Sensing grain and seed moisture and density from dielectric properties

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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 grain and seed showing their variation with frequency, moisture content, temperature, and bulk density, 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 newer techniques.

Keywords: sensing, dielectric properties, permittivity, cereal grain, oilseed, moisture content, density

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1 Introduction

Moisture content of cereal grain and oil seed determines 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, or test weight, of grain and seed is also an important factor in grading and trade, since it is often an indication of quality and thus influences price.

Because standard and reference methods for determining moisture content 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. Electrical, Near-InfraRed (NIR) and Nuclear Magnetic Resonance (NMR) methods have been explored for rapid sensing of moisture content. However, equipment for NIR and NMR techniques is more expensive than that for electrical measurements, and they generally require more time or sample preparation. Therefore, electrical measurements are more practical. They 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

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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.

2 Dielectric properties

The complex permittivity relative to free space is represented here as $\varepsilon = \varepsilon' - j\varepsilon''$, where ε' is the dielectric constant and ε'' 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 δ is used, where $\tan\delta = \varepsilon''/\varepsilon'$. The conductivity of the dielectric, $\sigma = \omega\varepsilon_0\varepsilon''$ S/m, is also of interest, where ε_0 is the permittivity of free space, 8.854×10^{-12} F/m, and $\omega = 2\pi f$, where f is 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 their permittivities or dielectric properties[9-10]. Examples are shown in Figure 1 for hard red winter wheat (*Triticum aestivum* L.), and in Figure 2 for soybeans (*Glycine max* L.). All moisture contents in this paper are expressed in percent by weight on the wet basis.

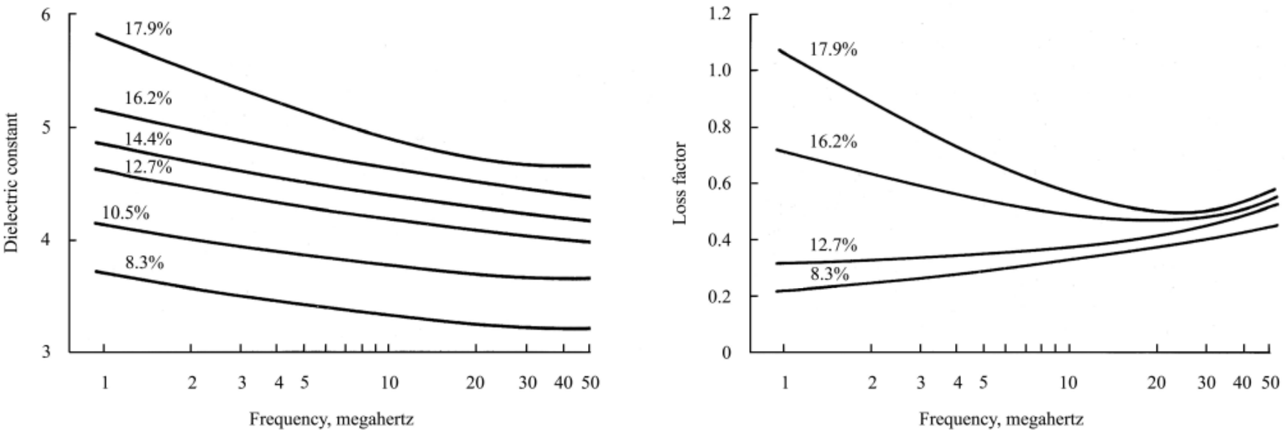

Figure 1 Permittivities of 'Nebred' hard red winter wheat at 24℃ and indicated moisture contents. Test weight: 768 kg/m^3 (59.7 lb/bu) at 13% moisture content[9]

