Development of a capacitance sensing system for monitoring moisture content of spray dried gelatin powders

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Abstract

For on-line, non-contact measurement of moisture content (MC) of spray dried products, a capacitance sensing system was developed using pairs of copper plates attached to the perimeter of the spray dryer measuring cylinder. The plates formed capacitors which were sensitive to changes in dielectric properties, which in turn were related to MC. The self-built system was tested on spray dried gelatin powders in three modes: a) an off-line mode to test the capabilities of the sensor at different MC levels (4% to 44% (d.b.)); and b) an on-line mode to measure MC of samples passing through the sensor enclosure. Results indicated this system was feasible to measure MC both statically and dynamically, but it had better performance for off-line samples ($R^2=0.98$, RMSE=1.9%); c) this system was also used in an ECT mode and showed the capability to reflect spatial distribution of deposition during spray drying.

Keywords

Moisture content; Capacitive sensor; Spray drying; Gelatin

1. Introduction

Spray drying technology is the most common method for drying heat-sensitive materials in food and pharmaceutical industries (Verma & Singh, 2015). Moisture content (MC) analysis is critical for the spray drying process since it greatly influences quality of spray dried products (Keshani et al., 2015; Maury et al., 2005). Several methods including oven drying, near infrared spectroscopy (NIR) have been developed to measure MC off-line (Ahn et al., 2014; Sauchat et al., 2015). However, many of them are not appropriate for spray drying where a real-time assessment of MC is required. For example, the oven drying method is destructive and typically it takes 24 hours to fully dry a sample. In a spray dryer system, one must turn off the machine and collect samples to test the MC, which makes the whole process time-consuming. The NIR is essentially a spot and surface MC measurement method, only a portion of sample flowing past the sensor could be practically scanned, so a single measurement might not be representative of the entire population inside the measuring vessel. It is imprecise for spray drying process when deposits are formed, the NIR ends up measuring the MC for deposits rather than powders moving through the vessel.

Dielectric methods have also been developed for MC predictions (e.g. Impedance analyzer (Souza et al., 2015), and Microwave moisture meters (Trabelsi et al., 2016)).

43 One of the most common dielectric transducers used is the capacitive sensor. It is a
44 rapid and non-contact method where parallel conductive plates are attached to the outer
45 shell of a measuring vessel, thereby creating what is essentially a capacitor, the
46 capacitance of which is related to the permittivities and quantities of dielectric
47 materials present between them, ~~which in turn is related to MC~~ (Pan, 2014; Pan et al.,
48 2016). The dielectric properties of most materials depend on many factors, including
49 frequency of the applied alternating electric field, chemical composition and structure
50 of the material, and especially permanent dipole moments associated with water and
51 any other molecules making up the material of interest. However, for hygroscopic
52 materials such as agri-foods, the amount of water in the material is generally a
53 dominant factor (Bergo et al., 2012; Venkatesh & Raghavan, 2004). Therefore, the
54 variation in capacitance can be a good indicator of MC in the material (Kandala &
55 Puppala, 2014). Compared to NIR, the capacitive sensor has the advantage to scan the
56 entire quantity of material within the measuring enclosure. However, when the
57 moisture is not evenly distributed within the sample, the single paired capacitance
58 sensor cannot provide any information about this variability. The use of multiple
59 electrodes can make this feasible (Li et al., 2012; Pan, 2014). The multi-electrodes
60 system can also yield a reconstructed image representing sample's spatial permittivity
61 distribution inside the measurement enclosure, which is referred to as electrical
62 capacitance tomography (ECT) (Marashdeh et al., 2015; Pan et al., 2016). Karim &
63 Ismail (2011) applied this technology in sensing soil moisture and its distribution inside

sand and clay mixtures based on the reconstructed permittivity distribution image. Sun et al (2008) used the ECT system in measuring mass flow rate of solid materials. Pan (2014) developed an on-line ECT moisture sensor for simultaneous measurement of MC in flowing wood chips. Gelatin and water were selected as test material in this paper as they both were dielectric materials. Due to the great difference in dielectric constant of water, gelatin, and air (air = 1, protein = 6-30, water = 80 (Li et al., 2013)), the ECT sensor should be able to differentiate between them and map their locations within, for example, a spray drying system. This would facilitate detection of the extent and location of spray deposits, a capability which could be used for quality control of the spray drying process. However, unlike NIR method, knowledge of the sample mass is required in a capacitance sensing system. A dual frequency sensing system was therefore developed to remove dependency on sample mass. The difference in sensor readings between the two frequencies should be only related to MC (Kandala et al., 2015).

