DIELECTRIC SPECTROSCOPY MEASUREMENTS ON FRUIT, MEAT, AND GRAIN

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ABSTRACT. *Dielectric spectroscopy data measured for several fresh fruits, fresh chicken breast, and hard red winter wheat are presented, and the dielectric behavior is discussed with respect to important variables. A brief review of reported measurements on these materials and description of the methods of measurement are included. Frequency ranges for the data are 10 MHz to 1.8 GHz and 200 MHz to 20 GHz. Variation of the dielectric constant and loss factor with frequency and temperature are shown graphically, and the influences of dipolar relaxation and ionic conduction are discussed.*

Keywords. *Dielectric constant, Dielectric properties, Dielectric spectroscopy, Fruit, Loss factor, Meat, Microwaves, Permittivity, Radio frequencies, Wheat.*

Spectroscopy is the analytical study of electromagnetic spectra, including the visible spectrum, ultraviolet and infrared radiation, and all other portions of the electromagnetic spectrum as well. Dielectric properties of materials are important in determining how electromagnetic energy in the radio-frequency and microwave range interacts with materials, and study of their dependence on wavelength or frequency is termed dielectric spectroscopy.

In this article, the term "permittivity" implies the relative complex permittivity, i.e., the permittivity of a material relative to free space, often called the complex dielectric constant, which is expressed as $\varepsilon = \varepsilon' - j\varepsilon''$, where ε' is the dielectric constant and ε'' is the dielectric loss factor. The dielectric constant is associated with the capability for energy storage in the electric field in the material, and the loss factor is associated with energy dissipation in the material or the conversion from electric energy to heat energy. Here, all loss mechanisms, both those due to dipole relaxation and ionic conduction, are included in the dielectric loss factor ε''.

With regard to agricultural products and materials, interest in dielectric properties has been associated with a variety of applications (Nelson, 1991). These have included the sensing of moisture content in grain (Nelson, 1977); radio-frequency and microwave dielectric heating for pest control (Nelson, 1996a, 1996b; Ikediala et al., 2000), seed treatment (Nelson and Stetson, 1985), and product conditioning (Nelson, 1981; Pour-El et al., 1981; Senter et al., 1984); remote sensing of crop condition (Ulaby and Jedlicka, 1982); and potential uses for quality measurements other than moisture content (Nelson, 1980; Nelson et al., 1995).

In connection with quality sensing in fruits, the dielectric properties of mature-green and full-ripe peaches at 2.45 GHz were examined to see whether these properties might be useful in distinguishing degree of maturity (Nelson, 1980). Permittivity measurements at the single frequency, 2.45 GHz, did not offer promise for detecting maturity. Following permittivity characterization measurements for 23 kinds of common fresh fruits and vegetables over the frequency range from 200 MHz to 20 GHz at 23°C (Nelson et al., 1994a, 1994b), similar measurements were taken over a narrow range of peach maturity, and evidence for possible distinction of maturity degree was obtained (Nelson et al., 1995).

Measurements obtained in a study to explore the frequency and temperature dependence of the dielectric properties of a few kinds of fruits and vegetables were reported for a temperature range from 5°C to 95°C (Nelson, 2003). Dielectric spectroscopy measurements over the same frequency range, 10 MHz to 1.8 GHz, were taken on honeydew melons to learn whether the data might be useful for sensing melon quality as determined by soluble solids content (SSC) or sweetness (Nelson et al., 2006). A high correlation between dielectric constant and loss factor, each divided by SSC, was observed when plotted in the complex plane, but the correlation was not found useful for predicting SSC (Guo et al., 2007). Similar measurements on watermelons over the same frequency range showed low correlations between dielectric properties and SSC (Nelson et al., 2007a). More recently, dielectric spectroscopy measurements on cantaloupe, honeydew melons, and watermelons over the frequency range from 200 MHz to 20 GHz did not reveal any obvious correlations that might be useful for sensing sweetness (Nelson et al., 2008).

