Measurement of Grain and Seed Microwave Permittivity for Moisture and Density Determination

Stuart O. Nelson and Samir Trabelsi
U. S. Department of Agriculture
Agricultural Research Service
Athens, Georgia, U. S. A.
stuart.nelson@ars.usda.gov, samir.trabelsi@ars.usda.gov

Abstract—The importance of moisture measurement in grain and seed is discussed, and a brief history of the development of moisture sensing instruments, based on sensing of dielectric properties of these materials, is presented. Data are presented graphically on the permittivities or dielectric properties of wheat, showing their variation with frequency and moisture content, and references are cited for further information. More recent developments on microwave measurements for moisture content and bulk density sensing are briefly described, and numerous studies are cited providing sources of information on these promising techniques.

I. INTRODUCTION

Moisture content of cereal grain and oil seed determines their suitability for harvest and storage, and it must also be measured whenever grain and seed are traded. If the moisture content of these commodities is too high for safe storage, they must be dried to avoid spoilage, and drying costs must be taken into account in determining fair pricing for trade. The bulk density of grain and seed is also an important factor in grading and trade since prices are generally quoted on a volume basis, and the bulk density, usually referred to as the test weight, is used in converting weights to volumes.

Because standard and reference methods for determining moisture in grain and seed involve tedious laboratory procedures and long oven-drying periods, rapid methods for moisture measurement have been essential in the grain and seed trade. Therefore, electrical measurements have been studied and used for a long time to provide rapid techniques for grain and seed moisture testing. It was discovered early in the 20th century that there was a logarithmic increase in resistance of wheat as moisture content decreased [1-2]. Grain moisture meters were subsequently developed based on this principle. Later, the use of capacitance measurements for moisture determination in grain was studied, and moisture meters were developed that utilized relationships between instrument readings and reference method moisture determinations [3-4]. The historical development of electrical grain moisture meters has been reviewed previously [2, 5-6].

Not until mid century were measurements begun to provide values for the permittivities, or dielectric properties, of grain and seed upon which the rapid sensing of moisture content depends [7-8]. Studies of the dependence of permittivities of grain and seed on influencing factors, including frequency, moisture content, density, and temperature [9-12], have enabled the continued improvement of grain and seed moisture meters to meet the needs of the agricultural industry.

II. DIELECTRIC PROPERTIES

The complex permittivity relative to free space is represented here as \( \varepsilon = \varepsilon' - j\varepsilon'' \), where \( \varepsilon' \) is the dielectric constant and \( \varepsilon'' \) is the dielectric loss factor. The real part of the permittivity represents the energy storage capability in the electric field in the dielectric material, and the imaginary part represents the energy dissipation capability of the dielectric by which energy from the electric field is converted into heat energy in the dielectric. Often, the loss angle of dielectrics is of interest, and the tangent of the loss angle \( \delta \) is used, where \( \tan \delta = \varepsilon'' / \varepsilon' \). The conductivity of the dielectric, \( \sigma = \omega \varepsilon_0 \varepsilon'' / \varepsilon' \), is also of interest, where \( \varepsilon_0 \) is the permittivity of free space, \( \varepsilon_0 = 8.854 \times 10^{-12} \text{ F/m} \), and \( \omega = 2\pi f \), where \( f \) represents frequency in Hz.

Early measurements of the dielectric properties of many kinds of grain and seed in the frequency range from 1 to 50 MHz revealed high correlations between the grain and seed moisture content and the their permittivities or dielectric properties [9-10]. An example is shown in Fig. 1 for hard red winter wheat. All moisture contents in this paper are expressed in percent by weight on the wet basis.

For both wheat and soybeans, dielectric properties are clearly correlated with moisture content and can therefore be used for moisture sensing. Permittivity measurements on hard red winter wheat over frequencies from 250 Hz to 10 GHz and moisture contents from 3 to 24% have been summarized with contour plots of the dielectric constant and loss factor as functions of moisture content and frequency [11].
Figure 1. Permittivities of 'Nebred' hard red winter wheat at 24°C and indicated moisture contents. Test weight: 768 kg/m³ (59.7 lb/bu) at 13% moisture content.

Temperature is another factor that influences the dielectric properties of grain and seed. The dielectric constant at any given frequency increases with temperature [13]. The increase in dielectric constant with increasing temperature is reasonably linear, although the deviation from linearity tends to increase at higher moisture contents and lower frequencies [14].

Also, the dielectric constant of grain and seed increases linearly with bulk density at all moisture levels, but the slope increases with increasing moisture content [13]. Over wider ranges of bulk density, the dielectric constant is not linear, but the square and cube roots of the dielectric constant are linear with bulk density [15-16]. These findings are also consistent with the well-known complex refractive index and Landau & Lifshitz, Looyenga dielectric mixture equations, respectively [17-18].

Utilizing linear relationships between frequency, moisture, temperature, and density and the dielectric constants or functions of the dielectric properties, mathematical models for the dielectric constant of several cereal grains and soybeans were developed from which close estimates of dielectric constants can be calculated for frequencies between 20 MHz and 2.45 GHz over wide ranges of moisture content at 24°C [10, 19-20] or as functions of moisture, density, and temperature at frequencies of 20, 300, and 2450 MHz [13].

