Parallel-plate capacitance sensor for nondestructive measurement of moisture content of different types of wheat.

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Abstract— A simple, low cost instrument that measures impedance and phase angle was used along with a parallel-plate capacitance system to estimate the moisture content (MC) of six types of wheat. Moisture content of grain is important and is measured at various stages of their processing and storage. A sample of about 150 g of wheat was placed separately between a set of parallel plate electrodes and the impedance and phase angle of the system were measured at frequencies 1 and 5 MHz. A semi- empirical equation was developed using the measured impedance and phase angle values, and the computed capacitance, and the MC values obtained by standard air-oven method. Multi Linear Regression (MLR) method was used for the empirical equation development using statistical software. In the present work, a low-cost impedance analyzer designed and assembled in our laboratory was used to measure the impedance and phase angles. MC values of wheat samples in the moisture range of 9% to 25%, not used in the calibration, were predicted by the equations and compared with their standard air-oven values. For over 97% of the samples tested from the six varieties of wheat, the predicted MC values were within 1% of the air-oven values. This method, being nondestructive and rapid, will have considerable application in the drying and storage processes of wheat and similar field crops.

Keywords: Impedance analyzer, parallel-plate electrodes, capacitance, phase angle, moisture content, wheat

I. Introduction

Wheat is an important crop grown, and used as a staple food in almost all the parts of the world. As soon as wheat is harvested measuring its moisture content (MC) before drying, is a crucial part of maintaining its quality. Wheat should be dried to 13.5 % MC for immediate sale [1]. It is recommended that wheat should be dried with natural air, but using hot air is not uncommon depending on the climatic conditions. During the drying process, MC of the wheat is measured periodically to determine if the required drying is achieved. Some of the electronic moisture meters presently used require either fixed or large quantities of wheat samples each time a measurement is made while others are destructive type. Utilizing the high correlation between the dielectric properties of grain and its MC, a method was developed to determine the MC of single kernels of corn [2].The technique was extended to measurements on small samples (15 to 30 kernels) of wheat [3] using a commercial impedance meter. While the commercial impedance meters performed well in the establishment of the impedance method for moisture determination, they have several extra features that are not needed for this work but make them expensive. Thus a low-cost meter that would measure the impedance parameters at the required frequencies on a moderately large sample of grains would be useful in the estimation of their moisture content, and would give a better average value of the MC of the bulk quantities. A low-cost impedance meter (CI meter) was designed, and used along with a parallel-plate capacitance system to estimate the MC of in-shell peanuts and yellow-dent field corn samples of about 150g [4]. The impedance meter measured the impedance and phase angle of the parallel-plate capacitance system holding the sample, at two frequencies 1 and 5 MHz, and from the measured values computed the MC of the sample. In this work, the CI meter was calibrated using samples from five wheat types and the calibration equation generated was used to predict the MC of samples, not used in the calibration, from these and another variety grown in New Mexico.

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II. Material and Methods

A. Basic Principles:

It was found earlier that the high correlation between dielectric properties of aqueous materials and their MC can be used in predicting the MC present in these materials. The variation in dielectric constant with MC for shelled yellow field-corn was found to be more pronounced between 1 and 5 MHz from earlier documented work [5]. 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 thickness A and separation d at two frequencies can be written as

$$C_1-C_2 = (\varepsilon_{r1}-\varepsilon_{r2})\, d/\varepsilon_0 \quad (1)$$

where, ε_{r1} and ε_{r2} are the dielectric constants of the material between the plates at the two frequencies and ε_0 is the permittivity of free space (8.854×10^{-12} farad/m). It was found earlier that though (C_1-C_2) was a good estimate of the MC, it alone was not able to predict the MC of the material with sufficient accuracy [6]. This was partially due to the volume of space that a sample of odd shaped material, such as grain, occupies between two parallel-plates would vary each time they are placed between the plates. Air gaps between the grain kernels, and the kernels and the capacitor walls would occur differently introducing errors. To compensate for these errors two other related electrical parameters, phase angle (θ) and impedance (Z) were also measured at these two frequencies, using the CI meter. The capacitance of the parallel-plate system was computed from the values of θ and

Z. Using the differences in the values of C, θ and Z at the two frequencies minimized the errors due to the air gaps. Using these differences and their square terms in an empirical equation, the average MC of about 150g -sample of wheat was determined within 1% of their air-oven values. The calibration equation used is as shown below:

$$MC = A_0 + A_1 (C_1 - C_2) + A_2 (\theta_1 - \theta_2) + A_3 (Z_1 - Z_2) + A_4 (C_1 - C_2)^2 + A_5 (\theta_1 - \theta_2)^2 + A_6 (Z_1 - Z_2)^2 \quad (2)$$

