THE MEASUREMENT OF DIELECTRIC PROPERTIES RELATED TO AGRICULTURAL PRODUCTS

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Abstract: The measurement methods relevant for any desired application depend on the nature of the dielectric material to be measured, both physically and electrically, the frequency of interest, and the degree of accuracy required [1]. Microwave measurements and the dielectric properties of materials are finding increasing application as new electro-technology is adapted for use in the agriculture and food processing industries. At MW frequencies, generally about 1 GHz and higher, transmission-line, resonant cavity, and free-space techniques have been commonly used.

1. INTRODUCTION

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 electric equipment. Measurement of the bulk dielectric properties (dielectric constant, dielectric loss factor) is not an end unto itself.

Rather, these properties are an intermediary vehicle for understanding, explaining, and empirically relating certain physico-chemical properties of the test material. Therefore, in this paper, an attempt is made to fully explore the existing knowledge of dielectric properties (complex permittivity), their role, and importance in the agricultural sector, and the concept of various measurement methodologies and their development at microwave frequencies.

Dielectric properties of agricultural products at frequencies from 300 to 3000 MHz dropped appreciably with increasing frequency [13], [17], [20]. The effect of moisture content on the dielectric properties of granular solids was reported at 9.4 GHz [15] over a wide range of temperature and moisture contents. Temperature dependence was not seen for dried solids but increased dramatically at higher moisture contents.

A quantitative model for the coupling of electrical energy in foods by radiative transfer has not yet been found. A variety of propagation models (both theoretical and numerical) has been considered, however these models have not been widely adapted. Methods of measuring the dielectric properties of granular materials at microwave frequencies and the factors affecting the dielectric properties of materials, such as frequency, moisture content, temperature, and bulk density, were reviewed by Nelson [9].

The mechanisms of interaction between grain contents with water and their effects on dielectric behavior and organoleptic quality and the basis for energy coupling and attenuation at microwave frequencies are of particular interest, mainly due to the reason that the interaction of constituents would explain the behavior of a whole food matrix subjected to electro-magnetic fields. This study would be useful for designing and formulating new process development.

2. BASIC MICROWAVE-MATERIAL INTERACTION ASPECTS

When microwaves are directed towards a material, part of the energy is reflected, part is transmitted through the surface and of this latter quantity, part of it is absorbed. The proportions of energy, which fall into these three categories, have been defined in terms of the dielectric properties. The fundamental electrical property through which the interactions are described is the complex relative permittivity of the material, ε^*. It is mathematically expressed as:

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \tag{1}$$

where: ε' = dielectric constant, and
ε'' = dielectric loss factor.

The absolute permittivity of a vacuum, ε_0, is determined by:

$$C_0 \mu_0 \varepsilon_0 = 1 \tag{2}$$

where: C_0 = speed of light, and
μ_0 = magnetic constant.
ε_0 = 8.854 x 10-12 F/m and
μ_0 = 1.26 x 10-6 H/m.

In other media (solid, liquid, and gaseous), the permittivity has higher values and is usually expressed relative to the value in vacuum [12]. The relative permittivity of a material, ε_r, is equal to $\varepsilon_{abs}/\varepsilon_o$, where ε_{abs}, is the absolute permittivity of the material. Materials, which do not contain magnetic components, respond only to the electric field. The penetration depth, d_p is usually defined as the depth into a sample where the microwave power has dropped to 1/e or 36.8% of its transmitted value.
Sometimes, d_p is defined as the distance at which the microwave power has been attenuated to 50% of transmitted power (P_{trans}).

The penetration depth is a function of ε' and ε'':

$$d_p = \frac{\lambda_0 \sqrt{\varepsilon'}}{2\pi\varepsilon''} \tag{3}$$

where: λ_0 is the free space microwave wavelength (for 2450 MHz, λ_0 = 122 mm).

