Application of Electrical Capacitance Tomography in Particulate Process Measurement – A Review

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Abstract

Particulate process measurement presents challenges because it often involves multiphase flow. Due to its advantages over other tomography modalities, electrical capacitance tomography (ECT) is widely applied in monitoring and measuring particulate processes. This paper presents a review on the application of ECT in particulate process measurement, including the monitoring of flow regime and solids distribution, solids flow velocity measurement, and fluidized bed dryers. The electrostatic phenomenon and the effect of electrostatics on the performance of ECT systems are also addressed. Finally, the challenges to ECT for particulate process measurement are given.

Keywords: Particulate Process; ECT; Tomography; Electrostatics; Review.

1. Introduction

Electrical capacitance tomography (ECT) is one of the industrial tomography modalities. It is based on measuring the change in capacitance of a multi-electrode ECT sensor due to the variation in concentration and/or distribution of dielectric materials. Using the capacitance data, a cross-sectional image of the material distribution in a pipeline or vessel can be reconstructed [1, 2]. Compared with other tomography modalities, the advantages of ECT can be briefly summarized: (i) Fast imaging speed (typically 100 frames/s), (ii) No radiation, (iii) Robust, (iv) Low cost, (v) Non-intrusive and non-invasive, (vi) Withstand high pressure (up to 150 bar) and high temperature (up to 300°C).
The first ECT system was developed in the end of 1980’s [3]. In the past 20 years, a lot of work has been done in the development of ECT systems and a few review papers were published on the hardware, sensor design, image reconstruction algorithms and applications of ECT [4-12]. Yang presented a review on the hardware design of ECT system [4]. The advantages and disadvantages of two capacitance measuring circuits, which are charge/discharge circuit and AC based circuit, were compared. At present, there are several commercial ECT products available, such as the charge/discharge ECT system (from Process Tomography Ltd) and the AC-ECT system (from ECT Instruments Ltd). During an image reconstruction process, the capacitance measurements from an ECT sensor are used to obtain the material distribution in a cross-section. Due to the “soft-field” effect of ECT, and the limited number of independent measurements, image reconstruction for ECT is an ill-posed and ill-conditioned problem, making the reconstructed image be sensitive to errors and noises of capacitance measurements. Image reconstruction algorithms can be divided into two types: single step algorithms (such as linear back projection, singular value decomposition and Tikhonov regularisation) and iterative algorithms (such as Newton–Raphson, Landweber iteration and algebraic reconstruction technique). The algorithms for ECT were reviewed by Yang et al. [10]. Some of the algorithms were investigated under typical distributions using both simulation and experimental data. Future developments in the field of the ECT image reconstruction were discussed [??]. The structure of an ECT sensor can significantly affect the performance of an ECT system. Recently, a review paper regarding the ECT sensor design was published [11]. The sensor diameter, the length and the number of electrodes as well as the size of earthed screens were discussed extensively.

Electrical tomography can be applied to monitor different processes. Dyakowski et al. reviewed the use of electrical tomography method to monitor and investigate the gas-solids and liquid-solids flows [8]. It was concluded that ECT systems were suitable for monitoring dry particulate flows, while ERT systems were recommended to monitor wet particulate flows. Although there are many review papers available, no paper has been published, systematically summarising the application of ECT in the particulate processes, including gas-solids pneumatic conveying [13-33], gravity flows [34-41], fluidized beds [42-69] and fluidized bed dryers [70-75]. In these processes, some important parameters have to be measured, such as the solids distribution, solids flow velocity and moisture content, which greatly influence the performance and efficiency of the processes. Besides, electrostatic phenomenon is common in pneumatic conveying and fluidized bed processes. It results in inaccurate measurement and even malfunction of some ECT system. The structure of this paper is arranged as follows. At first, the monitoring of flow regime and solids distribution using ECT is provided. Then the methods of solids velocity measurement using ECT are introduced, followed by the applications of ECT in fluidized bed dryers. Finally, electrostatic phenomenon and the effect of electrostatics on the performance of ECT are discussed. The named particulate process measurements are summarized in Fig. 1.

2. Measurement of flow regime and solids distribution using ECT

There are many types of flow regimes in the particulate processes. Fig. 2 shows the flow regimes for a vertical pneumatic conveying and fluidized bed system [76]. In general, there are two categories: dilute flow and dense
flow. In a dilute flow in a pipeline, the solids concentration is low and the particle velocity is high. With the decrease in gas velocity under a constant solids mass flow rate, the flow regimes would change from a dilute suspension flow to an annular flow or cluster flow. The annular flow and the cluster flow are commonly known as fast fluidization regime. In a dense flow, the solids concentration is high and the particle velocity is low. The flow regimes of turbulent fluidization would change from a slug flow to a bubbly flow and then to a fluidized flow with the decrease in gas velocity. The main difference between the slug flow and bubbly flow is the bubble size. For a slug flow, the bubbles have similar size to the pipe diameter, whereas in a bubbly flow there are many small bubbles. With further decrease in gas flow rate, the flow regime of particle rain and separated plug would occur. The particle rain flow is characterized by the falling particles from the bottom of one plug to the top of the next plug. To improve the efficiency and the performance, it is useful to monitor the change in flow regimes during a particulate process. The development of ECT provides opportunities for measuring the flow regime and solids distribution in these processes.

