D-7

SENSING DIELECTRIC PROPERTIES OF ARBITRARILY SHAPED BIOLOGICAL OBJECTS WITH A MICROWAVE RESONATOR

A.W.Kraszewski, S.O.Nelson and T.S.You

U.S. Dept. of Agriculture, Agricultural Research Service

R.B.Russell Agricultural Research Center, Athens, GA 30613

ABSTRACT

A rectangular waveguide resonator operating in the H_{107} mode at 6 GHz was used in determining the change in resonant frequency and the Q-factor of the cavity when loaded with single soybean seeds or corn kernels of various shapes and dimensions. By measuring those variables for a kernel oriented in two positions differing by 90 degrees with respect to the maximum E-field vector, the average values of ΔF and ΔT were found to be virtually shape-independent. The ratio $\Delta F/\Delta T$ is a size-independent and well-defined function of the material properties $(\epsilon' - 1)/\epsilon''$, and as such it can be related to the material density, moisture content, or other characteristic when all other properties remain unchanged.

INTRODUCTION

As electronic instruments for moisture content determination in grain and seeds provide a moisture content reading which is an average for all kernels in a sample (e.g. 100 g or more), there is need for an instrument that can determine the moisture content of individual kernels within samples. Resonant cavity techniques [1-3] offer means for such measurements in the frequency range where dimensions of objects are sensible smaller than those of the resonator. The material properties are evaluated by measuring the shift in resonant frequency and the change in the Q-factor of the cavity when the object is inserted into the cavity.

Two kinds of objects were tested: soybean, Glycine max L., seeds and corn, Zea mays L., kernels of various shapes and dimensions and different hydration levels. Their effect on parameters of a rectangular waveguide resonator operating in the H_{107} mode at 6 GHz were determined with an automatic network analyzer working in the transmission mode.

The shift of the resonant frequency is denoted by $\Delta F = f_o - f_s$, where subscripts o and s refer to the empty cavity and the cavity loaded with a seed at the center of the cavity, respectively. Energy dissipated in the object is expressed as a change in the cavity Q-factor

$$\frac{1}{Q_{Ls}} - \frac{1}{Q_{Lo}} = \frac{1}{Q_{Lo}}\left(\frac{V_o}{V_s} - 1\right) = \frac{\Delta T}{Q_{Lo}}$$

where V denotes the voltage transmission coefficient at resonance, $\Delta T=(10^k-1)$ is the transmission factor and $k=0.05(S_{21o}-S_{21s})$, with S_{21} being the voltage transmission coefficient at resonance, expressed in decibels.

EXPERIMENTAL RESULTS

Soybean seeds. These were seeds of nearly uniform spherical shape, with the ratio of the major to minor diameter ranging from 1.2 to 1.36. Major diameters ranged between 6.5 and 7.5 mm. The resonant cavity parameters are related to the material permittivity, $\epsilon = \epsilon' - j\epsilon''$, seed volume, and seed shape by the expressions [3]

$$\Delta F = (\epsilon' - 1)Kf_o\left(\frac{v_s}{v_c}\right)$$

and (1)

$$\Delta T = \epsilon'' K^2 Q_{Lo}\left(\frac{v_s}{v_c}\right)$$

where v_c is the volume of the empty cavity (214 cm^3), v_s is the volume of the object, and K is the shape factor accounting for all effects related to the shape of the object (depolarization, etc.). The ratio of these two quantities

$$X = \frac{\Delta F}{\Delta T} = \frac{(\epsilon' - 1)}{\epsilon''}\frac{C}{K} \qquad (2)$$

is a size-independent function of the material permittivity and the shape of the object, where $C = f_o/Q_{Lo}$ is a constant dependent on the parameters of an empty cavity. When all objects to be measured are of uniform shape [4], small variations in K are accounted for in the measurement errors and do not overshadow the main relation. Experimental results for X as a function of seed moisture content, M, for