B. The CI meter

The design and operation of the CI meter was described previously [7]. Three frequencies 1, 5 and 9 MHz. are generated by three crystal oscillators and were applied to a parallel-plate system, which acts as the impedance load (Z), alternately by switching through a multiplexer. The values of impedance (Z) and phase angle (θ) at 1 and 5 MHz were read from the instrument, and the real and imaginary components of Z at each frequency are calculated as R = |Z| Cos θ and X = |Z| Sin θ. The capacitance of the parallel-plate system with a peanut sample between the plates is obtained as:

$$C = -\frac{1}{2\pi f X} \quad (3)$$

The measurement system set up is shown in figure 1. The CI meter is provided with a regulated power supply that can be plugged into a 110 V AC line. It can also be operated on two 12 V rechargeable batteries provided for field operations. A lap top computer was used to control the operations, measure and register the data and calculate the moisture contents.

A cylindrical acrylic tube, fitted with a set of parallel-plate electrodes (Fig.1), served as the sample holder and sensor as described earlier [7]. Except for the electrodes, no metal parts were used in the assembly of the electrode system or the sample collecting system to prevent any interaction with the RF signal used in the measurements. With the drawer pushed all the way in, the cylinder was filled with the wheat samples and the impedance measurements were taken. After the completion of the measurements, the drawer is pulled out slowly, allowing the sample to fall into the drawer. The

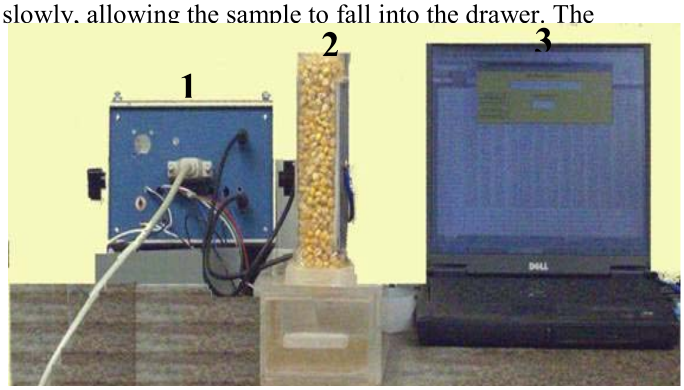

Figure 1. Impedance measuring system: RF Impedance measuring system: 1. CI meter, 2. Cylinder with electrodes, 3. Computer

drawer was emptied before another sample was placed in the cylinder for measurement. With the wheat sample occupying the space between the electrodes, the analyzer measured the impedance and phase angle of this electrode system at 1 and 5 MHz and a computer controlled and collected the data from the analyzer. Using these measurements in an empirical equation, the computer was programmed to calculate the moisture content in each sample.

C. Wheat Samples:

A total of six varieties of wheat, planted and harvested around the Texas panhandle and at the New Mexico State University Station near Clovis, were used in this study [8]. The wheat varieties[1] are Tam111, Duster, Scoutt 66, Endurance, Jagger, and Hatcher, planted during October 2010 and harvested during July 2011. All the sample lots were stored at 4 ^{0}C and 40% relative humidity. When the samples were received at the National Peanut Research Laboratory (NPRL), their MC was about 9%.[2] These lots were divided into 22 sublots and were placed in glass jars. Leaving the contents of one jar of each variety at its original MC level, appropriate amounts of water were added to the other jars to develop 22 moisture levels between 9% and 25%. Thus, from the available quantities six MC levels of Tam111, five of Duster, four of Hatcher, five of Jagger, and one each of Scoutt 66 and Endurance were developed for calibration and validation. Moisture content of each subsample was determined by the standard air-oven method by drying triplicate samples of 10g each for 19h at 130 ^{0}C [9]. Samples were weighed before and after drying and the MC of each sample was obtained as the percentage ratio of the weight loss to the original wet weight of the sample.

III. MEASUREMENTS

Impedance measurements were made on 30 samples from each sublot. Wheat samples were transferred from the jars into the cylinder fitted with the electrode system, till the space between the two plates of the cylinder was completely filled. The cylinder accommodated about 150 g of wheat samples. The room temperature during the measurements was maintained at 21 ± 1ºC. Wheat sample from one of the jars was transferred into the cylinder with the drawer sitting fully inside the box, till the space between the two plates of the cylinder was filled. In this position the impedance (Z) and phase angle (θ) were measured with the CI meter at 1and 5 MHz. The sample was then collected in the drawer by gently pulling it out and tapping on the cylinder for the sample to drop down. The drawer was emptied and reset in the box. The procedure was repeated on all wheat samples (sublots) from the rest of the jars.

