Electrical Impedance Tomography Spectroscopy Method for Characterising Particles in Solid-Liquid Phase

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Abstract:

Electrical impedance tomography (EIT) is one of the process tomography techniques to provide an on-line non-invasive imaging for multiphase flow measurement. With EIT measurements, the images of impedance real part, impedance imaginary part, phase angle, and magnitude can be obtained. However, most of the applications of EIT in the process industries rely on the conductivity difference between two phases in fluids to obtain the concentration profiles. It is not common to use the imaginary part or phase angle due to the dominant change in conductivity or complication in the use of other impedance information. In a solid-liquid two phases system involving nano- or submicro-particles, characterisation of particles (e.g. particle size and concentration) have to rely on the measurement of impedance phase angle or imaginary part. Particles in a solution usually have an electrical double layer associated with their surfaces and can form an induced electrical dipole moment due to the polarization of the electrical double layer under the influence of an alternating electric field. Similar to EIT, electrical impedance spectroscopy (EIS) measurement can record the electrical impedance data, including impedance real part, imaginary part and phase angle (θ), which are caused by the polarization of the electrical double layer. These impedance data are related to the particle characteristics e.g. particle size, particle and ionic concentrations in the aqueous medium, therefore EIS method provides a capability for characterising the particles in suspensions. Electrical impedance tomography based on EIS measurement or namely, electrical impedance tomography spectroscopy (EITS) could image the spatial distribution of particle characteristics. In this paper, a new method, including test set-up and data analysis, for characterisation of particles in suspensions are developed through the experimental approach. The experimental results on tomographic imaging of colloidal particles based on EIS measurement using a sensor of 8 electrodes are reported. Results have demonstrated the potential as well as revealed the challenge in the use of EIS and EITS for characterisation of particle in suspension.

Key words: electrical impedance tomography spectroscopy, particle, solid-liquid two phases, imaging

1. INTRODUCTION

The electrical impedance tomography (EIT) technique shares the same basic measurement principle with the electrical impedance spectroscopy (EIS). Both of them use the four electrodes system to provide an exciting current to two electrodes and measure the voltage difference between the other two electrodes. Electrical impedance spectroscopy cannot provide an "image" of the sample but can give impedance parameters over a wide range of frequencies. Electrical impedance tomography utilizes a set of electrodes (could be 8, 16, 32, or 64) to measure the impedance of samples from different electrodes pairs and then obtain the images by data acquisition and reconstruction process. The current form of EIT technique may provide images at several fixed frequencies[1]; however, electrical impedance tomography based on EIS measurement or namely, electrical impedance tomography spectroscopy (EITS) can produce imaging over a wide range of frequencies, using this principle[2].

Electrical impedance spectroscopy has been used to analyse the dielectric properties of materials (solid-liquid two phase system or colloids), and is also called dielectric spectroscopy[3]. The dielectric measurement of colloidal dispersions could provide the information about the interface between the solid (particles) and liquid (dispersing media)[4]. If an AC electric field $E = E_0 \exp(i\omega t)$ is applied to a particle, a dipole moment can be induced on the particle surface due to the deformation of the electric double layer. The macroscopic display of induced dipole moment is usually represented by the impedance parameters, including the impedance real part, imaginary part, phase angle and the relaxation frequency. These quantities are related to the surface properties of the particles or the solid phase, the nature of the dispersed medium, particle size and also the particle concentration. EITS technique is based on EIS measurement and could provide in-situ visualization for solid-liquid two phase. In addition the images of impedance imaginary part and phase angle part obtained by EITS provide the potential application of characterizing particles in liquid phase. In this paper, the electrical impedance spectra of the phantom with silica suspension in water were studied firstly. After that, the experimental results on tomographic imaging based on EIS measurement using a sensor of 8 electrodes are reported. The measurement strategy and the images of silica suspensions in water based on EITS measurement are reported and discussed.

2. EXPERIMENTAL DETAILS

2.1. Experimental setup

The devices for EITS measurement include an impedance analyzer, a cylinder shaped vessel with an 8-electrode sensor (Figure 1), and Perspex chamber (Figure 1). During EITS measurement, the cylinder shaped vessel is filled by water and the chamber is filled by the silica particle suspension. For the measurement of reference, both vessel and chamber were filled by the water with same conductivity. The general methodology of electrical impedance tomography (EIT) based on spectroscopic measurement is realised through applying an exciting current onto one pair of electrodes within an 8-electrode sensor and measuring the resulting voltages sequentially on other adjacent electrode pairs. Figure 2 shows a schematic of this adjacent data sensing strategy for an 8-electrode system. The frequency range of EIS measurement is from 1 Hz to 32 MHz. After all the electrodes were excited and voltages measured, the total number of electrical impedance spectra, 20, can be completed. Then 20 electrical impedance data at a certain frequency can be used for imaging reconstruction based on the back projection algorithm. The reconstructed cross-sectional image represents the electrical impedance distribution in a phantom.

