DIELECTRIC PROPERTIES OF AGRICULTURAL PRODUCTS AND THEIR USE IN MOISTURE SENSING AND OTHER APPLICATIONS

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ABSTRACT

Historical interest in dielectric properties of agricultural products and definitions of dielectric terms and basic principles governing their influence on electromagnetic energy are presented briefly. The nature of dielectric properties variation with frequency, temperature, and product density is discussed. Graphical data on the dielectric properties of products are presented that illustrate the dependence of these properties on moisture content, frequency, temperature, and density. Applications of the dielectric properties of agricultural products are cited that include radio-frequency (RF) and microwave heating for seed treatment, improvement of nutritional and keeping qualities of some products, and controlling insects in grain. Uses of dielectric properties for product quality measurement and the rapid determination of moisture content are described. Principles of moisture determination in bulk grain by RF and microwave measurements are briefly presented.

Key Words: Dielectric properties, Agricultural products, Moisture measurement

INTRODUCTION

Background Information

There has been interest in the electrical properties of agricultural products for useful purposes for more than 90 years. Briggs (1908) studied the dc electrical resistance of grain for purposes of rapidly determining its moisture content. His studies revealed a logarithmic increase in the resistance between two brass rod electrodes inserted into a wheat sample as the moisture content of the grain decreased. He also reported a nonlinear increase in resistance of the grain as temperature decreased. In later studies with ac measurements, changes in the capacitance of sample-holding capacitors, when wheat and rye samples were introduced between the capacitor plates, were correlated with grain moisture content and used for grain moisture measurement (Berliner and Rüter, 1929; Burton and Pitt, 1929). The subsequent development of electrical grain moisture meters has been reviewed by a number of authors (Martens and Hlynka, 1963; Ban and Suzuki, 1977; Nelson, 1977).

Use of electrical properties of grain for moisture measurement has been the most prominent agricultural application for dielectric properties data. In the early work, no quantitative data on the dielectric properties of the grain were reported. Interest generally focused on the influence of a grain sample on the response of an electrical circuit, and the instrument readings were calibrated with values measured by oven-drying techniques or other standard procedures for moisture determination. The need for quantitative values of the dielectric properties arose from research on the application of radio-frequency (RF) dielectric heating to agricultural problems.

The first quantitative data on the dielectric properties of grain were reported for barley along with a method for reliable measurement of those properties in the 1- to 50-MHz frequency range (Nelson et al., 1953). Quantitative dielectric properties data, obtained for similar reasons, were soon reported in the USSR for wheat and other grain and crop seeds (Knipper, 1959). Extensive measurements on grain and crop seeds in the 1- to 50-MHz range, taken over a decade of research on RF dielectric heating applications, were finally summarized and made available for use in electric moisture meter design and other applications (Nelson, 1965).

Data on the dielectric properties of grain and other agricultural products gradually became available over wider frequency ranges (Stetson and Nelson, 1972; Nelson and Stetson, 1975, 1976; Nelson, 1973b, 1981). More recently, dielectric properties data have been obtained for study in more detail at microwave frequencies (Kraszewski and Nelson, 1990; Kraszewski et al., 1995; Trabelsi et al., 1996).

Definition of Terms and Basic Principles

The fundamental ac characteristics of materials have been defined in detail previously in terms of electromagnetic field concepts (Nelson, 1973a) and in terms of parallel-equivalent circuit concepts (Nelson, 1965). For practical use, the dielectric properties of usual interest are the dielectric constant ϵ' and the dielectric loss factor ϵ'', the real and imaginary parts, respectively, of the relative complex permittivity, $\epsilon = \epsilon' - j\epsilon'' = |\epsilon| \, e^{-j\delta}$, where δ is the loss angle of the dielectric. Hereafter in this paper, "permittivity" is understood to represent the relative complex permittivity, i.e., the permittivity relative to free space, or the absolute permittivity divided by the permittivity of free space, $\epsilon_o = 8.854 \times 10^{-12}$ F/m. Often, the loss tangent, $\tan \delta = \epsilon''/\epsilon'$, or dissipation factor, is also used as a descriptive dielectric parameter, and sometimes the power factor ($\tan \delta / \sqrt{1 + \tan^2\delta}$) is used. The ac conductivity of the dielectric in S/m is $\sigma = \omega\epsilon_o\epsilon''$, where $\omega = 2\pi f$ is the angular frequency, with frequency f in Hz. In this paper, ϵ'' is interpreted to include the energy losses in the dielectric due to all operating dielectric relaxation mechanisms and ionic conduction.

The dielectric properties of materials dictate, to a large extent, the behavior of the materials when subjected to RF or microwave fields for purposes of heating or drying the materials. The power dissipated per unit volume in the dielectric can be expressed as

$$P = E^2\sigma = 55.63 f E^2 \epsilon'' \times 10^{-12} \text{ W/m}^3 \tag{1}$$

where E represents the rms electric field intensity in V/m. The time rate of temperature increase, dT/dt in °C/s, in the dielectric material caused by the conversion of energy from the electric field to heat in the material is

$$dT/dt = P/(c\rho) \tag{2}$$

where c is the specific heat of the material in kJ/(kg·°C), and ρ is its density in kg/m³. In drying applications, the latent heat of vaporization for water removed from the material must also be taken into account, because energy must be supplied for that purpose.

From Eq. (1) it is obvious that the power dissipation is directly related to the dielectric loss factor ϵ''; however, it may also be dependent on the dielectric constant ϵ' in that, depending on the treating arrangement, the electric field intensity may be a function of ϵ'. Two simple examples illustrate this influence of relative ϵ' values. In the RF dielectric heating of a layer of material of permittivity ϵ_1 of uniform thickness d_1 between parallel-plate electrodes, with an air gap of permittivity ϵ_2 and thickness d_2 between the material and one electrode, the rms electric field intensity in the material is

$$E_1 = \frac{V}{d_1 + d_2\left(\frac{\epsilon_1}{\epsilon_2}\right)} \tag{3}$$

where V is the rms potential difference between the electrodes. In a second example, a spherical inclusion of permittivity ϵ_2 embedded in an infinite medium of permittivity ϵ_1 will have an electric field intensity in the spherical material of

$$E_2 = E_1\left(\frac{3\epsilon_1}{2\epsilon_1 + \epsilon_2}\right) \tag{4}$$

(Stratton, 1941), where E_1 is the electric field intensity in the infinite medium. Thus, the value of the dielectric constants can have an important influence on the electric field intensity in the material to be heated, which according to Eq. (1) has an important influence on the power dissipation in that material.

