MOISTURE CONTENT MEASUREMENT OF POWDERED FOOD USING RF IMPEDANCE SPECTROSCOPIC METHOD

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ABSTRACT

This study was conducted to measure the moisture content of powdered food using RF impedance spectroscopic method. In frequency range of 1.0 to 30MHz, the impedance such as reactance and resistance of parallel plate type sample holder filled with wheat flour and red-pepper powder of which moisture content range were 5.93～17.07%w.b. and 10.87～27.36%w.b., respectively, was characterized using by Q-meter (HP4342). The reactance was a better parameter than the resistance in estimating the moisture density defined as product of moisture content and bulk density which was used to eliminate the effect of bulk density on RF spectral data in this study. Multivariate data analyses such as principal component regression, partial least square regression and multiple linear regression were performed to develop one calibration model having moisture density and reactance spectral data as parameters for determination of moisture content of both wheat flour and red-pepper powder. The best regression model was one by the multiple linear regression model. Its performance for unknown data of powdered food was showed that the bias, standard error of prediction and determination coefficient are 0.179% moisture content, 1.679% moisture content and 0.8849, respectively.

Key Word : RF impedance, moisture density, moisture content, powdered food, multiple linear regression, principal component regression, partial least square regression

INTRODUCTION

The moisture content of food is not only the most important quality factor but also one of the essential parameters affecting their physical and chemical properties related to the safety of storage, capability of processing and quality control. Many techniques can be used to measure the moisture content, the electrical methods have been developed and used widely. The method using RF impedance measures the capacitance and/or a-c (alternating current) resistance of the material between two electrodes forming a capacitor and from which the dielectric property is calculated. This method can be used with a wide range of moisture contents but has the source of measurement errors caused by changes of bulk density of wetted material within the electrodes, kinds of material and temperature of material. Other methods are infrared and near infrared spectrometry, microwave technique and nuclear magnetic resonance technique. These methods enable to measure the moisture content of materials with high accuracy. But because of high cost they are being usually used at laboratory level and it seemed not to fully proper for on-line monitoring of moisture content of materials yet. Even though the electrical method has some disadvantages, it may be attractive technique because that method has merits of rapid and accurate measurement in the wider range of moisture content, simple implementation and inexpensiveness compared with other methods.

Since various chemical components as well as moisture affect the electrical property, only one measuring frequency will be unfavorable to measure the moisture content. In the area of moisture content measurement for agricultural products, RF impedance at two or more frequencies are being studied and hence the characteristic of electrical measuring data is multivariate and/or spectral (Chanet et al., 1999, Nelson et al., 1990). Impedance spectroscopic method is a relatively new and powerful method for characterizing the electrical properties of materials (Macdonald, 1987, Chanet et al., 1999). Multivariate analyses on RF impedance of grain and seed have been reported (Lawrence et al., 1998) and some good promising methodologies for moisture content determination are being presented. However, there are not enough research results about the measurement of moisture content of powdered food. As mentioned above, in case of RF impedance method, one of the critical parameters in moisture content measurements is the variation of bulk density (Shahab and Nelson, 1988). Noh and Nelson (1989) proposed the moisture density parameter (moisture content×bulk density) as bulk density compensation factor in frequency range from 50Hz to 12GHz.

In this study, the moisture content measurement technique using RF impedance spectroscopic method was developed for powdered food. After various multivariate statistical analyses were compared, one calibration model was presented which can estimate moisture contents of any powdered foods.

THEORETICAL BACKGROUND

When the dielectrics such as agricultural products and food are placed within the electrodes being applied by alternating electric field, the electrodes including materials are represented in terms of the parallel equivalent circuit with capacitor and resistor as is shown in Fig. 1. Because of electrical loss of agricultural products and food the electrical phase shift, δ is occurred and hence the impedance is expressed as;

$$Z = R - jX_C \qquad (1)$$

where, Z is impedance in ohm, R is resistance in ohm, X_C is capacitive reactance in ohm and j is the imaginary number, $j^2 = -1$. The capacitive reactance is expressed as;

$$X_C = 1/(2\pi f C) \qquad (2)$$

where, C is capacitance in pF and f is frequency in Hz.