The aim of this study was to construct and test a capacitive sensor for measuring MC of a moving stream of spray dried gelatin powders. This was accomplished in three modes, the first of which was to build and test the sensor in an off-line mode in order to understand the output of the sensor for samples of known mass and MC under static conditions, establishing its limits of performance. The second objective was to develop an on-line version of the sensor capable of accurately estimating MC of spray-dried gelatin powders under operating conditions. The third stage is to develop an ECT

system to monitor the deposition status inside the spray dryer in order to quality control of the spray drying process.

2. Materials and Methods

A capacitance sensing system consisted of test capacitors, signal processing and data acquisition device, and a computer to collect data and control the experiment, which was applied to a lab scale spray dryer (B-290, BÜCHI Labortechnik AG, Flawil, Switzerland) and MC measuring tests were made on spray dried gelatin powders in three different modes (off-line, on-line, and ECT mode) (Fig. 1). To form the test capacitors for this sensor, copper plate electrodes were attached to the perimeter of the measuring cylinder, either on product collection vessel, cyclone or side outlet tube, depending on the testing mode being applied. The electrode plates were used in pairs, which could be viewed as a capacitive element, generating an electric field within the measuring cylinder. The strength of capacitance was related to the permittivity of the material between the electrodes. Gelatin and water both are dielectric materials, and both can be used as energy storage medium in a capacitor. A waveform generator (Keysight 33621A, Agilent Technologies, Santa Rosa, CA, USA) was used to generate excitation signals (500 or 800 kHz, 20 Vpp amplitude sine wave) for capacitance measurement. Each electrode was connected to a capacitance-to-voltage transducer (Fig. 2) so that the output signal could be collected using a commercial data acquisition device (NI 6210, National Instruments, Austin, TX, USA). Data processing software

LabVIEW (National Instruments, Austin, TX, USA) was used to determine the amplitude of the output signal relative to the input, and that ratio was correlated with MC.

Fig. 2 shows the schematic diagram of the capacitance-to-voltage conversion circuit. C_x is the sample capacitance between any pair of copper plates. The input excitation voltage (V_s) is set to be a sine wave with $|j\omega C_f R_f| \gg 1$ (j is imaginary unit, ω is angular frequency). The amplitude of the output voltage (V_o) is therefore proportional to the ratio of C_x ($V_o \approx -C_x/C_f \cdot V_s$).

The capacitances (C_x) being detected were quite small. Any stray capacitance arising from internal and external sources could potentially degrade the sensor performance. Multiple strategies were therefore applied to stabilize power variations and minimize noise in the system. All output circuits were fixed on a printed circuit board (PCB) to eliminate undesirable variation resulting from non-constant interaction between the individual elements. All wires for signals were shielded to eliminate stray capacitance between adjacent conductors. The length of wires between test circuits and electrodes was also fixed.

2.1 Off-line mode

A 4-electrode electrical capacitive sensor system was built to validate the accuracy of the sensor under static conditions (Fig. 3), which yielded 6 combinations of electrodes pairs (C_{12} , C_{14} , C_{23} , C_{24} , C_{34} , and C_{31}). Each pair of electrodes was then used to generate electric field and detect the permittivity of the test material. Sensor

electrodes were attached at uniform intervals around the external perimeter of the product collection vessel. Spray dried gelatin powder (~5-20 μm , spherical in shape, Wang, 2015) or water was held using a clean and dry plastic container, and placed in the product collection vessel located at the central or edge area within the sensor enclosure (Fig. 3). A switching network (ADG419, Analog Devices, Norwood, MA, USA) was used to couple the correct electrode pairs into the test circuit, so that the status of each electrode could be controlled by the data acquisition system.

