Capacitance Sensors for Nondestructive Moisture Determination in Grain, Nuts and Bio-fuel materials

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Abstract—Moisture content of grain, nuts and similar organic materials is an important property to be known to determine their time of harvest, and at various stages of their processing and storage. Several moisture measuring instruments are available in the market but for most of these instruments some sort of sample preparation is needed that involves shelling, grinding and weighing. The samples in this process are usually destroyed, and the measurement involves considerable time and labor. In this work, estimating moisture content (MC) of various types of grain, nuts, and bio-fuel materials from measurement of certain dielectric related properties of a parallel-plate capacitor holding samples of these materials between them at radio frequencies is presented.

I. INTRODUCTION

Previous research showed that the variation in dielectric constant with MC for shelled yellow field-corn was more pronounced between 1 and 5 MHz (Nelson, 1978). Thus, \((\varepsilon_{r1}-\varepsilon_{r2})\), the difference in the dielectric constants at 1 and 5 MHz or any other higher frequency, should be a good indicator of the moisture present in the material. The difference in capacitance of a parallel-plate system of plate area \(A\) and separation \(d\) at two frequencies can be written as

\[
C_1-C_2 = (\varepsilon_{r1}-\varepsilon_{r2}) (\varepsilon_0 A/d) \quad (1)
\]

where, \(\varepsilon_{r1}\) and \(\varepsilon_{r2}\) are the dielectric constants of the material between the plates at the two frequencies and \(\varepsilon_0\) is the permittivity of free space \(8.854 \times 10^{-12}\) Farad/m. Though \((C_1-C_2)\) has to be a good estimate of the MC, it was highly influenced by the sample size of the peanuts held between the plates (Kandala and Nelson, 1990). Variations in two other related electrical parameters, phase angle \((\theta)\) and dissipation factor \((D)\) were also considered and empirical equations were developed, to estimate MC of corn, wheat, shelled and in-shell peanut samples, that included terms, \((C_1-C_2), (\theta_1-\theta_2), \) and \((D_1-D_2)\) at 1 and 5 MHz (Kandala and Nelson, 2007). This minimized the errors due to the samples.

Dissipation factor is a measure of energy loss that results from subjecting a dielectric to an alternating current electric field. It is related to the Q factor of the peanut material and is a measure of the energy stored in the electric field relative to energy dissipated in any one period. The power dissipated depends on the equivalent resistance of the complex circuit, and thus the variation in the impedance

\[
MC = A_0 + A_1 (C_1-C_2) + A_2 (\theta_1-\theta_2) + A_3 (Z_1-Z_2) + A_4 (C_1-C_2)^2 + A_5 (Z_1-Z_2)^2 \quad (2)
\]

where, \(C_1, C_2, \theta_1, \theta_2, Z_1, Z_2\) are the capacitance, phase angle and impedance at 1 MHz and 5 MHz respectively. \(A_0...A_5\) are calibration constants. The calibration constants were evaluated from measurements on several samples of known MC values, and applying a least squares computation.

II. MOISTURE METER

An impedance meter called the CI meter (Chari’s Impedance meter) designed and developed by the first author was used to measure the two parameters, impedance \((Z)\) and phase angle \((\theta)\). Three frequencies 1, 5 and 9 MHz are generated by crystal oscillators as shown in the block diagram (Fig. 1) drawn for 1 MHz. The electronic circuits for the three frequencies are similar. These signals are applied to the parallel-plate electrode system \((z)\) alternately, by switching through a multiplexer. Initially, at 1.0 MHz, the current, flowing through this system with an impedance \(Z\), is fed into an op-amp. The same current flows through the range resistor \(R_r\). The output voltage of the op-amp and the original 1 MHz signal from the oscillator are rectified and measured as \(em_1\) and \(er_1\) respectively. This is done similarly at 5 and 9 MHz. The capacitance of the parallel-plate system is computed as: \(C = -1/2\pi f X\), where \(X = |Z| \sin \theta\).
III. MEASUREMENTS

A. In-shell Peanuts

Peanuts of the Georgia Green cultivar harvested in 2007, with an initial M.C (moisture contents are expressed in percent wet basis throughout this paper) of 7%, were used for these studies (Kandala and Sundaram, 2010). Appropriate quantities of water were added to these peanuts, to obtain twelve moisture levels with M.C values between 8% and 23% and the samples were allowed to equilibrate. The peanut pod samples, after conditioning, were separated into calibration and validation groups. The M.C values of the samples in each of these twelve moisture levels (called the sub-lots), were obtained by the standard air-oven method (ASAE Standards, 2003). Peanut samples were placed in the sub-lots, were obtained by the standard air-oven method. Measurements of phase angle and impedance were made with the CI meter. The procedure was repeated on 30 samples from each sub-lot.

