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Investigation on the Sensitivity Distribution in Electrical Capacitance Tomography System

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Abstract

The gas-solid-liquid three-phase flow is a very complicated flow pattern in pipeline transportation. By using electrical capacitance tomography (ETC) it can acquire the permittivity distribution of the multi-phase. The sensitivity distribution in ETC may affect the analysis of the permittivity distribution of the multi-phase. However, very limited work has been done in this issue. In order to investigate the sensitivity distribution in ETC, this paper employs the finite element method (FEM) to establish the principle and components of ECT. The FEM model of the sensitivity distribution as a function of the inter-electrode capacitance was discussed. Simulation tests were carried out to calculate the charge on the electrode pairs to access the potential distribution of the ETC. The analysis results show that the dielectric have great influence on the capacitance value and small distance between the electrode pair and the sensitivity field will produce high sensitivity value. Hence, the findings of this work can provide reference for the design of ECT in practice.

Keywords: *electrical capacitance tomography (ETC), pipeline transportation, finite element method (FEM)*

1. Introduction

In the river dredging engineering, the dredgers require long-distance pipeline to transport the mud to the destination. The dredged mud has characteristics of high concentration, non-uniform particles and complex composition [1-3]. And the process of transport is a high concentration of solid-liquid two-phase transportation. In course of transportation there are many technical issues, including high pipe resistance, high energy consuming, pipe blicking and short transporte distance, etc. These problems seriously affect the production efficiency of the dredger, the scope of operations and production costs. Gas-injected transportation is an important means to solve these problems, when controling the gas-solid-liquid three-phase flow in an ideal flow pattern, it can effectively reduce the pipe resistance, lengthen the transportation distance with less abrasion. Therefore, how to monitor and control the flow pattern are the key factors to save production costs and improve dredging efficiency [1].

Electrical capacitance tomography (ECT) is based on capacitive principle of process tomography [2]. Because of its non-radioactive, non-invasive, quick response, low cost and well safety performance, it has increasingly become an important detection techniques in multi-phase flow, and also been widely used in chemical, petroleum, medical and transportation industries [4-7]. In the pipeline transportation, the permittivity distribution is very important to investigate the flow pattern. ETC can acquire the permittivity distribution of the multi-phase. The sensitivity distribution in ETC system may affect the analysis of the permittivity distribution of the multi-phase. However, very limited work has been done in this issue. Hence it is crucial to study the sensitivity distribution in ETC system in the pipeline transportation.

In order to investigate the sensitivity distribution in ETC system, this paper employs the finite element method (FEM) to establish ECT simulation model and hence to investigate the sensitivity distribution. The influence factors of the ECT parameters have been discussed in this work.

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2. Research Method

ETC system mainly consists of three parts: the capacitance sensor, the data acquisition and signal processing model, and the image reconstruction model. The electrode pairs are mounted on the insulating pipe. The pipe is shied with shield mask, which constitutes the capacitive sensor. Different phases have different dielectric constants. The dielectric multi-phase changes with the sensitivity distribution, which leads to the change of electrode capacitance. So the electrode capacitance reflects the distribution of multi-phase. Data acquisition and signal processing model can obtain data of any electrode pair. The data is processed by the system and sent to the computer. The testing result reflects the distribution of every phase in pipeline. By using image reconstruction algorithm, it can illustrate the media distribution in the pipeline [4]. Figure 1 shows the sensor model.

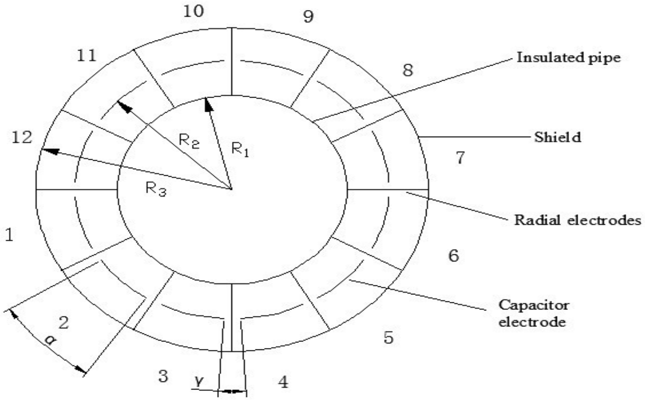

Figure 1. The Sensor Model

In Figure 1, R_1 is the inner-radius of pipe; R_2 stands for outer-radius of pipe; R_3 is the radius of the shielding; α is the electrode angle; γ is interval angle between the electrode pair.

In order to calculate the electrode capacitance, it should obtain the potential of every node in finite element mesh. At present, there are two methods to calculate the potential. One is the charge method and the other is the Gaussian theorem. The Gauss theorem is adopted in this work to get the capacitance values between the electrodes in a pipeline.

