Rapid and Nondestructive Determination of Moisture Content in Peanut Kernels from Microwave Measurement of Dielectric Properties of Pods

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Written for presentation at the  
2009 ASABE Annual International Meeting  
Sponsored by ASABE  
Grand Sierra Resort and Casino  
Reno, Nevada  
June 21 – June 24, 2009

Abstract. A method for moisture determination in peanut kernels from measurement of the dielectric properties of peanut pods at microwave frequencies is presented. The dielectric properties of peanut kernels and pods were measured in free space with a vector network analyzer and a pair of focused beam horn-lens antennas. A density-independent algorithm was used to determine moisture content in peanut kernels and pods. Moisture calibration equations with temperature correction were determined from a three-dimensional representation, and an explicit relationship between peanut pod moisture content and kernel moisture content was identified. Results presented at 6 GHz and temperatures ranging from 0.5 °C to 58 °C show that kernel moisture content can be predicted with a standard error of calibration of 0.79% and that of pods with a standard error of calibration of 0.95%.

Keywords. Peanut pods, peanut kernels, dielectric properties, microwave measurements, density-independent function, temperature, moisture content.
Introduction

Peanuts and peanut-based products constitute an important group of food products available in the market place. Modern farming, handling and processing of peanuts, along with prescribed government safety and quality standards, require rapid testing methods for peanut characterization. For instance, moisture content is the most important parameter in the peanut trade. At buying points, it is used to determine whether the peanuts meet the sale criterion which specifies that the kernel moisture content must be less than 10.49%, wet basis. Presently that decision is made following a tedious and lengthy grading process. After the samples are collected from a truck load, they are cleaned to remove foreign materials, then shelled, and finally the peanut kernels are tested for moisture content. In this paper, a microwave method is presented for moisture content determination in peanut kernels from measurement of the dielectric properties of peanut pods. The method is rapid and nondestructive and eliminates the need for shelling the peanut pods. The method consists of establishing a direct relationship between peanut pod moisture content and that of peanut kernels by equating their respective density-independent permittivity-based moisture calibration equations (Trabelsi et al., 1998; Trabelsi and Nelson, 1998). Results presented at 6 GHz and temperatures ranging from 0.5 °C to 58 °C indicate that kernels moisture content can be predicted with a standard error of calibration of 0.79% and that of pods with a standard error of calibration of 0.95%.

Materials and Methods

Sample Preparation

In this study, the peanut kernel and peanut pod samples consisted of 7 kg each of Runner type peanuts, cv. Georgia Green. Starting with samples of relatively low moisture content, different moisture levels were obtained by gradually increasing the original moisture content in increments of about 2%. For each moisture level, after the desired amount of water was added, the sample was stirred, placed in a sealed plastic bag and stored for at least 72 hours at 4 °C to equilibrate.

Dielectric Properties Measurements

The two components of the relative complex permittivity, \( \varepsilon = \varepsilon' - j\varepsilon'' \), of peanut kernels and peanut pods were determined from measurement of their corresponding scattering transmission coefficient, \( S_{21} \), in free space. Figure 1 shows the free-space transmission measurement arrangement that was used for this purpose. It consists of a Hewlett Packard 8510C vector network analyzer (VNA), a computer, two high quality coaxial cables with APC-7 connectors at their terminations, two linearly polarized, ultrabroadband (2 to 26 GHz) horn/lens antennas (BAE SYSTEMS model AHO-2077-N) providing a plane wave, a Styrofoam sample holder, and four sheets of radiation-absorbing material, ECCOSORB AN-79. The measurements were conducted in a room where the relative humidity and temperature were controlled. The sample holder is a Styrofoam box of rectangular cross section. When filled with the peanut kernels or peanut pods, the sample interacting with the incident wave formed a layer of thickness \( d \). The sample holder filled with peanuts was placed midway between the two antennas, which were 37 cm apart. For optimum use of the VNA dynamic range, samples of
thickness varying between 4.1 cm and 15.4 cm were used. The different thicknesses were obtained by placing Styrofoam spacers in the sample holder. For each sample, the bulk density \( \rho \) was determined by weighing the sample and then dividing the weight of the sample by the volume \( V \) of the sample holder. In general, \( \rho \) is expressed in g/cm\(^3\) or kg/m\(^3\) as follows:

\[
\rho = \frac{m_w + m_d}{V}
\]

where \( m_w \) is the mass of water and \( m_d \) is the dry mass of the material.

For each peanut kernel and peanut pod sample, measurements of the dielectric properties were carried out at three different bulk densities. Starting with a loosely packed sample, the sample was settled to increase its bulk density. After each microwave measurement sequence, three samples were taken for moisture content determination according to ASAE Standards (ASAE, 2002). The samples were oven-dried for 6 hours at a temperature of 130 °C. Moisture content in percent was calculated on the wet basis:

\[
M(\%) = \frac{m_w}{m_w + m_d} \times 100
\]

For measurements at different temperatures the samples were placed in temperature-controlled chamber for at least 24 hours. The sample temperature was measured with a digital thermometer.

Moisture content, bulk density, and temperature were assumed to be uniform throughout the sample.