The most common agricultural products have $\varepsilon'' < 25$, which implies a d_p of 6 -10 mm. The dielectric properties of materials dictate, to a large extent, the behavior of the materials when subjected to microwave fields for purposes of heating or drying [21].

3. METHODS OF MEASUREMENT OF DIELECTRIC PROPERTIES

The measurement of dielectric properties has gained importance because it can be used for non-destructive monitoring of specific properties of materials undergoing physical or chemical changes. There are several techniques to measure the dielectric properties of agri-food materials [3], [8], [16], [17]. The choices of measurement equipment and sample holder design depend upon the dielectric materials to be measured, the extent of the research, available equipment, and resources for the studies. A Vector Network Analyzer (VNA) is expensive but very versatile and useful if studies are extensive. Scalar network analyzers and impedance analyzers are relatively less expensive but still too expensive for many programs. For limited studies, more commonly available microwave (MW) laboratory measurement equipment can suffice if suitable sample holders are constructed.

The challenge in making accurate permittivity or dielectric property measurements is in designing of the material sample holder for those measurements and adequately modeling the circuit for reliable calculation of the permittivity from the electrical measurements. At MW frequencies, generally about 1 GHz and higher, transmission-line, resonant cavity, and free-space techniques have been commonly used. Principles and techniques of permittivity measurements have been illustrated [1], [2], [22].

Dielectric property measurement techniques can be categorized as reflection or transmission types using resonant or nonresonant systems, with open or closed structures for sensing of the properties of material samples [6]. Waveguide and coaxial line transmission measurements represent closed structures while the free-space transmission measurements and open-ended coaxial-line systems represent open-structure techniques, respectively. 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 [10].

In the earlier measurements by Roberts and von Hippel [14], the standing wave ratios (SWR's) were required to measure in line with and without the sample inserted. Based on the shift of the standing-wave node and changes in the widths of nodes, related to SWR's, sample length, and waveguide dimensions, etc., ε′ and ε" can be computed with suitable computer programs [11]. Similarly, the complex reflection coefficient of the empty and loaded sample holder can be measured using a network analyzer or other instrumentation, where similar determinations can be made as discussed above.

Microwave dielectric properties of wheat and corn have been reported at several frequencies by free-space measurements with a vector network analyzer. The dielectric sample holders with rectangular cross-sections were placed between the horn antennas and a similar radiating element [18]. The attenuation and phase shift are the two main components of the complex transmission coefficient, which permits the calculation of the dielectric constant (ε′) and dielectric loss factor (ε") of the material under test. It is important that an attenuation of 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 for free-space measurements [19].

3.1. Transmission line technique

Commonly available waveguide test equipment for 2450 MHz is designated WR-284. The dielectric properties can be easily and inexpensively obtained by the transmission line technique, particularly if one utilizes a slotted line and standing-wave indicator [11].

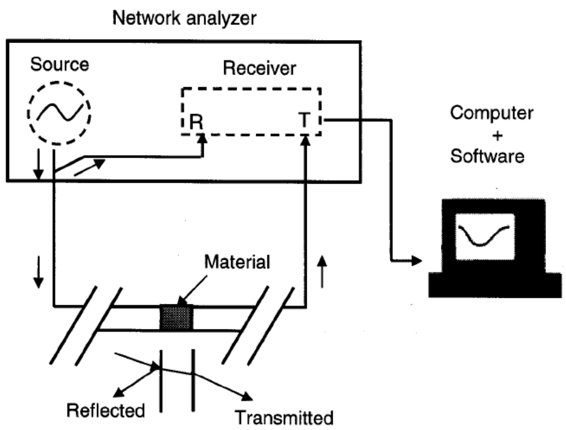

Fig. 1. Schematic of a transmission line – waveguide method (R = reflected power, T = transmitted power)

