Numerical study of displacement current phase tomography for gas-water two-phase flow

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Abstract. Electrical Tomography technology is widely used in the research and engineering practice of two-phase flow due to its advantages of non-radiation, non-intrusive and simple equipment structure. However, because of the electrical tomography sensitive field distribution of medium nonlinear (soft), the reconstructed images are often distorted, especially when faced with high conductivity and high dielectric constant two-phase flow (such as oil-field water of high salinity). Displacement current phase tomography (DCPT) is a new electrical tomography technology and it is proposed in 2017. An attractive feature of DCPT is that the relationship between the measured phase and the loss factor has a more extended linear range than the relationship between the measured capacitances in ECT and the permittivity distribution. In this paper, a 12-electrod DCPT with Landweber reconstruction algorithm is applied for gas-water two-phase flow imaging, and the reconstruction results are compared with electrical capacitance tomography (ECT) by numerical examples.

1. Introduction

Due to the influence of formation water and waterflood development, oil-water and gas-water two-phase flow are common flow form in petroleum exploitation and pipeline transportation. Accurate measurements of phase holdup distribution, velocity distribution and flow rate in the process of oil-water two-phase flow are very important to study the flow rule, improve production efficiency, ensure production safety and carry out intelligent management [1-3]. Inspired by medical tomographic imaging, the process tomographic imaging technology, which takes the spatial distribution of multiphase flow parameters as the main detection object, has developed rapidly in recent years. This technology provides a new detection method for obtaining the flow parameter information of multiphase flow within closed pipelines and comprehensively describing real-time flow state [4]. Electrical Capacitance Tomography (ECT) technology is widely used in the research and engineering practice of gas-liquid and liquid-liquid two-phase flow due to its advantages of non-contact, non-radiation and simple equipment structure. However, because of the electrical tomography sensitive field distribution of medium nonlinear (soft),
the reconstructed images of ECT are often distorted, especially when faced with high conductivity and high dielectric constant two-phase flow (such as oil-field water of high salinity).

Displacement current phase tomography (DCPT) is a new electrical tomography technology, which utilizes the phase information of displacement current in the electroquasistatic (EQS) regime to provide information about the distribution of the loss factor (or loss tangent) within the region of interest (RoI) [5-6]. Compared with ECT/ERT, the linearity of the sensitivity theory of DCPT is better, that is, when the dielectric constant and conductivity of the mixture change in a wider range, the Born approximation of DCPT can still be satisfied. The proposal of DCPT has brought a hope for the high-precision tomography of oil-water two-phase flow with high salinity. In this paper, the DCPT technology is used for gas-water two-phase flow imaging, and the reconstruction results of DCPT and ECT using the Lanweber reconstruction algorithm are compared by numerical examples.

2. Theory of reconstruction

2.1. Mathematical model of OF DCPT sensor

In displacement current phase measurement systems, it can be assumed that there is no current density in the region of interest (RoI) [5,7]. The mathematical model can be described by Laplace equation and boundary condition as follows:

\[
\begin{align*}
\nabla \cdot \vec{J}_i &|_{\partial \Omega} = 0 \\
u(x,y,z)|_{\partial \Omega} &= V_{e} \\
u(x,y,z)|_{\partial \Omega, \text{noexcitation}} &= 0
\end{align*}
\]  

(1)

where, \( \vec{J}_i \) is the current field when the electrode \( i \) is excited, \( V_{e} \) is the voltage of the excitation electrode, \( u(x,y,z) \) is the potential distribution function, \( \partial \Omega \) is the region of sensitivity, \( \partial \Omega_{\text{excitation}} \) is the boundary formed by the excitation electrode, \( \partial \Omega_{\text{noexcitation}} \) is the boundary formed by the no excitation.

The relationship between the loss factor \( \rho \) and measured phase \( \phi \) for each electrode pair can be established by the born approximation and can be expressed as:

\[
\Delta \phi = \frac{\delta \rho}{\varepsilon_e} \int_{\Omega_{\text{excitation}}} \frac{|E|^2}{\varepsilon} dv
\]  

(2)

Where \( E \) is the electric field, \( \varepsilon_e \) is the real part of the dielectric constant. The final formulation of DCPT can be described in a form similar to ECT as:

\[
\Delta \phi_i = \sum_{j=1}^{N_e} S_{ij} \Delta \rho_j
\]  

(3)

Therefore, DCPT sensitivity matrix can be defined as:

\[
S_{ij}(m) = -\frac{\phi_{ij}^0 - \phi_{ij}^0}{\rho(m) - \rho_0(m)}
\]  

(4)

where, divide the sensitive area of the DCPT sensor into \( n \) small units, and assume that there is an initial medium distribution in the sensitive area of the sensor. If the loss factor of the medium in the \( k \)-th unit of the sensitive area of the DCPT sensor changes from the initial value \( \rho_0 \) to \( \rho(k) \), the lumped admittance angle between the \( i \)-th and \( j \)-th electrodes changes from the initial value \( \phi_{ij}^0 \) to \( \phi_{ij}^0 \).

