becomes.

According to the conclusion of reference (Yan et al., 2003), when the ratio of axial length of electrode to outer radius of pipeline is larger than 1.5, the fringe effect of sensor can be ignored, namely, the sensor can be treated as two-dimensional field. The value of sensor described in the paper is much large than 1.5, so the sensor can be look on as simple 2-D structure. The operation frequency of capacitance measuring circuit is about 1 MHz, so the ECT sensor can be deal with electrostatic field theory.

If there exists no space charge inside the pipeline, the inner potential distribution can be described with 2-D Poisson equation (Xie et al., 1992; Jin Jianmin, 1998):

$$\nabla \cdot [\varepsilon_0 \varepsilon(x, y) \nabla \phi(x, y)] = 0$$  \hspace{1cm} (1)

Where

$(x, y)$ - spatial potential distribution

$\varepsilon_0$ - permittivity constant of free space

$\varepsilon(x, y)$ - spatial permittivity distribution

$\nabla \cdot$ - divergence operator

$\nabla$ - gradient operator

When electrode $i$ is in excitation mode, its Dirichlet boundary condition is
Where \( \Gamma_1, \Gamma_2, \ldots, \Gamma_8 \) are the spatial positions of the eight electrodes, \( Q_s \) is the earthed screen, \( V_c \) is the excitation potential. The forward problem is to take the inter-electrode capacitance at a certain dielectric distribution.

Solving Equ.1, the sensor potential distribution \((x, y)\) can be obtained. For the structure irregularity of sensor electrode pair and the inhomogeneity of dielectric distribution, Equ.1 doesn’t exist analytical solution, but it can be worked out through FEM. When using FEM to solve problem, the continuous field should be converted to a discrete form, namely, the solution domain should be divided into finite elements. For the convenience of numerical simulation, the FEM software ANSYS is used to build the geometry model of sensor and divide the cross section domain into triangle elements. The partition results such as node coordinates, boundary condition and relation between elements and nodes are extracted to calculate potential distribution in Matlab.

With potential distribution of sensor nodes, the inter-electrode capacitances can be obtained by following equation.

\[
C_{i,j} = \frac{Q(\Gamma_j)}{V_c} = \left( \frac{e_0}{V_c} \int_{(x,y)\in\Gamma_j} \varepsilon(x,y) \nabla \phi^{(i)}(x,y) \cdot d\Gamma_j \right) \quad (3)
\]

Where

- \( Q(\Gamma_j) \) - measured electric charge on electrode \( j, j = i+1, \ldots, 8 \)
- \( \phi^{(i)}(x,y) \) - potential distribution when electrode \( i \) is in excitation mode

The elapsed time of calculating a group of capacitances is determined by segmentation grade of grid, and node number and segmentation grade near electrodes are the main factors. Models of different pipeline thickness are built, and each electrode is divided into sixteen segments. Numerical simulation is implemented using Matlab on a PC with a Pentium IV 2.66G CPU and 512 Mbytes memory.

2.2 Effect of Pipeline Thickness on Sensor Capacitance

It is well known that the influence of a certain pipeline thickness to sensors with different inner radii is not the same. For the sake of scaling different sensors effectively, the concept of radius-electrode radio is defined (see section 2.1), so that it is more significant to evaluate the pipeline thickness.

The parameters of simulated ECT sensor, which used in dense-phase pneumatic conveying of pulverized coal, include inner radius \( R_1 \), outer radius \( R_2 \), earthed screen radius \( R_3 \), electrode stretch angle \( \theta \), axial length of electrodes \( L \), gas permittivity \( \varepsilon_{\text{gas}} \), solid permittivity \( \varepsilon_{\text{solid}} \), insulating pipeline permittivity \( \varepsilon_{\text{pl}} \) and filling layer permittivity \( \varepsilon_{\text{se}} \). The inner radius is constant, that is 5mm. The pipeline
thickness (R2-R1) is selected as 5mm, 4mm, 3mm, 2mm, 1mm and 0mm respectively, so eight sensors are structured, whose radius-electrode radios are 0.50, 0.56, 0.64, 0.71, 0.77, 0.83, 0.91 and 1 respectively. Standing capacitance (when the pipeline is filled with gas), capacitance change and change rate of capacitance, which is the ratio of capacitance change to standing capacitance, are calculated, are investigated. Because of symmetry, 8-electrode sensor has four typical structures of inter-electrode pair; hence only four inter-electrode pairs (C1-2, C1-3, C1-4 and C1-5) are listed, as showing in Fig. 3. The electrode stretch angle \( \theta \) is 40°, sensor axial length L is selected as 10cm, and permittivity (\( \varepsilon_{\text{gas}} \), \( \varepsilon_{\text{solid}} \), \( \varepsilon_{\text{pl}} \) and \( \varepsilon_{\text{se}} \)) is set to 1, 3.5, 4 and 2.5 respectively.