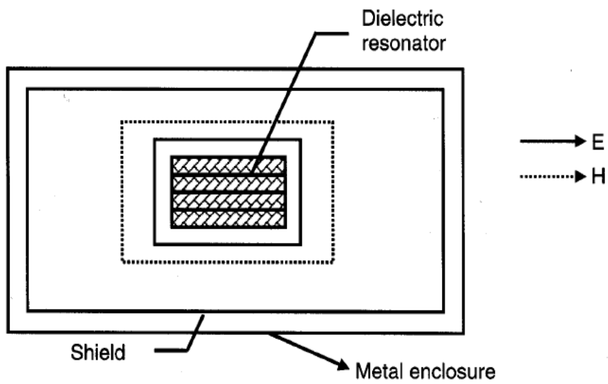

Fig. 2. Schematic of an open cavity (TE013) dielectric resonator (H = magnetic field, E = electric field)

A more sophisticated implementation of the technique utilizes a swept-frequency network analyzer, where the impedance is measured automatically as a function of frequency. Figure 1 represents a typical transmission measuring system using a vector network analyzer.

3.2. Resonators and transmission line

A microwave resonator (as shown in Figure 2), partly or completely filled with a material can also be used to determine permittivity. The resonator (perturbation technique) is usually calibrated with materials whose dielectric properties are known, usually with organic solvents such as methanol, ethanol, etc.

The measurement frequency range is from 50 MHz to more than 100 GHz. If the transmission line is enclosed (i.e., it is a waveguide), the permittivity of a material can also be measured without the resonator by putting it directly inside the waveguide. The method applies to all liquid and solid materials, but not to gases since their permittivity is too low. There are, however, problems with the sample preparation of solid materials. The accuracy is not as good as that of the transmission line with resonator.

In transmission line methods, a sample of the substance is put inside an enclosed transmission line. Both reflection and transmission are measured. Although this method is more accurate and sensitive than the more recent coaxial probe method, it has a narrower range of frequencies. As the substance must fill the cross-section of the transmission line (coaxial or rectangular), sample preparation is also more difficult and time consuming [4], [5]. When such methods are used to determine moisture content, the frequency used should be above 5 GHz to avoid the influence of ionic conductivity and bound water relaxation [7].

For this reason, some studies on dielectric properties and density relationships have been concentrated at high frequencies. However, the size of microwave components is usually proportional to the wavelength and therefore inversely proportional to frequency.

3.3. Free-space transmission techniques

Of the measurement techniques available, free-space techniques are also grouped under non-destructive and contact-less measuring methods. They do not require special sample preparation. Therefore, they are particularly suitable for materials at high temperature and for inhomogeneous dielectrics. In addition, they may be easily implemented in industrial applications for continuous monitoring and control. e.g, moisture content determination and density measurement [6], [7].

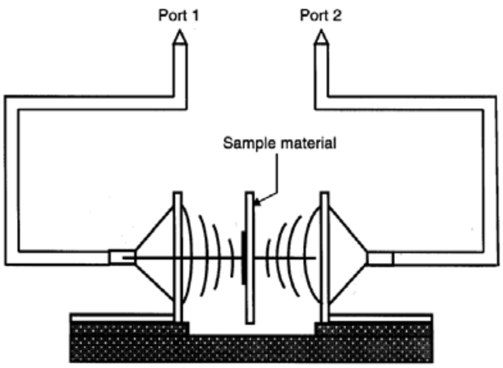

Fig. 3. Schematic of a free-space transmission technique for measuring reflection and transmission (Ports 1 and 2 are connected to the Vector Network Analyzer).

In a free-space transmission technique, a sample is placed between a transmitting antenna and a receiving antenna, and the attenuation and phase shift of the signal are measured. The results of which can be used to translate the material dielectric properties. Accurate measurement of the permittivity over a wide range of frequencies can be achieved by free space techniques. In most systems, the accuracy of ε' and ε'' determined depends mainly on the performance of the measuring system and the validity of the equations used for the calculation. The usual assumption made during this technique is that a uniform plane wave is normally incident on the flat surface of a homogenous material, and that the planar sample has infinite extent laterally, so that diffraction effects at the edges of the sample can be neglected. Figure 3 represents a free space measuring technique with the transmitting and receiving antenna elements.