Dielectric spectroscopy measurements from 10 MHz to 1.8 GHz on fresh chicken breast meat showed some potential for quality sensing, but further research is needed to better assess that potential (Nelson et al., 2007b; Zhuang et al., 2007). Variation of dielectric properties with temperature from 5°C to 85°C and dependence on other variables was noted.

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Dielectric spectroscopy measurements were reported on ground samples of hard red winter wheat of 11% to 25% moisture content at temperatures from 5°C to 95°C over the frequency range from 10 MHz to 1.8 GHz (Nelson and Trabelsi, 2006). In general, both the dielectric constant and loss factor decreased with increasing frequency and increased with increasing moisture content and temperature.

The purpose of this article is to present some typical data obtained by dielectric spectroscopy measurements on fruit, meat, and wheat with a discussion of the dependence of the dielectric properties on important variables.

Dielectric Spectroscopy Measurements

The electrical measurements necessary for permittivity 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). 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 (Nelson, 2003; Nelson and Trabelsi, 2006; Nelson et al., 2007a; Zhuang et al., 2007; Nelson et al., 2008).

Dielectric Spectroscopy Data

Typical permittivity (dielectric properties) data for a selection of different fruits are presented in figures 1 to 7. These data are from measurements taken on core samples of the edible internal tissue of the fruits. For detailed information on the measurements and the descriptions of the fruits, the reader is referred to the references cited in the captions of each figure. Only the tissue moisture contents, determined by oven-drying samples for 16 h at 100°C and calculation on the wet weight basis, are presented in the captions for each figure.

In figures 1 to 4, the variations of the dielectric constant and loss factor are shown for temperatures from 5°C to 65°C over the frequency range from 10 MHz to 1.8 GHz for apple, orange, banana, and cantaloupe. In this frequency range, the dielectric constant and loss factor both decrease monotonically with increasing frequency. Because of the presence of free ions and ionic conduction in these high-moisture-content tissues, both the dielectric constant and loss factor have very high values at the lower frequencies. They decrease in value as the frequency increases, and reveal the influence of dipolar polarization and losses at the higher frequencies. Somewhere in the frequency range between 20 and 80 MHz, the temperature coefficient for the dielectric constant of these four fruits changes from positive to negative, revealing a zero-temperature dependence at that particular frequency for each particular fruit. This point can also be considered as the frequency below which ionic conduction is dominant and above which dipolar processes become the dominant factor.

It is interesting to note that banana tissue (fig. 3), with 74% moisture content, has higher values for the dielectric constant and loss factor than some of the other fruit tissues with much higher moisture contents, about 90%. One usually expects the higher moisture tissues to have higher values for the dielectric properties, but it is clear that other factors also influence the dielectric behavior.

Dielectric spectroscopy data for the 200-MHz to 20-GHz range are shown for cantaloupe, honeydew melon, and watermelon in figures 5 to 7. In this frequency range, the influence of ionic conduction is evident at the lower frequencies, and the influence of water on the dipolar relaxation is obvious at the higher frequencies. At 24°C, pure liquid water has a relaxation frequency of about 19 GHZ (Kaatze, 1989), and the relaxation frequency, where the loss factor peaks in figures 5 to 7, is clearly evident in the region between 10 and 20 GHz.

Dielectric properties data for fresh chicken breast meat are shown in figure 8, where the dielectric behavior appears similar to that of the fruit tissues. However, the meat tissue has somewhat lower moisture content (76%) and generally higher loss factor values at low frequencies. The frequency of zero-temperature dependence for the dielectric constant of