The absorption of microwave energy propagating through a material depends upon the variables of Eq. (1). Thus, the dielectric properties of the material are important. The frequency of the wave is also a factor, and the power absorption also depends on the square of the electric field intensity. For a plane wave, the electric field intensity E, which has $e^{j\omega t}$ dependence, can be given as (von Hippel, 1954)

$$E(z) = E_o e^{j\omega t - \gamma z} \tag{5}$$

where E_o is the rms electric field intensity at a point of reference, t is time, γ is the propagation constant for the medium in which the wave is traveling, and z is the distance in the direction of travel. The propagation constant is a complex quantity,

$$\gamma = \alpha + j\beta = j\frac{2\pi}{\lambda_o}\sqrt{\epsilon} \tag{6}$$

where α is the attenuation constant, β is the phase constant, and λ_o is the free-space wavelength. The attenuation constant α and phase constant β are related to the dielectric properties of the medium as follows (von Hippel, 1954):

$$\alpha = \frac{2\pi}{\lambda_o}\sqrt{\frac{\epsilon'}{2}\left(\sqrt{1 + tan^2\delta} - 1\right)} \quad \text{nepers/m} \tag{7}$$

$$\beta = \frac{2\pi}{\lambda_o}\sqrt{\frac{\epsilon'}{2}\left(\sqrt{1 + tan^2\delta} + 1\right)} \quad \text{radians/m} \tag{8}$$

As the wave travels through a material that has a significant dielectric loss, its energy will be attenuated. For a plane wave traversing a dielectric material, the electric field intensity at the site of interest can be obtained by combining Eqs. (5) and (6) as follows:

$$E(z) = E_o e^{-\alpha z} e^{j(\omega t - \beta z)} \tag{9}$$

where the first exponential term controls the magnitude of the electric field intensity at the point of interest, and it should be noted that the magnitude of this term decreases as the wave propagates into the material. Since the power dissipated is proportional to E^2, $P \propto e^{-2\alpha z}$. The penetration depth, D_p, is defined as the distance at which the power drops to $e^{-1} = 1/2.783$ of its value at the surface of the material. Thus, $D_p = 1/2\alpha$. If attenuation is high in the material, the dielectric heating will taper off quickly as the wave penetrates the material. Attenuation is often expressed in decibels/meter (dB/m). In terms of power densities and electric field intensity values, this can be expressed as (von Hippel, 1954)

$$10\ log_{10}\left(\frac{P_o}{P(z)}\right) = 20\ log_{10}\left(\frac{E_o}{E(z)}\right) = 8.686\alpha z \tag{10}$$

The dielectric properties of the materials are very important in evaluating the penetration of energy that can be achieved. The attenuation in decibels, combining Eqs. (7) and (10), can be expressed in terms of the dielectric properties, when $(\epsilon'')^2 << (\epsilon')^2$, as follows:

$$\alpha \simeq \frac{8.686\pi\epsilon''}{\lambda_o\sqrt{\epsilon'}} \quad \text{dB/m} \tag{11}$$

A plane wave incident upon a material surface will have some of the power reflected, and the rest, P_t, will be transmitted into the material. The relationship is given by the following expression:

$$P_t = P_o\left(1 - |\Gamma|^2\right) \tag{12}$$

where P_o is the incident power and Γ is the reflection coefficient. For an air-material interface, the reflection coefficient can be expressed in terms of the complex relative permittivity of the material as (Stratton, 1941)

$$\Gamma = \frac{1 - \sqrt{\epsilon}}{1 + \sqrt{\epsilon}} \tag{13}$$

The power density diminishes as an exponential function of the attenuation and distance traveled (Eq. (9)) as the wave propagates through the material,

$$P = P_t e^{-2\alpha z} \tag{14}$$

with α expressed in nepers/meter. For attenuation in decibels, dB/cm = 0.08686 × (nepers/meter).

VARIATION IN DIELECTRIC PROPERTIES

The dielectric properties of most materials vary with several different factors. In hygroscopic materials such as agricultural products, the amount of water in the materials is generally a dominant factor. The dielectric properties also depend on the frequency of the applied alternating electric field, the temperature of the materials, and on the density and structure of the materials. In granular or particulate materials, the bulk density of the air-particle mixture is another factor that influences their dielectric properties. Of course, the dielectric properties of materials are dependent on their chemical composition and especially on the permanent dipole moments associated with water and any other molecules making up the materials of interest.

Frequency Dependence

With the exception of some extremely low-loss materials, i.e., materials that absorb essentially no energy from RF and microwave fields, the dielectric properties of most materials vary considerably with the frequency of the applied electric fields. This frequency dependence has been discussed previously (Nelson, 1973a, 1991). An important phenomenon contributing to the frequency dependence of the dielectric properties is the polarization arising from the orientation with the imposed electric field of molecules which have permanent dipole moments. The mathematical formulation developed by Debye (1929) to describe this process for pure polar materials can be expressed as

$$\epsilon = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + j\omega\tau} \qquad (15)$$

where ϵ_∞ represents the dielectric constant at frequencies so high that molecular orientation does not have time to contribute to the polarization, ϵ_s represents the static dielectric constant, i.e., the value at zero frequency (dc value), and τ is the relaxation time, the period associated with the time for the dipoles to revert to random orientation when the electric field is removed. Separation of Eq. (5) into its real and imaginary parts yields

$$\epsilon' = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + \omega^2\tau^2} \qquad (16)$$

$$\epsilon'' = \frac{(\epsilon_s - \epsilon_\infty)\omega\tau}{1 + \omega^2\tau^2} \qquad (17)$$

The relationships defined by these equations are illustrated in Fig. 1.

Thus, at frequencies very low and very high with respect to the molecular relaxation process, the dielectric constant has constant values, ϵ_s and ϵ_∞, respectively, and the losses are zero. At intermediate frequencies, the dielectric constant undergoes a dispersion, and dielectric losses occur with the peak loss at the relaxation frequency, $\omega_o = 1/\tau$.