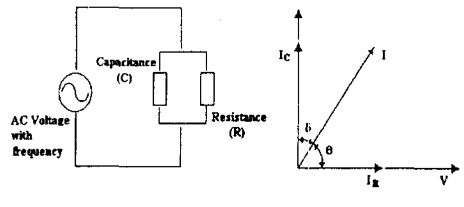


Fig. 1. RC equivalent circuit of parallel plate type electrodes filled with agricultural products or food.

Theoretically, permittivity of a material depends on the concentration and activity of permanent electric dipole molecules e.g., water and ionic bonded molecules e.g., sodium chloride, and on the degree of dipole alignment to the changes in electromagnetic field applied. Therefore, when the sample holder (capacitor) is filled with food samples, the dielectric property of food samples must be highly affected by moisture concentration in mass per unit volume (named as moisture density in this study) and temperature which affects molecular movement. The interaction of the applied electromagnetic field with wetted materials can be described by the complex dielectric permittivity (Nelson, 1982);

$$\varepsilon = (\varepsilon' - j\varepsilon'')\varepsilon_o \qquad (3)$$

where, ε is the complex dielectric permittivity and ε_o is the permittivity of free space(8.854×10^{-12}F/m). The real part, ε' is called the dielectric constant and an imaginary part, ε'' is called the dielectric loss factor. The dielectric constant describes the ability of a material to store electric field energy while the dielectric loss factor represents the loss of electric field energy in the material and is related to conductivity;

$$\sigma = 2\pi f \varepsilon_o \varepsilon'' \qquad (4)$$

where σ is conductivity(S/m).

MATERIALS AND METHODS

Powdered food sample preparation

The wheat flour and red pepper powder from the market place were experimented. The particle size of wheat flour was analyzed by using particle size analyzer (ELZONE, 280PC, Particle Data Inc., USA). Its mean size and standard deviation were 27.54μm and 6.92μm. The particle size of red-pepper powder was analyzed by using the Tyler's standard sieving method (ASAE Standards: S319, 1983-1984) and the mean size and standard deviation were 406.35μm and 280.08μm. The moisture content of food sample was controlled in the constant temperature and humidity chamber. The moisture content ranges of food sample were from 5.93%w.b to 17.07%w.b. for wheat flour and from 10.87%w.b. to 27.36%w.b. for red-pepper powder. The powdered food samples were filled with various filling method in the sample holder to make three levels of bulk density. The moisture content at wet basis was determined by the vacuum oven drying method (40-hours, 60°C, 2g). The moisture density used in this study as compensation factor for fluctuation of bulk density was defined as;

$$\theta = mc(decimal) \times \rho_b \qquad (5)$$

where, θ is moisture density in g/cm^3, *mc(decimal)* is moisture content of powdered food sample in decimal at wet basis and ρ_b is bulk density of powdered food samples in g/cm^3. All experiments were conducted at room temperature of 27±1°C.

Design of parallel plate type sample holder

The parallel plate type sample holder was made of aluminum plate (thickness =1.5mm) and as is shown in Fig. 2. The volume and distance between electrodes are 412.5cm^3 and 2.5cm, respectively. The theoretical capacitance (C_C) of the parallel plate type sample holder filled with powdered food of which dielectric constant is ε_s' is expressed as following equation;

$$C_C = \varepsilon_s' \varepsilon_o \frac{A}{d} \tag{6}$$

where, A is area of plate in m^2 and d is distance between parallel plates.

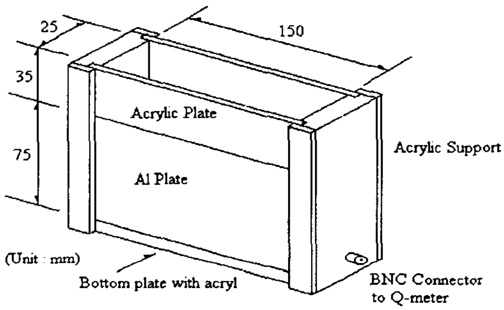


Fig. 2. Parallel plate type sample holder.