108 data points are shown in Fig.1. A simple analytical relation of the form

$$M = \frac{430}{X} + 0.9 \qquad (3)$$

with a correlation coefficient r = 0.991,

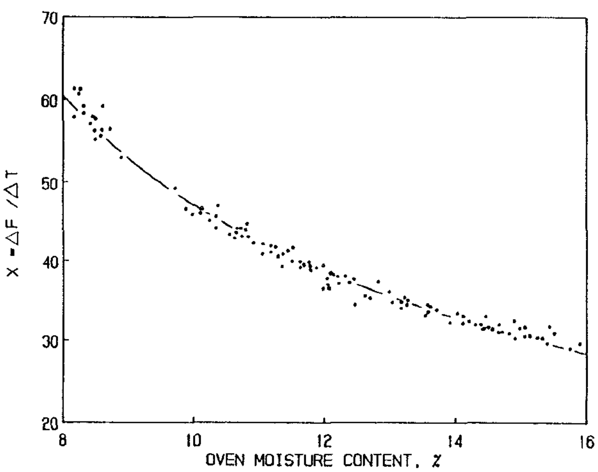

Fig.1. Parameter X as a function of moisture content for soybeans. Curve calculated from Eq.(3).

can be used as the calibration equation to predict the moisture content in soybean seeds, regardless of their dimensions.

Corn kernels. These are highly non-uniform, irregularly shaped objects, sometimes pyramidal, cuboidal, or disk-like, up to 14 mm long, with no flat surfaces, and seldom with surfaces parallel to each other. The maximum to minimum dimension ratio ranged from 1.25 to 4, for which the value of K may differ significantly. However, it has been observed that when a kernel is rotated about the x-axis of the cavity, both ΔF and ΔT follow $\cos^2\Theta$ behavior, where Θ is the angle of rotation. As shown in Fig.2 for two kernels of different size and shape, the measured values pass alternately through equally spaced regions of weak and strong coupling (interaction), separated by 90°, with the electromagnetic field inside the cavity. The amplitude of changes is smaller for the larger, nearly spherical kernel A (max. to min. dimension ratio of 1.27), than for the flat, disk-like kernel B (ratio of 2.20), but the value of X is similar for the two kernels (22.1 and 22.2), which corresponds to the same moisture content of 16.4 % resulting from the calibration curve shown in Fig 3.

The observed situation may be explained as follows: for two measurements with a kernel rotated by 90°, one obtains

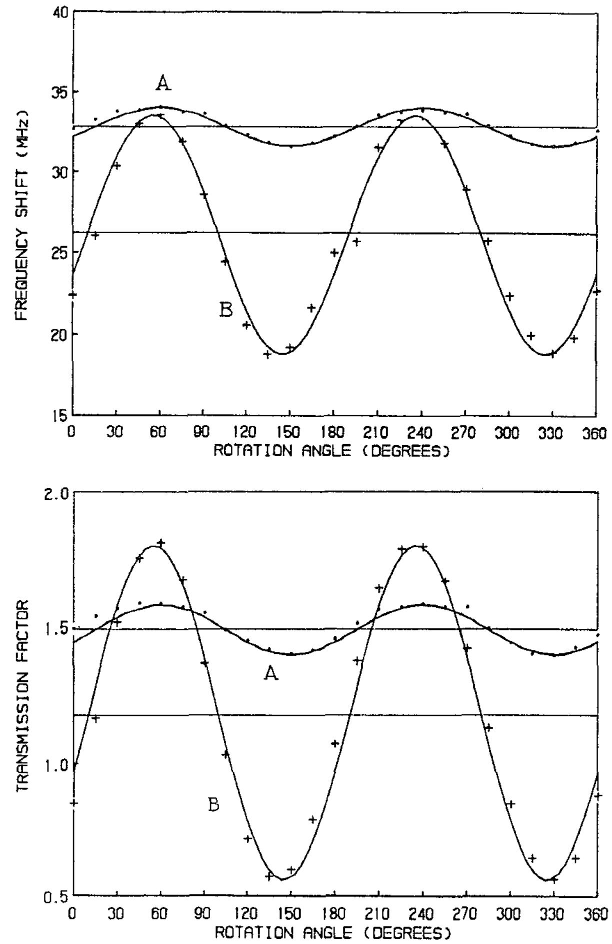

Fig.2. Resonant frequency shift, ΔF, and transmission factor ΔT, as a function of kernel orientation.