The Debye equation can be represented graphically in the complex ϵ'-vs.-ϵ'' plane as a semicircle with locus of points ranging from ($\epsilon' = \epsilon_s$, $\epsilon'' = 0$) at the low-frequency limit to ($\epsilon' = \epsilon_\infty$, $\epsilon'' = 0$) at the high-frequency limit (Fig. 2). Such a representation is known as a "Cole-Cole" diagram (Cole and Cole, 1941).

Since few materials of interest consist of pure polar materials with a single relaxation time, many other equations have been developed to better describe the frequency-dependent behavior of materials with more relaxation times or a distribution of relaxation times (Böttcher and Bordewijk, 1978). One such equation is the Cole-Cole equation (Cole and Cole, 1941),

$$\epsilon = \frac{\epsilon_s - \epsilon_\infty}{1 + (j\omega\tau)^{1-\alpha}} \qquad (18)$$

where α denotes the spread of relaxation times, and this empirical relaxation-time distribution parameter takes on values between 0 and 1.

Water in its liquid state, is a good example of a polar dielectric. However, water in its free liquid state appears in agricultural products very rarely. Most often it has dissolved constituents, is physically absorbed in material capillaries or cavities, or is chemically bound to other molecules of the material. Dielectric relaxations of absorbed water take place at lower frequencies than the relaxation of free water (Hasted, 1973), which occurs at 19.6 GHz for water at 25 °C. Depending upon the material structure, there may be various forms of bound water, differing in energy of binding and in dielectric properties. In heterogeneous systems, Maxwell-Wagner relaxations are also possible. Moist material, in practice, is usually an inhomogeneous mixture, often containing more than one substance with unknown dielectric properties. Thus, it is difficult to understand and predict the dielectric behavior of such material at different frequencies, temperatures, or hydration levels. At present, very little is known about the dielectric properties of moist materials of different structures containing water in various levels of binding. However, a complete understanding is not always necessary for the solution of practical problems.

Temperature Dependence

The dielectric properties of materials are also temperature dependent, and the nature of that dependence is a function of the dielectric relaxation processes operating under the particular conditions existing and the frequency being used. As temperature increases, the relaxation time decreases, and the loss-factor peak illustrated in Figure 1 will shift to higher frequencies. Thus, in a region of dispersion, the dielectric constant will increase with increasing temperature, whereas the loss factor may either

increase or decrease, depending on whether the operating frequency is higher or lower than the relaxation frequency. The temperature dependence of ϵ_∞ is generally negligible (Böttcher and Bordewijk, 1978), and while that of ϵ_s is larger, its influence is minor in a region of dispersion. Below the region of dispersion, the dielectric constant decreases with increasing temperature. Distribution functions can be useful in expressing the temperature dependence of dielectric properties, but the frequency and temperature dependent behavior of the dielectric properties of most materials is complicated and can perhaps best be determined by measurement at the frequencies and under the other conditions of interest.

Density Dependence

Since the influence of a dielectric depends on the amount of mass interacting with the electromagnetic fields, the mass per unit volume, or density, will have an effect on the dielectric properties. This is especially notable with particulate dielectrics such as pulverized or granular materials. In understanding the nature of the density dependence of the dielectric properties of particulate materials, relationships between the dielectric properties of solid materials and those of air-particle mixtures, such as granular or pulverized samples of such solids, are useful.

In some instances, the dielectric properties of a solid may be needed when particulate samples are the only available form of the material. This was true for cereal grains, where kernels were too small for the dielectric sample holders used for measurements (You and Nelson, 1988; Nelson and You, 1989) and in the case of pure minerals that had to be pulverized for purification (Nelson et al., 1989). For some materials, machining of samples to exact dimensions required for dielectric properties measurement is difficult, and measurements on pulverized materials are more easily performed. In such instances, proven relationships for converting dielectric properties of particulate samples to those for the solid material are important. Several well-known dielectric mixture equations have been considered for this purpose (Nelson and You, 1990; Nelson, 1992). The notation used here applies to two-component mixtures, where ϵ represents the permittivity of the mixture, ϵ_1 is the permittivity of the medium in which particles of permittivity ϵ_2 are dispersed, and v_1 and v_2 are the volume fractions of the respective components, where $v_1 + v_2 = 1$. Two of the mixture equations found particularly useful for cereal grains were the Complex Refractive Index mixture equation

$$(\epsilon)^{1/2} = v_1(\epsilon_1)^{1/2} + v_2(\epsilon_2)^{1/2} \tag{19}$$

and the Landau and Lifshitz, Looyenga equation

$$(\epsilon)^{1/3} = v_1(\epsilon_1)^{1/3} + v_2(\epsilon_2)^{1/3} \tag{20}$$

To use such equations to determine ϵ_2, one needs to know the dielectric properties (permittivity) of the pulverized sample at its bulk density (air-particle mixture density), ρ, and the specific gravity or density of the solid material, ρ_2. The fractional part of the total volume of the mixture occupied by the particles (volume fraction), v_2, is then given by ρ/ρ_2.

DIELECTRIC PROPERTIES DATA

Some of the data that have been obtained by measurements of the dielectric properties of various agricultural products will be presented here to illustrate the nature of their variation with the variables already discussed (Nelson, 1991). The variation of the dielectric constant and loss factor of hard red winter wheat over the 1- to 50-MHz range is shown in Fig. 3. The dielectric constant always decreases with increasing frequency, but the loss factor may increase or decrease as frequency increases, depending upon the frequency and the moisture content[1] of the wheat.

The frequency and moisture dependence of the dielectric properties of field corn are shown for a wider frequency range, 1 MHz to 11 GHz, in Fig. 4. The regularity of the relationship between the dielectric constant and both moisture and frequency is evident in all of these curves, but, as already noted, the behavior of the loss factor is much less predictable.

Although the moisture dependence is clearly evident in Figs. 3 and 4, plots of the dielectric constant and loss factor of rough rice (paddy), directly against moisture content, are illustrated in Fig. 5. The relationship between dielectric constant and moisture content is nearly linear over this frequency range.

