Investigation of Complex Permittivity/Conductivity Distribution by Electrical Tomography

R C Wang1,4, Y Gao1, G J Wang1, Q P Li1, Q Wang1 and H G Wang2,3

1Beijing residential building design and Research Institute Co., Ltd, Beijing 100005, China
2Institute of Engineering Thermophysics, Chinese Academy of Science, Beijing 100190, China
3University of Chinese Academy of Sciences, Beijing 100049, China

E-mail: ruicanw@163.com

Abstract. The electrical tomography technology is a multi-phase flow detection technology. This technology has the advantages of non-radiation, non-invasive and visualization, can be widely used in traditional energy field and new energy field. The permittivity and conductivity, as the basic electrical parameters of material, are closely related to the distribution of material in multiphase flow. However, in the actual multiphase flow, due to the non-uniform distribution of permittivity and conductivity in time and space, the accuracy and validity of measuring instruments are challenged. The main target of this research is to investigate the application of electrical capacitance tomography (ECT), electrical resistance tomography with voltage excitation (ERTv) and electrical resistance tomography with current excitation (ERTc) on the multiphase flow with complex permittivity and conductivity distribution. The final objective based on the above research is to provide suitable tomography modual for different multiphase flow process. The experimental results show that ECT is suitable for measuring dry gas-solid fluids. ERTv is better for measuring high water content gas-solid fluids and low conductivity gas-liquid fluids, while ERTc is better for measuring continuous phase conductivity gas-liquid fluids.

1. Introduction
Multiphase flows are widely existed in the field of traditional energy, likes energy, chemical, petroleum, metallurgy, pharmaceutical industry. In addition, multiphase flow also exists in the field of new energy, for example, when biomass is burned in a fluidized bed, there are different phases such as air, water vapour and biomass. Accurate measurement of the multiphase flow parameters is the key to optimize and control the process to improve the process effectively [1]. However, due to the complex multiphase flow characteristics involved in the industry process, it is difficult to measure the flow parameters directly. For example, in the pharmaceutical coating and drying process in a fluidized bed, the permittivity significantly changes due to the particle’s moisture change. With the increase of moisture content, the fluid changes from non-conductive to low conductive [2]. Similarly, in oil exploitation and transportation process, the heterogeneity of oil and water phase distribution results in the change of conductivity.

Electrical Tomography (ET), as a non-invasive and non-radiative visualization measurement technology, has attracted wide attention in the measurement of multiphase flow. Electrical Capacitance
Tomography (ECT) and Electrical Resistance Tomography (ERT) are two main commonly used working modes of ET. Their subjects covered permittivity $\varepsilon$ and conductivity $\sigma$ respectively [3].

In the measurement of parameters of gas-solid multiphase flow, ECT has extensive application. In 1989, Huang designed and manufactured the first ECT data acquisition system based on DC charge and discharge [4]. Since then, ECT has developed rapidly and has been widely used in the fields of gas-solid multiphase flow measurement in fluidized bed [5-9], oil pipeline transportation [10, 11], pneumatic transportation system [12 13], moisture separation [14], etc. However, ECT has problems in measuring continuous-phase conductivity multiphase flow. Li et al used ECT to measure liquid moisture in multiphase flow of oil, gas and water, and indicated the reconstructed image of ECT was distorted when WLR was more than 30% [15]. In addition, Wang et al. applied ECT in gas-solids multiphase flow and indicated that ECT performed well not when measuring multiphase flow with a moisture content of more than 25% [2]. It’s mainly due to the fact that as the moisture content increases, the fluid changes from non-conductive to low-conductive state, shorting the electrodes. Thus, ECT performs better in the measurement of non-conductive gas-solid flow [16].

Electrical resistance tomography (ERT) is mainly applied in measuring a multiphase flow with conductive continuous phase. It has been used in the industrial processes such as petroleum production and transportation, solid suspension monitoring and mixing of solid and liquid mixtures [17-19]. At present, the general ERT system adopts the strategy of current excitation and voltage measurement (ERTc). Leeds University, UK applied research on ERTc earlier. Williams et al. applied ERTc in the hydrocyclone separator to monitor the working conditions. The results show that the measurement results obtained by ERTc are basically consistent with the actual operation of the hydrocyclone separator [20]. However, when the ERTc electrode is covered by materials with low conductivity, the current source will be shorted, resulting in poor imaging quality [21].