Readings of the 6 different electrode combinations were collected when the sensor was in an empty state (nothing but air in the sensing area) and a full state (sensing area was fully occupied by water) to verify consistency of the sensor. Experiments were conducted with 200 replications and the values were averaged. The system noise level was evaluated by signal-to-noise ratio (SNR) values (Pan, 2014) with each capacitance combination measurement sampled 200 times sequentially. Different amount of test materials (water from 0.08g to 0.8g with 0.08g interval, gelatin from 0.2g to 2g with 0.2g interval) was put into the sensing area, and sensitivity tests (Student's t-test) were undertaken to determine the minimum quantity of water and gelatin that could be detected using the capacitive sensor. Sample weight that was significantly different from the reference ($P < 0.05$) was defined as the minimum detectable amount of test materials. Location tests (ANOVA test, null hypothesis H_0 : sensor outputs were the same at different locations) were carried out to evaluate differences in sensor output at different locations. The sum of all 6 combinations of sensor output with the sample in

place minus the background with the sensor in empty state was calculated as sensor response (V). 200 repeated readings were collected and averaged for each sample arrangement, and were analyzed by SAS software (SAS Institute, Cary, NC, USA).

For two-phase spray dried gelatin powders (containing both gelatin and water), the relationship among sensor output and water/gelatin quantity, could be viewed as the sum of contributions from each individual component, therefore, could be modeled as in Equation (1).

$$V = k_1 W_g + k_2 W_w + k_3 W_g W_w + k_4 \quad (1)$$

Where V is the sensor response (relative to empty state), W_g and W_w are the weight of pre-dried gelatin and water respectively, and k_1 , k_2 , k_3 , and k_4 were constant coefficients. Tests were conducted by placing different quantities of pre-dried gelatin (5-20g), water (0.4-4.4g) or fixed quantity of gelatin (10g) with varying amounts of water (0.4-4.4g) into the sensor and generated readings. The average of the 200 summed readings was recorded as sensor response. Gelatin was pre-dried to exclude the effect of water. Gelatin powders with different water content (4-44% MC (d.b.)) was prepared by mixing pre-dried gelatin with water, and placed overnight at room condition to reach an equilibrium state. A thermogravimetric based moisture analyzer (MF-50, A&D Engineering, Inc., San Jose, CA, USA) was used following the capacitive sensing system to verify the MC of gelatin powders.

2.2 On-line mode

A dual frequency capacitance sensor method (Kandala et al., 2015) was developed to measure MC for moving samples. Two set of capacitance sensors, the outputs of which were processed identically, were tested in series using two input signals at distinct excitation frequencies (500 kHz and 800 kHz) (Fig. 4). The dual frequency output result was calculated as the average response at 800 kHz minus that at 500 kHz. To be an effective sensor, the difference in sensor response should be only related to MC, and independent of other variables including sample weight and location within the enclosure.

2.3 Electrical capacitance tomography (ECT) mode

The 4 electrodes system was used in the ECT mode to compute a 2-D image representing the permittivity distribution within the measuring enclosure (side outlet tube). A linear back projection (LBP) approach was applied to estimate the relationship between capacitance sensor output and permittivity distribution, which transformed a set of measured capacitances (C) into an array of node permittivity (G) at fixed locations inside the sensor enclosure (Equation (2)).

$$G=S^TC \quad (2)$$

The sensitivity matrix S, which represents the electrical potential (field) distribution within the enclosure at a certain condition, was simulated by ANSYS Mechanical APDL (ANSYS, Canonsburg, PA, USA) using a finite element approach. The node number was set to 55, meaning the permittivity was calculated at 55 locations scattered throughout the enclosure. Boundary conditions were set as source electrode amplitude

equal to 10V, and detector electrode to 0V. A Landweber iteration algorithm was applied to improve the accuracy in estimation of G. PYTHONTM (Python Software Foundation, Delaware, USA) was used to convert G values to reconstructed images representing permittivity distribution using an interpolation scheme.

3. Results and Discussion

3.1 Validation of the capability of the sensing system

Any single pair of copper plates are able to form a capacitive sensor and measure MC of a dielectric material. Additional electrodes, however, could provide redundancy and potentially higher accuracy in measurements. Therefore, a 4 electrodes system was built to validate the capability of the concept. Since all electrodes and circuits were designed exactly the same, the single paired parallel plate capacitance measurements should provide the same result under the same conditions. As seen from Fig. 5, the capacitance values were almost the same ($P > 0.05$) if the two electrodes were separated at the same distance (e.g. $C_{12} = C_{23}$, $C_{31} = C_{24}$). Those variations were relatively small and within an acceptable range (with standard deviation $\sigma = \pm 0.0015$ for empty state, $\sigma = \pm 0.003$ for full state). Capacitance values decreased ($P < 0.05$) when the separation between two electrodes increased (e.g. $C_{12} > C_{31}$, $C_{23} > C_{24}$). The result highlighted the consistency in sensor response for both empty and full states, which strongly suggested the arrangement of electrodes and the data processing circuits were correctly designed and adequately built. Re-designed PCB with all wires and circuits mounting on it,

which provided more uniform and accurate locations of electronics, could also be considered in the future to improve system's stability.

