DIELECTRIC PROPERTIES MEASUREMENT TECHNIQUES 
AND APPLICATIONS

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ABSTRACT. The reasons for interest in the dielectric properties of materials are discussed. Terms are defined and principles involving dielectric properties of materials are summarized. Measurement techniques for determining dielectric properties of agricultural materials in the radio-frequency (RF) and microwave ranges are identified with reference citations given for detailed information. Finally, a few new potential applications for dielectric properties of materials are discussed and a few precautions are given for reliable determination of such properties by RF and microwave measurements.

Keywords. Dielectric properties, Permittivity, Measurements, Agricultural materials.

Dielectric properties of agricultural materials and products are finding increasing application as new technology is adapted for use in agriculture and related industries. The interest in dielectric properties of materials has historically been associated with the design of electrical equipment, where various dielectrics are used for insulating conductors and other components of electrical equipment. During much of the past century, materials research has provided many new dielectric materials for application in electronics. As the use of higher and higher frequencies came into practice, new materials, suitable for use in the radio-frequency, microwave, and millimeter wave regions of the electromagnetic spectrum, have been developed. The dielectric properties of these materials are important in the design of electrical and electronics equipment, and suitable techniques for measuring these properties for various applications have been developed as they were needed.

The interest in the dielectric properties of agricultural materials and products has been principally for describing the behavior of materials when subjected to high-frequency or microwave electric fields for dielectric heating applications and in their use for rapid methods of moisture content determination. The influence of the dielectric properties on the heating of materials by absorption of energy through radio-frequency dielectric heating, whether at high frequencies or microwave frequencies, has been well known for a long time, and many potential applications have been investigated (Brown et al., 1947; Thury, 1992; Roussy and Pearce, 1995; Metaxas and Meredith, 1983). With the advent of commercial microwave heating and the wide acceptance of microwave ovens for the home, the concepts of dielectric heating have become much more widely appreciated.

The use of dielectric properties for measuring moisture content of products such as cereal grains has been recognized for at least 90 years and has been in common use for more than 50 years (Nelson, 1977, 1991). However, the first dielectric properties for grain were not reported until 45 years ago (Nelson et al., 1953; Knipper, 1959). Since then much data and information on the dielectric properties of grain and other agricultural products have become available (Nelson, 1965, 1973a; ASAE Standards, 1998; Tinga and Nelson, 1973; Kent, 1987; Datta et al., 1995), and the influence of important variables on these dielectric properties has been evaluated (Nelson, 1981, 1991; Mudgett, 1995).

With the need for development of new sensing devices for the automation and control of various agricultural processes, there is a need for better understanding of the usefulness of dielectric properties of materials and methods for measuring these properties. Therefore, it is the purpose of this article to briefly summarize some of the measurement techniques with helpful comments and provide information related to some of their applications. Rather than explaining details of the various measurement techniques, readers are referred to appropriate sources for that information.

DEFINITIONS AND PRINCIPLES

The fundamental electrical 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 \( \varepsilon' \) and the dielectric loss factor \( \varepsilon'' \), the real and imaginary parts, respectively, of the relative complex permittivity, \( \varepsilon = \varepsilon' - j\varepsilon'' = |\varepsilon| e^{-j\delta} \), where \( \delta \) is the loss angle of the dielectric. Hereafter in this article, “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, \( \varepsilon_0 = 8.854 \times 10^{-12} \text{ F/m} \). Often,
the loss tangent, \( \tan \delta = \varepsilon''/\varepsilon' \), or dissipation factor, is also used as a descriptive dielectric parameter, and sometimes the power factor (\( \tan \beta / \sqrt{\varepsilon' \tan \delta} \)) is used. The ac conductivity of the dielectric in \( \text{S/m} \) is \( \sigma = \omega \varepsilon_0 \varepsilon'' \), where \( \omega = 2\pi \) is the angular frequency, with frequency \( f \) in Hz. In this article, \( \varepsilon'' \) 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 in \( \text{W/m}^3 \) can be expressed as:

\[
P = E^2 \sigma = 55.63\varepsilon_0 E^2 \varepsilon'' \times 10^{-12} \quad (1)
\]

where \( E \) represents the rms electric field intensity in \( \text{V/m} \). The time rate of temperature increase, \( \frac{dT}{dt} \) in \( ^\circ \text{C/s} \), in the dielectric material caused by the conversion of energy from the electric field to heat in the material is:

\[
\frac{dT}{dt} = P/(c \rho)
\]