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[1]Moisture contents of products are reported on the wet basis throughout this paper.

A more useful graphical presentation of dielectric properties data for reference over wide ranges of frequency and moisture content is shown in Fig. 6 for hard red winter wheat, where ϵ' and ϵ'' are shown as contour plots and as functions of both variables. The irregular behavior of the loss factor is also illustrated in these plots.

The variation in the dielectric constant of shelled corn with temperature is illustrated in Fig. 7 for three frequencies, 20 and 300 MHz and 2.45 GHz, and moisture contents of about 10 and 19%. The dependence here appears nearly linear; however, the relationships of both ϵ' and ϵ'' with temperature are nonlinear over wider ranges of temperature (Lawrence et al., 1990). In practice, linear approximations can generally be used, especially at lower moisture contents and over limited temperature ranges.

The variation of the dielectric constant with natural bulk densities of shelled, yellow-dent field corn, achieved by loosely filling and settling samples in a coaxial cylindrical sample holder, is illustrated in Fig. 8 for several moisture contents at 300 MHz. The Refractive Index and Landau and Lifshitz, Looyenga relationships also provide a relatively reliable method for adjusting the dielectric properties of granular and powdered materials with characteristics like grain products from known values at one bulk density to corresponding values for a different bulk density. It follows from Eqs. (19) and (20), respectively, that, for an air-particle mixture, where $\epsilon_1 = 1 - j0$, the permittivity ϵ_x of such a mixture at density ρ_x can be obtained from measured values of ϵ_y at density ρ_y as follows:

$$\epsilon_x = \left[\left[(\epsilon_y)^{1/2} - 1 \right] \frac{\rho_x}{\rho_y} + 1 \right]^2 \tag{21}$$

$$\epsilon_x = \left[\left[(\epsilon_y)^{1/3} - 1 \right] \frac{\rho_x}{\rho_y} + 1 \right]^3 \tag{22}$$

Either Eq. (21) or Eq. (22) should provide reliable conversions from one mixture density to another, but the Landau and Lifshitz, Looyenga relationship provided closer estimates within the range of measured densities in work with whole kernel wheat, ground wheat, and finely pulverized coal (Nelson, 1983b, 1984); so Eq. (22) is preferred.

The dielectric properties of many agricultural products, including animal tissues, foods, plant materials, fruits and vegetables, grain and seed, wood, and textiles were included in extensive tabulations prepared previously (Nelson, 1973a; Tinga and Nelson, 1973). More recently, an extensive tabulation and bibliography on dielectric properties of food materials has been published (Kent, 1987), and data for foods at 2.45 GHz have also been tabulated (Datta et al., 1995). These references provide data on many agricultural materials for certain frequencies and other specified conditions, but data are still not available for many materials. Therefore, models have been developed for cereal grains that provide estimated dielectric properties as functions of frequency, moisture content, density, and temperature (Nelson, 1979; Nelson, 1987; Kraszewski and Nelson, 1989).

APPLICATIONS OF DIELECTRIC PROPERTIES

Moisture Measurement

As already noted, electrical measurement of grain moisture content is probably the most important application of the dielectric properties of agricultural products to date. The strong correlations between the moisture content of grains and other products and their dielectric properties are evident in the dielectric properties data already presented. These correlations have been used in the development of grain moisture meters that have been in common commercial use for many years. More recent efforts have been devoted to the development of techniques for sensing moisture content in on-line applications. For this application, the fluctuation in bulk density of grain has caused serious problems, because changes in bulk density are sensed as changes in moisture content by traditional measurement techniques. Measurements at microwave frequencies, as suggested by Kraszewski and Kulinski (1976), offer a solution to this problem.

Measurement of attenuation A and phase shift Φ of 9.4 GHz plane waves propagating through layers of cereal grains of thickness t and bulk density ρ showed mainly linear relationships between these two wave parameters and the moisture content M of corn (Kraszewski, 1988; Nelson and Kraszewski, 1990). When A and Φ per unit thickness were divided by the bulk densities corresponding to each moisture content, the relationships of these parameters remained linear with moisture content. These relationships are expressed as follows:

$$\frac{A}{\rho l} = aM + b \tag{43}$$

$$\frac{\Phi}{\rho l} = cM + d \tag{44}$$

where a, b, c, and d are regression coefficients for a particular grain. Combining Eq. (43) and Eq. (44) and solving for M provides

$$M = \frac{dA - b\Phi}{a\Phi - cA} \tag{45}$$

which expresses the grain moisture content in terms of the measured attenuation and phase shift, independent of the grain bulk density. Eqs. (43) and (44) can also be combined and solved for ρ, giving

$$\rho = \frac{a\Phi - cA}{l(ad - bc)} \tag{46}$$

Although, in this example, $A/(\rho l)$ and $\Phi/(\rho l)$ are linear functions of moisture content, linearity is not required; only a defined function is necessary to permit the separation of the expressions for moisture content and density (Kraszewski, 1988).

The ratio of attenuation and phase shift has also been investigated as a density independent function for microwave determination of moisture content in food powders (Kress-Rogers and Kent, 1987) and found to be less density-sensitive than the ratio $(\epsilon' - 1)/\epsilon''$, suggested earlier by Meyer and Schilz (1981). For plane wave propagation through low-loss materials, the ratio of phase shift in radians to attenuation in nepers (Meyer and Schilz, 1981; Kent and Meyer, 1982) is expressed as

$$\frac{\Phi}{A} = \left(\frac{\epsilon' - 1}{\epsilon''}\right) \frac{2\sqrt{\epsilon'}}{\sqrt{\epsilon'} + 1} \tag{47}$$

To compare this Φ/A ratio and its density-independence with that of Eq. (45) for moisture measurement, Kraszewski (1988) calculated the Φ/A ratio for a large amount of data on grain and developed mathematical expressions for the ratio as a function of moisture content. Comparing this procedure to that represented by Eq. (45), the Φ/A ratio was only slightly less effective with a standard error of performance of 0.22% moisture compared to 0.17% for procedures based on Eq. (45). Two-parameter microwave measurement systems using similar techniques have been developed for successful moisture determination in grain (King et al., 1992, 1996; McLendon et al., 1993).