Electrical Resistance Tomography with Voltage Excitation (ERTv) is proposed to replace the traditional ERTc for measuring low-conductive dielectrics, consequently [22]. However, there are few related applications of ERTv at present, and there is no clear conclusion about the suitable measurement range of ERTv. Therefore, the main target of this research is to investigate the application of ECT, ERTv and ERTc on the multiphase flow with complex permittivity and conductivity distribution. And the final objective provides suitable tomography modual for different multiphase flow process.

2. Measurement principle and sensor design

2.1. Principle and composition
ECT and ERT are similar in system composition and working principle. They generally consist of array sensor, data acquisition system and computer for hardware control and image reconstruction. The array sensor is generally composed of detection electrode, insulation frame and shielding electrode, as shown in figure 1 and figure 2.

Figure 2 shows the schematic diagram of 8-electrode ECT, ERTc/ERTv sensors, respectively. The ECT electrode is placed outside the pipe wall, while ERT electrode needs to be placed inside the pipe wall. It’s mainly because that ERT needs immediate contact between the electrode and material under test to conduct current signals.
The principle of ECT and ERT can be described as that the exciting current/voltage is injected into the measured area through the exciting electrode to form a space sensitive field. While the distribution of medium in the measured field changes, the distribution of permittivity/conductivity will change accordingly, leading to the change of voltage/current values obtained by the boundary. Thus the measurement values of voltage/current include the distribution of medium in the field. The measured values are fed into the computer and processed by image reconstruction algorithm. Finally, images reflecting the distribution of the measured medium can be obtained.

![Schematic diagram of 8-electrode ECT sensor](image1)

![Schematic diagram of 8-electrode ERTc/ERTv sensor](image2)

**Figure 2.** 8-electrode ECT and ERTc/ERTv sensor

### 2.2. Image reconstruction algorithm

ECT/ERT involves the solution of forward problem and inverse problem. The forward problem is to solve the distribution of electromagnetic field by using the medium distribution and boundary conditions of the measured field. Conversely, the inverse problem is based on the electromagnetic field and boundary conditions to solve the medium distribution. The results of inverse problems are usually presented in the form of images, so the solution of inverse problems is called "image reconstruction".

As a simple and fast imaging algorithm, the Linear back projection (LBP) is commonly used, which can be calculated by

\[
g = S^T \cdot \lambda
\]

where \( S \) stands for the sensitivity matrix. For ECT, \( g \) stands for the regularized vector of permittivity, \( \lambda \) stands for the regularized vector of capacitance, For ERT, \( g \) stands for the regularized vector of conductivity, and \( \lambda \) stands for the regularized vector including relevant details of loss resistance. The \( S \) can be expressed as

\[
S_{ij}(x,y) = \iint_{p(x,y)} \frac{\nabla \phi_i(x,y)}{V_i} \frac{\nabla \phi_j(x,y)}{V_j} \, dx \, dy
\]

To ECT and ERT, \( S_{ij} \) represents the sensitive field at coordinates \((x,y)\), when the electrode \( i \) and \( j \) represent the encourage electrode with voltage values \( V_i \) and \( V_j \) respectively, \( \phi_i \) and \( \phi_j \) are the potential value respectively [23].

Correlation coefficient [24] \( (CC) \) is often used to evaluate the correlation between reconstructed image and real distribution. The higher the \( CC \), the better the reconstructed image quality. The \( CC \) can be expressed as

\[
CC = \frac{\sum_{i=1}^{N_p} (g_i - \bar{g})(\hat{g}_i - \bar{g})}{\sqrt{\sum_{i=1}^{N_p} (g_i - \bar{g})^2 \sum_{i=1}^{N_p} (\hat{g}_i - \bar{g})^2}}
\]
where $g$ and $\hat{g}$ stands for the permittivity or conductivity vector of the true distribution and the reconstructed image respectively, and $N_p$ stands for the pixels number.