2.1 Pneumatic conveying

Regarding the measurement of solids distribution in pneumatic conveying processes, Dyakowski worked on dense pneumatic conveying processes [19, 20]. Experiments were conducted on the horizontal and vertical pipelines of a dense-phase pneumatic conveying rig at University of Manchester Institute of Science and Technology (UMIST). The inner diameter of the pipe was 57 mm. The solids material for the experiments was polyamide chips, with approximate dimensions of 3 mm × 3 mm × 1 mm. A high-speed video camera and a twin-plane ECT sensor were used to investigate the flow dynamics and the results were compared. There were eight electrodes on each plane of the ECT sensor and the data acquisition rate of the ECT system is 100 frames/s. The shape of slugs was determined using a twin-plane ECT system [19], as shown in Fig. 3. The pixels from each frame were selected to give a longitudinal image of the slugs. A thresholding method was applied to sharpen the boundaries between the phases. As shown in Fig. 3, when the threshold was set to 0.5, the shape of the slugs’ body and the slugs’ front and tail could be clearly identified, which were consistent with images from the high-speed camera. Another advantage of ECT imaging is that the internal structure of plugs in a vertical pipeline could be extracted. The permittivity distribution of the plugs travelling upwards was obtained from the ECT images. It was shown that the density in the central part of the plugs was lower than the density of plugs near the wall. The porosity distribution inside the plugs was useful for calculation of inter-particle stresses distribution for validation of computational fluid dynamics (CFD) results. The ECT data were further processed by spectrum analysis and cross-correlation to show the unsteady nature of the flow. The bidirectional flow structure in the pipeline was identified by pixel-pixel correlation [20]. It was concluded that the ECT results could be used to improve the efficiency and safety of dense phase pneumatic conveying processes.

At National University of Singapore, research on application of ECT was conducted in monitoring the pneumatic conveying of solids. The pneumatic conveying processes in horizontal, vertical and inclined pipeline were monitored using ECT [13, 14]. In the horizontal pipeline, with the decrease in superficial air velocity, the flow regimes changed from a homogeneous flow, to a dunes flow, a flow over a settled layer and a slug flow.
The time-average particle concentration distribution under different flow regimes were obtained using ECT and showed similar results to the snapshots of high-speed video camera. The temporal variation in solids concentration distribution was also analyzed for the Linear Low Density Polyethylene (LLDPE) particles flowed past a 90° bend, as given in Fig. 4. The results show that the flow pattern was a flow over a settled layer in the horizontal pipe before the bend and changed to a ring-like structure in the vertical pipe after the bend [13].

In a vertical pipe, with the decrease in air velocity, the flow regimes changed from a dispersed flow, to a slugging flow and then to an annular capsule flow with a closed vent in the rotary valve, as measured by ECT and shown by a video camera. With an open vent, the flow regimes changed to a dispersed flow, a pulsing flow and a moving annular capsule flow. The effects of the vent on the flow characteristics were examined using ECT [14]. It revealed that the flow pattern oscillated with the closed vent and disappeared with the open vent. In a dispersed flow, the flow patterns of LLDPE particles and polypropylene particles under similar air and solids flow rates were different. The heavier LLDPE particles existed in a narrower wall region than polypropylene particles. The quasi-periodic flow patterns in a slugging flow and a pulsing flow were also shown by ECT.

ECT was applied to analyze the solids distribution in a 45° inclined riser after a bend [14]. Because of the solids’ acceleration after the bend, the solids concentration would initially decrease. With the increase in axial distance down-stream, due to the gravity sedimentation, the solids loading would increase and finally leveled off, representing a fully developed flow. The flow regimes of eroding dunes and flow over a settled layer in the inclined pipe were obtained by ECT. Fig. 5 shows the snapshot and ECT images of eroding dunes and flow over a settled layer in a 45° inclined pipe. ECT results show that there is an obvious curvature on the top surface of the settled layer. The phenomenon reveals that the particles in the center of the settled layer are picked up and deposit on the region near the side wall.

Zhang et al. investigated the flow dynamics of polypropylene particles transported in a 45° inclined pneumatic conveying pipe using ECT [16]. The presence of reverse flow and half ring flow regime in the inclined pipe was shown by ECT results. Fig. 6 shows the ECT images of these flow regimes. In a reverse flow regime, the solid particles near and above the center of the pipe move forward in relative high velocities, while most particles deposit and form a settled layer on the bottom of the pipe, shown as the red region in Fig. 6 (a). The particle layer flows backwards in a slow velocity opposite to the main flow direction. When the air velocity decreases further, half ring flow structure forms and most of the particles are adhered to the wall, as shown in Fig. 6 (b). The main reason for the presence of such a flow regime is the electrostatic effect.