Research aimed at development of density-independent moisture sensing techniques using lower radio frequencies has also shown promise (Lawrence and Nelson, 1993; Lawrence et al., 1994), since multiple-frequency measurements yielded density-independent moisture determinations with standard errors of 0.5% moisture content or less.

Studies on RF and microwave sensing of moisture content in single kernels of grain have also shown that single-kernel moisture contents can be obtained nondestructively by dual-frequency impedance measurements at 1 and 4.5 MHz (Kandala et al., 1989) and by resonant cavity measurements and microwave frequencies (Kraszewski et al., 1990).

RF and Microwave Heating

Dielectric heating at frequencies between about 1 and 100 MHz has been known historically as radio-frequency or RF dielectric heating. When microwave frequencies, roughly 1 GHz and higher, are used, it has been termed microwave heating. Although, technically, the radio-frequency part of the electromagnetic spectrum includes microwaves, the customary terminology just noted will be used here also. Historically, power oscillators became available first for the lower frequencies, so RF heating applications were explored earlier (Brown et al., 1947) than the later developing microwave heating. As microwave power sources became readily available, many of the earlier potential uses were revisited by researchers interested in the "new" possibilities offered by microwave heating. Agricultural dielectric heating interests have included the drying of grain and other products, treatment of seed to improve germination and growth, heating of products to improve their nutritional or other qualities, insect control, pasteurization, and sterilization.

In research on the effects of different variables on the effectiveness of RF exposures for improving seed germination (Nelson and Stetson, 1985), for controlling insects in infested grain (Nelson and Whitney, 1960; Nelson et al., 1966), and for improving the nutritional quality of soybeans (Pour-El et al., 1981) and the keeping quality of pecans (Nelson et al., 1985), the dielectric properties of the materials were needed for calculation of the electric field intensities used in the different experiments.

Also, the dielectric properties of materials to be heated by dielectric methods are of interest in calculating the loading of oscillators and the design of the power application equipment for either RF or microwave dielectric heating applications. These are common to any dielectric heating problem.

Stored-Grain Insect Control

In the study of insect control in grain by RF dielectric heating, the dielectric properties of the grain and the insects are important. The properties of hard red winter wheat and of adult insects of the rice weevil, *Sitophilus oryzae* (L.), were measured over the frequency range from 1 MHz to 12 GHz and examined for the optimum frequencies for selective dielectric heating of the insects (Nelson and Charity, 1972). Resulting values for the insects and the grain showed a very high insect-to-grain loss-factor ratio in the 10- to 100-MHz region, revealing an obvious advantage for selectively heating the insects at those frequencies. Analysis of the comparative heating rates of the insects and grain (Eqs. (1) and (2)), and taking into account the influence of relative ϵ' values according to Eq. (4), revealed that the loss-factor ratio was the dominant factor, and RF treatment in the range between 10 and 100 MHz should offer the highest insect-to grain power dissipation ratio. This interpretation of the dielectric properties data was confirmed by insect mortality studies following exposures of rice-weevil-infested wheat samples at frequencies of 39 MHz and 2.45 GHz (Nelson and Stetson, 1974). Comparative mortalities were achieved by 39-MHz treatment at much lower grain temperatures than those produced by 2.45 GHz treatment in the microwave region. Although rather thoroughly explored, RF treatment for stored-grain insect control has not become practical, because chemical controls are less expensive (Nelson, 1973b, 1996).

Product Quality Measurement

It seems reasonable to expect that dielectric properties of some agricultural products might be useful for rapid nondestructive quality determination. Microwave dielectric properties of several fruits and vegetables were measured with this prospect in mind (Nelson, 1980, 1983a). However, results of the measurements at single frequencies did not reveal correlations that would be useful for measuring maturity in peaches or for detection of the 'hard core' condition in sweet potatoes. More recent measurements over wide frequency ranges have revealed possible correlations between functions of the dielectric properties of peaches and their maturity (Nelson et al., 1995).

REFERENCES

1. Ban, T., and M. Suzuki. 1977. Studies on electrical detection of grain moisture content in artificial drying (Japanese). Techn. Rpt. No. 11, Institute of Agricultural Machinery, Omiya, Japan.
2. Berliner, E., and R. Rüter. 1929. Über Feuchtigkeitsbestimmungen in Weizen und Roggen mit dem DK Apparat. Zeitschr. Gesamte Mühlenvesen, 6:1-4.
3. Böttcher, C. J. F., and P. Bordewijk. 1978. *Theory of Electric Polarization*, Vol. II, Elsevier Science Publ. Co., Amsterdam.
4. Briggs, L. J. 1908. An electrical resistance method for the rapid determination of the moisture content of grain. Bureau of Plant Industry Circular No. 20, U. S. Department of Agriculture.
5. Brown, G. H., C. N. Hoyler, and R. A. Bierwirth. 1947. *Theory and Application of Radio-Frequency Heating.* D. Van Nostrand Co., New York
6. Burton, E. F., and A. Pitt. 1929. A new method for the rapid estimation of moisture in wheat. Can. J. Res. 1:155-162.
7. Cole, K. S., and R. H. Cole. 1941. Dispersion and absorption in dielectrics. I. Alternating current characteristics. J. Chem. Phys. 9:341-351.
8. Datta, A. K., E. Sun, and A. Solis. 1995. Food dielectric property data and their composition-based prediction. Ch. 9, *Engineering Properties of Foods*, M. A. Rao, and S. S. Rizvi, eds. Marcel Dekker, Inc., New York.
9. Debye, P. 1929. *Polar Molecules.*, The Chemical Catalog Co., New York.
10. Hasted, J. B. 1973. *Aqueous Dielectrics.* Chapman and Hall, London.
11. Kandala, C. V. K., S. O. Nelson and K. C. Lawrence. 1989. Non-destructive electrical measurement of moisture content in single kernels of corn. J. Agric. Eng. Res. 44:125-132.
12. Kent, M. 1987. *Electrical and Dielectric Properties of Food Materials.* Science and Technology Publishers, Essex, England.

13. Kent, M., and W. Meyer. 1982. A density-independent microwave moisture meter for heterogeneous foodstuffs. J. Food Eng. 1:31-42.