3. Experimental set-up

3.1. Facility

Figure 3 (a) shows the composition of ECT system, which composes of a computer for system control, an AC-ECT data acquisition system, and an 8-electrode sensor. Figure 3 (b) is a schematic diagram of ERTv system. The ERTv system composes of a computer with LABVIEW software, a NI USB-6341 DAQ for data acquisition, an 8-electrode sensor, and a circuit board for measuring and controlling switching states. The function of NI is to produce excitation signal and collect measurement signal, printed circuit boards (PCBs) are used to control the electrodes state and process signals, and computers are used to acquire resistance data and image reconstruction. The operating frequency of ERTv system is controlled at 10 kHz [25]. Figure 3 (c) is the ERTc system. The ERTc system composes of a computer for system control, an ERTc data acquisition system produced by Shenzhen Leengstar Technology Co., Ltd, and an 8-electrode sensor.

![ECT system](image1)

(a) The ECT system (①. ECT sensor, ②. ECT measurement system, ③. PC)

![ERTv system](image2)

(b) The ERTv system (①. ERTv sensor, ②. NI-DAQ, ③. Measurement and switching board, ④. PC)

![ERTc system](image3)

(c) The ERTc system (①. ERTc sensor, ②. ERTc measurement system, ③. PC)

Figure 3. Sensors and data acquisition device for static experiment

3.2. Experimental materials and parameters

To assess the performance of three measurement systems when measuring multiphase flow, corn flour with different rate of moisture content, tap water, pure water and air are applied. Table 1 shows the
particular parameters of these material. In addition, corn flour with different rate of moisture content, salt water with different conductivity are applied to research the influence of moisture content and conductivity on the measurement.

**Table 1.** Detailed parameters of measured material

| Index | Material    | Permittivity | Conductivity (µS/cm) |
|-------|-------------|--------------|----------------------|
| 1     | Air         | 1.0          | 0                    |
| 2     | Corn flour  | 6.1          | 0                    |
| 3     | Pure water  | 80.0         | 10                   |
| 4     | Tap water   | 80.0         | 270-290              |

4. Results and analysis

4.1. The effect of permittivity on image reconstruction for ECT and ERTv

Corn flour with different moisture content is applied to estimate the influence of permittivity on reconstruction image for ECT and ERTv, and air-corn annular flow and bubble flow are adopted. The PVC pipe placed in the sensor is used to help simulate the two flow patterns. Moisture content is the ratio of water quality to total mass. The reconstructed image of air-corn annular flow for ECT is shown in figure 4. In the real flow pattern, the blue area represents air and the red represents corn flour.

**Figure 4.** Reconstructed image of air-corn annular flow for ECT and ERTv

**Figure 5.** Correlation coefficient of annular flow for ECT and ERTv
It can be seen from the reconstruction image of ECT in figure 4, while corn flour with a moisture content of no more than 10% on the edge with air as background, ECT performs well. When the moisture content of corn flour is 20%, the red area in the reconstructed image is obviously shrinked. While the moisture content increases to 30% or 40%, the red area in the reconstructed image is seriously shrinked and the quality of reconstruction image is poor. It can be seen from the image reconstructed of ERTv, while the background material is air, the position of the red area in the reconstructed image appears obvious deviation, which is inconsistent with the real distribution of the medium. The main reason is that while the background material is air, it can not transmit electrical signals, which makes the measured value distorted.

It can be seen from the correlation coefficient of annular flow for ECT and ERTv in figure 5, the reconstructed image quality of ECT is better, and the image is consistent with the real condition of annular flow. It can be seen that when the moisture content is less than 20%, the quality of reconstructed image is better. With the increase of moisture content, the reconstructed image quality decreases significantly. The correlation coefficients of reconstructed images measured by ERTv are below 0.5, and the reconstructed images do not match the real distribution of medium.