2.2 Gravity flow

Gravity flows of solid particles are common in industrial processes. The flow characteristics of a gravity flow can be measured by ECT. The density waves of a gravity flow in a vertical pipe were investigated using a twin-plane ECT system [33]. The particle concentration and velocity were calculated from the reconstructed images. It showed that the time-average particle concentration was higher in the center of the pipe and the
particle velocity distribution in the pipe was relatively uniform. The particle concentration and velocity
measured by ECT were combined to calculate the mass flow rate of particles. The results of mass flow rate
measured from a load cell and ECT gave reasonable agreement, as shown in Fig. 7. Similarly, hopper discharge
processes were monitored using ECT. Researchers from Technical University of Lodz and Gdansk University of
Technology have done a lot of work [34-41]. Grudzien et al. conducted experiments using different hopper
orifice diameters (range from 5 mm to 80 mm) and two different solids materials (rice and polyamide pellets) to
investigate the hopper discharge behavior [36]. The height and inner diameter of the hopper were 640 mm and
140 mm. A single plane ECT sensor with eight electrodes was applied and the data acquisition rate of ECT
system was 50 frames per second. Two parameters were introduced to characterize the dynamics of the hopper
discharge process, which are funnel propagation velocity and hopper discharge rate. The funnel propagation
velocity and hopper discharge rate were calculated based on the transit time between characteristic points
indicated on the uploading and unloading dynamics diagrams. Niedostatkiewicz et al. investigated the gravity
flow in a cylindrical model silo with different initial bed densities and wall roughness using ECT [37]. The
diameter and the height of the cylindrical model silo were 0.2 m and 2 m. Dry sand was used as the solids
material, with the mean grain diameter of 0.8 mm. The ECT system used in this study had two sensors and each
sensor had 12 electrodes. By using the raw data, 1D evolution of solids concentration was obtained. The 2D
evolution of solids concentration was calculated using the reconstructed images. It was shown that the dry sand
behavior of the silo flow was significantly influenced by the initial bed density and wall roughness.
Niedostatkiewicz et al. also investigated the concentration changes during a confined granular flow in a
rectangular silo model using ECT [38]. Experiments of two initial sand densities and wall roughness grades
were conducted. The height, width and depth of the rectangular silo model were 0.34 m, 0.09 m and 0.07 m.
An ECT sensor with 48 electrodes was mounted outside the surface of the silo model. Particle Image Velocimetry
(PIV) was also used to compare the corresponding concentration results with ECT. Similar concentration
changes during the dynamic mass flow were obtained using ECT and PIV. Expect for measuring the solids
distribution, ECT was also applied by Grudzien et al. to detect the sand pulsation during a silo discharge process
[39]. The diameter and height of the silo were 0.2 m and 2.0 m respectively and the orifice diameter was 7 cm.
Raw ECT data near the wall region was used to analyze the pulsations. The experimental results revealed that
the sand pulsation had dissimilar levels for different silo regions and the pulsation was strongly influenced by
the wall roughness. With the silo with rough wall the pulsation vanished. ECT was also used for shear zone
measurements during a silo discharge process [40]. Experimental work was conducted under different initial
material packing densities and different silo wall roughness. The near wall shear zone profile, size and material
concentration inside the shear zone during the dynamic process were investigated based on ECT images. The
experimental results showed that increasing the wall roughness is an effective way to reduce the dynamic effect
during the discharge process, which is the result of the resonance between the hopper structure and the materials
inside. Grudzien et al. analyzed a silo mass flow during gravitational empty process using X-ray tomography
and ECT [41]. The obtained 1D and 2D results from X-ray tomography were compared with the ones obtained
under the same silo model using ECT to characterize the concentration changes and shear zone localization
along the silo wall. This comparison can provide interpretation of the ECT signal for monitoring the solids flow.
2.3 Fluidized bed

In a fluidized bed, the solids distribution and flow regime are important for the overall performance of the bed and they need to be monitored. Liu et al. worked on monitoring fluidized beds using ECT [42-45]. Because square or rectangular fluidized beds are widely used in industry, the particle behavior in the bottom zone of a square bed was investigated by a square-shape ECT sensor [42-43]. The cross-sectional solids distributions of bubbling, circulating and slugging beds were obtained from the reconstructed ECT images. The temporal fluctuations of average solids concentration and corresponding frequency spectra under different flow regimes were also obtained. The solids concentration fluctuation in a slugging bed was more obvious than bubbling and circulating fluidized beds (CFBs), with a peak of frequency spectrum at 1.9 Hz.

The solids distribution in the conical section of a cyclone in a CFB was measured using ECT [44], as shown in Fig. 8. Both 2D and 3D images are shown in Fig. 8. The 3D image is obtained by using an elementary iso-surfaces (EIS) method to smoothly connect the 2D image sequences to generate a 3D image. It can be seen that the solids distribution in the cyclone exists in clustering distribution. To analyze the cyclone performance, the solids behavior in this part of the cyclone was also investigated.

