Dielectric Properties of Dehydrated Apples as Affected by Moisture and Temperature

H. Feng, J. Tang, R. P. Cavalieri

Abstract. *Dielectric properties directly influence microwave drying characteristics of food products. A knowledge of dielectric properties of foods as a function of moisture content and temperature is essential in the design and control of microwave drying systems. Dielectric constant ε′ and loss factor ε″ of Red Delicious apples (*Malus domestica* Borkh.) were measured over a moisture content range of 4% to 87.5% at 22°C and 60°C. At high moisture content (>70%), free water dispersion and ionic conduction accounted for the dielectric behavior. At medium moisture (∼23%), ionic conduction played a major role. At low moisture contents (∼4%), bound water accounted for the major dispersion mechanism. A decrease in moisture content resulted in a decrease in ε′ and ε″. Based on this study, we expect a strong moisture leveling effect when drying apples from 50% to 4% at elevated temperatures in 915 MHz or 2.45 GHz microwave drying systems.*

Keywords. *Dielectric properties, Dielectric losses, Open–ended coaxial probe, Apple.*

Dielectric heating with microwave energy has found industrial applications in drying food products such as pasta. There is a renewed interest in exploring the unique characteristics of microwave heating for drying heat–sensitive materials (Szentmarjay et al., 1992; Funebo and Ohlsson, 1998). Potential drawbacks of microwave heating in a drying system that may adversely affect product quality (e.g., charring of high sugar content products) include: (1) non–uniform product temperature distribution due to inherent non–uniform microwave fields within a drying chamber, and (2) difficulty in controlling product final temperature at low moisture contents, as compared to hot–air drying (Lu et al., 1999). Feng and Tang (1998) and Feng et al. (1999a, 1999b) combined microwave heating with spouted bed fluidization to overcome these drawbacks. The microwave and spouted bed (MWSB) drying method was used to dry high sugar content diced apples and blueberries. It sharply reduced drying times and improved product quality, compared to conventional hot air drying methods. Further studies of the MWSB process for scale–up and for the development of effective process control, however, require a thorough understanding of the interaction between microwave energy and foods over a wide range of moisture content and at elevated temperatures.

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Interaction between a food product and microwave energy is governed by the relative complex permittivity ($\varepsilon = \varepsilon' - j\varepsilon''$) of the product. The real component of the complex permittivity (ε', known as the dielectric constant) is related to energy storage, and the imaginary component (ε'', the loss factor) is related to energy dissipation. Both properties are influenced by product composition, temperature, and moisture. Comprehensive reviews by Nelson (1973), Kent (1987), and Sun et al. (1995) provided good sources of information on dielectric properties for selected food and agricultural materials. Some of the data compiled in these reviews were measured at different temperatures. Few studies examined the effects of both temperature and moisture. Little has been reported on effects of moisture content and temperature on the dielectric properties of fruits and vegetables as related to drying processes. The objective of this research was to study the dielectric properties of apples over a wide range of moisture contents encountered in dehydration at room temperature (22°C) and at an elevated temperature (60°C).

Materials and Methods

Sample Preparation

Samples of fourteen (for measurement at 22°C) or eight (for measurement at 60°C) moisture contents (4% to 87%; all moisture contents presented in this article were calculated on a wet basis) were prepared from fresh Red Delicious apples (*Malus domestica* Borkh.) or from diced apples that had been commercially dried to 22.4%. The latter is commonly referred to as "evaporated" apple in the industry and is used in pie filling, muffins, etc. Fresh apples with an average moisture content of 87.5% were obtained from a local grocery. They were diced and dehydrated to obtain moisture contents between 23.8% and 87.5% by a hot–air tray dryer (Armfield Ltd., Hampshire, U.K.). The evaporated diced apples were provided by TreeTop, Inc. (Selah, Wash.). They were dried from diced fresh apples of $12.7 \times 9.5 \times 6.4$ mm to 22.4% in commercial hot–air dryers. The evaporated apples were further dried with a microwave and spouted bed (MWSB) dryer, as described by Feng and Tang (1998), to prepare samples with moisture contents below 22.4%. The hot air of the spouted bed was 70°C and the microwave power was set at 2.3 W/g (on wet basis). The moisture content of samples was determined by drying at 70°C and 13.3 kPa for 7 hours (AOAC, 1990).