**Figure 1. Measurement arrangement.**

For the computation of the dielectric properties, \( \varepsilon' \) and \( \varepsilon'' \), it is assumed that a plane wave is traversing a layer of low-loss material. They are calculated from the modulus, \( |S_{21}| \), and measured phase, \( \phi \), of \( S_{21} \) as follows:

\[
\varepsilon' = \left[ 1 - \frac{(\phi - 360n)}{360d} \right] \left( \frac{c}{f} \right)^2
\]

\[
\varepsilon'' = \frac{-20\log|S_{21}|}{8.686 \pi d} \left( \frac{c}{f} \right) \sqrt{\varepsilon'}
\]
where \( c \) is the speed of light in m/s, \( f \) is the frequency in Hz, \( d \) is the thickness of the layer of material in meters, and \( n \) is an integer to be determined (Trabelsi et al., 2000). The two components of the complex permittivity, as expressed in equations (3) and (4) are the average values for the whole sample.

**Results and Discussion**

For moisture determination in materials with changing bulk density from measurement of their dielectric properties, one can use density-independent calibration functions (Kraszewski et al., 1998; Trabelsi and Nelson, 1998). In this study a density-independent calibration function expressed in terms of \( \varepsilon' \) and \( \varepsilon'' \) was used (Trabelsi et al., 1998):

\[
\psi = \sqrt{\frac{\varepsilon''}{\varepsilon'(a_f\varepsilon' - \varepsilon'')}}
\]  

(5)

where \( a_f \) is the slope determined from the complex-plane representation of the dielectric properties divided by bulk density as shown in Figures 2 and 3. At 6 GHz, for all temperatures and all moisture contents, \( a_f \) was 0.48 for peanut kernels and 0.52 for peanut pods.

![Figure 2. Complex-plane representation of dielectric loss factor divided by bulk density versus dielectric constant divided by bulk density for peanut kernels at 6 GHz and temperatures between 0.6 °C and 58.7 °C.](image-url)
Figures 4 and 5 show variation of the density-independent function $\psi$ with moisture content and temperature of peanut kernels and pods, respectively. For both materials, $\psi_{k,p}$ increases linearly with oven moisture content and temperature with the data lying in a plane. Therefore, for each material, a regression of the form:

$$\psi_{k,p} = A_{k,p}M + B_{k,p}T + C_{k,p}$$

(6)

can be used to correlate $\psi_{k,p}$ with moisture content and temperature of peanut kernels and peanut pods, respectively. Table I provides regression coefficients and coefficients of determination for peanut kernels and peanut pods. Both materials have high coefficients of determination, $r^2$. Therefore, moisture calibration equations for moisture determination in each material can be derived from equation (6) and regression coefficients provided in Table I. Following are the moisture calibration equations obtained for peanut kernels and pods:

$$M_k = \frac{\psi_k - 0.0024T - 0.0514}{0.022}$$

(7)

$$M_p = \frac{\psi_p - 0.0017T - 0.058}{0.018}$$

(8)

To evaluate performance of calibration equations (7) and (8) in predicting moisture content from measurement of the dielectric properties, the standard error of calibration (SEC) was calculated.
Values of the SEC are shown in Table 1. These values are somewhat higher than those obtained at a single temperature (Trabelsi and Nelson, 2006) because of the scattering generated by peanut samples of high moisture contents at high temperatures.

Figure 4. Variation of density-independent permittivity function $\psi_k$ with moisture content and temperature for peanut kernels at 6 GHz and temperature between 0.6 °C and 58.7 °C.
Figure 5. Variation of density-independent permittivity function $\psi_p$ with moisture content and temperature for peanut pods at 6 GHz and temperature between 0.5 °C and 57.4 °C.

Table I. Regression statistics and coefficient of determination corresponding to equation (6) for peanut kernels and peanut pods at 6 GHz and indicated moisture, temperature, and bulk density.

<table>
<thead>
<tr>
<th>Peanuts</th>
<th>Moisture content range, %</th>
<th>Temperature range, °C</th>
<th>Bulk density, g/cm$^3$</th>
<th>$A_{k,p}$</th>
<th>$B_{k,p}$</th>
<th>$C_{k,p}$</th>
<th>$r^2$</th>
<th>SEC, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kernels</td>
<td>6.8–18.8</td>
<td>0.6 – 58.7</td>
<td>0.518 – 0.697</td>
<td>0.022</td>
<td>0.0024</td>
<td>0.051</td>
<td>0.968</td>
<td>0.79</td>
</tr>
<tr>
<td>Pods</td>
<td>8 – 20.9</td>
<td>0.5 – 57.4</td>
<td>0.289 – 0.412</td>
<td>0.018</td>
<td>0.0017</td>
<td>0.058</td>
<td>0.952</td>
<td>0.95</td>
</tr>
</tbody>
</table>

In many practical situations, it would be useful to determine kernel moisture content from dielectric measurements on unshelled peanut pods (Butts et al., 2004). This can be achieved by equating the pod calibration function to that of the kernel calibration function and solving for kernel moisture content $M_K$ in terms of pod moisture content $M_p$. With the regression constants obtained for equation (6) and shown in Table I, the relationship between kernel moisture content and pod moisture content can be written as:

$$M_K = 0.837M_p - 0.0299T + 0.0069$$ (9)
Equation (9) provides peanut kernel moisture content directly from dielectric measurements on peanut pods without having to shell them. This equation is valid for the frequency and the temperature range at which the dielectric properties of peanut pods were measured.

**Conclusion**

A method for nondestructive and simultaneous determination of moisture content in peanut pods and peanut kernels from a single permittivity measurement of peanut pods at microwave frequencies has been developed. Moisture calibration equations for both peanut kernels and peanut pods were derived from measurements at 6 GHz and standard errors were established for moisture content prediction. An equation correlating moisture content of peanut kernels with that of peanut pods was established, so that kernel moisture content can be obtained directly from measurements on unshelled peanut pods. This method is particularly suitable for routine measurements on large quantities of peanuts.

**References**