![Fig. 3 Capacitance against radius-electrode ratio](image-url)
For the particularity of position, capacitances of adjacent electrodes are much larger than the others. For the convenience of plotting, standing capacitance and capacitance change of adjacent electrodes are reduced to 1/10.

Capacitance is proportional to permittivity, thus \( \varepsilon_{pl} \) is large than \( \varepsilon_{gas} \). With the increase of radius-electrode radio, the gas phase acts a more and more important role, so the standing capacitances of four typical electrode pairs reduce (see Fig. 3(a)). But the standing capacitance tendency curve of adjacent electrode is different from the others. Capacitance of adjacent electrodes has significant change at high radius-electrode radio, but the non-adjacent ones have more obvious changes at low radius-electrode radio.

The tendency curve of capacitance change against \( \rho \) is shown in Fig. 3(b). In adjacent electrode pair, capacitance change increases monotonously with the increase of \( \rho \), and turns from negative to positive. However, there exist maximum points in non-adjacent electrode pairs, and all the maximum values is at the same position where \( \rho = 0.85 \). So sensor with this \( \rho \) is more suitable to capacitance measurement.

Fig.3(c) is change rate of capacitance against \( \rho \). Change rate of capacitance reflects how much capacitance of electrode pair is affected by the inner dielectric. In the ideal condition (\( \rho=1 \)), change rate of capacitance is only related to permittivity, that is about 2.5 ((3.5-1)/1). At limit case of \( \rho=0 \), change rate of capacitance have no relationship with inner dielectric, namely, 0. Therefore, the effect of pipeline is little when \( \rho \) is near to 2.5, whereas the effect is great when \( \rho \) is near to 0. All of the change rate of capacitance rise with the increase of \( \rho \). The effect of inner dielectric to opposite electrode pair is the largest, especially at high \( \rho \). However it has little effect on adjacent electrode pair when \( \rho \) is little than 0.85. The influence of pipeline to electrode pairs decreases followed by C1-2, C1-3, C1-4 and C1-5.

2.3 Effect of Pipeline Thickness to Sensitivity map

Sensitivity distribution function \( S_{i,j}(k) \) is defined as: relative capacitance change between electrode i-j due to permittivity change of \( k \)th element. When inner dielectric is gas and solid phase, it can be described as follows:

\[
S_{i,j}(k) = \mu(k) \cdot \frac{C_{i,j}(k) - C_{gas}}{(C_{solid} - C_{gas})(\varepsilon_{solid} - \varepsilon_{gas})}
\]

Where
\[
\begin{align*}
k & \text{- serial number of element (k=1, 2, ..., M)} \\
M & \text{- total number of finite elements inside the pipeline} \\
\varepsilon_{gas} & \text{- permittivity of gas phase} \\
\varepsilon_{solid} & \text{- permittivity of solid phase} \\
C_{i,j}(k) & \text{- capacitance when permittivity of kth element is } \varepsilon_{solid} \text{ and the others are } \varepsilon_{gas} \\
\mu(k) & \text{- correlation factor of kth element related to area, which is the ratio of inner pipeline area to kth element area.}
\end{align*}
\]
Based on Equ.4, the sensitivity matrix $S_{NM}$ can be taken, in which $N$ is the total number of electrode pair in 8-electrode sensor. The calculated sensitivity maps with different $\rho$ are shown in Fig. 4.
The largest sensitivity is nearby electrode 1 and electrode 2. The sensitivity is negative near to electrode 1 and 2 when $\rho \leq 0.71$. The shapes of sensitivity maps have no obvious variation except for intensity. With the increase of $\rho$, the maximum of sensitivity decreases. Nevertheless, when $\rho \geq 0.77$, sensitivity near to the two electrodes turns positive and the maximum of sensitivity decreases with the increase of $\rho$. Incidentally, capacitance change of adjacent electrodes turns positive at $\rho = 0.67$ (see Fig.3(b)), while maximum of sensitivity at $\rho = 0.71$ is still negative. It is not ambivalent because capacitance change reflects global variety and maximum of sensitivity represents local value. Fig. 5 is the variety tendency of maximum of sensitivity between adjacent electrodes. Maximum of sensitivity exists a broken point when $\rho$ is between 0.71 and 0.77, but not a continuous monotonic curve.