FIGURE 1: Cylindrical vessel with an 8-electrode sensor and the Perspex chamber

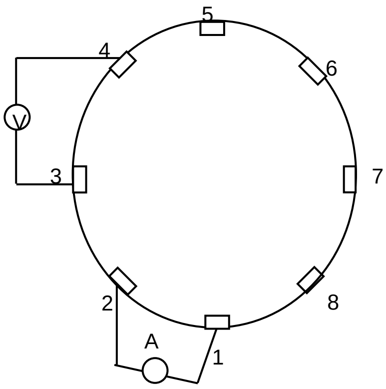


FIGURE 2: The schematic of adjacent data sensing strategy for an 8-electrode sensor

2.2. Materials and methods

Aqueous silica suspensions were ordered from Fuso Chemical Co., Ltd. Japan. The silica suspension with particle size of 220 nm and particle concentration of 23.5 wt% was used in EITS measurement of the phantom with one silica suspension in water. Two silica suspensions with particle size of 220 nm and 35 nm (19.5wt% particle concentration) were used in EITS measurement of the phantom with two silica suspensions in water. In both of the experiments, the conductivities of water and silica suspensions were kept same. When the vessel and chamber were all filled by water, it was treated as reference.

3. RESULTS AND DISCUSSIONS

3.1. EIS on colloidal silica suspension

The electrical impedance spectra for the phantom of silica suspension in water were measured at different electrode pairs (electrode pairs 1 and 2 are fixed for current exciting) and the result is shown in Figure 3. Five arcs can be observed in Figure 3 (a), which shows the dielectric response of the phantom at different electrode pairs under the external electric field. Figure 3 (b) shows that the impedance real parts start decrease at about 10 kHz, which shows the relaxation occurs at this frequency range. Several peaks can be observed in the plot of impedance imaginary parts (figure 3 (c)), which is the characteristic of relaxation caused by the polarization of electrical double layer aroud the silica particles. It can be seen that the relative change of impedance imaginary part measured at different electrode pair is low at 1000 Hz, but it becomes much bigger at 80 kHz. The big relative change could be beneficial for good quality of image, therefore in the imaging reconstruction process, the impedance data at 80 kHz was used in order to get images with good quality. Figure 3(d) shows the phase angles measured at different electrode pairs as a function of frequency. Similar with Figure 3 (c), the relative change of impedance phase angles measured at different electrode pair is very small at 1000 Hz, but it becomes much bigger at 80 kHz. Therefore, in the next section, the images were reconstructed based on the EIS data at 1000 Hz and 80 kHz, respectively, using the back projection algorithm.

3.2. Tomographic images on colloidal silica suspensions

Firstly, the images of silica suspension (220 nm, 23.5 wt%) in water are discussed. Figures 4 and 5 show the reconstructed images of silica suspension (220 nm, 23.5 wt%) in water obtained at 1000 Hz and 80 kHz, respectively. From Figure 4, no significant effect of colloidal suspension can be observed in all of the images at low frequency. From Figure 5 (b) and (c), the effect of silica suspension can be observed clearly in the imaginary part and phase angle images with a yellow or green coloured strip existing in the middle of the phantom. No obvious effect of silica suspension can be observed in the images of impedance real part and magnitude (Figure 5 (a) and (d)).

As discussed in section 3.1, the imaginary part image and phase angle image represent the electric polarisation of double layers on the surface of colloidal particles. Since the conductivity of the silica suspension in chamber is adjusted to the same value as the conductivity of water in the vessel, no contribution from conductivity is involved in the images of the imaginary part and phase angle. The only contribution is from the electric polarisation of colloidal particles. Our research on electrical impedance spectra of silica suspensions has proved that the electric polarisation of colloidal particles relates to the particle size[5]. Therefore, in the secondary part of the experiments, the images of two silica suspensions of different particle size are studied.

Figure 6 shows the reconstructed images of two silica suspensions (220 nm and 35 nm) with the same concentration and conductivity of water obtained at 316 kHz. Because the conductivities of two silica suspensions are adjusted to the same value as the conductivity of water, the relative changes of impedance parameters are very small. In order to get images of good quality, the frequency of 316 kHz was chosen to get large relative changes. From Figure 6 (b) and (c), the effect of silica suspensions can be observed by a yellow or green colour strip existing in the middle of the phantom. However, the difference due to the particle size cannot be observed. The possible reasons are complicated. One of the possible reasons is that the relative changes caused by different particle size are so small that they cannot be distinguished in the reconstructed pictures. Another possible reason is the common mode voltage effect, which cannot be fully eliminated in the hardware and operation and therefore cause systemic error in the tomographic measurements. Also, the limitations of the imaging resolution from an 8-electrode EITS sensor could be the possible reason.