2.2. Landweber reconstruction algorithm

As an iterative algorithm, Landweber algorithm has a good compromise in terms of reconstruction quality and speed. Compared with the Non-iterative algorithm, it has higher imaging accuracy and the algorithm complexity is not high. The Landweber iterative algorithm evolved from the steepest descent method, which is based on the least squares method and is a common method in the field of tomography.
The main principle of the algorithm is to correct the solution in the direction of the negative gradient of the residual [8-9]. Taking DCPT as an example, the minimization objective function of DCPT reconstruction can be obtained as formula (5) from the definition of optimization theory and vector norm:

\[ f(g) = \min \frac{1}{2} \| Sg - \varphi \|^2 = (Sg - \varphi)^T (Sg - \varphi) \]  

(5)

where, \( S \) is the sensitivity matrix, \( g \) is the normalized loss factor distribution, \( \varphi \) is the normalized impedance angle.

The gradient of the objective function is:

\[ \nabla f(g) = S^T (Sg - \varphi) \]  

(6)

Based on the principle of the steepest descent method, taking the negative gradient direction as the optimal search direction, the iterative formula for DCPT reconstruction can be described as formula (7):

\[ g_{k+1} = g_k - \alpha_k S^T (Sg_k - C) \]  

(7)

where, \( \alpha_k \) is the optimal step, \( k \) is the number of iterations.

3. Numerical experiment

Both COMSOL Multiphysics and MATLAB are used for numerical simulation and data processing, and AC/DC module (Electrostatics and Current) are applied to set up the model.

For DCPT sensor, a typical 12-electrode array sensor is used and the configurations is shown in figure 1 and the dimensions is listed in table 1.

![Figure 1. Section view of sensor](image)

![Figure 2. Axial view of sensor](image)

| TABLE 1 Parameters of the 3 DCPT sensors | value |
|----------------------------------------|-------|
| Electrode number                       | 12    |
| Electrode opening angle \( \alpha \)   | 26 degree |
| Electrodes length \( L \)              | 125mm |
| Pipe diameter                          | 24mm  |
| The thickness of the pipe              | 2mm   |

With the 12-electrode array sensor, a total 66 admittance angle can be obtained: \( \varphi_{1,2} , \varphi_{1,3} , \varphi_{1,4} , \ldots , \varphi_{1,12} , \varphi_{2,3} , \varphi_{2,4} , \ldots , \varphi_{2,12} , \varphi_{3,12} . \)
4. Simulation Results
In the numerical simulation, 6 classic flow patterns are tested for each sensor, case 1 to case 6 in figure 3. For air-water two phase flow, the relative dielectric constant and electrical conductivity of water are 80 and 1 S/m. For Landweber iterative algorithm, the iterative step $\alpha_k = 2.53 \times 10^{-10}$, the iteration number $k = 500$. The ECT method (with same sensor and reconstruction algorithm as DCPT) is also evaluated for comparing with DCPT.

In order to evaluate the quality of reconstructed images, correlation coefficient, which refers to the relationship between real dielectric constant distribution and reconstructed images, is used as evaluation parameters. The closer the correlation coefficient is to 1, then the better the reconstructed image quality will be [10]. The expressions of relative image error and correlation coefficient are as follows:

$$
\rho = \frac{\sum_{i=1}^{m} (g_i - \bar{g})(\hat{g}_i - \bar{\hat{g}})}{\sqrt{\sum_{i=1}^{m} (g_i - \bar{g})^2 \sum_{i=1}^{m} (\hat{g}_i - \bar{\hat{g}})^2}}
$$

(8)

where $m$ is the pixel numbers of the imaging area, $g$ and $\hat{g}$ are the grayscale values in the reconstructed image and the true image separately, $\bar{g}$ and $\bar{\hat{g}}$ are the average grayscale values in the reconstructed image and the true image separately. The correlation coefficients of the constructed images with DCPT and ECT are shown in figure 4.
As shown in figure 3, both ECT and DCPT with Landweber algorithm can reconstruct approximate distribution of the 6 cases, but the accuracy of the imaging is different. From the quantitative analysis in figure 4, the correlation coefficients of DCPT are higher than that of ECT, except case 2, and the average correlation coefficients of DCPT and ECT are 0.673 and 0.593. So, compared with the reconstructed images of the conventional ECT methods, the overall performance of DCPT are better.

5. Conclude
Displacement current phase tomography (DCPT) is a new electrical tomography technology and it is proposed in 2017. Due to its good linearity feature, this paper applied a 12-electrod DCPT with Landweber reconstruction algorithm for gas-water two-phase flow imaging, and the reconstruction results were compared with electrical capacitance tomography (ECT) by numerical examples. The results shown that, for the tested 6 cases, the overall performance of DCPT are better than that of ECT.

Acknowledgment
This work was supported by the Natural Science Basic Research Plan in Shaanxi Province of China (No. 2019JQ-822), and the National Natural Science Foundation of China (No. 41874158) and Xi’an Shiyou University Postgraduate Innovation and Practice Ability Training Project (No. YCS18211003).

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