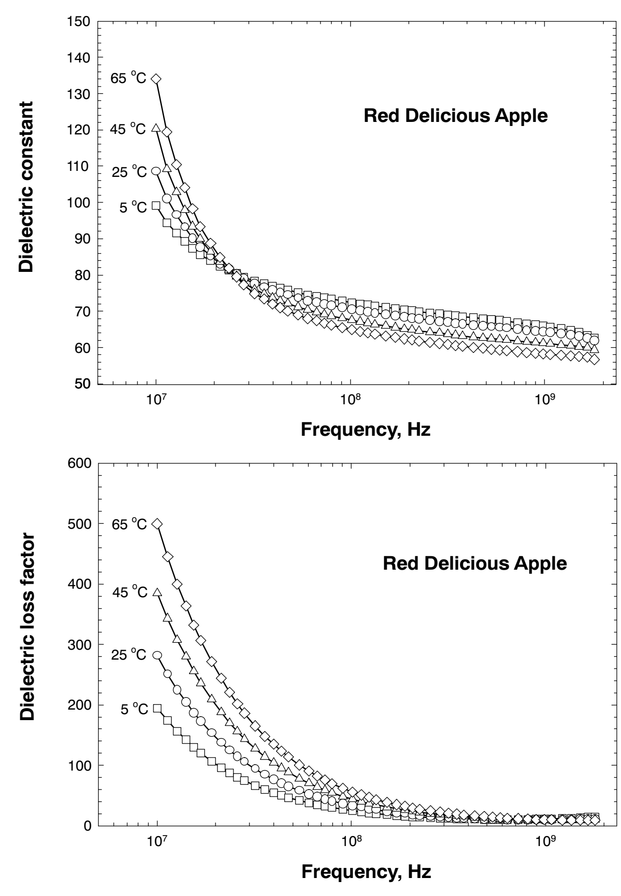

Figure 1. Frequency and temperature dependence of fresh apple permittivity, moisture content 85% (Nelson, 2003).

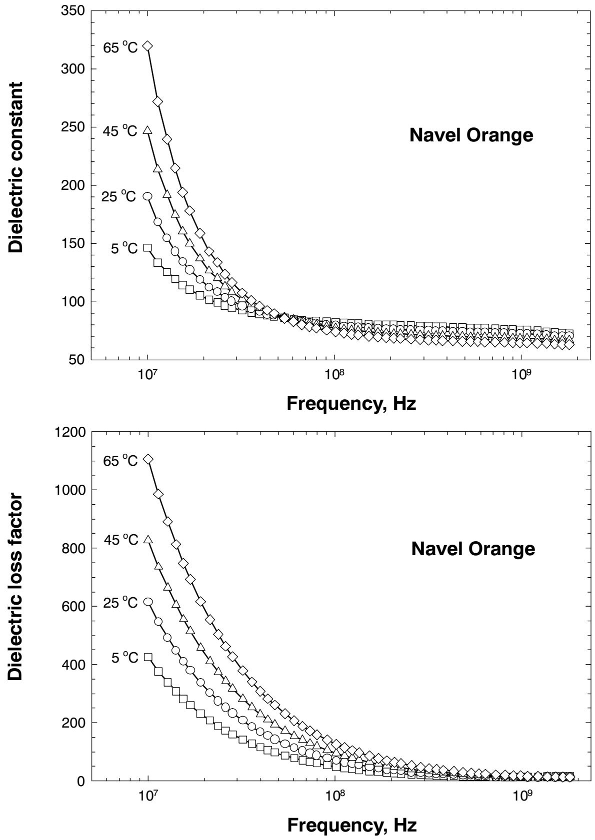

Figure 2. Frequency and temperature dependence of fresh navel orange permittivity, moisture content 89% (Nelson, 2003).