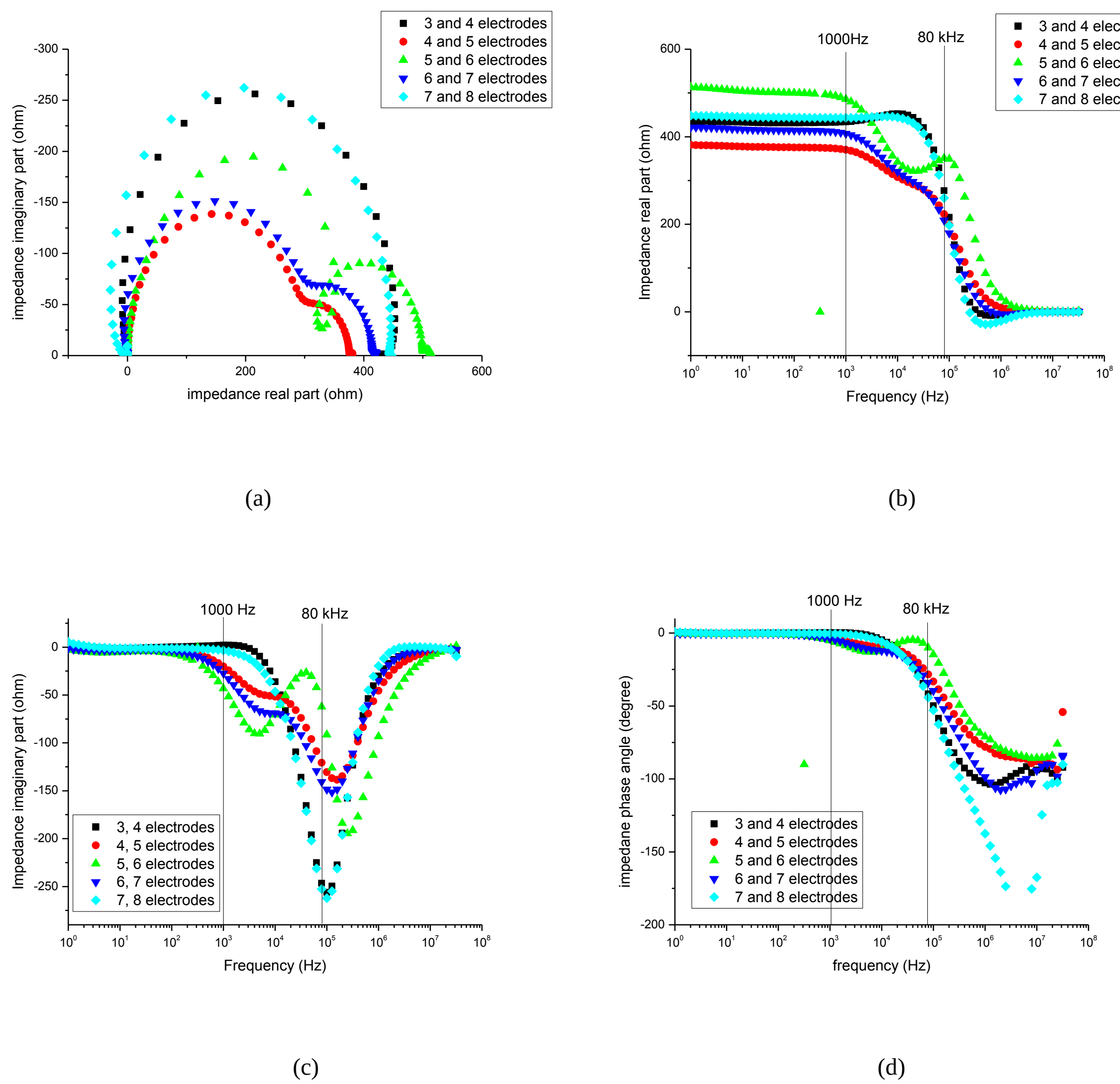
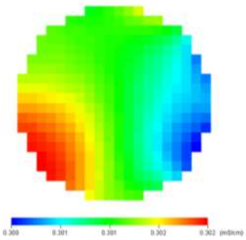
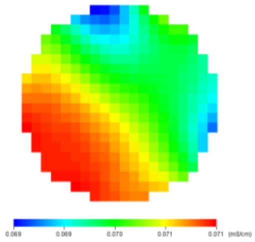


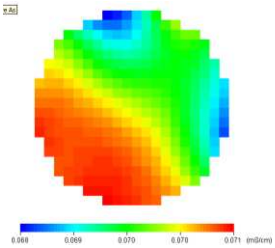
FIGURE 3: Impedance spectra for the phantom of silica suspension in water: (a) cole-cole plot of impedance; (b) impedance real part vs. frequency; (c) impedance imaginary part vs. frequency; (d) phase angle vs. frequency plots.