Trabelsi et al. [18] accounted for multiple reflections, mismatches, and diffraction effects at the edges of the sample as they are generally considered the main sources of errors. To enhance the measurement accuracy, special attention must be paid to the choice of the radiating elements, the design of the sample holder, and the sample geometry and location between the two radiating elements.

4. MATHEMATICAL EXPRESSIONS

This section includes the extracted information from a range of reported literatures, classical text [8]. It is suggested that readers refer to the above resources for complete theoretical derivations of the expressions for dielectric constant and dielectric loss factor. They are indirectly estimated based on measured parameters such as; reflection coefficient, phase and amplitude portion of the signal, change in resonant frequency and Q-factor, attenuation, etc.

There is hardly any information that is available for general formula for all materials, particularly agricultural materials. The authors have comprised this information based on the available information and personal research work in this domain over years.

A transmission dielectric measurement system may take the form of a guided or a free space transmission system depending upon whether the applicator used is a coaxial line or a waveguide or a pair of horn antennas with test material in between. A network analyzer ratios the magnitudes (m) and the phases (p) of the transmitted (Tra) and the reference (Ref) signals to produce the transmission coefficient (T), which is used to calculate the permittivity (ε') of the test material as follows. The following procedure is for a guided transmission system. However the same procedure can beused for the free space transmission system substituting $1/\lambda C_0 = 0$ as the cut-off wavelength, λC_0, for the system becomes infinity. In general, these calculations are programmed in a digital computer to enhance the system speed.

$$\varepsilon' = \left(\frac{\lambda_0}{2\pi}\right)^2 \left[\left(\frac{2\pi}{\lambda_c}\right)^2 - \left(\alpha^2 - \beta^2\right)\right] \tag{4}$$

$$\varepsilon'' = \left(\frac{\lambda_0}{2\pi}\right)^2 \left(2\alpha\beta\right) \tag{5}$$

The unknowns α and β are calculated using equation 6, which is a function of α and β for *T*, a measured quantity, and other parameters are given by equations 7 – 11. Equation 6, gives the transmission coefficient.

$$T = \frac{\left(1 - \Gamma^2\right)\exp\left(-\gamma L\right)}{1 - \Gamma^2 \exp\left(-2\gamma L\right)} \tag{6}$$

where: L = sample length,
γ = propagation coefficient given by equation (7), and
Γ = reflection coefficient given by equation (8)

$$\gamma = \alpha + j\beta \tag{7}$$

$$\Gamma = \frac{Z - Z_0}{Z + Z_0} \tag{8}$$

In equation (7), α and β, respectively, represent the attenuation and the phase change coefficients of the applicator with test material, and Z and Z_0 in equation (8) are, respectively, the characteristic impedances of the applicator with and without the test material, and are given by:

$$Z = \frac{j\varpi\mu_0}{\gamma} = \frac{2\pi\eta_0}{\lambda_0}\frac{\beta\left(1 + j\frac{\alpha}{\beta}\right)}{\alpha^2 + \beta^2} \tag{9}$$

$$Z_0 = \frac{j\varpi\mu_0}{\gamma_0} = \frac{2\pi\eta_0}{\lambda_0\beta_0} \tag{10}$$

$$\beta_0 = \frac{2\pi}{\lambda_0}\sqrt{1 - \left(\frac{\lambda_0}{\lambda_c}\right)^2} \tag{11}$$

where: μ_0=air permeability of air-filled applicator,
η_0=air intrinsic impedance of air-filled applicator,
γ_0=propagation coefficient of air-filled applicator,
β_0=phase change coefficient of air-filled applicator.