According to the power theorem, the function of based on the Thomson theorem is defined as follows [5]:

$$J(\varphi) = \iint_{\Omega} \left\{ \frac{\varepsilon(x,y)}{2} \left[(\frac{\partial \varphi(x,y)}{\partial x})^2 + (\frac{\partial \varphi(x,y)}{\partial y})^2 \right] - \rho \varphi(x,y) \right\} dxdy \tag{1}$$

Where, $\varepsilon(x,y)$ is the permittivity distribution function. The boundary conditions is:

$$\begin{aligned} &\Gamma : \varphi(x,y) = \varphi_0 \\ &\varphi = \frac{\varepsilon(x,y)}{2\Delta} \left[\sum_{p=1}^{3} a_p + b_p x + c_p y)\phi_p \right] \end{aligned} \tag{2}$$

Where, coefficients a_p, b_p, c_p are determined by the position of the points; Δ stands for area of a triangle in the finite element mesh; φ_p stands the potential at the vertex of a triangle.

Substitute Equation (2) into Equation (1), we can obtain:

$$J_e(k) = \frac{\rho \Delta}{3}, (k = i, j, m) \tag{3}$$

Where, K_e is the coefficient matrix, K_e is related to the charging density, and U_e is the potential of the three nodes.

From the deducing above, it can get the potential of whole field and especially the potential of every electrode. Then by Gauss theorem, it can counted out:

$$C_{i,j} = \frac{Q}{V_i - V_j} = \frac{\varepsilon_0}{V_{i,j}} \int_{\Gamma_j} \varepsilon(x,y) \nabla \phi(x,y) \cdot ds \tag{4}$$

Where, V_i is the incentive potential, as the detection electrodes are grounded: $V_j = 0$; ε is the permittivity close to the detection electrode; Γ_j is the surface surrounded by the detection electrode.

The value of $\nabla\phi(x,y)$ can be obtained from the potential of near nodes both in inner and outer layers. Assuming that the whole field contains *m* units, we can get:

$$E_i = \frac{\phi_i - 0}{d_i}, (i = 1, \ldots m) \tag{5}$$

The integration on the E_i unit is as follows:

$$Q_0 = \left(\frac{\phi_1 - 0}{d_1} \cdot d + \ldots + \frac{\phi_m - 0}{d_m} \cdot d \right) \Big\|_{\phi: inner\ potential} + \left(\frac{\phi_1 - 0}{d_1} \cdot d + \ldots + \frac{\phi_m - 0}{d_m} \cdot d \right) \Big\|_{\phi: out\ potential} \tag{6}$$

Where, d_i is the distance between the two electrode and d is the minimum length of the mesh.

In the system, establish the two dimensional model of the section, Equation (6) can converse the area integration into line integration when ignoring the thickness of radial electrode.

Capacitance sensitivity field of the ECT system has the characteristics of "soft field". The media at different locations has different affects on the same electrode capacitance. While media at the same locations has different affects on different electrode capacitance. The function of sensitivity field is a key factor to the quality of the image. There are two methods to obtain the function of sensitivity distribution: the Finite Element method and experimental method. In this article, it uses former to calculate the distribution of sensitivity field. The capacitance sensor contains 12 electrodes. As the electrodes are distributed and finite element are split with highly symmetry. Here it only calculates the sensitivity field between electrode pairs 1-2, 1-3, 1-4, 1-5, 1-6 and 1-7 in Figure 1.

Assuming that the whole field is divided into *m* units, while if *i* is incentive electrode, *j* is the testing electrode, then the sensitivity distribution can defined as follows:

$$S_{i,j}(k) = \frac{C_{i,j}(k) - C_{i,j}(\varepsilon_1)}{C_{i,j}(\varepsilon_2) - C_{i,j}(\varepsilon_1)} \frac{1}{\varepsilon_2 - \varepsilon_1} \mu(k) \tag{7}$$

Where, $C_{i,j}(k)$ is the capacitance value between electrode pair *i-j* when the *k*th element is filled with higher permittivity material in the lower permittivity background and $\mu(k)$ is an area correction factor, which is assigned to the ratio of the area of the largest element to the area of the *k*th element [6, 8].

3. Results and Analysis

In this paper, the parameters of capacitance sensor are set as follows: $R_1 = 55mm$, $t = 5mm$, $R_3 = 80mm$, $d = 1mm$, $L = 21mm$, $\alpha = 18^\circ$ and $\gamma = 12^\circ$. Where, R_1 - radius of pipe, t - thickness of pipe, R_3 - radius of shield, d - thickness of testing electrode, L - length of electrode in radial direction, α - angle of electrode, γ - the interval angle between electrode pair. The permittivity of gas, mud and glass are 1, 80 and 5, respectively. The field is divided as Figure 2.

Set 15 volts on incentive electrode, all the other electrodes are grounded, and the voltage is 0 volts.