IV. DATA ANALYSIS

The samples for calibration were picked randomly out of the 22 sublots making sure that the moisture groups with the lowest and highest MC values are included and the moisture range in between is adequately covered. Using the MC values and the measured impedance values of the calibration group, which consisted of two moisture levels each of Tam111 and Duster, and one level each of Jagger, Scoutt 66 and Endurance varieties, values of the calibration constants of equation (2)

[1] Mention of company or trade names is for purpose of description only and does not imply endorsement by USDA.

[2]Moisture contents are expressed in percent wet basis throughout this paper.

were determined by Multiple Linear Regression (MLR) analysis. MLR was done using Unscrambler software [10]. Substituting the values of the constants, and the measured values of θ and Z, and the computed value of C (Eqn. 3) of the validation samples, in equation (2), the MC of each wheat sample in the validation lot was calculated and compared with the values determined by the air-oven method

V. RESULTS AND DISCUSSION

From the measured values of C, θ and Z on the calibration sub-lots with the CI meter, and using Unscrambler procedures for regression analysis, 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

This calibration had an R^2 value of 0.99, and all the terms used in equation (2) had a probability of a greater absolute t value (Pr>|t|) under the null hypothesis for the variables [11], less than 0.0001. These constants along with the values of impedance, phase angle and capacitance (obtained from equation (3)) were used in equation (2) to calculate the MC of each of the 30 samples from the calibration sub-lots. The calculated values were averaged over the 30 samples in each moisture group and were compared with their air-oven values, and are shown in table 1 along with their standard deviations, differences and predictability. Predictability is defined as the percentage of samples in each moisture group for which the predicted MC values were within 1% of their air-oven values.

Table 1. Calibration Sublots : Comparison of CI meter and air-oven MC measurements

Wheat Variety[a]	Moisture content (%)				
	Oven value	Predicted by equation (2)			
		Mean[b]	Std. Dev	Difference: Oven–Pred.	Predict-ability [c]
Tam111	9.11	9.29	0.45	-0.18	100
Duster	11.33	11.65	0.23	-0.32	100
Duster	13.56	13.04	0.28	0.52	100
Tam111	16.67	16.38	0.23	0.29	100
Scoutt66	19.78	20.43	0.26	-0.65	97
Endurance	22.67	22.38	0.30	0.29	100
Jagger	24.67	24.63	0.16	0.04	100

[a] All from 2011 harvest. [b] Mean of 30 sample measurements. [c] Predictability is the % of samples in each moisture group for which the predicted MC is within 1% of the air-oven value.

Shown in table 2 are the fitness measures for the calibration lots. The SEC[3] was 0.49% MC (with p=6 and n= 210). The predictability was good at all the MC levels. The calculated values averaged over 30 samples from each moisture group agreed well with their air-oven values, and the predictability ranged from 97% to 100%. The standard deviation for 30 samples at any moisture level was under 0.5%. An R^2 value of 0.99, an SEC of 0.49, a low bias value, and a high rate of predictability suggest that this model is suitable for MC predictions. This was further verified from the fitness measures obtained for the validation sets.

Table 2. Fitness measures for the calibration lots of wheat

R^2	RMSEC	SEC	Bias
0.99	0.49	0.49	0.001

Shown in table 3 are the MC values for 15 validation sets consisting of three varieties used in the calibration, and an additional variety, Hatcher, not used in the calibration. The moisture levels of the three varieties used in the validation are different from the levels used in the calibration. The MC values were predicted using the measured values of impedance and phase angle, and the calibration constants in equation (2), averaged over 30 samples in each group, and compared with their air-oven values. Also shown are the standard deviations and the predictability of each moisture group. The predictability was 87% or better for any moisture level and averaged about 98% over the 15 validation levels.

Table 3. Validation Sublots: Comparison of CI meter and air-oven MC measurements

Wheat Variety	Moisture Content (%)				Predict-ability[1] (%)
	Oven Value	Predicted by equation (2)			
		Mean[2]	Std. Dev.	Difference: Oven-Pred.	
Hatcher	9.33	9.68	0.18	-0.35	100
Hatcher	9.67	9.63	0.23	0.04	100
Hatcher	9.78	9.62	0.25	0.16	100
Duster	10.00	9.81	0.23	0.19	100
Tam111	10.67	10.30	0.23	0.37	100
Hatcher	12.14	11.33	0.19	0.81	97
Tam111	12.89	12.11	0.28	0.78	87
Tam111	14.89	14.14	0.29	0.75	90
Jagger	16.67	16.89	0.20	-0.22	100
Duster	17.78	17.89	0.32	-0.11	100
Jagger	18.22	18.30	0.35	-0.08	100
Tam111	18.44	19.16	0.26	-0.72	93
Jagger	19.11	19.15	0.30	-0.04	100
Duster	20.00	20.56	0.24	-0.56	100
Jagger	23.56	23.69	0.25	-0.13	100

[1]Mean of 30 samples in each moisture group. [2]Predictability is the % of samples in each moisture group for which the predicted MC is within 1% of the air-oven value.