III. MOISTURE CONTENT SENSING

Because of the correlations between dielectric properties and moisture content illustrated in Figure 1, many commercial instruments have been developed and used for measuring grain and seed moisture content as already noted. Over the past sixty years or so, most of these grain moisture meters utilized frequencies between 1 and 20 MHz and sensed changes in capacitance of parallel-plate or coaxial sample holders when grain samples were introduced between the electrodes [5, 21]. However, dc conductance meters are still used on some grain dryers and for some specialty applications [22]. Moisture meters based on RF measurements on capacitive sample holders require corrections for the influence of temperature and bulk density, or test weight [5, 11, 23]. These corrections have been applied through calibration charts or automatically built into the instruments. Thus, accuracy of the moisture measurements required in the grain and seed trade has been achieved by continual improvements and calibration testing, but there is still some dissatisfaction with reliability in higher moisture ranges, above 20 to 25 percent for cereal grains. Recalibrations are also required occasionally because of differences in some growing locations and variations in seasonal growing conditions.

IV. MICROWAVE SENSING

Early work on sensing moisture content in grain by measurements at microwave frequencies was initiated by Kraszewski and coworkers who examined attenuation and phase shift of waves traversing a grain layer [24-25]. At microwave frequencies above about 3 GHz, the ionic conduction responsible for calibration variations at the lower frequencies is nonexistent. Further studies with microwave measurements revealed that the ratio of attenuation to phase shift could provide a means for sensing moisture content independent of density fluctuations in grain and possibly for use of a single calibration for several kinds of cereal grain [26-27]. Additional studies on soft and hard red winter wheat confirmed the density-independent nature of simultaneous attenuation and phase measurements for moisture sensing, the provision of bulk density from the same measurements, and the usefulness of a single calibration for both kinds of wheat [28].

Many studies followed these initial efforts, further developing principles for microwave moisture sensing in grain and seed independent of bulk density [29-33]. Density-independent functions of the dielectric properties for predicting moisture content from measured dielectric properties of wheat and corn were compared in several studies [34-36]. Means of compensating measurements for the influence of temperature variation were also included [37-40]. These studies also included the development of unified or potentially universal calibrations for corn, wheat, barley, oats, grain sorghum, rapeseed and soybeans [41-43].

Principles of the density-independent moisture calibration function developed by Trabelsi [33-34] have been
described previously for use in measuring both moisture content and bulk density of grain and seed [44-46], but a brief description is provided here. Measurements on a large number of samples of hard red winter wheat of different moisture contents, bulk densities, and temperatures are summarized in plots for measurements at 11.3 and 18.0 GHz in Fig. 2.

Note that, for permittivities determined by these measurements at a given frequency, all of the points fall along a straight line and that differences in either moisture content or temperature amount to translations along that same line. The lines for each frequency intersect the \( \varepsilon' / \rho = 0 \) axis at a common point, \( \varepsilon' / \rho = k \), which represents the value of \( \varepsilon' / \rho \) for 0% moisture content or the value at very low temperatures. Any change in frequency amounts to a rotation of the straight line about that intersection point. Thus, for a given frequency, the equation of the line is expressed as

\[
\varepsilon' / \rho = a / (\varepsilon' / \rho - k)
\]

where \( a \) is the slope at a given frequency. It was determined that the slope varied linearly with frequency. Considering that

\[
\tan \delta = \varepsilon' / \varepsilon',
\]

where \( \delta \) is the loss angle of the dielectric, expresses the distribution between dissipated and stored energy in a dielectric, and that \( \tan \delta \) varies with bulk density, it was divided by bulk density. Solving the equation for the straight line for \( \rho \), we have

\[
\rho = a / k.
\]

For a given frequency, \( a \) is a constant, and for a given material, \( k \) is a constant. Thus, the bulk density is provided in terms of the permittivity alone, without regard to temperature or moisture content. Using this expression for \( \rho \), we can write

\[
\tan \delta / \rho = ka / \left( \varepsilon' / (a, \varepsilon' - \varepsilon^* - \varepsilon^*) \right).
\]

For a given frequency and particular kind of material, \( ka \) is a constant, and a new density-independent moisture calibration function can be defined as follows:

\[
\psi = \sqrt[\varepsilon']{\varepsilon' / (a, \varepsilon' - \varepsilon^*)}.
\]

The quadratic relationship between the calibration function and moisture content was determined empirically [34].

This calibration function has been studied for a large set of measurements on hard red winter wheat over practical ranges of moisture content, bulk density, and temperature [39]. By plotting \( \psi \) against moisture content and temperature, the following equation was obtained:

\[
\psi = bM + aT + c,
\]

for which values of the constants, \( a, b, \) and \( c \), were determined by regression analysis. The equation for moisture content,

\[
M = (\psi - aT - c) / b,
\]

is then given in terms of the density-independent calibration function \( \psi \), which, at any given frequency, depends only on the grain permittivity. The dielectric constant and loss factor can be determined by any suitable microwave measurement.

Further research with this density-independent moisture calibration function has shown that very similar values of regression constants were obtained for kinds of grain as different as wheat and corn [39]. In other comparisons, the same constants performed very well for wheat, oats, and soybeans, and for corn wheat and soybeans, which have very different characteristics with respect to kernel shape, size, and composition [31, 42]. These findings support the idea of a universal calibration, which would provide a significant advantage and should encourage the development of microwave moisture sensors for on-line applications for grain and other granular materials in agriculture and other industries. Should the universal nature of the calibration extend beyond grain and oilseeds to other granular and powdered dielectric materials of interest in other industries, the incentive for development of moisture sensing microwave devices would be even stronger. A moisture meter, based on these principles has been built and tested successfully [47].

**CONCLUSIONS**

Grain and seed permittivities are useful for the rapid sensing of their moisture content, and instruments operating at frequencies of 1 to 20 MHz have been used for this important application for many years. Microwave frequencies now show promise for sensing both moisture content and bulk density in both static and flowing materials.

**REFERENCES**