$$\Delta F_1 = (\epsilon' - 1) K_1 f_o \left(\frac{v_s}{v_c}\right)$$

$$\Delta T_1 = \epsilon'' K_1^2 Q_{Lo} \left(\frac{v_s}{v_c}\right) \qquad (4a)$$

and

$$\Delta F_2 = (\epsilon' - 1) K_2 f_o \left(\frac{v_s}{v_c}\right)$$

$$\Delta T_2 = \epsilon'' K_2^2 Q_{Lo} \left(\frac{v_s}{v_c}\right) \qquad (4b)$$

where the shape factors K_1 and K_2 are related to their extremum values:

$$K_1 = K_{min} + (K_{max} - K_{min})\cos^2\Theta$$

$$K_2 = K_{min} + (K_{max} - K_{min})\cos^2(\Theta \pm \pi/2).$$

Taking the average of the two measured values, one has

$$\Delta F_{avg} = \frac{\Delta F_1 + \Delta F_2}{2} = (\epsilon' - 1) K_{avg} f_o \left(\frac{v_s}{v_c}\right)$$

$$\Delta T_{avg} = \frac{\Delta T_1 + \Delta T_2}{2} = \epsilon'' K_{avg}^2 Q_{Lo} \left(\frac{v_s}{v_c}\right) \qquad (5)$$

with

$$K_{avg} = \frac{K_1 + K_2}{2} = \frac{1}{2}(K_{max} + K_{min}),$$

which leads to the size-independent function as before

$$X = \frac{\Delta F_{avg}}{\Delta T_{avg}} = \frac{(\epsilon' - 1)}{\epsilon''} \frac{C}{K_{avg}} \qquad (6)$$

As in the case of soybeans, the function is highly correlated with moisture content in corn kernels. The experimental data for 53 yellow-dent field corn kernels of maximum-to-minimum dimension ratio ranging from 1.25 to 4.0 and various hydration levels are shown in Fig.3. The calibration equation fitting the experimental data has a simple form of

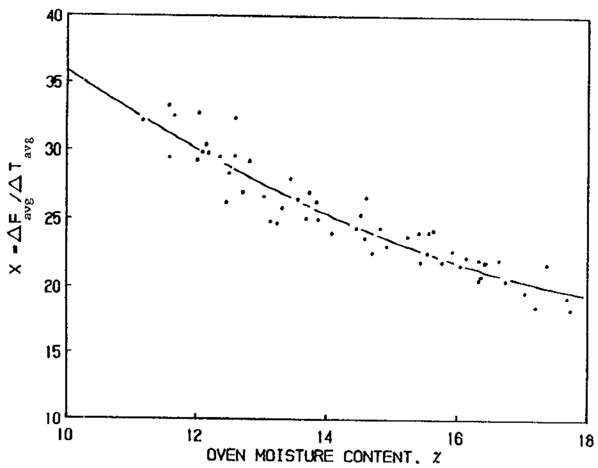

Fig.3. Parameter X (averaged) as a function of moisture content for corn kernels. Curve calculated from Eq.(7).

$$M = \frac{281}{X} + 2.9 \qquad (7)$$

and a correlation coefficient $r = 0.94$.

Verification of results. To check the validity of the calibration equations (3) and (7), other sets of seeds of different dimensions and hydration levels containing 55 seeds each were measured. Their moisture contents were determined by standard oven methods and compared to those calculated from the calibration equations. The histograms presented in Fig.4 show the distribution of differences between those two methods. For soybeans, the mean value of the differences is 0.15 % moisture, and the standard deviation of the difference (SEP - standard error of performance) is 0.51 % moisture. For corn kernels, the mean difference and SEP values are 0.02 and 0.62 % moisture, respectively.