(2)

where \( c \) is the specific heat of the material in \( \text{kJ/(kg·°C)} \), and \( \rho \) is its density in \( \text{kg/m}^3 \). 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 equation 1, it is obvious that the power dissipation is directly related to the dielectric loss factor \( \varepsilon'' \); however, it may also be dependent on the dielectric constant \( \varepsilon' \) in that, depending on the geometry and the electric field configuration, the electric field intensity may be a function of \( \varepsilon' \). Two simple examples illustrate this influence of relative \( \varepsilon' \) values. In the RF dielectric heating of a layer of material of permittivity \( \varepsilon_1 \) of uniform thickness \( d_1 \) between parallel-plate electrodes, with an air gap of permittivity \( \varepsilon_2 \) and thickness \( d_2 \) between the material and one electrode, the rms electric field intensity in the material is:

\[
E_1 = \frac{V}{d_1 + d_2} \left( \frac{\varepsilon_1}{\varepsilon_2} \right) \quad (3)
\]

where \( V \) is the rms potential difference between the electrodes. In a second example, a spherical inclusion of permittivity \( \varepsilon_1 \) embedded in an infinite medium of permittivity \( \varepsilon_2 \) will have an electric field intensity in the spherical material of:

\[
E_2 = E_1 \left( \frac{3\varepsilon_1}{2\varepsilon_1 + \varepsilon_2} \right) \quad (4)
\]

(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 equation 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 equation 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 an \( e^{j\omega t} \) dependence, can be given as:

\[
E(z) = E_0 e^{j\omega t - j\beta z} \quad (5)
\]

(von Hippel, 1954) where \( E_0 \) is the rms electric field intensity at a point of reference, \( t \) is time, \( \gamma \) 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,

\[
\gamma = \alpha + j\beta = \frac{2\pi}{\lambda_0} \sqrt{\varepsilon' - 1} \quad (6)
\]

where \( \alpha \) is the attenuation constant, \( \beta \) is the phase constant, and \( \lambda_0 \) is the free-space wavelength. The attenuation constant \( \alpha \) and phase constant \( \beta \) are related to the dielectric properties of the medium as follows (von Hippel, 1954):

\[
\alpha = \frac{2\pi}{\lambda_0} \sqrt{\frac{\varepsilon'}{2} \left( 1 + \tan^2 \delta - 1 \right)} \quad (7)
\]

\[
\beta = \frac{2\pi}{\lambda_0} \sqrt{\frac{\varepsilon'}{2} \left( 1 + \tan^2 \delta + 1 \right)} \quad (8)
\]

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 equations 5 and 6 as follows:

\[
E(z) = E_0 e^{-\alpha z} e^{j(\omega t - \beta z)} \quad (9)
\]

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 \( e^{-1} = 1/2.7183 \) 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/m (dB/m). In terms of power densities and electric field intensity values, this can be expressed as (von Hippel, 1954):

\[
10 \log_{10} \left( \frac{P_0}{P(z)} \right) = 20 \log_{10} \left( \frac{E_0}{E(z)} \right) = 8.686\alpha z \quad (10)
\]

where \( P_0 \) is the incident power, and \( P(z) \) is the power at distance \( z \) into the material.

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

$$\alpha = \frac{8.686 \pi \epsilon''}{\lambda_0 \sqrt{\epsilon'}} \text{ dB/m} \quad (11)$$

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:

$$P_t = P_0 (1 - |\Gamma|^2) \quad (12)$$

where $\Gamma$ 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).

$$\Gamma = \frac{1 - \sqrt{\epsilon}}{1 + \sqrt{\epsilon}} \quad (13)$$

The power density diminishes as an exponential function of the attenuation and distance traveled (eqs. 1 and 9) as the wave propagates through the material:

$$P = P_0 e^{-2 \alpha z} \quad (14)$$

with $\alpha$ expressed in nepers/m. One neper is equivalent to 8.686 dB, so the number of dB/cm 0.08686 times the attenuation in nepers/m.