Bubbling and slugging flow regimes in a square cross-sectional area of CFB were studied by Wang et al. using CFD modeling and ECT measurement [45]. Two image sequences in the bubbling and slugging fluidized bed regime are shown in Fig. 9 (a). It is shown that the cross-section is occupied by the solid particles with scattered bubbles in the bubbling and slugging regimes. In the slugging fluidization, there are obvious single or two more large bubbles in the cross-section and the solids concentration is lower than that in the bubbling bed. Fig. 9 (b) shows the time variation in two bubbles elongation in the bubbling and slugging beds, from which the information about the interactions among bubbles can be obtained. The bubble diameter in the bubbling fluidized bed was also obtained by ECT, with a mean diameter of 4.35 cm. The frequency spectrum, probability density function and autocorrelation function of the solids concentration fluctuations under different regimes were calculated to investigate the chaotic particle behavior in the bed. By fitting the power spectra as power-law, the dominate frequency near the wall and in the center of the bed under different fluidization regimes could also be obtained.

A system with three ECT sensors was used by Takei et al. to visualise the solids distribution in a down-flow fluidized bed, which had a specially designed solids distributor [52-55]. Air was supplied to the center and the sides of the pipeline. The temporal and spatial characteristics of solids distribution were calculated from the reconstructed images. The results showed that with the new distributor, solids distribution at the inlet of downer was more uniform. With the measuring position moved downstream, the solids concentration decreased and solids distribution became uniform. The experimental results from ECT were also used to verify a 3D numerical model. The axial and radial solids concentration profiles from simulation results exhibited satisfactory agreement with that observed in the experiment.
A research group led by Fan used ECT to monitor the flow dynamics of fluidized beds [56-69]. The choking phenomenon for both group A and B particles in CFBs was studied [58, 59]. For FCC catalyst particles (group A particles), the choking phenomenon in the riser of CFB was studied using the quasi-3D images, which were obtained by stacking the 2D ECT images. When the air velocity was lower than the transport velocity \( U_{tr} \), solids distribution in the lower parts of the riser under different solids circulation rates was given. At lower solids circulation rate, there were double solids ring flow structure and three-region flow structure (solids ring in the wall region, solids cluster in the core region and dilute gas ring between them). The flow structure underwent abrupt change during choking transition. The solids cluster in the center of the pipe suddenly disappeared and the flow structure of large dilute gas core region and thick dense solids wall region was formed at the lower part of the riser. There was a sharp variation in the time-average cross-sectional solids concentration during this period. However, the distinct flow structure variation in the lower part of riser during choking transition did not occur when the air velocity was higher than \( U_{tr} \). The choking transition of sand particles (group B particles) resulted in different types of slugs in the riser of the CFB. Wall slugs and gas intervals were formed when the air velocity was lower than \( U_{tr} \), whereas open slugs with particle clusters inside were formed when the air velocity was higher than \( U_{tr} \). The time-average solids concentration had a sharp change under different gas velocities (lower and higher than \( U_{tr} \)) during the choking transition. An abrupt change in the standard deviation of cross-sectional solids concentration was observed with the increase in solids circulation rate at a low gas velocity (<\( U_{tr} \)). However, at a high gas velocity (>\( U_{tr} \)), the standard deviation remained unchanged in the beginning, then increased gradually and finally leveled off with the increase in solids circulation rate.

The effects of pipe diameter on the flow structure and pressure drop during the choking transition for both group A and B particles were examined [62]. In a pipe of 5 cm diameter, there was a minimum point of the pressure gradient for both group A and B particles when the flow regime changed from dilute transport to fast fluidization, whereas there was no minimum pressure gradient in a pipe of 10 cm diameter due to the weak effect of wall friction in the larger pipe. However, the flow structures during this transition for both group A and B particles were similar to each other in the two pipes. Different flow structures in different pipe diameters were formed for group B particles when the flow regime changed from fast fluidization to dense phase fluidization under the condition of the air velocity was lower than \( U_{tr} \). There were solids plugs in the pipe of 5 cm diameter and wall slugs in the pipe of 10 cm diameter. ECT results also showed the change in flow structures for group B particles in the pipe of 5 cm diameter after choking transition. With the decrease in air velocity, three different types of solids distributions were obtained, which are open slugs, solids plugs with solids clusters inside and solids plugs respectively.

### 2.4 3D imaging of particulate processes

3D ECT technique was developed by a research group at Ohio State University, who called ECVT [63, 64, 68], as well as a research group at Technical University of Lodz [77]. Unlike quasi 3D imaging, which obtained a 3D image by stacking 2D images together, 3D ECT technique acquired the 3D image directly from the measured capacitance data. The 3D ECT sensor structure and the 3D image reconstruction algorithm were two important
parts to make direct 3D imaging possible. A 3D ECT sensor utilized the fringing effect to produce field variation in the axial direction, which was undesirable for 2D imaging. A 3D ECT sensor not only measured the capacitance between the electrode pairs in the same plane but also the capacitance from the electrode pairs of different planes. The 3D image reconstruction was accomplished by implementing the algorithm of neural-network multi-criterion optimisation image reconstruction (NN-MOIRT), developed earlier for 2D ECT [78, 79]. The image reconstruction algorithm was modified by introducing a 3D sensitivity matrix to replace the 2D sensitivity matrix, and providing additional network constraints including 3D to 2D image matching function. Fig. 10 compares the quasi-3D images obtained by stacking a sequence of 2D images, and the real 3D images obtained by ECVT in a CFB of 10 cm diameter with 200 μm sand particles (group B particles). The results from quasi-3D images and real 3D images show similar flow structures, which reflected the flow features of choking transition in the gas-solids CFB.