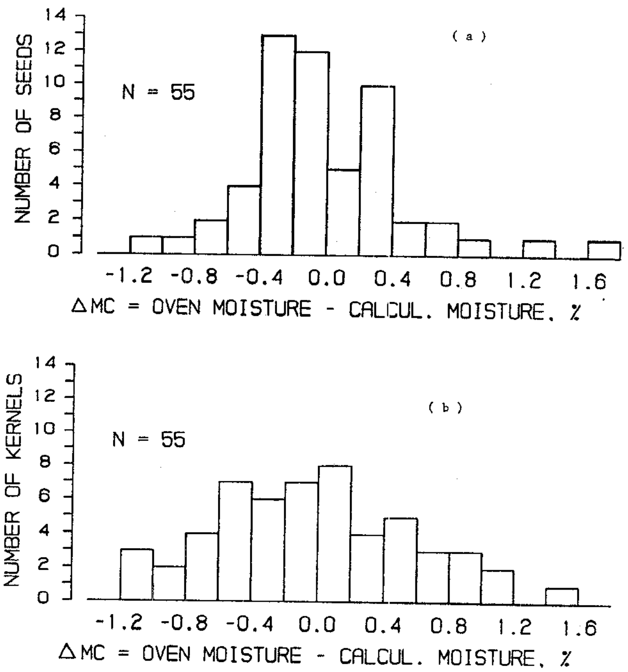

Fig.4. Distribution of differences between oven moisture content determination and moisture content calculated from calibration equations: (a) Eq.(3) for soybeans, and (b) Eq.(7) for corn krnels.

DISCUSSION AND CONCLUSIONS

The measured cavity parameters, shift of resonant frequency and change in Q-factor, depend on the permittivity, shape, and volume of an object placed in the cavity, as well as on its orientation and location in the cavity. The ratio of these two measured cavity parameters is, to great extent, a size-independent function, but its value depends on the shape of the object. Repeating the measurement with the object rotated 90 degrees, with respect to the cavity x-axis, provides another set of data which permits calculation of a ratio of averaged values that is proven to be a shape-independent function. Thus, this ratio can be a direct function of the object permittivity which can be related to the material density, or moisture content, or other characteristic of interest.

Two measurements should be taken on nonuniformly shaped objects rotated by 90 degrees in the resonant cavity or in two identical cavities rotated by that angle. All measurements are relative, i.e. a difference of two resonant frequencies or two transmission coefficients is of interest. Therefore, a high long-term stability of the measuring system is not required.

Available data on nonuniform corn kernels rotated in a C-band cavity show a larger spread when plotted against moisture content than do similar results for more uniformly shaped soybean seeds. The explanation may be twofold:

- every rotated kernel is measured twice, thus the effect of errors in the measuring system may be doubled when compared with soybeans that are measured only once;
- linear dimensions of corn kernels (up to 14 mm) were relatively large compared to the half-wavelength (29 mm) at the operating frequency.

More experimental data is needed to clarify these points, and work should be repeated at a lower frequency to improve the object dimension-to-wavelength ratio.

This cavity measurement procedure is a simple, nondestructive and potentially continuous method for determining the properties (density or moisture content, for example) of single kernels and seeds, regardless of their shape and size variation. The method could be used for other biological objects, including other grains, nuts, and fruits, provided that their volume is small compared to the volume of the resonator. Other types of microwave resonators could also be used for the purpose.

REFERENCES

[1] H.E.Bussey, "Measurement of the RF properties of materials - a survey", Proc.IEEE, vol.55, pp.1046-1053, 1967.

[2] R.F.Harrington, Time-Harmonic Electromagnetic Fields, McGraw-Hill Book Co., New York, 1961, p.317.

[3] R.A.Waldron, The Theory of Waveguides and Cavities, Maclaren, London, 1967.

[4] A.W.Kraszewski, T.S.You and S.O.Nelson, "Microwave resonator technique for moisture content determination in single soybean seeds", IEEE Trans. Instrum. Meas., IM-38, pp.79-84, 1989.