**MEASUREMENT PRINCIPLES AND TECHNIQUES**

The measurement techniques appropriate for any particular application depend on the frequency of interest, the nature of the dielectric material to be measured, both physically and electrically, and the degree of accuracy required. Many different kinds of instruments can be used, but any measurement instrument that provides reliable determinations of the required electrical parameters involving the unknown material in the frequency range of interest can be considered.

For the radio frequencies, a material can be modeled electrically at any given frequency as a series or parallel equivalent circuit. Therefore, if one can measure the radio-frequency (RF) circuit parameters appropriately, the impedance or admittance for example, the dielectric properties of that material at that particular frequency can be determined from equations that properly relate the way in which the permittivity of the material affects those circuit parameters. The challenge in making accurate dielectric properties or permittivity measurements is in designing the material sample holder for those measurements and adequately modeling the circuit for reliable calculation of the permittivity from the electrical measurements.

Techniques for permittivity, or dielectric properties, measurements in the low-frequency medium-frequency, and high-frequency ranges were reviewed by Field (1954), including the use of various bridges and resonant circuits. Dielectric properties of grain samples were determined from measurements with a precision bridge for audio frequencies from 250 Hz to 20 kHz with samples confined in a coaxial sample holder (Corcoran et al., 1970). At very low frequencies, attention must also be paid to electrode polarization phenomena which can invalidate measurement data, and the frequency below which this affects measurements depends on the nature and conductivity of the materials being measured (Foster and Schwan, 1989; Kuang and Nelson, 1998).

A large amount of dielectric properties data were obtained in the 1- to 50-MHz range on grain and seed samples with a Q-Meter based on a series resonant circuit (Nelson et al., 1953; Nelson, 1965, 1973a, 1979a). Techniques were developed for higher frequency ranges with coaxial sample holders modeled as transmission-line sections with lumped parameters and measured with an RX-Meter for the 50- to 250-MHz range (Jorgensen et al., 1970) and for the 200- to 500-MHz, range measured with an Admittance Meter (Stetson and Nelson, 1970).

Components of the sample holders used in the earlier studies with the RX Meter and Admittance Meter were assembled to provide a shielded open-circuit coaxial sample holder for grain, and a technique was developed for measurements from 100 kHz to 1 GHz with two impedance analyzers and use of proper calibrations and the invariance-of-the-cross-ratio technique (Lawrence et al., 1989). The shielded open-circuit coaxial sample holder was also used by Bussey (1980) and by Jones et al. (1978) for determining dielectric properties of grain with high-frequency bridge measurements from 1 to 200 MHz.

A coaxial sample holder, designed to accommodate flowing grain, was modeled and characterized by full two-port scattering parameter measurements, with the use of several alcohols of known permittivities, and signal flow graph analysis to provide dielectric properties of grain over the range from 25 to 350 MHz (Lawrence et al., 1998).

For measurements at frequencies above those just mentioned, a number of microwave measurement techniques are available. At microwave frequencies, generally about 1 GHz and higher, transmission-line, resonant cavity, and free-space techniques have been useful. Principles and techniques of microwave dielectric properties measurements have been discussed in several reviews (Westphal, 1954; Altschuler, 1963; Redheffer, 1964; Bussey, 1967; Franceschetti, 1967; Baker-Jarvis, 1990). Microwave dielectric properties measurement techniques can be classified as reflection or transmission measurements using resonant or nonresonant systems, with open or closed structures for the sensing of the properties of material samples (Kraszewski, 1980). Closed-structure methods include waveguide and coaxial-line transmission measurements and short-circuited waveguide or coaxial-line reflection measurements. Open-structure techniques include free-space transmission measurements and open-ended coaxial-line or open-ended waveguide measurements. Resonant structures can include either closed resonant cavities or open resonant structures operated as two-port devices for transmission measurements or as one-port devices for reflection measurements.
With the development of suitable equipment for time-domain measurements, techniques were developed for measuring dielectric properties of materials over wide ranges of frequency (Fellner-Feldegg, 1969; Nicolson and Ross, 1970; van Gemert, 1973; Kent, 1975; Kwok et al., 1979; Bellamy et al., 1985). Since modern microwave network analyzers have become available, the methods of obtaining dielectric properties over wide frequency ranges have become even more efficient. Extensive reviews have included methods for both frequency-domain and time-domain techniques (Kaatze and Giese, 1980; Afsar et al., 1986).