14. King, R. J., J. C. Basuel, M. J. Werner, and K. V. King. 1996. Material characterization using microwave open reflection resonator sensors. Sec. III, *Microwave Aquametry --Electromagnetic Wave Interaction with Water-Containing Materials*, A. W. Kraszewski, ed., pp. 153-175. IEEE Press, Piscataway, NJ.

15. King, R. J., K. V. King, and K. Woo. 1992. Microwave moisture measurement of grains. IEEE Trans. Instrum. Meas. 41(1):111-115.

16. Knipper, N. V. 1959. Use of high-frequency currents for grain drying. J. Agr. Eng. Res. 4(4):349-360. (Translated from Nauch. Trud. Elektrif. Selkhoz. 2: 185, 1956).

17. Kraszewski, A. 1988. Microwave monitoring of moisture content in grain—further considerations. J. Microwave Power Electromag. Energy 23(4):236-246.

18. Kraszewski, A., and S. Kulinski. 1976. An improved method of moisture content measurement and control. IEEE Trans. Ind. Electron. Control Instrum. IECI-23(4):364-370.

19. Kraszewski, A., and S. O. Nelson. 1989. Composite model of the complex permittivity of cereal grain. J. Agric. Eng. Res. 43:211-219.

20. Kraszewski, A., and S. Nelson. 1990. Study on grain permittivity measurements in free space. J. Microwave Power Electromag. Energy 25(4):202-210.

21. Kraszewski, A. W., S. Trabelsi, and S. O. Nelson. 1995. Microwave dielectric properties of wheat. Proc. 30th Microwave Power Symposium, July 9-12, Denver, CO, pp. 90-93.

22. Kraszewski, A. W., S. O. Nelson and T.-S. You. 1990. Use of a microwave cavity for sensing dielectric properties of arbitrarily shaped biological objects. IEEE Trans. Microwave Theory Techn. 38(7):858-863.

23. Kress-Rogers, E., and M. Kent. 1987. Microwave measurement of powder moisture and density. J. Food Eng. 6:345-376.

24. Lawrence, K. C., and S. O. Nelson. 1993. Radio-frequency density-independent moisture determination in wheat. Trans. ASAE 36(2):477-483.

25. Lawrence, K. C., S. O. Nelson and A. W. Kraszewski. 1990. Temperature dependence of the dielectric properties of wheat. Trans. ASAE 33(2):535-540.

26. Lawrence, K. C., W. R. Windham, and S. O. Nelson. 1994. Wheat moisture determination by 1- to 110-MHz swept-frequency admittance measurements. ASAE Paper No. 94-6051, Amer. Soc. Agric. Engrs., St. Joseph, MI.

27. Martens, V., and I. Hlynka. 1963. Determination of moisture in Canadian grain by electric moisture meter, in *Humidity and Moisture—Measurement and Control in Science and Industry*, A. Wexler, ed.-in-chief, Vol. 4, Principles and Methods of Measuring Moisture in Liquids and Solids, P. N. Winn, Jr., ed., pp. 125-133, 1963.

28. McLendon, B. D., B. G. Branch, S. A. Thompson, A. Kraszewski, and S. O. Nelson. 1993. Density-independent microwave measurement of moisture content in static and flowing grain. Trans. ASAE 36(3):827-835.

29. Meyer, W., and W. Schilz. 1981. Feasibility study of density-independent determination of the moisture content of solids. J. Phys. D: Appl. Phys. 13:1823-1830.

30. Nelson, S. O. 1965. Dielectric properties of grain and seed in the 1 to 50-mc range. Trans. ASAE 8(1):38-48.

31. Nelson, S. O. 1973a. Electrical properties of agricultural products—a critical review. Trans. ASAE 16(2):384-400.

32. Nelson, S. O. 1973b. Insect-control Studies with microwaves and other radiofrequency energy. Bul. Entomol. Soc. Amer. 19(3):157-163.

33. Nelson, S. O. 1973c. Microwave dielectric properties of grain and seed. Trans. ASAE 16(5): 902-905.

34. Nelson, S. O. 1977. Use of electrical properties for grain-moisture measurement. J. Microwave Power 12(1):67-72.

35. Nelson, S. O. 1978. Frequency and moisture dependence of the dielectric properties of high-moisture corn. J. Microwave Power 13(2):213-218.

36. Nelson, S. O. 1979. RF and microwave dielectric properties of shelled, yellow-dent field corn. Trans. ASAE 22(6):1451-1457.

37. Nelson, S. O. 1980. Microwave dielectric properties of fresh fruits and vegetables. Trans. ASAE 23(5):1314-1317.

38. Nelson, S. O. 1981. Review of factors influencing the dielectric properties of cereal grains. Cereal Chem. 58(8):487-492.

39. Nelson, S. O. 1983a. Dielectric properties of some fresh fruits and vegetables at frequencies of 2.45 to 22 GHz. Trans. ASAE 26(2):613-616.

40. Nelson, S. O. 1983b. Observations on the density dependence of the dielectric properties of particulate materials. J. Microwave Power 18(2):143-152.

41. Nelson, S. O. 1984. Density dependence of the dielectric properties of wheat and whole-wheat flour. J. Microwave Power 19(1):55-64.

42. Nelson, S. O. 1987. *Models for the dielectric constants of cereal grains and soybeans.* J. Microwave Power 22(1):35-39.

43. Nelson, S. O. 1991. Dielectric properties of agricultural products. *Digest of Literature on Dielectrics*, A. de Reggie, ed., IEEE Trans. Electr. Insul. 26(5):845-869.

44. Nelson, S. O. 1992. Estimation of permittivities of solids from measurements on pulverized or granular materials. Ch. 6 in *Dielectric Properties of Heterogeneous Materials*, A. Priou, Ed., Vol. 6., Progress in Electromagnetics Research, J. A. Kong, ch. ed., Elsevier Science Publishing Co., New York.

45. Nelson, S. O. 1996. Assessment of RF and microwave electric energy for stored-grain insect control. Trans. ASAE 39(3):In Press.

46. Nelson, S. O., and L. F. Charity. 1972. Frequency dependence of energy absorption by insects and grain in electric fields. Trans. ASAE 15(6):1099-1102.