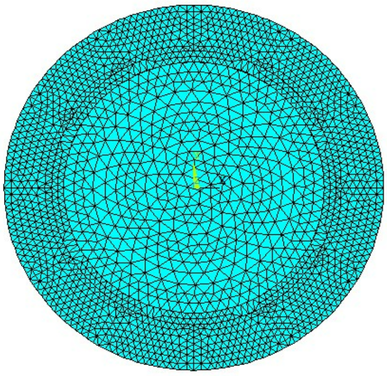

Figure 2. Finite Element Grid

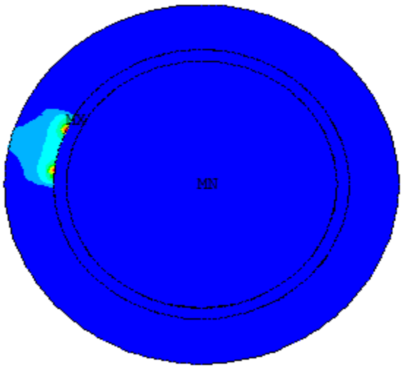

Figure 3. Distribution of Electric Field

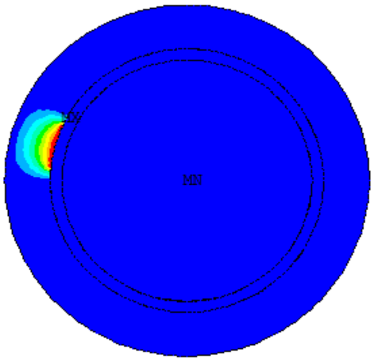

Figure 4. Distribution of Potential

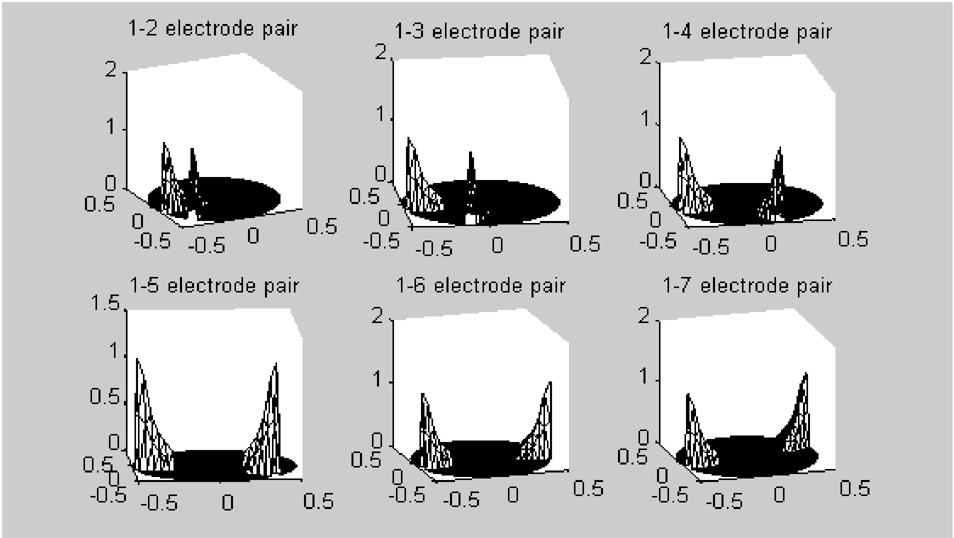

Figure 5. Distribution of Sencitivity Field

For a 12 electrode sensor, simulate the system based on the above parameters. Table 1 shows the electrode capacitance between every electrode pairs.

Table 1**.** Electrode Capacitance of Empty and Full Pipes

Electrode pair	C_{1-2}	C_{1-3}	C_{1-4}	C_{1-5}	C_{1-6}	C_{1-7}
Empty	2.381	0.1021	0.0582	0.0335	0.0251	0.0152
Full	3.8511	0.3587	0.2154	0.1154	0.0721	0.0651

Table 2 gives the values of the sensitivity field.

Table 2. The Value of Sencitivity Field

Electrode pair	C_{1-2}	C_{1-3}	C_{1-4}	C_{1-5}	C_{1-6}	C_{1-7}
Distance	66.78	7.85	3.45	0.88	0.059	0.048
Sencitivity value	-1.32	-1.14	-0.51	-0.43	-0.27	-0.16

From Table 1 and Table 2 it can be noticed that the dielectric have great influence on the capacitance value and small distance between the electrode pair and the sensitivity field will produce high sensitivity value.

4. Conclusion

In the river dredging engineering, pipeline transportation is essential for the normal operation of the dredgers. Generally, there is complex multi-phase flow in the pipeline transportation. The effective control of the flow pattern can save production costs and improve dredging efficiency. The permittivity distribution is very important to investigate the flow pattern, which is significantly influenced by the sensitivity distribution in ETC system. In order to study the sensitivity distribution in ETC system in the pipeline transportation, this paper employs the FEM to investigate the sensitivity distribution. The findings of the simulation tests show that the dielectric and the distance between electrode pair and sensitivity field have obvious influence on the sensitivity distribution in ETC system. It is reasonable to design suitable parameters of dielectric and the distance in the ETC to control the sensitivity distribution. As a result, good performance of control of the flow pattern may be obtained and hence to save production costs and improve dredging efficiency.

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