Shown in table 4 are the fitness measures for the validation group of samples. The validation set also came up with a

[3] $SEC = \left(\frac{1}{n-p-1} \sum_{i=1}^{n} e_i^{\,2} \right)^{\frac{1}{2}}$ where n is the number of observations, p is the number of variables in the regression equation with which the calibration is performed, and e_i is the difference between the observed and reference value for the i^{th} observation.

good R^2 value of 0.98 and the standard error of prediction (SEP)[4] was 0.60. The SEP value is close to the SEC value and

Table 4. Fitness measures for the validation sublots

R^2	RMSEC	SEP	Bias
0.98	0.62	0.60	-0.146

the R^2 value compares well with that of the calibration group. A low bias indicates the closeness of the mean calculated values to the air-oven values confirming that the prediction model is dependable. The SEC value of 0.49 and the SEP value of 0.60 were better than the 0.88 for SEC and 0.91 for SEP obtained earlier with small wheat samples (Kandala et al., 1996). Shown in Fig. 2 is the comparison of the predicted and the air-oven values of the seven calibration wheat lots. An R^2

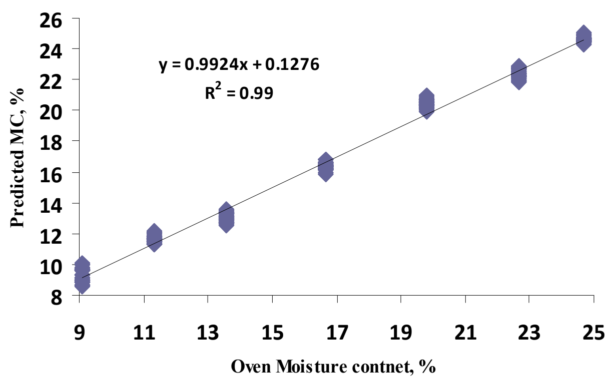

Fig. 2. Comparison of oven and predicted moisture content values for the calibration lots

value of 0.99 further indicates the fitness of the calibration equation. Similarly in Fig. 3, the MC values of the validation samples of wheat are compared with their respective air-oven

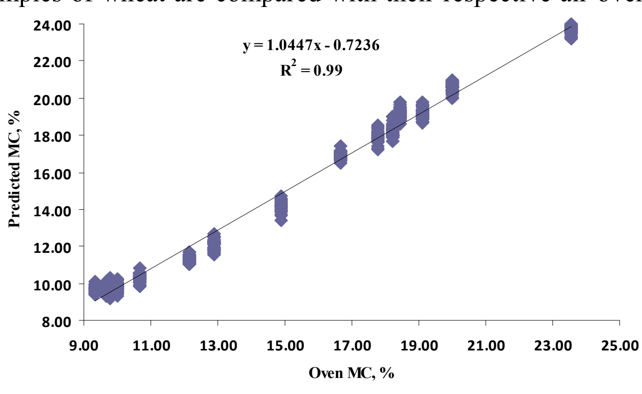

Fig.3. Comparison of the oven and predicted moisture content values for the validation lots

[4] $SEP = \left(\frac{1}{n-1} \sum_{i=1}^{n} (e_i - \bar{e})^2 \right)^{\frac{1}{2}}$ 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^{th} sample, and $\bar{e}$ is the mean of e_i for all of the samples.

and plotted. The predicted MC values compare well with their corresponding air-oven values with an R^2 value of 0.99. The calibration equation predicted the MC values of different varieties quite well with a single calibration equation, developed with randomly picked MC levels from the different available varieties. Moreover, the measurement is rapid and nondestructive and there was no need to measure the volume or weight of the wheat samples.

VI. CONCLUSIONS

From the measurements of impedance and phase angle using a low-cost impedance meter the moisture content of 150 to 200g of wheat samples could be determined rapidly and nondestructively. There was no need to know the weight or volume of the samples. The moisture range of the samples tested was between 9% and 25%. Calibration was done with five different wheat varieties, and validation was done on all these varieties, and one additional variety. For 98% of the samples tested from the six varieties, the predicted MC values were within 1% of their air-oven values. This meter performed well for all the six varieties of wheat in predicting the MC with a single calibration equation. Using impedance measurements taken at two frequencies has helped in eliminating the errors due to air gaps that would occur randomly when the sample is filled between the plates. Moisture content being an important parameter to be measured and monitored at various stages of wheat production and storage, this low-cost instrument would be useful for the grain industry.

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