Due to the ability of real-time 3D imaging for the domain of arbitrary shape and geometry, 3D ECT has gained a wide range of applications in the particulate processes. 3D shape and behavior of horizontal gas jet and gas/solids mixture jet in a 30 cm bubbling fluidized bed were measured using 3D ECT [67]. Fig. 11 shows 3D shape of a horizontal gas jet. A threshold value of 0.5 for the relative solids holdup, which was selected based on the comparison between ECVT and MRI measurement [66], was applied to determine the boundary of the gas jet. In the beginning of the process, the gas jet remained symmetric at its horizontal axis. As the jet penetrated, the width of jet expanded and the volume of jet increased. The local solids holdup from the ECT results showed that there was low solids concentration core region and high solids concentration boundary layer in the jet. The influence of gas bubble from the bottom of the bed on the behavior of horizontal gas jet was also investigated. The coalescence of the gas jet with the gas bubble made the jet lost its symmetric shape and resulted in larger penetration distance in the fluidized bed. During the penetration of the gas/solids mixture jet, the tail of the jet shrank near the nozzle. The maximum penetration length of the mixture jet was larger than that of the pure gas jet.

3D solids flow structures in a CFB were studied using 3D ECVT images [69]. In the riser, there was a symmetric flow structure with a high solids concentration annulus region and a low solids concentration core region. The thickness of the annulus region decreased with the increase in superficial gas velocity. The solids distribution in the horizontal parts of the bend had a core-annulus structure. In the annulus region, the solids concentration near the top of the region was higher than that in other parts of the region. A solids dune was visualized at the bottom of the horizontal bend and the shape of the dune was not symmetric because of different velocities at two sides of the horizontal pipe. Fig. 12 shows the radial distributions of the time-average solids concentration in the bend. A reversed S shape solids concentration distribution along the diagonal line is given in Fig. 12 (b). From the outer corner to the center of the bend, the solids holdup increases and then decreases.

For reference, details of some cited publications in this section are given in Table 1. It contains the information of size and type of installation, size and type of particles, type of ECT sensor, data acquisition rate, data processing method and obtained results. In particular, the data analysis methods in ECT can be divided into two
groups, which are visualization of reconstructed images and raw capacitance data analysis. Although visualization in the form of 2D image and 3D image is more common than raw data analysis, the method related to the raw measurement data, measured between different combinations of the electrodes, should not be under-estimated. The advantages of this method are that it takes less time than the image reconstruction method and the result of this method does not contain the reconstruction errors. This enables a fast utilization of the measurement data to monitor the industrial processes.

3. Velocity measurement using ECT

Flow velocity in a particulate process can be estimated by a twin-plane ECT sensor. The solids concentration fluctuations \( \alpha(x, y, z, t) \) at two cross-sections can be gathered. The cross-sectional average solids concentration at the two planes can be calculated by

\[
\bar{\alpha}_s(z, t) = \frac{1}{A} \int_a \alpha(x, y, z, t) dx dy
\]

where \( A \) is the cross-sectional area. The time-average cross-sectional solids concentration is given by

\[
\bar{\alpha}(z) = \frac{1}{T} \int_0^T \bar{\alpha}_s(z, t) dt
\]

where \( T \) is the averaging period. The correlation coefficient of up-stream and down-stream cross-sectional average solids concentrations can be computed as

\[
C(d) = \frac{1}{T} \int_0^T \left[ \bar{\alpha}_s(z_1, t) - \bar{\alpha}(z_1) \right] \left[ \bar{\alpha}_s(z_2, t+d) - \bar{\alpha}(z_2) \right] dt
\]

where \( d \) is the time delay, \( z_1 \) and \( z_2 \) are up-stream and down-stream planes. The average solids velocity \( V_{ss} \), can be estimated from \( V_{ss} = \frac{L}{D} \), where \( L \) is the distance between the two planes and \( D \) is the value when \( C(d) \) is the maximum.

Not only the average solids velocity, the solids velocity profile at the cross-section can also be estimated using a twin-plane ECT. The solids concentration fluctuations at corresponding pixels from the two planes can be cross correlated.

\[
c(x, y, d) = \frac{1}{T} \int_0^T \left[ \alpha(x, y, z_1, t) - \bar{\alpha}(x, y, z_1) \right] \left[ \alpha(x, y, z_2, t+d) - \bar{\alpha}(x, y, z_2) \right] dt
\]

This method is called as pixel-pixel correlation. The particle velocity \( V_s(x, y) \) at corresponding pixel \((x, y)\) can be estimated and the particle velocity profile in the cross-section can be obtained.