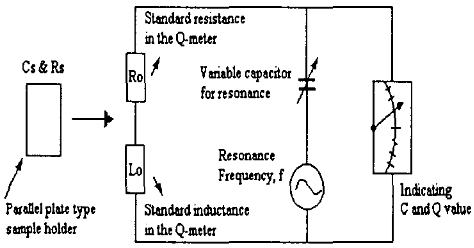


Fig. 3. RF impedance measurement system.

RF impedance measurement system

RF impedance of moist samples was characterized by using the Q-meter (HP4342) as shown in Fig. 3. The range of the measuring frequency was selected from 1 to 30MHz because at lower frequency, the impedance of the sample holder filled with powdered food may be affected by the ionic conductivity and the other chemical components such as mineral contents in the powdered food. From the Q-meter measurement system, the capacitance (C_S) of the sample holder filled with powdered food is expressed as;

$$C_S = C_1 - C_2 \tag{7}$$

where, C_1 is capacitance(pF) at first resonance point of Q-meter without sample holder and C_2 is capacitance at second resonance point of Q-meter with sample holder filled with powdered food.

The resistance (R_S) of the sample holder including the powdered food is expressed as;

$$R_S = \frac{1}{2\pi f C_1}\left(\frac{1}{Q_2} - \frac{1}{Q_1}\right) \tag{8}$$

where, Q_2 is the Q value of the Q-meter at second resonance point with sample holder filled with powdered food and Q_1 is the Q value of the Q-meter at first resonance point without sample holder. With the equations of (2) (3), (4), (7) and (8), it may be assumed that the RF impedance of sample holder filled with powdered food is proportional to the permittivity or dielectric property of the powdered food sample.

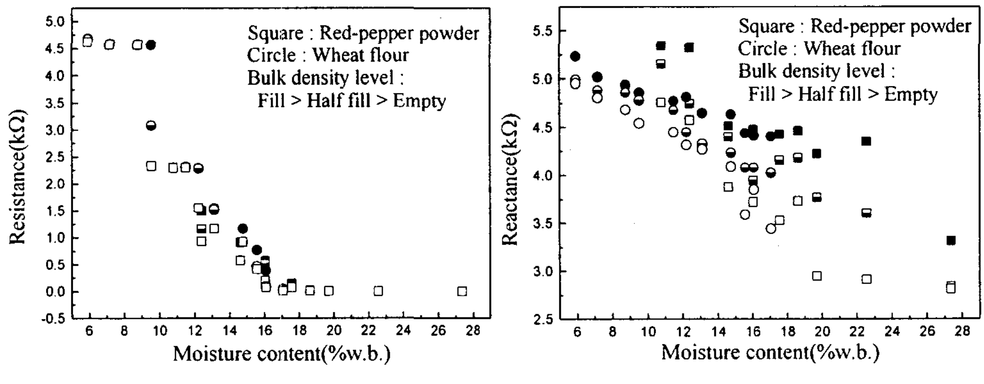
Multivariate data analysis

Multivariate analyses such as multiple linear regression (MLR), principal component regression (PCR) and partial least square regression (PLSR) were performed to evaluate the relationship between RF impedance and moisture content of powdered food. Usually these statistical approaches are very useful for analyzing the multivariate data having various response variables such as RF impedance. A commercial software package called SAS (Statistical Analysis Software) and MATLAB software were used. After significant spectral frequencies were selected by using RSQUARE procedure of SAS, the regression models for determination of moisture content were developed and estimated. The calibration models for determination of moisture content were evaluated and validated by using determination coefficients, standard error of calibration (SEC), standard error of prediction (SEP) and bias (Osborne et.al.,1993, Williams and Norris, 1990).