Dielectric sample holder design for the specific materials is an important aspect of the measurement technique. The Roberts and von Hippel (1946) short-circuited line technique for dielectric properties measurements provides a suitable method for many materials. For this method, the sample holder can be simply a short section of coaxial-line or rectangular-waveguide with a shorting plate or other short-circuit termination at the end of the line against which the sample rests. This is convenient for particulate samples, because the sample holder, and also the slotted line or slotted section to which the sample holder is connected can be mounted in a vertical orientation so the top surface of the sample can be maintained perpendicular to the axis of wave propagation as required for the measurement. The vertical orientation of the sample holder is also convenient for liquid or particulate materials when the measurements are taken with a network analyzer instead of a slotted line.

Dielectric properties of cereal grains, seed, and powdered or pulverized material have been determined with various microwave measurement systems assembled for such measurements. Twenty-one-mm, 50-Ω coaxial-line systems were used for these measurements at frequencies from 1 to 5.5 GHz (Nelson, 1973b; Nelson et al., 1980, 1989). A 54-mm, 50-Ω coaxial sample holder, designed for minimal reflections from the transition, was used with this same system for measurements on larger-kernel cereals such as corn (Nelson, 1978, 1979b). A rectangular-waveguide X-band system was used to determine dielectric properties of grain and seed samples at 8 to 12 GHz (Nelson, 1972). A rectangular waveguide K-band system was used for measurements on fruit and vegetable samples (Nelson, 1983) and on ground and pulverized materials for measurements at 22 GHz (Nelson et al., 1989; You and Nelson, 1988; Nelson and You, 1989, 1990).

The Roberts and von Hippel method (1946) requires measurements to determine the standing-wave ratios (SWRs) in the line with and without the sample inserted. From the shift of the standing-wave node and changes in node widths related to SWRs, sample length, and waveguide dimensions, etc., ε′ and ε″ can be calculated with suitable computer programs (Nelson et al., 1972, 1974). Similar determinations can be made with a network analyzer or other instrumentation by measurement of the complex reflection coefficient of the empty and filled sample holder.

Computer control of impedance analyzers (Lawrence et al., 1989) and network analyzers (Waters and Brodwin, 1988) has facilitated the automatic measurement of dielectric properties over wide frequency ranges. Special calibration methods have also been developed to eliminate errors caused by unknown reflections in the coaxial-line systems (Kraszewski et al., 1983; Lawrence et al., 1989).

Microwave dielectric properties of wheat and corn have been measured at several frequencies by free-space measurements with a network analyzer and dielectric sample holders with rectangular cross-sections between horn antennas and other types of radiating elements (Kraszewski and Nelson, 1990; Kraszewski et al., 1996, 1997; Trabelsi et al., 1997). Measurement of the complex transmission coefficient, the components of which are attenuation and phase shift, permits the calculation of ε′ and ε″. For free-space permittivity measurements, it is important that an attenuation of about 10 dB through the sample layer be maintained to avoid disturbances resulting from multiple reflections between the sample and the antennas, and the sample size, laterally, must be sufficiently large to avoid problems caused by diffraction at the edges of the sample (Trabelsi et al., 1998).

Open-ended coaxial-line probes have been used successfully for convenient broad-band permittivity measurements (Grant et al., 1989; Blackham and Pollard, 1997) on liquid and semisolid materials of relatively high loss, which includes most food materials. This technique has been used for permittivity measurements on fresh fruits and vegetables (Tran et al., 1984; Nelson et al., 1994a, b, 1995). The technique is subject to errors if there are significant density variations in the material, or if there are air gaps or air bubbles between the end of the coaxial probe and the sample, and the technique is not suitable for determining permittivities of very low-loss materials (Nelson and Bartley, 1997), but it has been used to provide broad-band information on granular and pulverized materials when sample bulk densities were established by auxiliary permittivity measurements (Nelson et al., 1997; Nelson and Bartley, 1997; Nelson et al., 1998).