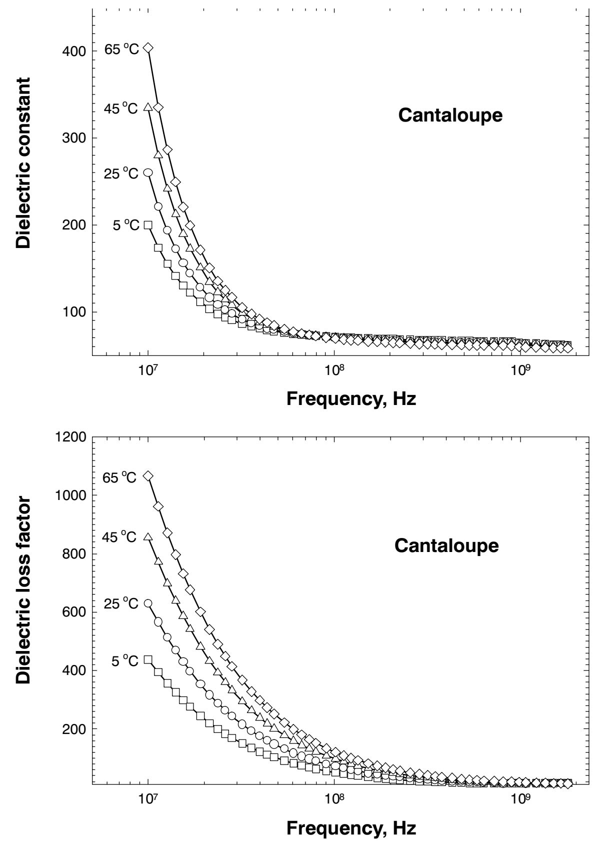

Figure 4. Frequency and temperature dependence of fresh cantaloupe permittivity, moisture content 87% (Nelson, 2003).

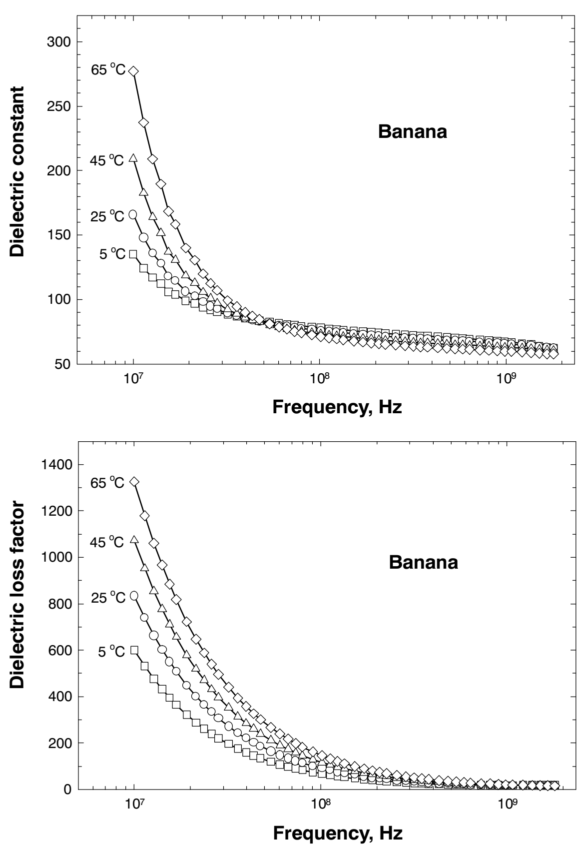

Figure 3. Frequency and temperature dependence of fresh banana permittivity, moisture content 74% (Nelson, 2003).

the meat tissue appears at a higher frequency (200 MHz) than those of the fruit tissue.

Dielectric spectroscopy data on hard red winter wheat at 11.2% moisture content are shown in figure 9. These data were measured on ground wheat to facilitate reliable measurements with the 3-mm open-ended coaxial probe. However, dielectric properties of whole-kernel wheat and ground wheat of the same density are very similar (Nelson, 1984). Because of the much lower moisture content (11.2%), the dielectric properties of wheat are much lower than those of the high-moisture fruits and chicken breast meat. They follow similar trends with frequency and temperature, except that there is no reversal of the dielectric-constant temperature coefficient for the wheat, most likely because of the absence of free water in the wheat.

Discussion

The influence of liquid water on the dielectric behavior of melon tissues has already been mentioned. Dielectric properties measurements on pure liquid water at 25°C over the same frequency range, 200 MHz to 20 GHz, are shown in figure 10, and similarities in the frequency-dependent dielectric behavior of water and the melon tissues are obvious at the higher frequencies (2 to 20 GHz). The behavior of water is well described by the Debye relaxation equation (Hasted, 1973; Nelson, 1973; Kaatze, 1989). The Cole-Cole plot of the dielectric properties in the complex plane is also useful in describing the dielectric behavior of many pure substances (Hasted, 1973; Nelson, 1973). A Cole-Cole plot for the measure-

