The importance of dielectric properties of food materials is discussed with respect to their influence on the heating of materials by radio-frequency and microwave energy and their use for rapid, nondestructive sensing of quality characteristics of such materials. Data are presented graphically showing the frequency and temperature dependence of the dielectric constant and loss factor of wheat, fresh chicken breast meat, several fresh fruits, and apple juice, representing food materials with a wide range of moisture content. The influence of moisture or water content on the dielectric behavior of these materials is discussed, and that behavior is explained in terms of dipolar relaxation and ionic conduction.

**INTRODUCTION**

Although moisture or water content is important in foods for many reasons, it is also the dominant factor affecting the dielectric properties of foods and their interaction with radio-frequency (RF) and microwave electric fields. The dielectric behavior of foods when exposed to such fields, with respect to dependence on frequency and temperature, is also highly influenced by moisture content and the degree of water binding with constituents of the food materials.

Knowledge of the dielectric properties of food materials became increasingly important as applications of RF and microwave heating developed for food preparation. Since the dielectric properties of materials determine their absorption of energy from the electric fields and also the electric field distributions in the materials, these properties, along with thermal properties, are important in understanding the behavior of such materials when exposed to RF and microwave electromagnetic fields. The fundamental relationship between power absorption and important variables is expressed as

\[ P = \sigma E^2 = 55.63 \times 10^{-12} f \varepsilon^* E^2 \]  

(1)

where \( P \) is the power dissipated per unit volume (W/m\(^3\)), \( E \) is the rms electric field intensity in the material (V/m), \( \sigma = \omega \varepsilon_0 \varepsilon^* \) is the electric conductivity (S/m), where \( \omega = 2\pi f \) is the angular frequency, with frequency \( f \) in Hz, \( \varepsilon_0 = 8.854 \times 10^{-12} \) is the permittivity of free space (F/m), and \( \varepsilon^* \) is the dielectric loss factor, the imaginary part of the complex relative permittivity \( \varepsilon = \varepsilon' - j\varepsilon'^* \), where the real part \( \varepsilon' \) is the dielectric constant of the material. These properties have previously been defined and discussed in more detail, both from the viewpoint of electrical circuits [Nelson, 1965] and electromagnetic fields [Nelson, 1973]. The influence of the dielectric properties...
on the distribution of electric field intensity in materials has also been discussed previously [Nelson, 1996].

Another reason for interest in the dielectric properties of food materials is their usefulness in sensing certain quality characteristics. RF electric fields can penetrate such materials readily, and therefore, if their interaction with the interior of the food products can be correlated with quality characteristics of interest, rapid, nondestructive techniques can be developed for such quality measurements. Measurement of moisture content in grain and seed by electronic moisture meters is one well-established application [Nelson, 1977; Nelson, 1991; Nelson, 2006]. New microwave techniques have been and continue to be explored for improving such measurements of moisture content and bulk density as well [Kraszewski et al., 1997; Kraszewski, 1988; Trabelsi et al., 1998; Trabelsi et al., 1999; Trabelsi and Nelson, 2007; Trabelsi and Nelson, 2008]. Potential sensing of quality in fruits and vegetables has been considered [Guo et al., 2007a; Guo et al., 2007b; Nelson, 1980; Nelson, 2003; Nelson et al., 1995; Nelson et al., 2007b]. Permittivities of other food products, including poultry meat and scallops [Kent and Anderson, 1996], pork products [Kent et al., 2002], fish [Kent et al., 2007], fresh chicken breast meat [Zhuang et al., 2007] and chicken eggs [Guo et al., 2007c], have also been explored [Nelson, 2008]. New techniques for interpreting dielectric properties data for application to quality sensing have also been investigated [Nelson, 2006; Nigmatullin et al., 2006; Nigmatullin and Nelson, 2006a; Nigmatullin and Nelson, 2006b].