In the classical pixel-pixel correlation, the trajectories of particles were assumed to be parallel to the pipe axis. However, the actual particle’s movement in the pipe was complex. The particles may have lateral movements in the pipe. As a result, a best-correlated pixel method was introduced [80]. Compared with the traditional
pixel-pixel correlation, which only correlated the corresponding pixels, in the best-correlated pixel method, the cross-correlation between a pixel from the first plane and the corresponding pixel and its neighbors from the second plane was calculated, as shown in Fig. 13. The solids axial velocity and lateral velocity in the pipe cross-section could then be obtained. Zhang et al. applied the best-correlated pixel method to characterize the particle movements in the dispersed flow, reverse flow and half-ring flow regimes and compared the results with that from particle image velocimetry (PIV) [16]. In the reverse-flow regime, the axial velocities obtained by the best-correlated pixel method are shown in Fig. 14. There are three parts in the pipe cross-section, which are dilute region, transition region and dense region. In the dilute region, where $y$ is between 0.35 and 1, the calculated velocities are relatively high and positive. In the dense region, where $y$ is between 0 and 0.18, the velocities are very small and negative. A transition region exists between the dilute and dense regions. It is observed that the solid particles in this region flow backward with higher negative velocities than the dense region.

The solids transverse velocity in horizontal and vertical pneumatic pipelines was estimated by Datta et al. using ECT [24]. It was calculated by correlating successive images from the same plane. In each interrogation window, the concentration fluctuations of the pixels in one image were correlated with the pixels in the next image. The maximum correlation between two coordinates in each interrogation window was then identified. With the distance between the two spatial points and time delay between the successive images, the transverse velocity was calculated. Fig. 15 shows the vectors and the magnitudes of the slug transverse velocity in dense phase horizontal pneumatic conveying. It was concluded that the slug in the cross-section moves towards the bottom of the pipe.

Regarding cross-correlation calculation of the signals from a twin-plane ECT sensor, the data acquisition rate of the system has great influence on the accuracy of velocity measurement. Under a fixed distance between the two planes, a faster data acquisition rate means that the time resolution of cross-correlation can be improved. With a fixed time resolution, if the data acquisition rate becomes faster, the distance between the two planes can be reduced, resulting in more correlated signals and hence improved cross-correlation [11]. The determination of the time window (average period $T$) is also important in cross-correlation calculation. The calculations should be performed with a determined time window. According to Mosorov’s investigation, the time window should have a pattern of signals, which enable correct calculation of the transit time [28]. It is concluded that the values of transit time are correct only when the time window covers the plug bodies. In the best-correlated pixel method, the selection of the neighbors’ area of the corresponding pixel should take the velocity component of lateral direction and the computation time into consideration. If the area is too small, the correct lateral velocity component is difficult to obtain. However, if the area is too large, the calculation will take a long time, which may not reflect the dynamic change of the process.

However, due to the non-gaussianity and non-stationarity of two-phase flow signals, the cross-correlation method has some problems under certain conditions. In some flow patterns, the correlation function has no clear peak, and it is difficult to calculate flow velocity using the cross-correlation method. To solve this problem, a
method based on the frequency domain analysis of the measured capacitance data was introduced by Mosorov to calculate the solids velocity [81]. By this method, the effect of solids flow regime on the velocity measurement can be reduced. A method using the dynamical lag correlation exponent was also proposed by Xue et al. [25] to measure the velocities of coal ash using a twin plane ECT. It calculates the time delay by finding the minimum point in the dynamical lag correlation exponent, which is more robust to the noise of ECT signal.

4. Application of ECT in fluidized bed dryer

ECT has been applied in fluidized bed dryers to monitor the rapid changes in hydrodynamic regime. With the information, a desirable operation regime of the dryer can be maintained. The capacitance from ECT is influenced by the permittivity distribution in the bed. For the wet solids material, the relative permittivity of the material is affected by both the solids concentration and the moisture content. Due to the loss of water content, huge reduction in the bed permittivity occurs during the drying process, which results in a big problem for ECT measurement. Chaplin et al. overcame this problem by utilizing a calibration method [70]. A linear fit line of the capacitance of packed bed under different moisture contents was obtained to correct the influence of the changing permittivity. To verify the ECT measurements and analyze the influence of permittivity models, X-ray tomography was utilized to measure solids distributions in the fluidized bed dryer. ECT results using the Böttcher permittivity model provided good agreement with X-ray data when the moisture content was higher than 5 wt%. The parallel model showed a better estimate of the solids distribution when the moisture content was lower than 5 wt%. Chaplin et al. also applied ECT technique to identify the changes in bed hydrodynamics during the drying process [71]. The capacitance data from opposite electrodes and adjacent electrodes were analyzed using S-statistic without the need of image reconstruction. Intensive variation in bed behavior near the wall of the dryer was found, while little variation was identified in the center of the dryer.

