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Measurement of fluidised bed dryer by different frequency and different normalisation methods with electrical capacitance tomography

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A B S T R A C T

To investigate the effect of moisture content, excitation frequency and normalisation model on image reconstruction with a fluidised bed dryer, an electrical capacitance tomography (ECT) sensor was mounted near the bottom of the drying chamber. An ECT system based on an HP4128 impedance analyser was used to measure capacitance and loss conductance between the electrode pairs in the sensor. It has been found that the capacitance depends on not only the particle moisture but also the excitation frequency. With a low moisture content, the relationship between capacitance and frequency is simple and linear. With a high moisture content, however, the relationship becomes more complex and non-linear. For image reconstruction, different normalisation models have been used: series, parallel, Maxwell and Böttcher models. The results show that with a low moisture content, these models give nearly the same image errors. With the increase in moisture content, the difference between these models becomes more and more obvious. With different gas–solids flow patterns, the four models also give slightly different images. In the end of this paper, solids distribution and averaged solids concentration profile for dynamic test with different excitation frequencies in a fluidised bed dryer are given.

1. Introduction

Fluidised bed dryers have been widely used in the pharmaceutical, food, chemical process and other industries for many years [1]. To investigate the solids distribution during a drying process, electrical capacitance tomography (ECT) has been applied to lab-scale fluidised bed dryers [2–4]. While there are some advantages of using ECT to investigate fluidisation processes over the conventional methods [5,6], the application of ECT in fluidised bed dryers has encountered some difficulties because of the moisture content changes during the drying process [4,7]. Typically, during a drying process, the moisture content of granule changes from say 30% to 1%, which results in the change in the dielectric properties of material [8,9], including permittivity, dielectric loss and conductivity. The changes in permittivity and conductivity results in the change in measured capacitance and conductance. In the past, the excitation frequency is normally kept constant and also in the low frequency range, typically between 100 kHz and 200 kHz [2–4]. With a fixed low frequency, good results can be obtained when the moisture content is lower than a certain level, say 18% [4]. With a high moisture content, however, images are reconstructed less accurately and sometimes a wrong solids distribution may be given.

As well known, the dielectric properties of many materials are frequency-dependent and a function of material moisture and density [10,11]. To improve the measurement accuracy, it is necessary to use an ECT system with a suitable frequency.

The ultimate objectives of this research are to provide accurate measurement of gas–solids distribution and moisture content in fluidised bed dryers and to control fluidised bed dryers effectively for improved operation efficiency.

2. Dielectric properties and normalisation methods

The main dielectric properties to be considered include permittivity and loss factor. The permittivity ε' referred to a free space is the capacitance of a unit volume of matter divided by the permittivity of free space. The loss factor ε'' can be defined as the conductance of a unit volume of matter divided by $\omega\varepsilon_0$, where w is the relaxation factor and ε_o is the permittivity of free space. The complex permittivity and the loss tangent of the material are

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{1}$$

$$\tan\delta = \varepsilon'' / \varepsilon' \tag{2}$$

where δ is the loss angle of a dielectric material.

The dielectric properties of wet bulk granule depend on the density and moisture content of the material as well as the frequency. The effects of moisture content and frequency on capacitance and loss

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conductance are considered here. In general, the dielectric properties of granule are known to be dependent on the moisture content, bulk density, temperature and frequency [5,9]. In this study the dielectric properties of samples are measured at different excitation frequencies in a range of 50 kHz–13 MHz and with the moisture content in the range of 1.5–38%. The effect of bulk density of solids on the dielectric properties is neglected. Some details about the effect of bulk density can be read in [5,11,12].

In this research, four normalisation models are used: series, parallel, Maxwell and Bötttcher models [2], which are given by

$$\text{Series model}: \; C_{NS} = \frac{C_M - C_L}{C_H - C_L} \tag{3}$$

$$\text{Parallel model}: \; C_{NP} = \frac{\frac{1}{C_M} - \frac{1}{C_L}}{\frac{1}{C_H} - \frac{1}{C_L}} \tag{4}$$

$$\text{Maxwell model}: C_{NM} = \frac{C_{NS} \cdot (2.0 + k)}{(3.0 + C_{NS}) \cdot (k - 1.0)} \tag{5}$$

$$\text{Bötttcher model}: \; C_{NB} = \frac{k \cdot C_{NS}}{3 \cdot C_{NS} \cdot (k - 1) + 1} + \frac{2}{3} \cdot C_{NS} \tag{6}$$

In Eqs. (5) and (6), C_M is the measured capacitance, C_L is the capacitance when the ECT sensor is empty, C_M is the capacitance when the sensor is filled with wet granule and k is the ratio of C_H and C_L.

The high permittivity is for wet granule and the low permittivity is for hot air. The relationship between the measured capacitance and the normalised capacitance for different distribution was presented in a previous paper [13]. Eqs. (3)–(6) are used to evaluate the effects of frequency on image reconstruction for different solids distributions with different moisture content.