$$\begin{array}{c}
\text{Fig.5 Sensitivity maximum of adjacent electrodes}
\end{array}$$

$S_{1,3}$ is the sensitivity distribution between electrode 1 and 3. When $\rho < 0.71$, sensitivity peak is present between the two electrodes near to the pipeline, but not near to the electrodes. This is because the pipeline is so thick that inner pipeline wall is far from the electrode, which results in the two sensitivity peaks integrate into one. However, when $\rho$ is larger than 0.77, the effect of pipeline is weakened, so that there are two peaks of sensitivity map near to electrode 1 and 3.

$S_{1,4}$ is the sensitivity distribution between electrode 1 and 4. There exists two sensitivity peaks close to electrode 1 and 4 respectively. The distance between electrode 1 and 4 is far, the pipeline thickness can not conceal the characteristic that the sensitivity near electrode is high. Further more, the two peaks can be differentiated more obviously with the increase of $\rho$. When $\rho$ is larger than 0.77, negative sensitivity presents near to the two peaks.

$S_{1,5}$ is the sensitivity distribution between electrode 1 and 5. Shapes of sensitivity map in opposite electrode pair are similar to each other, look like saddles. The sensitivity peaks present near to electrode 1 and 5. Therefore the opposite electrode pair has minimum effect of pipeline. Similar to $S_{1,4}$, there also exist negative sensitivity near to the peaks when $\rho$ is higher.

3. EFFECT OF PIPELINE THICKNESS ON IMAGE RECONSTRUCTION

Image reconstruction takes an important role in ECT, which is to reconstruct permittivity
distribution inside the pipeline using measured capacitances of inter-electrode pairs. There are three principal problems presented in ECT image reconstruction. Firstly, the relation between permittivity and capacitance is not linear, and linear algorithm will result in imaging error; Secondly, number of capacitances is much less than number of image element; and thirdly, ECT inverse problem is ill-posed, which induces that the imaging result is much sensitive to measuring error and noise. Furthermore, sensor pipeline intensifies the difficult of image reconstruction.

For the convenience of combination of forward and inverse problem, the partition of image reconstruction is the same as in forward problem. Then the image of inner pipeline is reconstructed using the capacitance data, which obtained by forward simulation (see Eqn.3) at a given permittivity distribution. The capacitance is normalized so that the measured data is dimensionless, which is easy to process image and reduce the effect of measurement error (Yang Lijian et al., 2002).

The normalized capacitance is defined as:

$$\lambda_{i,j} = \frac{(C_{i,j}^m - C_{i,j}^{gas})}{(C_{i,j}^{solid} - C_{i,j}^{gas})}$$  \hspace{1cm} (5)

Where

- $C_{i,j}^m$ - Measurement capacitance of electrode $i$ and $j$ at a given flow distribution
- $C_{i,j}^{gas}$ - Capacitance of electrode $i$ and $j$ when the pipeline is empty
- $C_{i,j}^{solid}$ - Capacitance of electrode $i$ and $j$ when the pipeline is full

Theoretically, normalized capacitances should be between 0 and 1, but it may be negative or large than 1 in adjacent electrode pair, especially when $\rho$ is small, because of discontinuous permittivity distribution and radial screen.

LBP is the earliest algorithm used in ECT image reconstruction (Xie et al., 1989). Although mathematically not accurate and can only get qualitative image, LBP algorithm is still widely used in on-line image reconstruction because of its simplicity and celerity. If the effect of dielectric permittivity to sensitivity map can be ignored, the gray level $g(k)$ of $k$th element in reconstructed image can be expressed as:

$$g(k) = \frac{\sum_{i=1}^{7} \sum_{j=i+1}^{8} \frac{C_{i,j}^m - C_{i,j}^{gas}}{C_{i,j}^{solid} - C_{i,j}^{gas}} S_{i,j}(k)}{\sum_{i=1}^{7} \sum_{j=i+1}^{8} S_{i,j}(k)}$$  \hspace{1cm} (6)