SNR values were large enough (>43 dB) to support the conclusion that the capacitive sensor as built was a stable and low noise system (Table 1). The variation in summed capacitances ($\text{SNR} > 59$ dB) was significantly smaller than any single capacitance ($\text{SNR} < 47$ dB). It was, therefore, reasonable to use the capacitance (or voltage) sum as the sensor response predicting overall average permittivity change within the entire sensing area. This implied the use of the multiple-electrode system was equivalent to a single-paired-plate capacitance sensor, but perhaps provided greater stability in the presence of variability in the material being tested.

The sensor response was different for the same sample placed at varying radial locations (Table 2). The sensor response at the central location tended to be smaller than the edge locations for the same object, which reflected the different sensitivity at central and edge locations. This effect reduces sensor accuracy, therefore, a ratio normalization method was developed to eliminate variations in sensor output. The normalized sensor response (V_n) was calculated as in Equation (3).

$$V_n(i, j) = (V_{(i, j)} - V_{e(i, j)}) / (V_{f(i, j)} - V_{e(i, j)}) \quad (3)$$

Where, $V_{(i, j)}$ was the direct reading between electrode i and j , $V_{e(i, j)}$ and $V_{f(i, j)}$ were measurements from paired electrode i and j at empty and full states, respectively. As seen from Table 2, the normalized P-value of ANOVA test was higher compared with

the original P-value, which indicated the sensor output variation with sample location was greatly reduced.

Adding samples into measuring vessel was equivalent to replacing some volume of air with gelatin and water, increasing the overall permittivity. A highly correlated linear relationship between weight of materials tested and sensor response was observed from Fig. 6-Fig. 7, which suggested that the capacitance measuring circuit was reliable.

Water slope (0.0076) was greater than gelatin (0.0009) as the permittivity of water was larger than gelatin. The statistical analysis in Table 3 shows P-values for water and gelatin weight coefficients were < 0.0001 , which implied the significant influence on capacitance from both materials, and that they were individually discernible when mixed. However, the P-value for the interaction term, indicated as $W_g W_w$, was 0.6787, and was therefore deemed as being insignificant in estimating capacitance. After removing the interaction effect, both water and gelatin remained significantly related to the sensor response ($P < 0.0001$). Since the wet weight of gelatin (W) was simply the sum of its constituents ($W_g + W_w$), $W_g/W = 1/(1+MC)$. The relationship among capacitance readings (V), MC and W can be rewritten as in Equation (4).

$$1/(1 + MC) = \alpha \bullet V/W + \beta \bullet 1/W + \gamma \quad (4)$$

Where α , β , and γ are constant coefficients, which could be estimated experimentally.

A mass-based MC prediction model was, therefore, built for this self-built system to estimate MC in spray dried gelatin powders (Equation (5)):

$$1/MC = -137.977 \bullet V/W + 0.107 \bullet 1/W + 1.101 \quad (5)$$

251 Root mean square error ($RMSE = \sqrt{\frac{\sum_{i=1}^n (y_e - y_m)^2}{n}}$) was used to describe the differences
252 between estimated and measured MC (%) (Fig. 8), given the measured value is y_m and
253 the estimated value is y_e . MC was predicted with $R^2 = 0.98$ and $RMSE = 1.9\%$, which
254 indicated the capacitive sensor was reliable for off-line MC measurement.

255

256 3.2 Measurement of MC of moving samples

257 MC of static samples could be measured accurately if the weight of the bulk sample
258 was known. However, it is impossible to measure mass or mass flow rate in a dynamic
259 application of the capacitive sensor. The dual frequency sensing system was therefore
260 developed to remove dependency on sample mass. The sampling rate would also be a
261 consideration for measuring MC for moving samples, especially in cases where rapid
262 determination of MC was required. For instance, the width of the electrode (copper
263 plate) was 2.5 cm, so if the flow rate of spray dried gelatin powders was set to be 0.5
264 m/s in B-290 Spray dryer, the time duration for powders passing through the sensing
265 area was only 0.05 s. Application of the 4-electrode system involved the sequential
266 measurement of capacitance between each unique pair of electrodes, although the
267 sampling rate was set to 250 kHz and sample number was 200 (only took 0.0072 s to
268 read-in 200 data points for data acquisition device), it would take 0.06 s for LabVIEW
269 program to complete data collection for 6 different capacitance combinations, which
270 included capacitance data sampling, amplitude calculation, and switch system control.
271 This sampling rate ($16.7 \text{ Hz} = 1/0.06 \text{ s}$) exceeded minimum sampling requirement (20
272 $\text{Hz} = 1/0.05 \text{ s}$) to capture the full information for moving samples, which was felt to be