5. CONCLUSIONS

Domestic microwave ovens operate at 2450 MHz. However, a large commercial oven might be destined to operate at any of the other approved ISM frequencies, which could give gains in cost efficiency, processing time, or product quality. A key factor in such a choice is the overall permittivity of the product being processed. Dielectric measurements and computer modeling can help to choose the optimum frequency.

Researchers need to understand microwave performance and optimize product design instead of using expensive "trial and error" guesswork. Dielectric measurements also have uses in package design, process control, and physical/chemical analysis.

Any measuring system needs improvement and accuracy considerations. The need, suitability and operating conditions all play a dominant role in evaluating the performance of such systems. Selection and design of sample holder, nature of material under test, experimental conditions, and the degree of accuracy expected, instrumentation capabilities, and interpretation tools all govern the choice of the complete measurement system. Not all materials can be tested by one single method at all conditions since the intended application and usefulness of measured properties are important to be considered. Applications range from moisture sensing, modeling dielectric properties with process variables (temperature, frequency, bulk density, composition, particle size and shape, etc.), design of microwave heating applicators, and so on. Since biological materials are transient in nature, it is difficult to standardize the tools for dielectric measurements; however, applying proper calibration and mathematical routines one can minimize errors and generate useful information on the material under test. The following section deals with some of the recent developments in the permittivity measurement domain. The details can be obtained by referring to cited literature. The authors of this paper have attempted to compare different measuring techniques based on selected criteria, since there is no literature reported on general and qualitative/quantitative aspects. Table 1 shows a general comparison of the microwave dielectric measurement systems based on collective information available in the literature and the authors' own experiences in this field.

Tabel 1. A general comparison of the microwave dielectric measurement systems [10]

	Slotted line reflection system	Guided wave transmission system	Free space transmission system	Filled cavity resonance system	Partial filled cavity resonance system	Probe reflection system
Frequency	Broad band	Banded	Banded	Single	Single	Broad band
Sample size	Moderate	Moderate	Large	Large	Very small	Small
Temperature control	Difficult	Difficult	Very easy	Very easy	Very easy	Easy
Accuracy for: Low-loss material High-loss material	 Very low Low	 Moderate Moderate	 Moderate Moderate	 Very high Does not work	 High Low	 Low High
Sample preparation	Easy	Difficult	Easy	Very difficult	Very difficult	Easy
Tested material	Solids, softs	Solid, soft	Large flat sheets	Solids, softs, liquids	Solids	Solids, softs, liquids
Measured parameter	Permittivity	Permittivity, permeability	Permittivity, permeability	Permittivity, permeability	Permittivity, permeability	Permittivity,
To test material	Destructive	Destructive	Non-destructive	Destructive	Destructive	Non-destructive
Commercial vendors	No	Yes	Yes	No	No	Yes

There are other uses for dielectric properties measurements (not related to microwave heating of food) that can be of interest to agri-food researchers. Some of them are [10]:

- An important use of the dielectric properties of grain and other agricultural products in their exploitation for rapid, nondestructive sensing of moisture in materials.
- More recently, techniques have been studied for sensing the moisture content of single grain kernels, seeds, nuts, and fruits so that instruments for measuring the moisture content of individual objects can be developed.

Techniques for the measurement of dielectric properties of agri-food materials are many and varied. The choices of measurement equipment and sample holder design depend upon the dielectric materials to be measured. Dielectric sample holder design for the particular materials of interest is an important aspect for the measurement method. The importance of understanding the interaction of material subjected to electro-magnetic fields is addressed. Continued research and development are aimed at providing tools for better management of factors important in sensing, preserving, processing, and maintaining the quality of agricultural and food materials for ever growing consumer expectations.