47. Nelson, S. O., and A. W. Kraszewski. 1990. Grain moisture content determination by microwave measurements. Trans. ASAE 33(4):1303-1307.

48. Nelson, S. O., and L. E. Stetson. 1974. Comparative effectiveness of 39- and 2450-MHz electric fields for control of rice weevils in wheat. J. Econ. Entomol. 67(5):592-595.

49. Nelson, S. O., and L. E. Stetson. 1975. 250-Hz to 12-GHz dielectric properties of grain and seed. Trans. ASAE 18(4):714-715,718.

50. Nelson, S. O., and L. E. Stetson. 1976. Frequency and moisture dependence of the dielectric properties of hard red winter wheat. J. Agric. Eng. Res. 21:181-192.

51. Nelson, S. O., and L. E. Stetson. 1985. Germination responses of selected plant species to RF electrical seed treatment. Trans. ASAE 28(6):2051-2058.

52. Nelson, S. O., and W. K. Whitney. 1960. Radio-frequency electric fields for stored grain insect control. Trans. ASAE 3(2):133-137, 144.

53. Nelson, S. O., and T.-S. You. 1989. Microwave dielectric properties of corn and wheat kernels and soybeans. Trans. ASAE 32(1):242-249.

54. Nelson, S. O., and T.-S. You. 1990. Relationships between microwave permittivities of solid and pulverised plastics. J. Phys. D: Appl. Phys. 23:346-353.

55. Nelson, S. O., L. H. Soderholm and F. D. Yung. 1953. Determining the dielectric properties of grain. Agr. Eng. 34(9):608-610.

56. Nelson, S. O., L. E. Stetson, and J. J. Rhine. 1966. Factors influencing effectiveness of radio-frequency electric fields for stored-grain insect control. Trans. ASAE 9(6):809-815.

57. Nelson, S. O., S. D. Senter and W. R. Forbus, Jr. 1985. Dielectric and steam heating treatments for quality maintenance in stored pecans. J. Microwave Power 20(2):71-74.

58. Nelson, S. O., D. P. Lindroth, and R. L. Blake. 1989. Dielectric properties of selected minerals at 1 to 22 GHz. Geophys. 54(10):1344-1349.

59. Nelson, S. O., W. R. Forbus, Jr., and K. C. Lawrence. 1995. Assessment of microwave permittivity for sensing peach maturity. Trans. ASAE 38(2):579-585.

60. Noh, S. H., and S. O. Nelson. 1989. Dielectric properties of rice at frequencies from 50 Hz to 12 GHz. Trans. ASAE 32(3):991-998.

61. Pour-El, A., S. O. Nelson, E. E. Peck, B. Tjhio and L. E. Stetson. 1981. Biological properties of VHF- and microwave-heated soybeans. J. Food Sci. 46(3):880-885, 895.

62. Stetson, L. E., and S. O. Nelson. 1972. Audiofrequency dielectric properties of grain and seed. Trans. ASAE 15(1):180-184, 188.

63. Stratton, J. A. 1941. *Electromagnetic Theory*, p. 206. McGraw Hill Book Co., New York.

64. Tinga, W. R., and S. O. Nelson. 1973. Dielectric properties of materials for microwave processing — tabulated. J. Microwave Power 8(1):23-65.

65. Trabelsi, S., A. W. Kraszewski, and S. O. Nelson. 1996. Microwave dielectric properties of shelled corn. Proc. 31st Microwave Power Symposium, July 28-31, Boston, MA, pp. 8-11.

66. von Hippel, A. 1954. *Dielectric Materials and Applications.* The Technology Press of M. I. T. and John Wiley & Sons, New York.

67. You, T.-S., and S. O. Nelson. 1988. Microwave dielectric properties of rice kernels. J. Microwave Power 23(3):150-159.
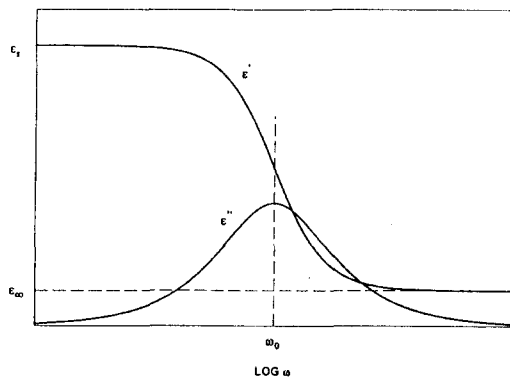
Fig. 1. Dispersion and absorption curves for the Debye model for a polar substance with a single relaxation time.
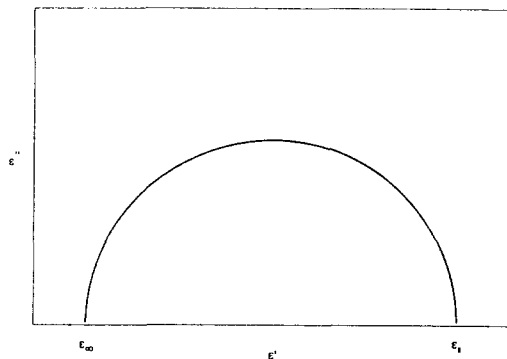
Figure 2. Cole-Cole plot for a polar substance with a single relaxation time.
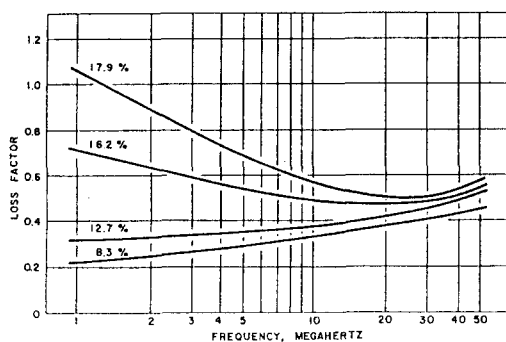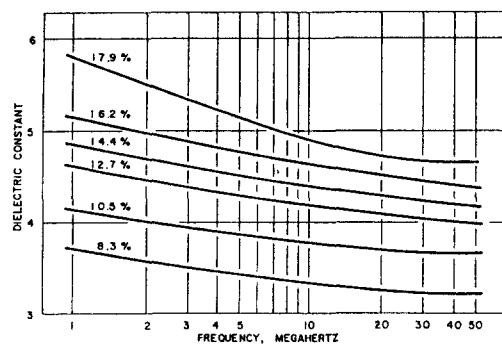