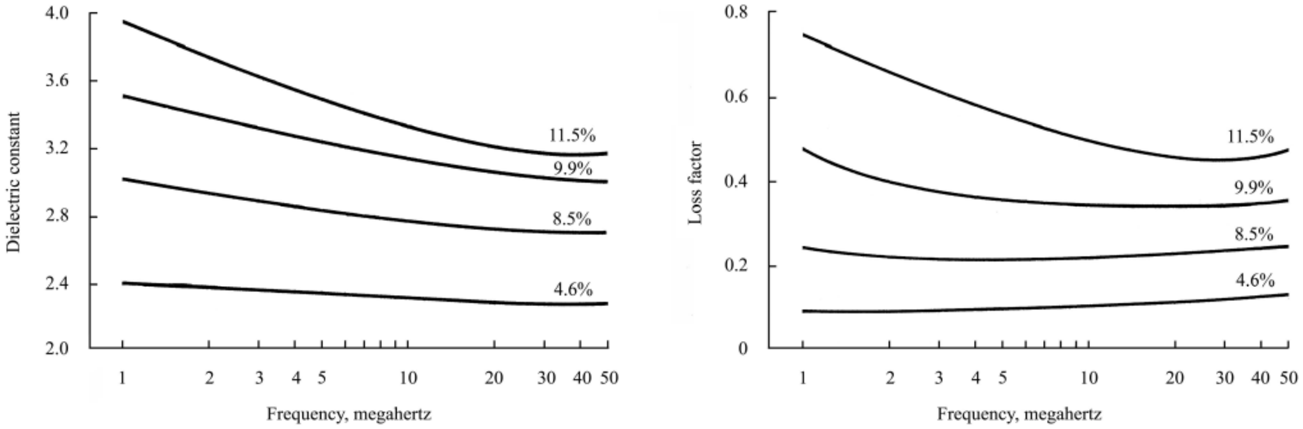

Figure 2 Permittivities of 'Hawkeye' soybeans at 24℃ and indicated moisture contents. Test weight: 738 kg/m^3 (57.3 lb/bu) at 7.5% moisture content[9]

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 wide ranges of frequency and moisture content are summarized with contour plots of the dielectric constant and loss factor as functions of moisture content and frequency in Figure 3. Behavior of the dielectric constant is regular with respect to both moisture content and frequency, but the variation of the dielectric loss factor is much less regular due to the influence of dielectric relaxation processes.

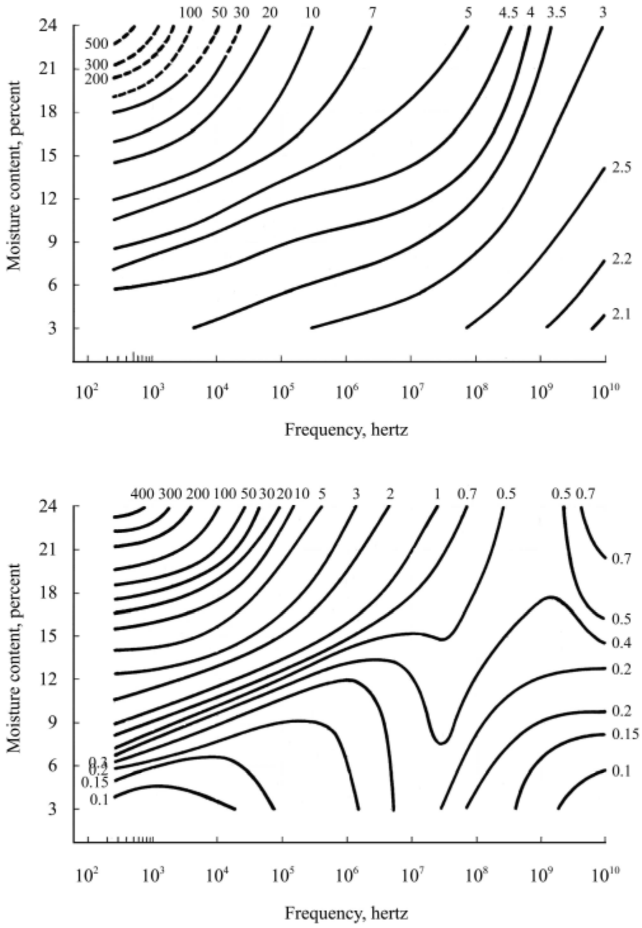

Figure 3 Dielectric constants, ε', and loss factors, ε'', for hard red winter wheat at 24℃ at frequencies from 25 Hz to 10 GHz and moisture contents from 3% to 24% at natural densities. Mean values for seven cultivars[11,12]

Temperature is another factor that influences the dielectric properties of grain and seed. Figure 4 shows the variation of the dielectric constant for shelled corn (*Zea mays* L.) of two different moisture contents at frequencies of 20, 300, and 2,450 MHz[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, as shown in Figure 5, the dielectric constant of shelled corn increases linearly with bulk density at all moisture levels, and this was shown at frequencies of 300 MHz and 2.45 GHz as well for normally encountered densities[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].