REFERENCES

[1] Altschuler, H.M. (1963), *Dielectric constant*. Handbook of Microwave Measurements, eds. M. Sucher and J. Fox, 530- 536. New York, NY: Brooklyn Polytechnic Press.
[2] Bussey, H.E. (1967), *Measurement of RF properties of materials - A survey.* Proceedings of IEEE Conference 55(6), pp. 1046- 1053.
[3] de Loor, G.P. and F.W. Meijboom. (1966), *The dielectric constant of foods and other materials with high water contents at microwave frequencies.* Journal of Food Technology 1, pp. 313-322.
[4] Engelder, S.E. and C.R. Buffler. (1991), *Measuring dielectric properties of food products at microwave frequencies*. Microwave World 12(2), pp. 6-15.

[5] HP. (1992). *Dielectric probe kit 85070A*. Palo Alto, CA: Research and Development Unit, Test and Measurements Laboratories, Hewlett Packard Corporation.
[6] Kraszewski, A.W. (1980). *Microwave aquametry - A review.* Journal of Microwave Power 15(4), pp. 209-220.
[7] Kraszewski, A. (1996), *Microwave Aquametry – Electromagnetic Interaction with Water Containing Materials.* Piscataway, NJ: IEEE Press.
[8] Maghiar T., Şoproni D., (2003), *Tehnica încălzirii cu microunde*, Editura Universității din Oradea
[9] Nelson, S.O. (1994), *Measurement of microwave dielectric properties of particulate materials.* Journal of Food Engineering 21(3), pp. 365-384.
[10] Nelson, S.O. (1998), *Dielectric properties measuring techniques and applications.* ASAE Paper No. 983067. St. Joseph, MI: ASAE.
[11] Nelson, S.O., L.E. Stetson and C.W. Schlaphoff. (1974), *A general computer program for precise calculation of dielectric properties from short-circuited wave-guide measurements.* IEEE Transactions of Instrumentation and Measurement 23(4), pp. 455-460.
[12] Nyfors, E. and P. Vainikainen. 1989. *Industrial Microwave Sensors*, chapter 2. Boston, MA: Artech House, Norwood.
[13] Pace, W.E., W.B. Westphal and S.A. Goldblith. (1968), *Dielectric properties of commercial cooking oils. Journal of Food Scienc*e 33: 30-36.
[14] Roberts, S. and A. von Hippel. 1946. *A new method for measuring dielectric constant and loss in the range of centimetre waves.* Journal of Applied Physics 17, pp. 610-616.
[15] Stuchly, M.A. and S.S. Stuchly. 1980. *Dielectric properties of biological substances - Tabulated.* Journal of Microwave Power 15, pp. 19-26.
[16] Sucher, M. and J. Fox. (1963), *Handbook of Microwave Measurements.* New York, NY: Polytechnic Press Institute.
[17] Thompson, D.R. and G.L. Zachariah. (1971), *Dielectric theory and bioelectrical measurements [Part II. Experimental (Apples)]*. Transactions of ASAE 14(2), pp. 214-215.
[18] Trabelsi, S., A.W. Kraszewski and S.O. Nelson. (1997), *A new density-independent function for microwave moisture content determination in particulate materials.* Proceedings of IEEE Instrumentation and Measurement Technology Conference.
[19] Trabelsi, S., A.W. Kraszewski and S.O. Nelson. (1998), *Nondestructive microwave characterization for bulk density and moisture content determination in shelled corn.* Measurement Science and Technology 9, pp. 570-578.
[20] Tran, V.N., S.S. Stuchly and A.W. Kraszewski. (1984), *Dielectric properties of selected vegetables and fruits at 0.1 - 10 GHz.* Journal of Microwave Power 19(4), pp. 251-258.
[21] Venkatesh, M.S. and G.S.V. Raghavan. (2004), *An overview of microwave processing and dielectric properties of agri-food materials.* Biosystems Engineering 88(1), pp. 1-18.
[22] Westphal, W.B. (1954), *Distributed circuits, permittivity and dielectric properties measuring techniques.* In Dielectric Materials and Applications, ed. A. von Hippel, 22-35. New York, NY: John Wiley and Sons.