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Imaging conductive materials with high frequency electrical capacitance tomography

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ABSTRACT

Electrical capacitance tomography (ECT) is known as an imaging technique for dielectric permittivity imaging. A novel ECT sensor model at a high excitation frequency is proposed to examine the capability of the ECT system to image both conductivity and permittivity contrasts. The proposed model uses a complex impedance forward model for the ECT system. This new model indicates that in higher excitation frequency both conductive and dielectric imaging may be feasible. Normally, capacitance tomography is designed for the measurements of imaginary part and resistance tomography is used to take the measurements of real part. The drawback of a typical capacitance tomography at a low excitation frequency, such as 200 kHz is that it cannot be used to measure the conductive phase of a conductive/dielectric mixed fluid, e.g. the gas/water flow. By increasing the excitation frequency, the capacitive impedance of the conductive material decreases and dielectric phenomena of the conductive fluid dominates so that it is possible to use capacitance tomography to characterise the dielectric/conductive flows. This paper presents a development of capacitance tomography with a high excitation frequency in measuring the gas/liquid mixture i.e. gas/water and gas/oil multiphase distributions. Both theoretical and experimental results are presented to verify this feasibility study.

1. Introduction

In recent years, multi-modality of electrical capacitance and electrical resistance tomography systems are been developed for process tomography applications [12,16,21]. The complicated dielectric/conductive gas/liquid multiphase flows can be measured by this dual modality imaging method. The conventional electrical capacitance tomography (ECT) and electrical resistance tomography (ERT) modalities were combined as a dual-modality sensing system (see Table 1). [8,9,11,21] based on the similarity between ECT and ERT in structures and measuring circuits. A permittivity distribution is reconstructed by the ECT data while a conductivity distribution is created by the ERT data [4,12,21]. Theoretically the physical properties of a material are not limited to either permittivity or conductivity, but are a combination of them. When the conductivity of the material is very low, the effect of conductivity on the capacitance measurement circuit can be ignored. In this case the ECT is used to image the permittivity distribution [11]. If the conductivity is high, a conventional ECT will not work because the measuring circuit is approximately shortened by the conductivity path (i.e. the real part of the complex impedance). In this case ERT is required to image the conductivity distribution [16,20].

Although the ECT and ERT sensors can be created as one system, in general they are connected individually to two data acquisition units to collect the capacitance and resistance separately. The drawback of the dual-modality system is that the ERT sensor is intrusive, so that for some industrial applications, it is incompatible. For example, in pharmaceutical industry, for imaging mixing of solids

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Table 1
Current dual-modality tomography systems.

Organisation	Modality	Comments
Cape Town University	ECT/ERT	PSD, microcontroller
ITS company	ECT/ERT	ITS M3C electrical tomography system, 1 MHz
Keele	ERT/EIT	10 kHz to 5 MHz, network analyser
Sheffield	ERT/EIT	16 Electrodes, 2 kHz to 1.6 MHz, DSP
Tianjin University	ECT/ERT	16 ECT/ERT electrodes on one plane, DSP controller
Zhejiang University	ECT/ERT	16-Electrode ERT/12-electrode ECT system, microcontroller

and water phases during the granulating and drying process. The intrusive ERT sensor may cause the varying in physical propriety of the drug particles. In petroleum industry, although the intrusive ERT can characterise the flow regimes of the water phase, the challenge sensor design particularly for holding a high pressure is a major issue.

In this paper an ECT system with an AC voltage with high excitation frequency is proposed to measure the permittivity distributions of these complicated dielectric/conductive multiphase distributions, as with the increase of frequency, the conductance phenomena of the mixture decreases and the capacitance phenomena dominates.

2. Principle

2.1. Complex impedance model

Because the physical sensing dimension of the ECT sensor is significantly smaller than the wavelength of the excitation AC voltage wave, the propagation delay can be ignored and the electro quasi-static (EQS) laws can be applied to the time-varying fields [3,5]. Applying an EQS approximation in Maxwell's equation, the impedance tomography model obeys the following equation:

$$-\nabla\cdot(\sigma(x,y)+j\omega\varepsilon_0\varepsilon_r(x,y))\nabla\phi(x,y)=0 \tag{1}$$

where $\phi(x,y)$ is the electric potential, $E(x,y) = -\nabla\phi(x,y)$ is intensity of the electric field, ω is the angular frequency, $\sigma(x,y)$ is the conductivity of the mixture, $\varepsilon_r(x,y)$ is the permittivity of the mixture, and ε_0 is the permittivity of vacuum.

Fig. 1a shows a typical ECT sensor. The complex impedance of the measured mixture is considered as an equivalent capacitor and resistor in parallel in measuring circuit. In general when the sensor at a low excitation frequency and the mixture has low conductivity, the capacitor dominates, on the contrary when mixture is conductive the resistor dominates. The complex impedance (Z) is defined as the total opposition a device offers to the flow of an alternating current at a given AC-based excitation frequency [19], and is represented as a complex quantity with a phase angle θ, which is graphically shown on a vector plane (see Fig. 1b).

In Fig. 1b, the complex impedance consists of a real part (resistance, R) and an imaginary part (reactance, X), for ECT reactance is capacitance (C). In a parallel connection, the complex impedance can be expressed as:

$$Z=\frac{RX_c^2}{R^2+X_c^2}+j\frac{R^2X_c}{R^2+X_c^2} \tag{2}$$

where X_c is capacitive impedance, $X_c = 1/(\omega C)$. Referring to the parallel model, Eq. (2) can be expressed by admittance:

$$Z=G+j\omega C \tag{3}$$

For the measurement of a conductive mixture, the real part of the complex impedance in Eq. (3) dominates, thus resistance (R) is measured in ERT mode:

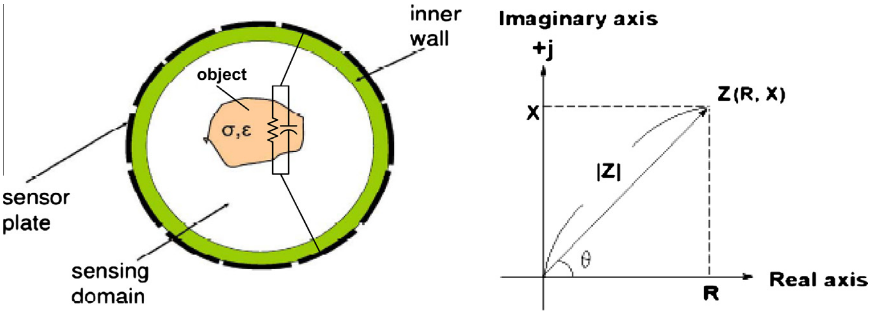
$$R=1/G=|Z|\cos\theta \tag{4}$$

For the measurement of a dielectric component, the imaginary part of the complex impedance dominates, and X_c can be detected by ECT mode:

$$X_c=C=|Z|\sin\theta \tag{5}$$

The phase angle (θ) in the case of domination in dielectric, it is 90°. In the case of dominated conductivity it is 0°, where ERT is fully working.

Fig. 2 illuminates the simulated potential distribution with different permittivity distributions. A constant AC-based [19] excitation voltage with 200 kHz frequency is applied on an electrode. If the materials are purely dielectric ($\sigma = 0$ µS/cm), the potential distribution is only affected by the permittivity. The penetration depth is



(a) cross-section of ECT sensor (b) impedance vector

Fig. 1. Complex impedance of the measured mixture in a conventional ECT sensor.