Considerable research on the dielectric properties of food materials has been reported in the literature. Principles, with respect to variation of dielectric properties with frequency, temperature, and constituents of foods have been reviewed [Mudgett, 1995; Nelson and Datta, 2001], and dielectric properties have been tabulated [Datta et al., 1995; Nelson, 1973; Tinga and Nelson, 1973], and presented graphically for many types of food materials [Nelson and Datta, 2001].

This paper deals with the dielectric behavior of certain food materials with a wide range of moisture contents and the influence of moisture content on the dielectric behavior of those food materials.

**Dielectric Properties Measurements**

The electrical measurements on these food materials necessary for dielectric properties determination were obtained with a Hewlett-Packard 85070B open-ended coaxial-line probe, a Hewlett-Packard 4291A Impedance/Material Analyzer for the 10-MHz to 1.8-GHz range, and a Hewlett-Packard 8510C Network Analyzer for the 200-MHz to 20-GHz range. A temperature-controlled stainless steel sample cup and water jacket assembly, designed and built for use with the 85070B probe [Nelson et al., 1997], was used to provide temperature control for the samples. Permittivities (dielectric constants and loss factors) were calculated with Agilent Technologies 85070D Dielectric Probe Kit Software, modified for use with the HP 4291A Analyzer by Innovative Measurement Solutions, and used directly with the HP 8510C Analyzer. This software provided permittivity values from the reflection coefficient of the material in contact with the active tip of the probe [Blackham and Pollard, 1997]. Typical measurement accuracies of 5% are specified by the manufacturer for this method.

For further information on the equipment used, sample preparation, physical measurements, and the procedures followed, the reader is referred to earlier publications, where detailed descriptions are provided. [Guo et al., 2007a; Nelson, 2003; Nelson et al., 2007b; Nelson and Trabelsi, 2006; Nelson et al., 2008; Zhuang et al., 2007]. All moisture contents were determined by oven-drying methods following standard procedures with specified oven temperatures and drying times and with samples held in desiccators to cool before reweighing to determine moisture content.

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1Mention of company or trade names is for purpose of description only and does not imply endorsement by the U. S. Department of Agriculture.
Dielectric Properties Data

Figure 1. Frequency dependence of the dielectric properties of ground hard red winter wheat of 11.2% moisture content at indicated temperatures over the frequency range from 10 MHz to 1.8 GHz [Nelson and Trabelsi, 2006].

Figure 2. Frequency dependence of the dielectric properties of ground hard red winter wheat of 25.0% moisture content at indicated temperatures over the frequency range from 10 MHz to 1.8 GHz [Nelson and Trabelsi, 2006].

on a wet basis. Foods may contain both free and various forms of bound water. Fresh fruit and vegetable tissues have high moisture contents and significant amounts of unbound water, whereas water in grain at common moisture contents is most likely all bound water.

Dielectric Properties Data

To best illustrate the dielectric behavior of various food materials with respect to dependence on frequency and temperature as influenced by moisture content, data are presented graphically. In Figures 1 and 2, the dielectric constants and loss factors of hard red winter wheat are presented for two different moisture contents, 11.2% and 25.0%, wet basis, from 10 MHz to 1.8 GHz. Because of the relatively large dimensions of wheat kernels (ca. 6 by 3 mm) compared to the 3-mm diameter open-ended coaxial-line probe used for the permittivity measurements, samples were ground to provide a more homogeneous sample [Nelson and Trabelsi, 2006]. However, dielectric properties of whole-kernel and ground wheat of the same bulk density are very similar [Nelson, 1984], so the results shown are illustrative of wheat permittivity at a density of about 0.8 g/cm³. Trends in the behavior of the wheat dielectric properties at the two different
moisture contents are similar in that both decrease consistently with increasing frequency. However, the values of both the dielectric constant and loss factor are much greater for the wheat at 25% moisture than at 11.2% moisture content. Both the dielectric constant and the loss factor also increase consistently with increasing temperature.