The reconstructed image of air-corn bubble flow for ECT and ERTv is shown in figure 6. During the experiment, the permittivity of the background medium is changed by changing the moisture content of the background medium in the sensor.

| Flow pattern | Sensor | Moisture content |
|--------------|--------|-----------------|
| ECT          | 10%    | 15%             |
|              | 20%    | 25%             |
|              | 30%    | 40%             |
| ERTv         |        |                 |

Figure 6. Reconstructed images of wet corn-air bubble flow for ECT and ERTv

It can be seen from figure 6 that when the moisture content of background medium is 10% in bubble flow, ECT has the best image reconstruction effect. With the moisture content of background increasing, the reconstructed image quality decreases by degrees. When the moisture content of background is not more than 20%, the ECT reconstruction image can represent the real distribution of medium more accurately. While the moisture content exceeds 20%, the reconstructed image of ECT shows obvious distortion, which is not consistent with the real distribution of the measured medium. On the contrary, the reconstructed image of ERTv is not obviously distorted with the increase of background moisture content. While the background moisture content is 10%~40%, the ERTv reconstructed image represents the real distribution of the measured medium more accurately.

Figure 7 shows the correlation coefficient of wet corn-air bubble flow for ECT and ERTv. It shows that the correlation coefficient of ECT reconstructed image decreases gradually from 0.85 to 0.3 with the increase from 10% to 40% of moisture content. On the contrary, while the moisture content is 10%, the correlation coefficient of ERTv reconstructed image is the lowest, which is about 0.7. When the moisture content is between 10% and 20%, the correlation coefficient decreases gradually with the increase of moisture content. When the moisture content of the background medium reaches 20%, the correlation coefficient of the reconstructed image maintains above 0.8, and does not change significantly with the change of moisture content. It shows that ERTv can accurately represent the distribution of the measured medium in bubble flow.
4.2. Analysis of full-field measurements

The moisture content of the medium has a great influence on the image reconstruction, and the moisture content is closely related to the permittivity. To study the relationship between the moisture content and permittivity of corn flour, ECT was used to test the corn flour with moisture content of 0%, 10%, 15%, 20%, 25%, 30% and 40% for full field. The analysis was based on the measured value for the empty field. Figure 8 shows the fluctuation curve of the raw data measured.

It can be seen from the figure 8, when the full-field medium is air and corn flour with different moisture content, the fluctuation trend of the measurement by ECT is basically the same. When the measured area is filled with air, the fluctuation amplitude is the largest and the value is the smallest at the trough. While corn flour fills the measured area, the fluctuation amplitude decreases gradually with the increase of moisture content of corn flour, and the measurement in the trough is getting larger and larger.

The average value of the raw data obtained when air fulfills the measured area is taken as the base point, and the average value of measurement of corn flour with different moisture content are recorded as the relative permittivity. Figure 9 shows the change of relative permittivity with the moisture content of the medium. This figure shows the relationship between the moisture content of corn flour and the relative permittivity. As can be seen from figure 9, the relative permittivity increases approximately linearly with the increase of moisture content.
Figure 9. Relative permittivity of corn flour with different moisture content measured by ECT

4.3. The effect of conductivity on image reconstruction for ERTc and ERTv

The effects of different conductivity and flow pattern on the ERTc and ERTv reconstructed images were studied by static experiments. Experiments were carried out by adding salt with different mass fractions to tap water. Various saline with different concentration gradients and two different flow patterns were designed. In the flow pattern, the red part represents air and the blue part represents salt water.

| Flow pattern | Sensor | Conductivity (μS/cm) |
|--------------|--------|----------------------|
|              |        | 289                  |
|              |        | 552                  |
|              |        | 800                  |
|              |        | 1880                 |
|              |        | 2560                 |

![Graph showing relative permittivity vs. moisture content](image)

Figure 10. Reconstructed images of saline-air in annular flow and bubble flow for ERTc and ERTv