B. Wheat

A total of six varieties of wheat, Tam111, Duster, Scoutt 66, Endurance, Jagger, and Hatcher, planted and harvested in Texas and New Mexico, were used in this study (Kandala et al, 2012). The MC of the samples initially was about 9%. Appropriate amounts of water were added to the samples to develop 22 moisture levels between 9% and 25%. Thus, six MC levels of Tam111, five of Duster, four of Hatcher, five of Jagger, and one each of Scoutt 66 and Endurance were developed. M.C of each subsample was determined by the standard air-oven method (ASAE, 1994).

C. Wood chips and Powders

Measurement of M.C of wood chips and related powders is important in the pulp and bio-fuel industries (Biermann, 1993; Nystrom and Dahlquist, 2004). Measurements of phase angle and impedance were made on pine and hard wood chips placing them in the cylindrical sample holder, used above for grain and peanuts. Calibration equations were developed as before, separately, for pine and hard wood chips. Measurement of M.C for bio-fuel materials in the form of powders was also done using the CI meter using a parallel-plate system. The plates were held horizontally with the lower plate held rigidly while the upper plate could slide up and down by about 20 mm. The sample powder was packed into a Petri dish about 20 mm diameter and 10 mm thick, and was placed between the plates with both plates in contact with it, and measurements of phase angle and impedance were made with the CI meter.

IV. RESULTS AND DISCUSSION

For peanuts, from the capacitance value, measured values of impedance and phase angle, and the oven determined M.C value of the samples in the calibration lots, the semi-empirical equation developed by Multi Linear Regression (MLR) model using statistical software (the Unscrambler) was:

\[
\text{MC peanut} = -9.71 + 0.56 \theta_1 - 3.71 C_1 - 25.13 Z_1
\]

where \( C_1, \theta_1 \) and \( Z_1 \) are the capacitance, phase angle and impedance values at 1MHz and \( C_2, \theta_2 \) and \( Z_2 \) are the capacitance, phase angle and impedance values at 5MHz. The M.C values of the pod samples in the five validation lots calculated by using equation (3) were compared with the air-oven values and the results are summarized in table I. The predictability was better than 95% for all the levels tested. Standard error of prediction, SEP (SEP = \( \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (e_i - \bar{e})^2} \)) where \( n \) is the number of observations, \( e_i \) is the difference in the moisture content predicted and that determined by the reference method for the \( i \text{-th} \) sample, and \( \bar{e} \) is the mean of \( e_i \) for all of the samples was 0.70, and a bias value of -0.35, indicates the closeness of the mean calculated values to the standard values [Moore, D.S., 2000].

For wheat samples, from the measured values of \( C, \theta \) and \( Z \) on the calibration sub-lots of wheat, the values obtained for the constants \( A_0, \ldots, A_6 \) in equation (2) were: \( A_0 = -27.235 \), \( A_1 = 0.0032 \), \( A_2 = 4.734 \), \( A_3 = 20.476 \), \( A_4 = -0.000088 \), \( A_5 = -0.405 \), \( A_6 = -2.694 \). In figure 2, comparisons of the predicted and the air-oven values of the wheat validation lots are shown. Predictability was 87% or better for any moisture level and about 98% over the 15 levels. The prediction had a \( R^2 \) value of 0.98 and an SEP of 0.60. The CI meter predicted the M.C values of different varieties with a single calibration equation.

Using the respective calibration equations, MC of pine and hard wood samples in the moisture range between 5% and 50% was determined and compared with their air-oven
values. The results are shown in figures 3 and 4. For the seven moisture groups (30 samples in each group) of pine

Wood validation samples, the CI meter predicted the MC values close to their oven values with an $R^2$ value of 0.99 and an SEP of 1.37. Similarly, for seven moisture groups of hard wood samples used for validation the CI meter predicted the MC values close to the oven values with an $R^2$ of 0.99 and an SEP of 1.56.

Measurement of MC for bio-fuel materials in the form of powders was also done using the CI meter using a parallel-plate system. The plates were held horizontally with the lower plate held rigidly while the upper plate could slide up and down by about 20 mm. The sample powder was packed into a Petri dish about 20 mm diameter and 10 mm thick, and was placed between the plates with both plates in contact with it, and measurements of phase angle and impedance were made with the CI meter. Measurements were done for pine wood and switchgrass powders, in the MC range of 6% to 25%, with the CI meter, and the results are shown in figures 5 and 6.

V. CONCLUSION

From the measurements of impedance and phase angle using a low-cost impedance meter and a capacitance sensor the average moisture content of 150 to 200g of in-shell peanuts, grain such as wheat, and bio-fuel samples could be determined. The weight or volume of the samples need not be measured. Ability to measure the MC of peanuts while they are in their shells would eliminate the need to shell them and clean them saving considerable time.

VI. REFERENCES