RESULTS AND DISCUSSION

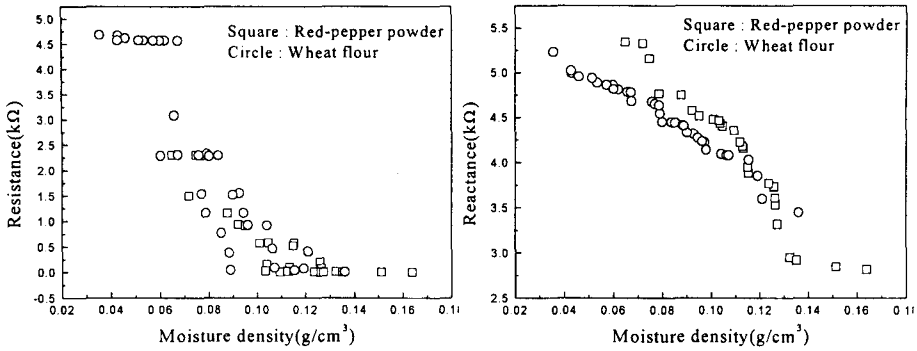
RF impedance of powdered food

Dependence of the RF impedance on powdered food with various moisture contents and bulk densities at frequency of 10MHz are shown in Fig. 4. The reactance and resistance were varied with moisture content and bulk density. At other frequencies, the effects of moisture content and bulk density on RF impedance are very similar to the results at frequency of 10MHz. Fig. 4 proves that RF impedance of powdered food is significantly affected by moisture content and bulk density. The variations in the RF impedance of these powdered food samples with various moisture densities are illustrated in Fig. 5. The effects of fluctuations in bulk density on RF impedance are significantly reduced and hence the moisture density defined in Eq.(5) may be a highly significant parameter to measure the moisture content of powdered food.



(a) Resistance (kΩ) (b) Reactance (kΩ)

Fig. 4. Moisture content and bulk density effects on the RF impedance of wheat flour and red-pepper powder at 10MHz and room temperature of 27±1°C.



(a) Resistance (kΩ) (b) Reactance (kΩ)

Fig. 5. Moisture density effect on the RF impedance of wheat flour and red-pepper powder at 10MHz and room temperature of 27±1°C.

Calibration model for moisture content determination

With MLR, PCR and PLSR, the calibration models for determination of moisture content were developed and compared. The PCR is concentrating the data to their most dominant dimensions and the PLSR is concentrating the data to their most relevant dimensions. The computations for PCR and PLSR are usually performed iteratively, with factors being constructed and added to the regression one by one until the procedures are stopped. To develop the PCR and PLS regression models, NIPALS (Nonlinear Iterative Partial Least Squares) algorithm was used (Williams and Norris, 1990). The number of optimal factors to be retained is usually determined by cross validation method (Svante and Michel, 1998). The MLR model was developed using REG procedure in the SAS package. From the results of RSQUARE procedure in the SAS software, all measuring frequencies are found to be significant. The multiple linear regression model was assumed as;

$$y = a_1x_1 + a_2x_5 + a_3x_{10} + a_4x_{20} + a_5x_{30} + a_6 \tag{9}$$

where, y is the moisture density, x_i is the reactance or resistance at frequency of i–MHz and from a_1 to a_6 are regression coefficients.

And the j^{th} linear combination or component, t_j for PCR and PLSR was represented as (Osborne, et al., 1993, Williams and Norris, 1990);

$$t_j = w_{j1}x_1 + w_{j2}x_5 + w_{j3}x_{10} + w_{j4}x_{20} + w_{j5}x_{30} \tag{10}$$

with

$$w_{jn} = \frac{\mathrm{cov}(x_n, y)}{\sqrt{\sum_{k=1}^{p} \mathrm{cov}^2(x_k, y)}} \tag{11}$$

where, w_{jn} is weight vector, *cov* notes the covariance, n is varying from 1 to p and p is number of variables.

The results of analyses are summarized in Table 1. The reactance is more significant factor for moisture density or moisture content than the resistance. The results of MLR is found to be very favorable method compared with PCR and PLSR in this study.

Table 1. Results obtained by PCR, PLSR and MLR.