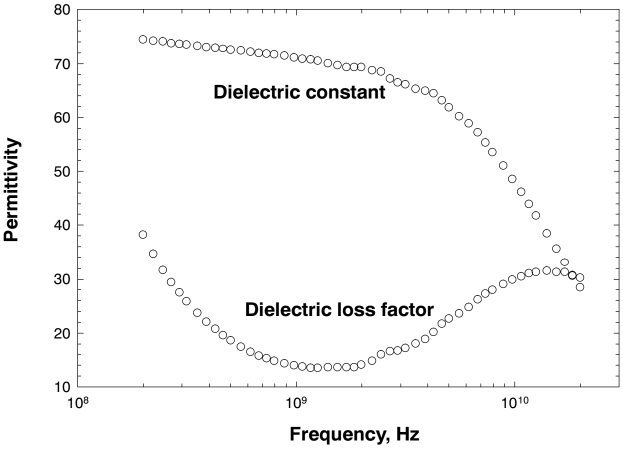

Figure 5. Frequency dependence of the permittivity of fresh cantaloupe at 24°C, moisture content 87% (Nelson et al., 2008).

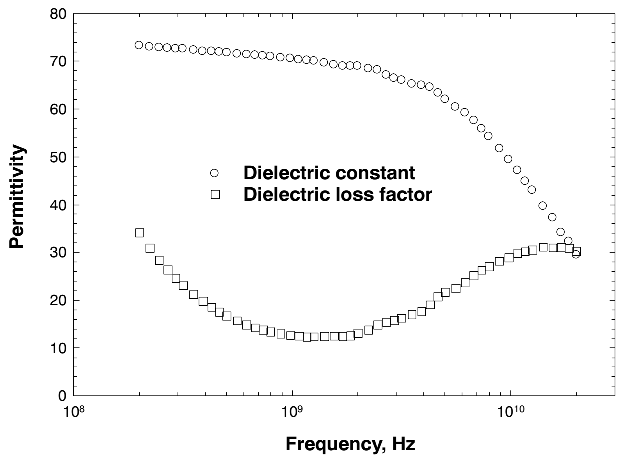

Figure 6. Frequency dependence of fresh honeydew melon permittivity at 24°C, moisture content 90% (Nelson et al., 2008).

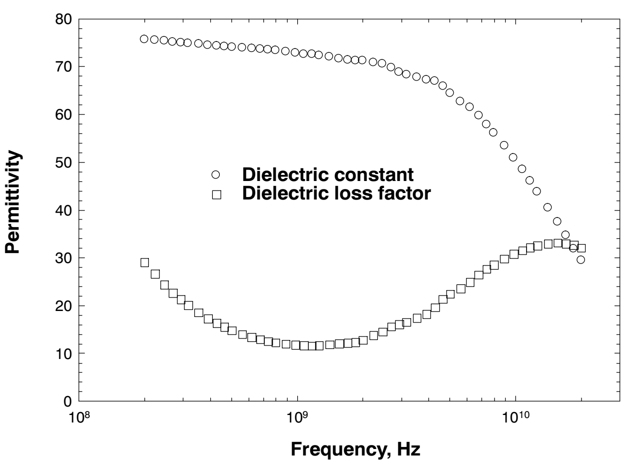

Figure 7. Frequency dependence of fresh watermelon permittivity at 24°C, moisture content 90% (Nelson et al., 2008).

ments on water illustrated in figure 10 is shown in figure 11, where the resulting semicircular arc is obtained. For proper description of the dielectric behavior of the melon tissue and other biological materials, however, contributing phenomena other than dipolar relaxation also need to be taken into account, such as the ionic conduction at lower frequencies,