Fig. 3. Frequency dependence of the dielectric constant and loss factor of 'Nebred' hard red winter wheat at 24 °C and indicated moisture contents (Nelson, 1965).
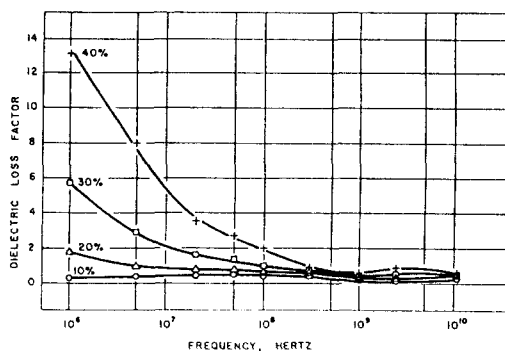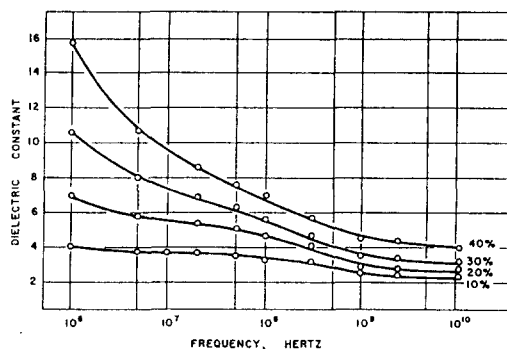
Fig. 4. Frequency dependence of the dielectric constant and loss factor of shelled, yellow-dent field corn at 24 °C and indicated moisture contents (Nelson, 1978).
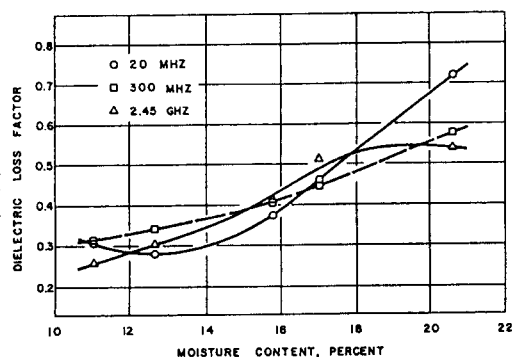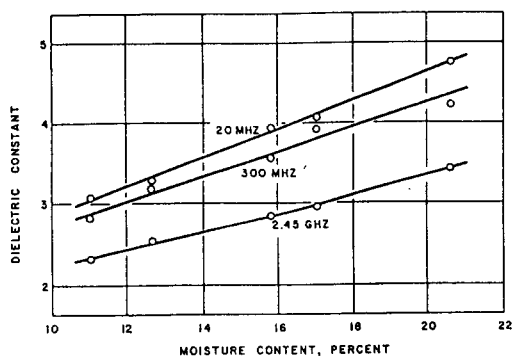
Fig. 5. Moisture dependence of the dielectric constant and loss factor of 'Lebonnet' rough rice, *Oryza sativa* L., at 24 ℃ and indicated frequencies (Noh and Nelson, 1989).
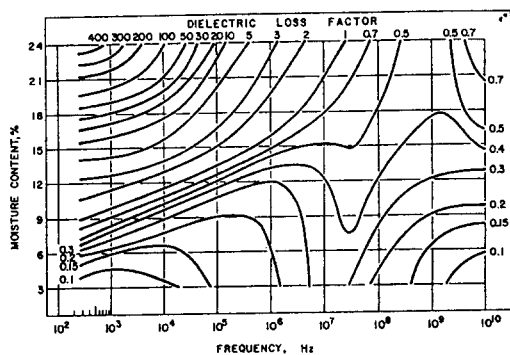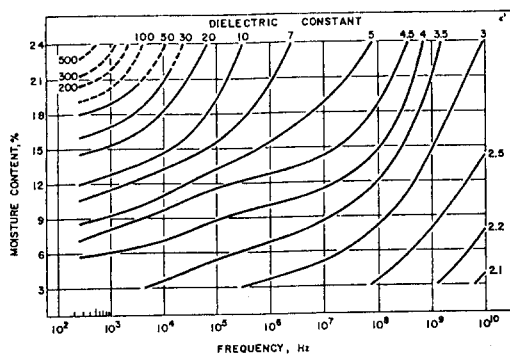
Fig. 6. Contour plots of the dielectric constant and loss factor of hard red winter wheat at 24 ℃ as a function of frequency and moisture content (Nelson, 1981).
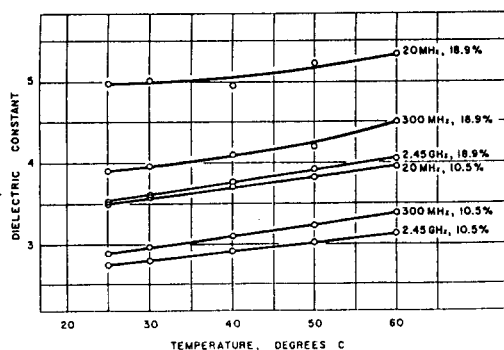
Fig. 7. Temperature dependence of the dielectric constant of shelled, yellow-dent field corn at indicated frequencies and moisture contents (Nelson, 1979).
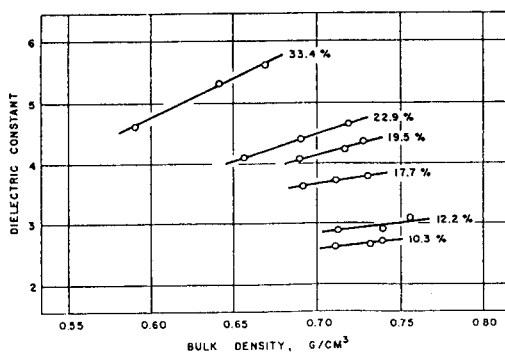
Fig. 8. Dependence of the dielectric constant of shelled, yellow-dent field corn of indicated moisture contents on bulk density at 300 MHz and 24 ℃ (Nelson, 1979).