lower than necessary to capture variabilities in MC. To compensate for the low sampling rate, the tests were constrained to a single paired parallel-plate reading. The total time for one capacitance cycle measurement was only about 0.01 s, which allowed to take 5 repeating measurements for any single sample. The average of 5 readings was used to calculate the amplitude, which could be expected to improve the accuracy and reliability of MC measuring system. The cyclone was selected as the measuring cylinder in the on-line tests for several reasons. Firstly, gas and spray dried powders were separated at the cyclone, so the MC measured would solely refer to gelatin, rather than a dilute gelatin and gas mixture. Secondly, the centrifugal force and inertia in cyclone caused the gelatin particles to move outward towards the vessel outer walls, which eliminated the calculations necessary for location normalization. The strong centrifugal force also reduced the possibility to form deposits in the cyclone area, so that the accuracy of the MC measurement would not be affected by the deposits.

Fig.9 shows an example of sensor response at two different frequencies (500 and 800 kHz) using on-line mode. The coefficient of determination of this on-line MC prediction model was 0.9, with several outliers observed. This is accurate enough in engineering aspect. A portion of this lowered accuracy compared with the off-line mode ($R^2 = 0.98$) could be attributed to the insufficient sampling rate used. AC/DC transducer, such as signal multiplier plus low-pass filter (Tanzawa, 2015; Yang & York, 1999), and envelope detector (Bakshi & Godse, 2009) that could greatly reduce the minimum requirement of sampling rate for data acquisition system could be used in

the future. Other data processing software, such as C++, that could be much faster than LabVIEW in data acquisition and switches control may also be a good way to reduce time cost during measuring period.

3.3 Visualization of the deposition status of spray dried powders

The ability to characterize permittivity distribution across different portions of the enclosure was an important motivation in developing the ECT mode in this study. Four electrodes system was applied, so that electrical potential distribution of this system only had 2 unique states, e.g. C_{12} , C_{31} (Fig. 10). Electrical potential distribution of other combinations would be the same but shifted. Therefore, if electrical potential distributions of C_{12} , C_{14} , C_{23} , C_{24} , C_{34} , C_{31} were V_1 , V_2 , V_3 , V_4 , V_5 , V_6 (55×1 vector), respectively, the S^T would be $[V_1, V_2, V_3, V_4, V_5, V_6]$ (55×6 matrix). Then, an estimated permittivity distribution G could be computed and thought of as a vector element associated with some fixed locations (55×1 vector). This information was used to yield a cross-sectional image representing the radial permittivity distribution inside the measuring enclosure (side outlet tube), which was expected not only to detect the MC of the powders, but also the area and location of the deposits (Fig. 11). Permittivity information could be extracted from the color in the image. The central part was always in a lower energy state (yellow), which could be explained by the presence of air. The edge part was in a higher energy state (red), which could be attributed by the formation of deposit. According to that information provided by the reconstructed image,

operators could investigate the deposition status inside the spray dryer, and then decide when to turn off the spray dryer for instrument cleaning, which makes it possible to achieve quality control for the spray drying system. Increasing the electrode numbers could divide the sensing area into more segments, which would improve the resolution of reconstructed images. However, it may also decrease the sampling rate achievable for a given data acquisition system.

4. Conclusion

A capacitance sensing system consisted of capacitance-to-voltage transducer, copper electrode and switching network was built and multiple strategies were applied to minimize variations and noise for the test circuits. Results of tests indicated it was a reliable and stable system, which was feasible to measure MC of spray dried gelatin powders both statically ($R^2 > 0.98$) and dynamically ($R^2 > 0.9$) with acceptable accuracy. The sensor was also capable to visualize the deposition status inside the spray dryer, which shown potential to be applied in quality control of continuous spray drying processes. Although this MC measuring system was developed for spray dryer, it could also be applied to other devices where real time and non-contact mode is required. Future work should focus on approaches to enhance system accuracy and stability.