The Landweber iteration has been used to reconstruct solids distribution [13,14]. Because of the non-linear problems, a relaxation factor must be employed to ensure convergence and to seek an iterative solution to strongly non-linear equations [15,16]. The Landweber iteration algorithm is written as

$$G^{n+1} = G^n \cdot (1.0 + \tau) + \alpha \cdot S^T \cdot (C_N - S \cdot G^n) \cdot (1 - \tau) \tag{7}$$

where α is the step length or gain factor and τ is the relaxation factor.

An optimum method can be used to choose the step length [6]. However, there are no general rules for choosing the best value for the relaxation factor. The optimum value depends on a number of factors, e.g. the nature of the problem, the number of grid points, the grid spacing, and the iteration procedure used [16]. When τ is set to be zero, the iteration becomes the conventional Landweber iteration. If it is negative, the iteration is called under-relaxation. If it is positive it is called over-relaxation [16]. In this research, the value is chosen by trial-and-error.

3. Experiment method

It is well known that the gas–solids behaviour in a fluidised bed is more complicated than other gas–solids process, e.g. pneumatic conveying and spouted beds [17,18]. To verify the above assumption, an ECT sensor was mounted near the bottom of a lab-scale fluidised bed dryer from Sherwood (Tornado M501). An ECT system based on an HP4128 impedance analyser [19] was used to measure capacitance and loss conductance between electrode pairs in the ECT sensor. During the experiment, the frequency was changed from 50 kHz to 13 MHz and the moisture content changed from 1.5 to 38%. The fluidised bed dryer with the measurement instrument is shown in Fig. 1.

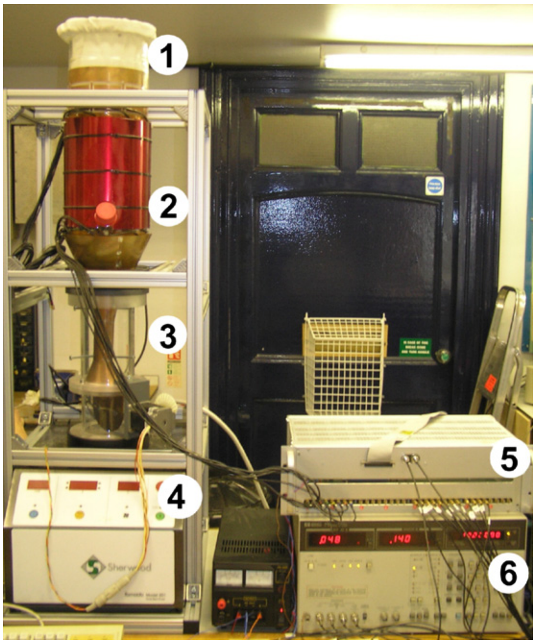

Fig. 1. Lab-scale fluidised bed dryer with instrument and control interface.

The choice of normalisation model is important for image reconstruction of different distributions [20]. The series, parallel, Maxwell and Bötttcher models are used to normalise the measured capacitance. Four typical gas–solids distributions, i.e., annular, core, stratified and mixing distributions, were tested with the normalisation models and the effects of excitation frequency on image reconstruction were examined. To evaluate the image quality, two parameters, namely image error and capacitance residual, were used [15].

A type of wet granule, semolina, was used. The properties of this type of granule can be found in a paper [21]. For preparation of the wet granule with different moisture content, water was sprayed onto dry material and mixed in a low-speed food mixer (KENWOOD CHEF) for 10–20 min. The granulation product was then sieved through a 1.5 mm screen to remove large particles due to agglomeration of wet fine particles and make sure each batch to start from the same bulk density. The moisture content was measured by an HB43 moisture meter from Mettler-Toledo as a reference. The impedance analyser was programmed to measure the dielectric properties of granule at different excitation frequencies in a range from 50 kHz to 13 MHz. Details of the system hardware and operation were described in [19]. The ECT sensor has 8 electrodes, with the wall of the fluidised beds dryer as the frame of the sensor, and is enclosed by an earthed screen to eliminate external interface. An opposite electrode pair, 1 and 5, is used to determine the dielectric properties. The permittivity, conductivity and dielectric loss can be deduced from the measured capacitance and conductance. For the above impedance analyser based ECT system, the data acquisition rate is 0.05 frames per second. This is much slower than the AC-based ECT system, which can generate image data at 250 frames per second [22] for an 8-electrode system.

4. Static test results

The experiments were carried out in a laboratory with a room temperature of 20 ± 2 °C. To reduce the effect of bulk particle density, for each batch, the samples were poured into the glass tube and then fluidised for half minutes by cold air at the minimum fluidisation condition. After switching off the air supply, the samples settled down