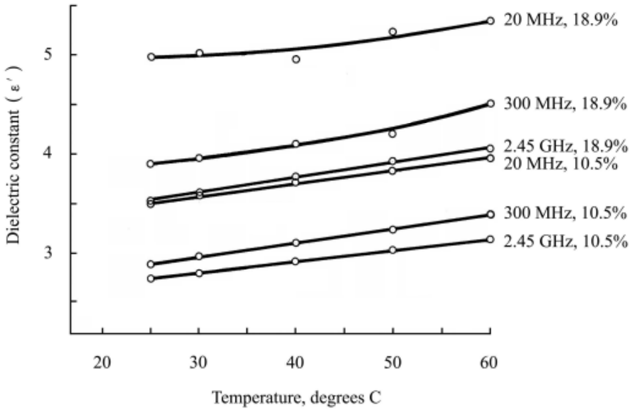

Figure 4 Temperature dependence of the dielectric constants, ε', of shelled yellow-dent field corn at indicated frequencies and moisture contents[24].

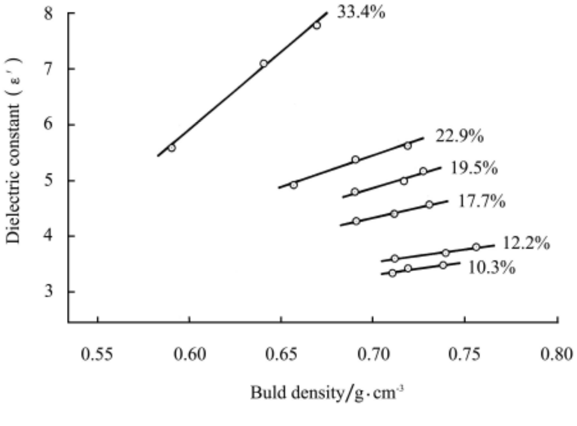

Figure 5 Density dependence of the dielectric constant of shelled yellow-dent field corn at 24 ℃, 20 MHz, and indicated moisture contents[13]

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℃ [10,19,20] or as functions of moisture, density, and temperature at frequencies of 20, 300, and 2,450 MHz[13].

3 Moisture content sensing

Because of the correlations between dielectric properties and moisture content illustrated in Figures 1 to 3, 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 were used earlier and 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 improvement and calibration testing, but there is still some dissatisfaction with reliability in higher moisture ranges, above 20% to 25% for cereal grains. Recalibrations are also required occasionally because of differences in growing locations and variations in seasonal growing conditions. At microwave frequencies above about 3 GHz, the ionic conduction largely responsible for calibration variations at the lower frequencies, is negligible. Therefore, measurements at microwave frequencies are of interest for moisture sensing in grain and seed.

Early work on sensing moisture content in grain by microwave measurements was initiated by Kraszewski and coworkers who examined attenuation and phase shift of waves traversing a grain layer[25,26]. Studies on permittivities of several materials, including grain, revealed that $(\varepsilon'-1)/\varepsilon'$ is a relatively density-independent function for use in predicting moisture content of particulate materials[27-30]. The ratio of attenuation and phase shift was also investigated as a density-independent function for microwave sensing of moisture content[27,30-31]. Further studies with microwave measurements confirmed the usefulness of this ratio for sensing moisture content independent of bulk density fluctuations in grain and indicated a possibility for a single calibration for several kinds of cereal grain[32,33]. 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[34]

Many studies followed these initial efforts, further developing principles for microwave moisture sensing in grain and seed independent of bulk density[35-39]. Density-independent functions of the dielectric properties for predicting moisture content from measured dielectric properties of wheat and corn were compared in several studies[40-42.] Means of compensating measurements for the influence of temperature variation were also studied[43-46]. These studies included the development of unified or potentially universal calibrations for corn, wheat, barley, oats, grain sorghum, rapeseed and soybeans[47-49].

Principles of the permittivity-based calibration functions developed by Trabelsi[38,40] have been described previously for use in measuring both moisture content and bulk density of grain and seed[50-52], 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 complex-plane permittivity plots for measurements at 11.3 and 18.0 GHz in Figure 6.