Model	Estimation	Red-pepper powder			Wheat flour		
		Reactance	Resistance	N	Reactance	Resistance	N
MLR	SEC	0.0055	0.0140	27	0.0026	0.0108	33
	R^2	0.9559	0.7123		0.9907	0.8457	
PCR	NO. of component	4	4		5	3	
	SEC	0.0133	0.1042		0.0071	0.0692	
	R^2	0.7432	0.4123		0.9310	0.5302	
PLSR	NO. of component	2	3		4	3	
	SEC	0.0123	0.1046		0.0075	0.0699	
	R^2	0.7434	0.5339		0.9235	0.5296	

R^2 and N stand the determination coefficient and number of data, respectively.

The multiple linear regression model with 31 different samples of red-pepper powder and wheat flour was developed as Eq.(12). Its root mean square error and determinant coefficient were 0.00946 g/cm^3 and 0.9385, respectively. This equation can be used for determination of moisture content regardless of kinds of food samples.

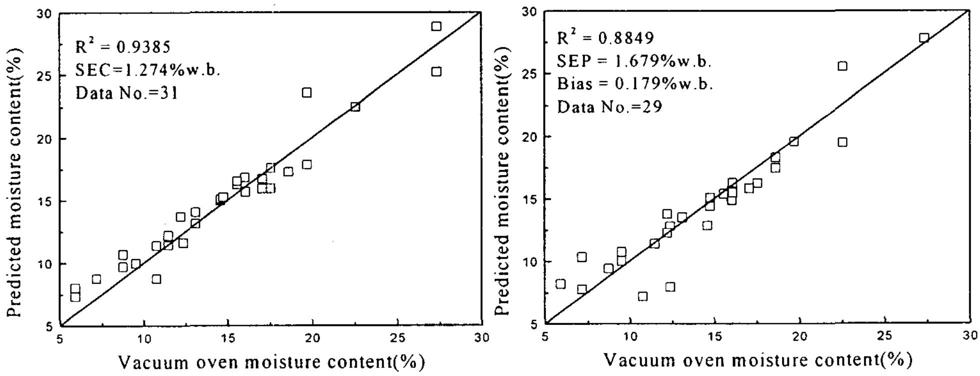
$$\theta = 0.0026X_1 - 0.0014X_5 - 0.0924X_{10} + 0.0712X_{20} + 0.0475X_{30} + 0.1884 \quad (12)$$

where, X_i is the reactance at frequency of i-MHz.

With the Eq.(5) and (13) the moisture content($MC(\%)$) is expressed as;

$$MC(\%) = (0.0026X_1 - 0.0014X_5 - 0.0924X_{10} + 0.0712X_{20} + 0.0475X_{30} + 0.1884) \times \frac{1}{\rho_b} \times 100 \quad (13)$$

The performance of Eq.(13) was validated with 29 different samples of red-pepper powder and wheat flour as is shown in Fig. 6(b). The bias, SEP and determination coefficient of the validation data set are 0.179%, 1.679% and 0.8849, respectively, as compared with vacuum oven drying method. Therefore it may be concluded that it is possible to determine the moisture content of powdered food with one multiple linear calibration equation.



(a) Calibration (b) Validation

Fig. 6. Moisture content predicted with Eq.(13) versus vacuum oven moisture content values for the calibration data of 31 and the validation data of 29 powdered samples in this study.

CONCLUSIONS

The aim of this study was to measure the moisture content of powdered food using RF impedance spectroscopic method. The impedance such as reactance and resistance was analyzed by using the parallel plate sample holder as moisture sensor and Q-meter (HP4342). The reactance and resistance of sample holder filled with red-pepper powder and wheat flour of which moisture content ranges are 10.78-27.36% and 5.93-17.07% at wet basis, respectively, were decreased as increasing moisture content and bulk density. To reduce the effect of bulk density on RF impedance, the moisture density which was defined as product of moisture content and bulk density was estimated. With the multivariate data of RF impedance spectra, principal component, partial least square and multiple linear regressions were analyzed and compared. The multiple linear regression model having moisture density and reactance spectral data was developed. Its performance for unknown data of powdered food was showed that the bias, standard error of prediction and determination coefficient are 0.179%, 1.679% and 0.8849, respectively

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