Results of dielectric properties measurements on fresh chicken breast meat over the frequency range from 10 MHz to 1.8 GHz at temperatures from 5 to 65 °C are shown in Figure 3 [Nelson et al., 2007c; Zhuang et al., 2007]. Behavior of both the dielectric constant and loss factor is similar to that for wheat, with respect to frequency, in that they decrease consistently with increasing frequency. However, the properties for fresh chicken breast meat are much greater than the corresponding values for wheat, even at the 25% moisture level. The moisture content of the meat was 76%, which is also much greater than that of the wheat. In addition, there is a reversal of the temperature coefficient of the dielectric constant as frequency increases, which was not noted in the dielectric behavior of wheat. Below about 200 MHz, the temperature coefficient is positive for the dielectric constant, but it changes to negative at the higher frequencies.

Dielectric properties of a fresh fruit of similar moisture content, 74%, are shown in Figure 4 for banana over the same frequency range at temperatures from 5 to 65 °C [Nelson, 2003]. The behavior of the dielectric properties of banana are
similar to that of the chicken breast meat, with dielectric constants of about the same magnitude. However, the dielectric loss factor values for banana are considerably less than those of the chicken breast meat. Also, the frequency where temperature dependence disappears for the dielectric constant is about 50 MHz compared to 200 MHz for the meat.

For fresh fruit tissue of apples, with 85% moisture content, the dielectric properties over the same frequency and temperature ranges are shown in Figure 5 [Nelson, 2003]. Here, both the dielectric constant and loss factor have lower values than corresponding values for banana or chicken breast meat. The point of change in the sign of the temperature coefficient for the dielectric constant is a little above 20 MHz.

Dielectric properties of fresh cantaloupe tissue of 87% moisture content over the same frequency and temperature ranges are presented in Figure 6 [Nelson, 2003]. Here the dielectric constants are greater than either those of apple or banana, but the loss factor values for the cantaloupe are intermediate between those of apple and banana at corresponding frequencies and temperatures. The temperature coefficient for the dielectric constant changes sign at about 70 MHz.

For navel orange tissue of 89% moisture content, dielectric constants and loss factors over the same frequency and temperature ranges are shown in Figure 7 [Nelson, 2003]. Dielectric
constants of fresh orange tissue are somewhat less than those of cantaloupe, but greater than those of apple and only a little larger than those of banana tissue. The frequency of zero temperature dependence for the orange tissue dielectric constant is also about 50 MHz like that of the banana tissue.

Dielectric properties of cantaloupe of 87% moisture content at 24 °C, over the frequency range from 200 MHz to 20 GHz, are shown in Figure 8 [Nelson et al., 2008], where scales are such that the dielectric constant and loss factor can be presented on the same graph. Here, the dielectric constant decreases consistently with increasing frequency, but the loss factor decreases with frequency to a minimum between 1 and 2 GHz, and then increases to a maximum somewhat below 20 GHz.

The dielectric properties of honeydew melon and watermelon at 24 °C, both of 90% moisture content, over the same 200-MHz to 20-GHz frequency range, are presented in Figures 9 and 10 [Nelson et al., 2008]. Both the dielectric constants and loss factors of the three types of melons (Figures 8 – 10) are quite similar. They have similar values for the three melons and exhibit similar frequency dependence.

The sugar content of the various fresh fruit tissues was determined by measurement of the total soluble solids content of juices expressed from the tissues, but those data are not presented in this paper, because correlations between dielectric properties and soluble solids content were very low [Guo et al., 2007a; Nelson, 2003; Nelson, 2005; Nelson et al., 2007a; Nelson et al., 2007b]. Some of these studies were made to learn whether a correlation between dielectric properties and soluble solids content might exist that could be useful for nondestructive sensing of sweetness in melons. Even though soluble solids content, which is mostly sugars in fruits, ranged from about 4% to about 14%, no useful correlations were identified, and the influence of these amounts of sugar on the dielectric relaxation observed was negligible [Guo et al., 2007a; Nelson et al., 2008].

Finally, the dielectric properties of apple juice are presented for the frequency range from 200 MHz to 20 GHz in Figure 11, where the influence of temperature change is also shown. For the dielectric constant, the reversal of the sign of the temperature coefficient appears slightly below 20 GHz and in this instance that change of temperature-coefficient sign for the loss factor appears at about 800 MHz.