From the reconstructed images of ERTc and ERTv in figure 10. It can be seen that the reconstructed image obtained by ERTc cannot detect the presence of salt water while the background medium is air. It shows that the ERTc system is not suitable for measuring the saline-air annular flow. The reconstructed image of ERTv shows the distribution of medium in the image is quite different from the real distribution. Therefore, ERTc and ERTv are not suitable for the case that air as background medium. This is because while measuring with ERT, the electrodes need to contact the conductive medium directly to conduct electrical signals. Due to the air is not conductive, it is impossible to transmit the electrical signal to the measuring electrode effectively, which leads to abnormal imaging and cannot represent the real distribution of medium.
The reconstructed image of ERTc for saline water with different conductivity as background does not change significantly with the increase of the conductivity. However, the reconstructed image of ERTv can represent the distribution of medium in the measured while the background conductivity does not exceed 800 μS/cm. However, when the conductivity of background medium increases to 1880 μS/cm, the red area representing the air is distorted obviously in the reconstructed image. When the conductivity continues to rise to 2560 μS/cm, the reconstructed image is seriously distorted and cannot accurately represent the real distribution of medium in the measured area. Figure 11 shows the correlation coefficients of ERTc and ERTv reconstructed images in bubble flow. The same conclusion can be drawn from the images.

![Figure 11. Correlation coefficient of bubble flow with different conductivity in bubble flow for ERTc and ERTv](image)

Generally speaking, the ERTc system is more stable than ERTv system for measuring saline-air bubble flow with different conductivity, and the measurement range of ERTc system is wider. When the conductivity of background medium is 2560 μS/cm, the image distortion is serious. When the conductivity of background medium is more than 2560 μS/cm, ERTv has a poor performance.

5. Conclusion
The performance of ECT, ERTv and ERTc in imaging multiphase flow with different moisture content, different conductivity and different flow patterns are studied in this paper. Table 2 shows the main measurement results of ECT, ERTv and ERTc under different flow patterns (‘√’ indicates acceptable, ‘×’ indicates unacceptable and ‘-’ indicates no measurement, “partial” means it can be measured under a part of conditions). The results show that the image qualities of ECT, ERTc and ERTv strongly depend on the flow patterns in experiment. The following conclusions can be drawn:

(1). ECT has better performance in the flow regime of core flow than in the bubble flow. The reconstructed image agrees well with the true distribution when the water content is less than 20%.

(2). ERTv performs better in bubble flow regime than in core flow regime, and the image qualities are especially good for wet particles with higher water content and the conductivity should be no more than 2560 μS/cm.

(3). ERTc also has better performance in bubble flow regime than in core flow regime. In addition, ERTc behaves well in the multiphase flow with continuous phase conduction.

| Sensor | Core-air flow | Saline-air flow |
|--------|---------------|-----------------|
|        | Annular flow | Bubble flow | Annular flow | Bubble flow |
| ECT    | √             | partial       | -             | ×            |
| ERTv   | ×             | √             | ×             | partial     |
| ERTc   | ×             | ×             | ×             | √            |

Table 2. Main results
Acknowledgement
The authors would like to thank the National Natural Science Foundation of China (No.61320106004 and No.61771455) for supporting this work.