For the purpose of demonstrating the effect of pipeline thickness to image reconstruction, LBP algorithm is adopted to reconstruct the image of different flow patterns (stratified flow, core flow and annular flow) under the condition of $\rho = 0.5$ and $\rho = 0.83$. Image gray level is classified to five grades, and the reconstruction result is shown in Fig. 6 and Fig. 7.
Fig. 6 Image Reconstruction at $\rho=0.5$

Fig. 7 Image Reconstruction at $\rho=0.83$
It is obvious that the reconstructed image at $\rho=0.83$ is better than the one at $\rho=0.5$ from the comparison of Fig.6 and Fig.7. Consequently, pipeline thickness has significant influence not only on capacitance but also on image reconstruction. The image fidelity is better in core and annular flow than in stratified flow when $\rho$ is 0.83. But it is on the contrary when $\rho$ is 0.5. In the condition of low radio-electrode radio, effect of pipeline thickness on opposite electrode pair is the least among these electrode pairs. The relation between opposite electrode pair and these flow patterns, which are symmetric with respect to circle center, is much less, so the reconstructed image fidelity under core and annular flow is not satisfactory. If an image filter threshold is introduced (Xie et al., 1993), image fidelity can be improved effectively.

4. CONCLUSION

There are two major computational problems in ECT: the forward problem and the inverse problem. The forward problem is to determine inter-electrode capacitance by solving the partial differential equations from permittivity distribution, and the inverse problem is to obtain permittivity distribution from measurement capacitance with a suitable algorithm.

The effect of pipeline thickness on ECT forward and inverse problem, such as capacitance, sensitivity and image reconstruction, is discussed completely by FEM numerical simulation. The influence of pipeline to electrode pairs decreases followed by 1-2, 1-3, 1-4 and 1-5. Maximum capacitance change is gotten at $\rho=0.85$, which is beneficial for capacitance measurement and image reconstruction. With the decrease of radius-electrode radio $\rho$, the distortion of ECT sensor sensitivity becomes more serious.

The sensor characteristic with low $\rho$ is mainly manifested by opposite electrodes. However, opposite electrode pairs at low $\rho$ cannot reflect specialty of flow patterns which are symmetric with respect to circle center. Therefore, reconstructed image under flow patterns which are symmetric with respect to circle center is dissatisfactory, thus it is much better in these flow patterns such as stratified flow which is not symmetric with respect to circle.

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NOMENCLATURE

| Symbol | Description                | Unit |
|--------|----------------------------|------|
| $R_1$  | pipeline inner radius      | [m]  |
| $R_2$  | pipeline outer radius      | [m]  |
| $V_c$  | excitation potential       | [F]  |
| $C_{i,j}$ | capacitance between electrode $i$ and $j$ | [F] |
| $N$    | total number of electrode pair |      |
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\[
M \quad \text{total number of finite elements inside the pipeline} \\
\kappa \quad \text{serial number of element} \\
S_{i,j}(k) \quad \text{sensitivity of } k\text{th element between electrode } i \text{ and } j \\
g(k) \quad \text{gray level of } k\text{th element} \\
C_{i,j}^m \quad \text{Measurement capacitance of electrode } i \text{ and } j \quad [F] \\
C_{i,j}^{\text{gas}} \quad \text{capacitance of electrode } i \text{ and } j \text{ when the pipeline is empty} \quad [F] \\
C_{i,j}^{\text{solid}} \quad \text{capacitance of electrode } i \text{ and } j \text{ when the pipeline is full} \quad [F]
\]

**Greek Letters**

\[
\rho \quad \text{radius-electrode ratio} \\
\Phi \quad \text{spatial potential} \quad [V] \\
\nabla \quad \text{divergence operator} \\
\nabla \quad \text{gradient operator} \\
\varepsilon_0 \quad \text{permittivity constant of free space} \\
\varepsilon(x, y) \quad \text{spatial permittivity distribution} \\
\Gamma_i \quad \text{spatial positions of electrode } i \\
\varepsilon_{\text{gas}} \quad \text{permittivity of gas phase} \\
\varepsilon_{\text{solid}} \quad \text{permittivity of solid phase} \\
\mu(k) \quad \text{correlation factor of } k\text{th element related to area} \\
\lambda_{i,j} \quad \text{normalized capacitance between electrode } i \text{ and } j
\]

**Subscripts**

\[
i \quad i\text{-th electrode} \\
j \quad j\text{-th electrode} \\
k \quad k\text{-th element}
\]

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