**DISCUSSION AND CONCLUSION**

Considering all of the dielectric properties data presented and their behavior with respect to moisture content of the different food products, several general observations can be noted.
Figure 8. Frequency dependence of the permittivity of fresh cantaloupe at 24 °C, moisture content: 87% [Nelson et al., 2008]

Figure 9. Frequency dependence of fresh honeydew melon permittivity at 24 °C, moisture content: 90% [Nelson et al., 2008].

Figure 10. Frequency dependence of fresh watermelon permittivity at 24 °C, moisture content: 90% [Nelson et al., 2008].
The dielectric constant always decreases with increasing frequency. For wheat below 25% moisture content, the dielectric constant and loss factor both increase with increasing temperature in the frequency range from 10 to 1800 MHz. For other food materials, such as fresh chicken breast meat and fresh fruits, with moisture contents above about 70%, the dielectric constant increases with temperature at frequencies below about 20 MHz, but at some point in the range between 20 MHz and 200 MHz, the temperature coefficient of the dielectric constant changes sign and the dielectric constant decreases with increasing temperature at higher frequencies. At frequencies below about 1 GHz, the dielectric loss factor appears to increase consistently with increasing temperature.

With respect to the reversal of the dielectric-constant temperature coefficient in the frequency range between 20 and 200 MHz, this phenomenon can be explained by the dominance of one of two dielectric loss mechanisms operating in these food materials. At lower frequencies, the large values for the dielectric properties are accounted for by the polarization and loss associated with ionic mechanisms. These mechanisms diminish as frequency increases, and above the point of temperature independence for the dielectric constant, the polarization and loss associated with dipole orientation becomes dominant. The dielectric behavior of pure liquid water at 25 °C, as shown in Figure 12 [Nelson and Trabelsi, 2008; Nelson et al., 2008], is illustrative of dielectric dipole relaxation, whereas the influence of ionic conduction on dielectric behavior is evident at the lower frequencies in all of the other graphic data illustrated in this paper for food materials.

The influence of free liquid water on the dielectric behavior of the fresh melon tissues is also clearly shown in comparing that of pure liquid water (Figure 12) with those of the melons in Figures 8 – 10. Free water at 25 °C exhibits a dipole relaxation centered at 19.24 GHz [Kaatze, 1989]. The dielectric behavior of the melon tissues is also influenced by chemically bound water and ions in solution at the lower frequencies. Whereas the losses for pure water decrease monotonically at both frequencies above and below the relaxation frequency (19.24 GHz for pure water at 25 °C) as shown in figure 12 for frequencies below 19 GHz, the loss factors for the melon tissues decrease below the relaxation frequency to a minimum between 1 and 2 GHz and then increase due to ionic conduction as frequency continues to decrease.

The influence of free water is also evident in the dielectric behavior of apple juice as shown in Figure 11. In this instance, the peak of the relaxation curve just below 20 GHz is clearly noted in the dielectric loss factor at 10 °C. At higher temperatures, the relaxation frequency
shifts to higher frequencies beyond the 20-GHz limit shown in Figure 11, with consequent decreases in both the dielectric constant and loss factor with increasing temperature. At lower frequencies, the dielectric constant decreases with increasing temperature, as does the dielectric constant of pure water [Kaatze, 1989], and the loss factor increases with increasing temperature owing to the influence of temperature on ionic conduction. In Figure 5 for fresh apple tissue and in Figure 7 for fresh orange tissue, there is a hint of temperature coefficient reversal for the dielectric loss factor at frequencies a bit below 20 GHz. This is also explained by the approach to the dielectric relaxation region as frequencies increase above 20 GHz.

Thus, the dielectric behavior of the food materials illustrated in this paper, and other foods as well, are highly influenced by their water content. For those foods with very high water content, the influence of free liquid water is dominant, but bound water also exerts some influence. For lower moisture content food materials, the influence of bound water is important in addition to the composition of the materials, and ions in solution have an important role in determining the dielectric behavior of food materials, particularly at lower frequencies.

REFERENCES


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