References
[1] Che D F and Li H X 2007 Multiphase Flow Technology and Application Xi’an Jiaotong University Press
[2] Wang H G, Zhang J L, Ramli M F, Mao M X, Ye J M, Yang W Q and Wu Z P 2016 Imaging wet granules with different flow patterns by electrical capacitance tomography and microwave tomography Meas Sci Technol 27(11) 1-13
[3] Wang H X 2013 Electrical tomography Science Press
[4] Huang S M and Plaskowski A B 1988 Capacitance-based tomographic flow imaging system Electron. Lett 24(7) 418-19
[5] Kühn F T, Schouten J C, Mudde R F and Bleekvanden C M and Scarlett B 1996 Analysis of chaos in fluidization using electrical capacitance tomography Int. J. Multiphase Flow 23(3) 361
[6] Makkawi Y T and Wright P C 2002 Fluidization regimes in a conventional fluidized bed characterized by means of electrical capacitance tomography Chem Eng Sci 57(13) 2411-37
[7] Chaplin G, Pugsley T, Lee L V D, Kantzas A and Winters C 2005 The dynamic calibration of an electrical capacitance tomography sensor applied to the fluidized bed drying of pharmaceutical granule Meas Sci Technol 16(6) 1281
[8] Warsito W and Fan L S 2005 Dynamics of spiral bubble plume motion in the entrance region of bubble columns and three-phase fluidized beds using 3D ECT Chem Eng Sci 60(22) 6073-84
[9] Wang H G, Yang W Q, Dyakowski T and Liu S 2006 Study of bubbling and slugging fluidised beds by simulation and electrical capacitance tomography AIChE J 52(9) 3078-87
[10] Yang W Q, Stott A L and Beck M S 1995 Development of capacitance tomographic imaging systems for oil pipeline measurements Rev Sci Instrum 66(8) 4326-32
[11] Ismail I, Gamio J C, Bukhari S F A and Yang W Q 2005 Tomography for multi-phase flow measurement in the oil industry Flow Meas Instrum 16(2) 145-55
[12] Jaworski A J and Dyakowski T 2001 Application of electrical capacitance tomography for measurement of gas-solids flow characteristics in a pneumatic conveying system Meas Sci Technol 12(8) 1109
[13] Yang W Q and Liu S 2000 Role of tomography in gas/solids flow measurement Flow Meas Instrum 11(3) 237-44
[14] Yang W Q, Chondronasios A, Nattrass S, Nguyen V T, Betting M, Ismail I and McCann H 2004 Adaptive calibration of a capacitance tomography system for imaging water droplet distribution Flow Meas Instrum 15(5) 249-58
[15] Li Y, Yang W Q, Xie C G, Huang S M, Wu Z P, Tsamakis D and Lenn C 2011 Gas/oil/water flow measurement by electrical capacitance tomography Meas Sci Technol 24(7) 074001
[16] Yang W Q, Yang C Y, Wang H G, Cui Z Q and Gao Z T 2013 Online monitoring of gas-solid two-phase flow using projected CG method in ECT image reconstruction Particuology 11(2) 204-15
[17] Ismail Isnial A S, Ismail I, Zoveidavianpoor M, Mohsin R, Piroozian A, Misnan M S and Sariman M Z 2015 Review of oil–water through pipes Flow Meas Instrum 45 357-374.
[18] Mann R, Dickin F J, Wang M, Dyakowski T, Williams R A, Edwards R B, Forrest A E and Holden P J 1997 Application of electrical resistance tomography to interrogate mixing processes at plant scale Meas Sci Technol 52(13) 2087-97
[19] Sardeshpande M V, Kumar G and Aditya T 2016 Mixing studies in un baffled stirred tank reactor using electrical resistance tomography Flow Meas Instrum 47 110-21
[20] Williams R A, Jia X and West R M 1999 Industrial monitoring of hydrocyclone operation using
electrical resistance tomography \textit{Miner Eng} \textbf{12}(10) 1245-52

[21] Sun J and Yang W Q 2013 Fringe effect of electrical capacitance and resistance tomography sensors \textit{Meas Sci Technol} \textbf{24}(7) 464-75

[22] Sun J and Yang W Q 2015 A dual-modality electrical tomography sensor for measurement of gas–oil–water stratified flows \textit{Measurement} \textbf{66} 150-60

[23] Wang R C, Frias M A R, Wang H G, Yang W Q and Ye J M 2018 Evaluation of electrical resistance tomography with voltage excitation compared with electrical capacitance tomography \textit{Meas Sci Technol} \textbf{29}(12) 125401

[24] Xie C G, Huang S M, Hoyle B S, Thorn R and Beck M S 1992 Electrical capacitance tomography for flow imaging: system model for development of image reconstruction algorithms and design of primary sensors \textit{IEE P-Circ Dec Syst} \textbf{139}(1) 89-98

[25] Frias M A R and Yang W Q 2017 Effect of parasitic resistance in electrical resistance tomography with voltage excitation \textit{2017 IEEE International Conference on IST}