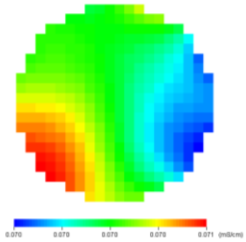
(a) real part image



(b) imaginary part image

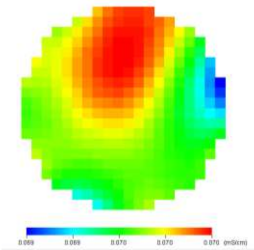


(c) phase angle (tan (θ)) image

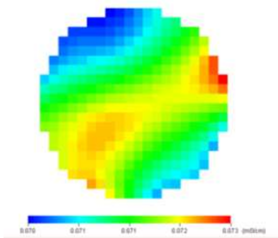


(d) magnitude part image

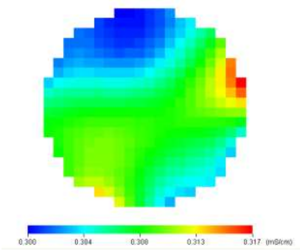
FIGURE 4: Reconstructed images of silica suspension (220 nm, 23.5 wt%) in water obtained at 1000 Hz (a) real part image, (b) imaginary part image, (c) phase angle (tan (θ)) image, and (d) magnitude part image



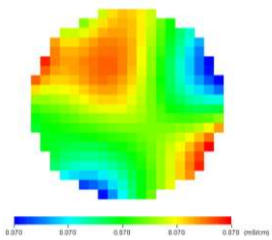
(a) real part image



(b) imaginary part image

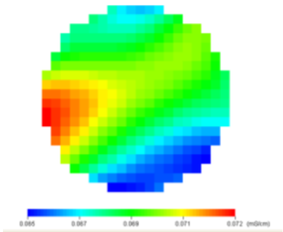


(c) phase angle (tan (θ)) image

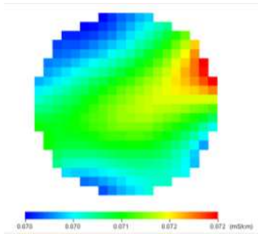


(d) magnitude part image

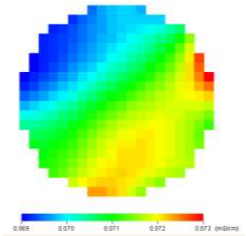
FIGURE 5: Reconstructed images of silica suspension (220 nm, 23.5 wt%) in water obtained at 80 kHz (a) real part image, (b) imaginary part image, (c) phase angle (tan (θ)) image, and (d) magnitude part image



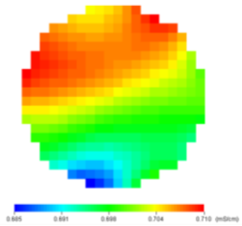
(a) real part image



(b) imaginary part image



(c) phase angle (tan (θ)) image



(d) magnitude part image

FIGURE 6: Reconstructed images of two silica suspensions (220 nm and 35 nm, 19.5 wt%) in water obtained at 316 kHz (a) real part image, (b) imaginary part image, (c) phase angle (tan (θ)) image, and (d) magnitude part image

4. CONCLUSION

The electrical impedance tomography imaging based on EIS measurement has been verified experimentally. The feasibility of applying the electrical impedance tomography technique for particle characterisation has been studied by measuring the images of silica suspensions in water. At the frequency of 79.4 kHz, the imaginary part and phase angle images of silica suspension can be observed and show the characterisation of the electrically polarised double layer on the particle surface. However, the particle size effect cannot be observed experimentally from EITS measurement. The phase angle image of particle suspensions with different particle size shows an abnormal strip pattern. The possible reasons for this result could be the common mode voltage effect on the measurement and the limits of the imaging resolution from an 8-electrode EITS sensor.

For the future work, the instrumentation could be improved to decrease the effect of common mode voltage in the electrical impedance tomography imaging measurement. Becides, in order to decrease the time consuming, the current EITS technique based on the manually operation could be improved by developing fast spectral sensing method, which should be a good choice for applying the EITS method for imaging the spatial and temporal distribution of particle characteristics in solid-liquid two phase system.

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