Online monitoring of solids moisture in batch fluidized bed dryers using ECT was presented by Wang et al. [73]. It was found that the capacitance from adjacent electrodes was only affected by the moisture content and thus it was used to estimate the solids moisture content. The influence of temperature on the measurement results was also compensated and the measurement error was reduced to 5%. A single closed loop control strategy was put forward to implement process control and improve operation efficiency. With solids moisture content measured by ECT, an optimum inlet air velocity was calculated. To evaluate the control performance of the drying process, two criteria of the objective function and the thermal efficiency were introduced. The results of the objective function and the thermal efficiency with control and without control are given in Fig. 16. It is shown that by controlling the air flow rate to the dryer, the objective function can be reduced and the thermal efficiency can be improved.

5. Electrostatic phenomenon and its effect on ECT

In a particulate process, electrification is inevitable due to the friction and the collision between particle-particle and particle-wall. This phenomenon stimulates undesirable particle deposition and adhesion. Excessively
charged particles tend to discharge in the form of fire and explosion, which poses safety disasters in industry. To minimize the negative influence of this phenomenon, it is necessary to investigate the charging mechanism during the process. Two review papers were published by Matsusaka to illustrate the electrification of particles \[82, 83\]. The basic theories of charge generation and transfer were summarized.

The electrification phenomenon and its effect on solids flow behavior in a pneumatic conveying system was studied by the research group led by Wang in Singapore \[84-87\]. Faraday cage, digital electrometer, and modular parametric current transformer were applied to measure the charge density of the particles, the induced current on the wall and the charged particles’ equivalent current respectively. These parameters were used to characterize the electrification phenomenon under different operation conditions. In their study, it was shown that with the decrease in air flow rate, the electrostatic characteristics of the gas-solids flow changed and the charge density of the particles, the induced current on the wall and the charged particles’ equivalent current increased, which resulted in the occurrence of half-ring and ring flow regimes. The influence of the electrostatic charges on the solids flow behavior gradually increased with time, which led to particle clustering even at the condition of high air velocity. The composition of solid particles and the material of pipe wall had great effects on the electrification phenomenon in a pneumatic conveying system. The electrostatic effects reduced with the use of high relative humidity air and the addition of antistatic agent in the conveying system. The influences of particle size distributions and particle shape on the electrostatic characteristics were investigated using the attrition products from a rotary valve \[85\]. The particles formed under extensive attrition tended to acquire more electrostatic charges. The charge density of particle mixtures increased with the increase in small size particles in the mixture. The particles of the shape formed under more shearing attritions tended to have a higher variation in charge. The electrostatic equilibrium state and charging process in the pneumatic conveying pipelines were also analyzed \[86\]. Based on the experimental results, it took more time to reach the electrostatic equilibrium state from a horizontal pipeline, a vertical pipeline to a pipe bend. The time required depended on the flow characteristics and the solids behavior. More time was required for the system with complex flow regimes. At the electrostatic equilibrium state, higher electrostatic field strength occurred near the pipe wall and decreased from the wall to the center. The electrostatic field strength was the highest at the bend, at which electrostatic spark occasionally generated. The factors such as pipe material, air humidity and addition of anti-static agent greatly influenced the equilibrium state of the conveying system.

Considering the presence of an electrostatic field, the transport of solid particles in a vertical pipe as well as an inclined pipe was numerically investigated \[87\]. The obtained simulation results showed similar flow regimes with previous experimental measurements obtained by high speed camera and ECT. The flow regime of eroding dunes in an inclined pipe of the pneumatic conveying system was reproduced by the numerical simulation, as shown in Fig. 17. When the electrostatic field strength was low, the air could blow the solid particles in the forward movement, as shown in Fig. 17 (a-c). With the increase in strength of the electrostatic field, more particles deposited on the bottom of the pipe. When the electrostatic field strength was high enough, the flow regime of eroding dunes could be identified, as shown in Fig. 17 (d). The solid particles in this regime showed complete backwards movement in the pipe.
Zhu et al. investigated the accumulation and dissipation of electrostatic charges in pneumatic conveying of solid particles using ECT [15]. In their study, it was considered that the capacitances measured by an ECT sensor were contributed from the solids permittivity distribution and the charges accumulated on the wall. The capacitance due to charges on the wall was recorded by temporarily turning off the solids supply and keeping air velocity constant. Considering the charges on the wall, the solids mass flow rate calculated from ECT results showed good agreement with the results from the load cell measurement. The effects of superficial air velocity and anti-static agent on the charge accumulation and dissipation were analyzed using ECT results. Under a smaller superficial air velocity, the disturbance to the capacitance signal due to electrostatic charges was larger, because more charges were generated in a dense solids flow. With the addition of anti-static agent, there was a new layer on the particles and on the wall, which influenced the collision between particle-wall and particle-particle and reduced the generation of electrostatic charges.

When ECT is applied in a particulate process, electrification would result in measurement errors and even malfunction of some ECT system. The effects of the electrostatic charges and the electrostatic sparks on the ECT measurements were analyzed by Zhang et al. [17]. In their study, the influence of electrostatic charge distribution on the ECT measurements was explained by a switch capacitor configuration model, as shown in Fig. 18. It was concluded that the errors of ECT measurements were caused by the uneven distribution of the electrostatic charges in the pipeline. In the experimental analysis, the charges generated from bends of different angles were introduced to a separate non-conductive pipe, where the ECT measurements were conducted. The results showed that compared with that from the 45° and 135° bends, the electrostatic charges from the 90° pipe bend most significantly influenced the ECT measurements. When the electrostatic charges were accumulated to a high magnitude, electrostatic spark occurred. Fig. 19 shows the influence of electrostatic spark on the ECT image, which results in a completely distorted ECT image.