The choices of measurement technique, equipment, and sample holder design depend upon the dielectric materials to be measured, and the frequency or frequency range of interest. Vector network analyzers are expensive but very versatile and useful if studies are extensive. Scalar network analyzers and impedance analyzers are simpler and less expensive and can be appropriate for some programs. For limited studies, more commonly available microwave laboratory measurement equipment can suffice if suitable sample holders are constructed. When data are required at only one microwave frequency, a resonant cavity technique may be the logical choice (Bussey, 1967; Rzeppecka, 1973). Such cavities can be easily constructed with rectangular waveguide sections or from waveguide flanges and waveguide stock (Kraszewski and Nelson, 1996). Construction of a cylindrical cavity (Risman and Bengtsson, 1971; Li et al., 1981) may be advantageous, depending on the needs. For temperature-dependent studies, a cavity with provision for alternate dielectric properties measurement and microwave heating of the sample for temperature control may be advantageous (Bosisio et al., 1986). At common microwave frequencies, a measurement system can often be assembled from microwave laboratory components and using a short waveguide section with a shorting plate as the sample holder (Nelson, 1972) and an available general computer.
program (Nelson et al., 1972, 1974) for calculation of the dielectric properties.

**Applications for Dielectric Properties**

Many applications for dielectric properties data are evident from the references cited. As stated in the Introduction, the principal needs for information on the dielectric properties of agricultural materials have been their use in explaining the behavior of the materials when exposed to dielectric or microwave heating and their use for rapid sensing of moisture content. These continue to be the major interests. In studying the behavior of foods during microwave heating, the dielectric properties of the food materials and their constituents is critical information (Mudget, 1995; Datta et al., 1995). The dependence of these properties on temperature is also very important in such applications. Dielectric properties over a wide range of frequencies are also useful in describing the dielectric relaxation phenomena in materials (Kuang and Nelson, 1997).

Similarly, in the applications for sensing moisture content in grain and other materials, the dependence of the dielectric properties on other variables, such as temperature and bulk density is important (Nelson, 1981, 1991). Recent studies have revealed potential for determining grain moisture content independent of bulk density and also for determining bulk density from dielectric properties measurements (Kraszewski et al., 1997; Trabelsi and Nelson, 1998), with indications that temperature information may also be extracted from the measured dielectric properties of grain. These are mentioned as potentially new applications for dielectric properties data.

Extension of dielectric properties sensing to the monitoring of moisture content in moving grain (Lawrence et al., 1998; Kraszewski et al., 1997; Trabelsi and Nelson, 1998) promise applications important to improving yield determination on combines and other harvesters for precision farming operations. These techniques are also applicable to control of grain dryers and other grain processing equipment for improving energy use efficiency and improvement of product quality.

Other potential applications include the sensing of product maturity (Nelson et al., 1995). While such possible applications have received little attention, research may well identify other correlations between dielectric properties of products and their condition or suitability for particular uses, which permit rapid sensing for application in automated sorting systems (Schmilovitch et al., 1996) or other processes.

The necessary dielectric properties data for evaluation of potentially new applications can generally be obtained only by careful measurement. Research on some products has produced models that estimate the dielectric properties reasonably well (Mudget, 1995; Datta et al., 1995; Nelson, 1987), but, in general, the needed properties can only be determined accurately by direct measurement under the specified conditions important for the application.

Therefore, the best techniques and equipment for such measurements must be selected and developed. As with any measurements, a good understanding of the principles and techniques is important, and the measurements must always be questioned to be sure that reliable data are being obtained. An analysis of possible errors in determinations resulting from uncertainties in the measurements is generally advisable. Often measurements can be checked by measurements on a few materials for which the dielectric properties are well known. However, such materials are not as plentiful as often desired, especially with dielectric constants and loss factors in the desired ranges similar to those of the materials being studied. Confidence can sometimes be achieved by measurements with two different systems or techniques and comparison of resulting data.

Finally, the use of wide-frequency-range dielectric properties data is expected to offer promise for entirely new applications for which dielectric spectroscopy techniques will provide the necessary tools for evaluation. The application of modern measurement techniques and statistical and computational procedures along with sound principles of dielectric properties measurement may well provide successful new applications that can be implemented.

**References**