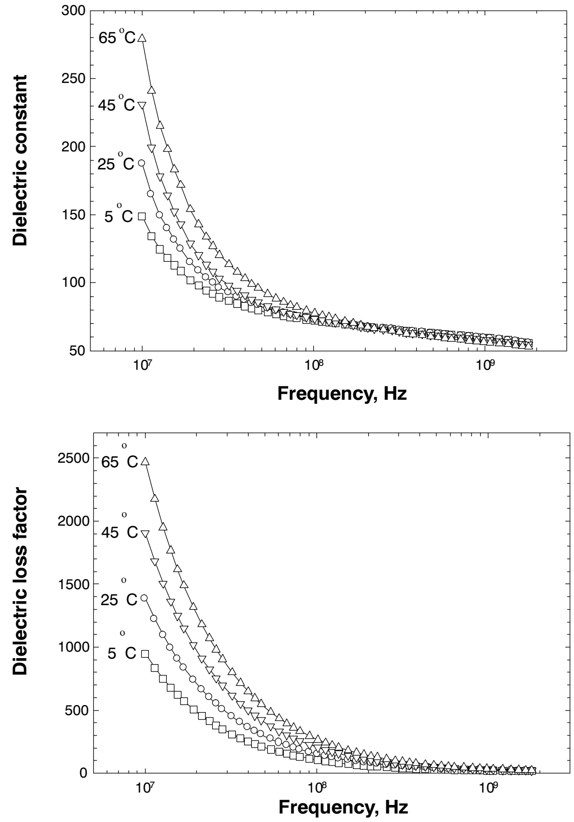

Figure 8. Frequency and temperature dependence of the dielectric properties of fresh chicken breast meat, moisture content 76% (Nelson et al., 2007b).

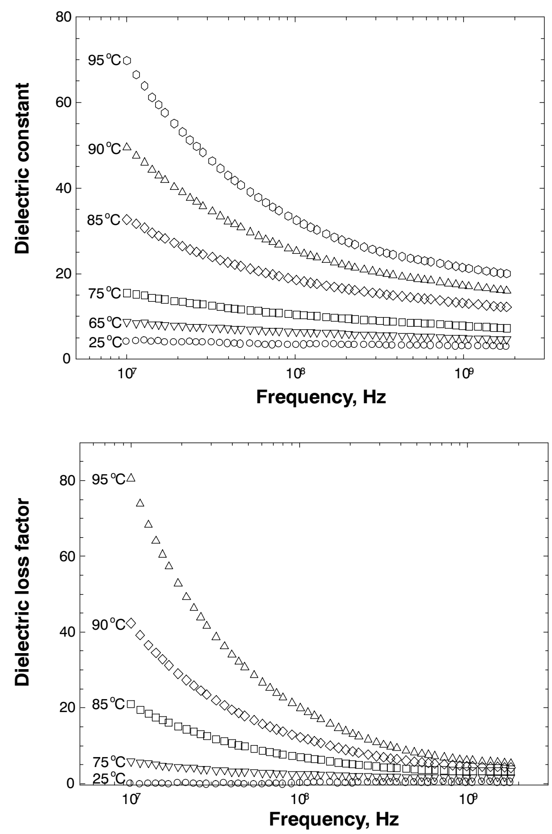

Figure 9. Frequency and temperature dependence of the dielectric properties of ground hard red winter wheat, moisture content 11.2% (Nelson and Trabelsi, 2006).

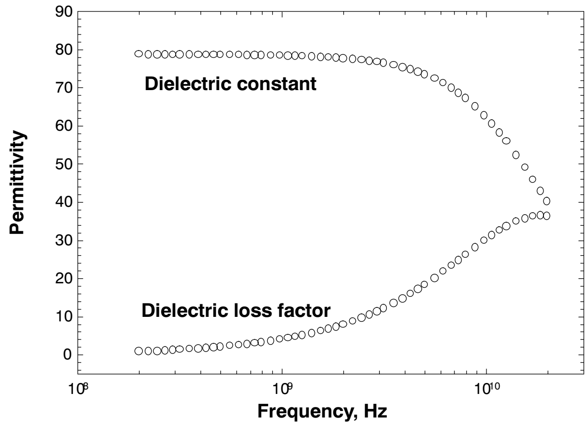

Figure 10. Frequency dependence of the dielectric properties of pure liquid water at 25°C (Nelson et al., 2008).