Note that, for permittivities determined by these measurements at a given frequency, all of the points fall along a straight line and those differences in either moisture content or temperature amount to translations along that same line. The lines for each frequency intersect the ε'/p axis at a common point k, which represents the value for 0% moisture content or the value at very low temperatures. Any change in microwave 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 $\varepsilon''/p = a_f((\varepsilon'/p)-k)$ where a_f is the slope at a given frequency. It was determined that the slope varied linearly with frequency. Solving the equation of the straight line for ρ, we have $\rho = \frac{a_f\varepsilon' - \varepsilon''}{a_f k}$. For a given frequency, a_f 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. Considering that $\tan\delta = \varepsilon''/\varepsilon$, where δ is the loss angle of the dielectric, expresses the distribution ratio of dissipated and stored energy in a dielectric, and that $\tan\delta$ varies with bulk density, it was divided by bulk density. Using this expression for ρ, we can write $\frac{\tan\delta}{\rho} = a_f k\left(\frac{\varepsilon''}{\varepsilon'(a_f\varepsilon' - \varepsilon'')}\right)$. For a given frequency and particular kind of material, $a_f k$ is a constant, and a new density-independent moisture calibration function can be defined as $\psi = \sqrt{\frac{\varepsilon''}{\varepsilon'(a_f\varepsilon' - \varepsilon'')}}$. The quadratic relationship between the calibration function and moisture content was determined empirically[40]. 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[45]. By plotting ψ against moisture content and temperature, the points define a plane in three-dimensional space, Figure 7, and 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 ψ, 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[45]. 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[39,48]. 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 greater.

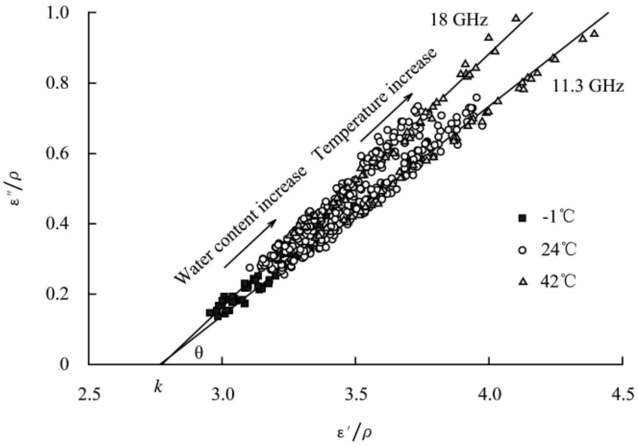

Figure 6 Complex-plane plot of the dielectric constants and loss factors, divided by bulk density, ρ, of hard red winter wheat of various moisture contents and bulk densities at indicated temperatures for two frequencies, 11.3 and 18.0 GHz[40].

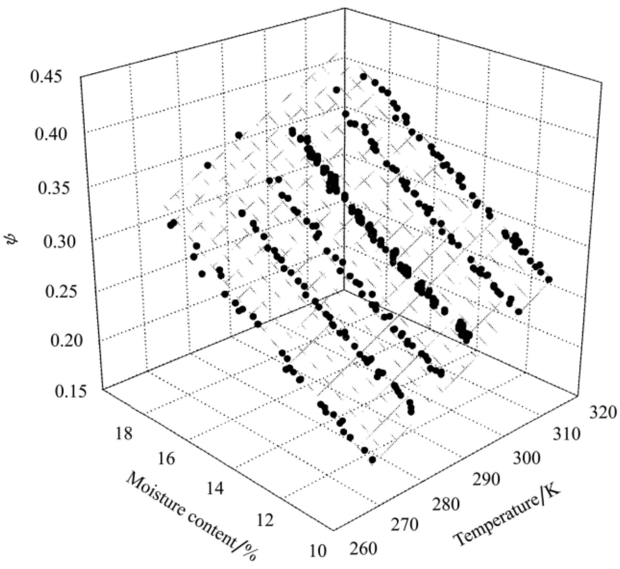

Figure 7 Moisture and temperature dependence of density-independent moisture calibration function ψ at 14.2 GHz for hard red winter wheat[45].

4 Conclusions

The permittivities of cereal grains and oilseeds vary with the frequency of the applied electric field, moisture contents of these materials, their temperatures, and bulk densities. Thus, grain and seed permittivities are useful for the rapid sensing of moisture content, and instruments operating at frequencies of 1 to 20 MHz have been used for this important application for many years. Use of grain and seed permittivities measured at microwave frequencies now show promise for sensing both moisture content and bulk density in both static and flowing materials. Because of advantages offered by measurement at the higher frequencies, commercial development of microwave moisture meters for grain and seed can be expected to improve reliability and utility of such instruments in the grain and seed industries.

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