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Fig. 1(a) Experimental setup for MC measurement and **(b)** enlarged image of the central part: (1) computer for data processing and system control, (2) copper plates on side outlet tube for ECT mode, (3) copper plates on cyclone for on-line mode, (4) copper plates on product collection vessel for off-line mode, (5) PCB board, (6) data acquisition device, (7) waveform generator, (8) power supply.

Fig. 2 Schematic diagram of the capacitance-to-voltage transducer circuit (Op-amp, sample capacitance (C_x), feedback capacitor (C_f), feedback resistor (R_f), input voltage (V_s), output voltage (V_o), adapted from Pan (2014)).

Fig. 3 Illustration of the off-line mode. (a) Electrodes (1, 2, 3, 4), 4 electrodes form 6 different electrode combinations and provide 6 independent capacitance values (C_{12} , C_{14} , C_{23} , C_{24} , C_{34} , and C_{31}); (b) Measuring cylinder: collection vessel; (c) Center location (C); (d) Edge location (E1, E2, E3, E4).

Fig. 4 Illustration of the on-line mode. Sensor measurement was tested in series (a second excitation frequency after the regular one). 1. Electrode excited by 500 kHz signal, 2. Electrode excited by 800 kHz. 3. Measuring cylinder: cyclone.

Fig. 5 Sensor output at empty and full state for all 6 electrode combinations

Fig. 6 Linear regression between sensor response (V) and water content (g)

Fig. 7 Linear regression between sensor response (V) and gelatin content (g)

Fig. 8 Plots of MC estimated by capacitive sensor vs. MC determined by moisture analyzer ($R^2=0.98$ and RMSE=1.9%)

Fig. 9 Example of sensor response at two different frequencies (500 and 800 kHz) using on-line mode

Fig. 10 Electrical potential distribution simulated by ANSYS APDL for (a) C_{12} and (b) C_{31}

Fig. 11 Simulated spatial permittivity (deposit) distribution inside the side outlet tube of spray dryer. Blue and yellow indicated low normalized permittivity. Red represented high normalized permittivity.

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Fig. 2 Schematic diagram of the capacitance-to-voltage transducer circuit (Op-amp, sample capacitance (C_x), feedback capacitor (C_f), feedback resistor (R_f), input voltage (V_s), output voltage (V_o), adapted from Pan (2014)).

Fig. 3 Illustration of the off-line mode. (a) Electrodes (1, 2, 3, 4), 4 electrodes form 6 different electrode combinations and provide 6 independent capacitance values (C_{12} , C_{14} , C_{23} , C_{24} , C_{34} , and C_{31}); (b) Measuring cylinder: collection vessel; (c) Center location (C); (d) Edge location (E1, E2, E3, E4).

Fig. 4 Illustration of the on-line mode. Sensor measurement was tested in series (a second excitation frequency after the regular one). 1. Electrode excited by 500 kHz signal, 2. Electrode excited by 800 kHz. 3. Measuring cylinder: cyclone.

Fig. 5 Sensor output at empty and full state for all 6 electrode combinations

Fig. 6 Linear regression between sensor response (V) and water content (g)

Fig. 7 Linear regression between sensor response (V) and gelatin content (g)

Fig. 8 Plots of MC estimated by capacitive sensor vs. MC determined by moisture analyzer ($R^2=0.98$ and RMSE=1.9%)

Fig. 9 Example of sensor response at two different frequencies (500 and 800 kHz) using on-line mode

Fig. 10 Electrical potential distribution simulated by ANSYS APDL for (a) C_{12} and (b) C_{31}

Fig. 11 Simulated spatial permittivity (deposit) distribution inside the side outlet tube of spray dryer. Blue and yellow indicated low normalized permittivity. Red represented high normalized permittivity.

Table 1. SNR for each electrode combination (in dB)

C ₁₂	C ₁₄	C ₂₃	C ₂₄	C ₃₄	C ₃₁	Sum
43.53	46.16	45.95	46.06	46.25	45.73	59.36

Table 2. Results of sensitivity test (t-test) and location test (ANOVA test)

	Minimum detectable amount of the test materials		Location variation test	
	Edge	Center	Original	Normalized
Water	0.32 g	0.4 g	P=0.0718	P=0.4236
Gelatin	1 g	1.4 g	P=0.0832	P=0.2928