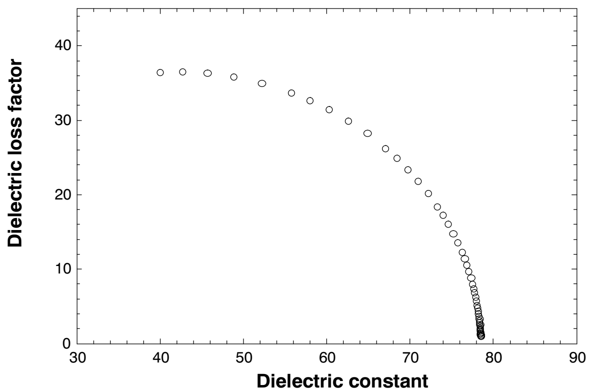

Figure 11. Cole-Cole plot for pure liquid water at 25°C.

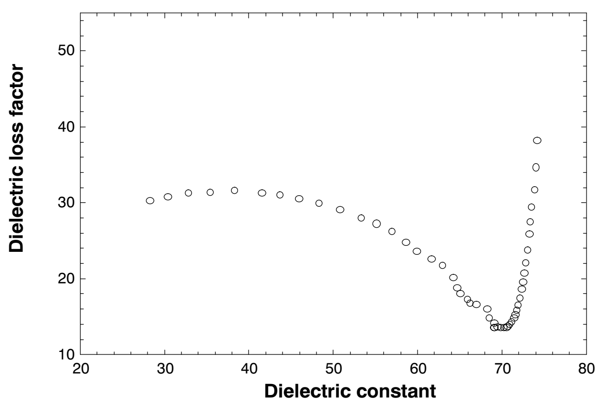

Figure 12. Cole-Cole plot for fresh cantaloupe permittivity data shown in figure 5.

the behavior of bound water, and the influence of constituents other than water.

Cole-Cole plots for the permittivity of wheat of 11% to 25% moisture content have been presented previously (Nelson and Trabelsi, 2006). A Cole-Cole plot for the permittivity data shown for cantaloupe in figure 5 is presented in figure 12. A well-defined circular arc is shown for the data between about 2 and 20 GHz, but at lower frequencies, ionic conduction results in significant departure from Debye-type behavior. In addition, the center for the circular arc is well below the zero-loss-factor axis, which indicates a distribution of relaxation times rather than a single relaxation time for a pure substance. Thus, the 2- to 20-GHz behavior could be reasonably well described by the Cole-Cole equation with a suitably determined distribution parameter (Hasted, 1973; Nelson, 1973).

Conclusions

Dielectric properties of fresh fruit, fresh chicken breast meat, and hard red winter wheat differ greatly, mainly because of the wide differences in moisture content. In general, higher values of dielectric properties can be expected with materials of higher moisture content, but exceptions are noted in the case of banana tissue of 74% moisture content, which has greater values for both the dielectric constant and loss factor than those of some fruits with moisture contents of about 90%. Both dielectric constant and loss factor decrease monotonically with increasing frequency, except that the loss factor can increase or decrease with frequency in regions of dielectric relaxation. At frequencies well below the relaxation region, below about 800 MHz, the loss factor increases with increasing temperature. For the fruits, the dielectric constant increases with increasing temperature in regions dominated by ionic conduction, but as frequency increases, the temperature coefficient for the dielectric constant changes from positive to negative at the higher frequencies where the dipolar losses are dominant. The influence of free liquid water with its dielectric relaxation frequency of 19 GHz at 24°C is evident in the dielectric spectroscopy data for the fruits, where a prominent dielectric relaxation is exhibited between 10 and 20 GHz. Although pure liquid water follows the Debye dielectric behavior, Cole-Cole plots for the fresh melon permittivity data show that the Cole-Cole equation can describe the behavior between 2 and 20 GHz, but that ionic conduction causes significant departure from dipolar Debye behavior at frequencies below 2 GHz. Dielectric behavior similar to the fruits is exhibited by fresh chicken breast meat with a moisture content of 76%. The dielectric behavior of wheat of 11.2% moisture content is different from the other materials in that values of the dielectric constant and loss factor are lower and the temperature coefficient for the dielectric constant remains positive throughout the 10 MHz to 1.8 GHz frequency range.

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