Gao et al. investigated the electrostatic effect on ECT using capacitance and electrostatic arrays [88]. The effects of the charge distribution on the ECT measurements were analyzed by simulation and experiment. It was concluded that compared with the particle charges in the center, the charges near the pipe wall had greater influence on the ECT results and the capacitance data from the ECT electrodes near the charges were greatly affected.

6. Conclusions and discussion

Due to the advantages of fast speed, non-intrusive and non-invasive, low cost and no radiation, ECT has been widely applied in particulate processes. The flow regime can be monitored and solids distribution can be measured using the reconstructed images. Particle velocity and velocity profile in a cross-section can be estimated by cross-correlating the average and pixel concentration signals. Recently, ECT has been applied to the fluidized bed dryers. With ECT, on-line monitoring of the dryers can be accomplished. Electrification phenomenon is prevailing in the particulate process. More attention should be paid to the electrostatic effect on
the performance of ECT to protect the measurement system from damaging and obtain accurate results.

Although ECT has been widely applied in the solids distribution measurement and flow regime analysis in pneumatic conveying systems and fluidized beds, the reconstructed image still has the problem of low quality and low resolution. 3D ECT needs to improve the imaging speed and resolution to give more information about the moving object during a process. Besides, when ECT is applied in dilute-phase particle flows, it will encounter serious problem, which is not solved until now. The results of velocity measurement using twin-plane ECT may often depend on flow regime or flow rig. The sensor structure and data acquisition rate of ECT system significantly influence the measurement results. Due to the complexity of particle flows, more methods are required to improve the robustness and reliability of the velocity measurement. Electrostatic phenomenon is common in pneumatic conveying and fluidized bed processes. Many factors influence the charge generation and transfer, such as particle type, pipe material and experimental condition. Further investigation into charging mechanism during these processes needs to be done. Electrostatics may result in inaccuracy in the measurements and even malfunction of some ECT system. More work is required to minimize the electrostatic effects and compensate the ECT measurement results.

Although encouraging results have been shown, the application of ECT in particulate processes still meets the following challenges:

(1) The inhomogeneous sensitivity distributions of ECT sensors make the central part of reconstructed images being of low quality. The internal electrodes, which are proposed for measuring droplet distribution in EHDA process [89], can improve the sensitivity in the center of the sensor and it may be a possible solution.

(2) Due to the small change in permittivity and corresponding weak capacitance signal, it is difficult to use ECT for dilute flow measurement (i.e. solids volume fraction is below 5%). It is known that the inter-electrode capacitance $C_m$ of an ECT sensor can be represented by:

$$C_m = \frac{C_w \varepsilon_r C_0}{C_w + \varepsilon_r C_0}$$

(6)

where $C_w$ is the capacitance of the insulating wall, $C_0$ is the material capacitance when the sensor is filled with air and $\varepsilon_r$ is the relative permittivity of the measured solids material. To improve the capability of ECT for dilute flow measurement, a possible way is to reduce the range between higher and lower calibration point. During the calibration process, the lower calibration capacitance $C_{m1}$ can be obtained when the measurement section is filled with air and the higher calibration capacitance $C_{m2}$ can be obtained when measurement section is filled with the solids material whose permittivity $\varepsilon_2$ is lower than the measured material $\varepsilon_r$.  

14
\[
C_{m1} = \frac{C_wC_0}{C_w + C_0}
\]
\[
C_{m2} = \frac{C_w\varepsilon_2C_0}{C_w + \varepsilon_2C_0}
\]

As a result, the detection capability of ECT can be increased. However, because different solids materials are used during calibration, the real fractions of measured materials should be calculated considering the permittivity differences. Using the lower calibration capacitance \(C_{m1}\) and higher calibration capacitance \(C_{m2}\), \(C_w\) and \(C_0\) can be calculated:

\[
C_0 = \frac{C_{m1}C_{m2}(\varepsilon_2 - 1)}{\varepsilon_2(C_{m2} - C_{m1})}
\]
\[
C_w = \frac{C_{m1}C_{m2}(\varepsilon_2 - 1)}{\varepsilon_2C_{m1} - C_{m2}}
\]

Having the value of \(C_w\) and \(C_0\), it is easy to obtain the real capacitance \(C_m\) when the sensor is filled with measured solids material with the relative permittivity \(\varepsilon_r\). Then the ECT system can be recalibrated and the real solids fraction can be calculated.

(3) In some particulate processes, there are two types of particles in the system, such as coal and inert particle in the coal gasification process. To improve the performance and efficiency of the process, the distribution of different types of solid particles should be monitored. However, it is a challenge to identify their individual distribution using current ECT systems. Combining ECT with another type of sensors or multi-modality tomography system may be a possible solution.

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