Open–Ended Coaxial–Line Dielectric Properties Measuring System

The open–ended coaxial probe technique was used to measure dielectric properties of apple samples. This method was selected for the following reasons: (1) it allows simple sample measurement and data analysis, (2) the instrumentation is commercially available, and (3) dielectric properties can be obtained over a wide frequency range in a single measurement and with adequate accuracy for thermal calculations (Engelder and Buffler, 1991). The dielectric properties measuring system consisted of an HP 85070B open–ended coaxial probe (Hewlett Packard, Fullerton, Cal.) and an HP 8752C vector network analyzer. An HP software program provided the permittivity based on the measured reflection coefficient (Engelder and Buffler, 1991). The system was calibrated by measurements on air, short (a metal block to short the coaxial cable), and triple–distilled water at each temperature. This dielectric measurement system allows measurement of dielectric properties of relatively lossy materials over the frequency range between 30 MHz and 3000 MHz, including two microwave frequencies of 915 MHz and 2450 MHz that are allocated by the U.S. Federal Communications Commission (FCC) for industrial, scientific, and medical (ISM) heating applications.

Temperature Control

Dielectric properties of apple samples were measured at 22°C and 60°C. Temperatures greater than 60°C caused significant softening in the fresh apple tissues and, therefore, were not selected. The probe was conditioned in a NCPCO Model 630–7 air oven (National Appliance Co., Portland, Ore.) for measurements at 60°C. A transparent Perspex sheet of 9.5–mm thickness was used as the oven door and helped prevent heat loss during the measurements. A circular opening of 90 mm diameter in the door provided access for handling the sample. The opening was covered with a rubber sheet to reduce heat loss when placing a sample under the probe. Prior to each measurement, apple samples were sealed in glass jars, immersed in a Digi–Bath water bath (Laboratory Devices Inc., Hollston, Mass.), and heated to 60°C. Preheated samples were then removed from the water bath and placed under the probe in the oven, which was preset at 60°C for dielectric measurements.

Effect of Sample Size and Thickness on Measurement Accuracy

Effects of sample size and thickness on the measurement accuracy of dielectric properties must be considered in developing a measurement method for low–moisture samples. These effects can be best understood by examining the electric field distribution and energy absorption at the tip of the open–ended coaxial probe. The typical configuration of an open–ended coaxial probe is shown in figure 1. Anderson et al. (1986) showed that, in air, the maximum electric field intensity occurred at a radial distance of 1.2a from the central axis of the probe, while another small peak occurred at 0.98b. The intensity of the residual field outside b was less than 6% of the maximum field intensity. Hence, they concluded that the field intensity was negligible beyond the conductor's outer radius (c). Swicord and Davis (1981) presented a similar electric field distribution in the vicinity of an open–ended coaxial probe. They showed that 90% of the energy from the probe was absorbed in lossy materials within a hemisphere of radius b. Seaman et al. (1989) conducted experimental studies to confirm the confined aperture field at the tip of an open–ended probe. The work conducted by these researchers (Seaman et al., 1989; Swicord and Davis, 1981; Anderson et al., 1986) demonstrated, both theoretically and experimentally, that the electric field at the coaxial probe tip is confined within the outer conductor outer radius (c). The probe used in the present study has dimensions of a = 0.45 mm, b = 1.4 mm, and c = 2.4 mm. Therefore, a sample size greater than 2c = 4.8 mm was considered to cause negligible error.

The open–ended coaxial probe technique requires a sample thickness large enough to simulate a slab that is electrically semi–infinite in size (Stuchly and Stuchly, 1980). Studies conducted by Fan et al. (1990) have demonstrated that a sample with a thickness equal to the outer conductor inner diameter (2b) can be considered as an electrically semi–infinite body. Seaman and Seals (1991) proposed that for low–loss fruit skin, the effective thickness was 2 to 5 mm for the probe with a 2b value of 2.2 mm. It is, therefore, reasonable to assume that a sample thickness of 2c = 4.8 mm should be adequate for our tests. An experiment was conducted with dehydrated diced apples, 3.3 (±0.7) mm thick, to validate this assumption. Two conditions were considered: an apple piece supported by a metal block, and an apple piece supported by a plastic foam. Because of the high porosity, the foam block had dielectric properties close to air. These arrangements represented two extreme conditions in the dielectric measurements (Anderson et al., 1986). Seven pieces at 6% moisture content were measured in each arrangement, and three readings were taken for each piece. The measured dielectric properties at 2450 MHz are given in table 1. Statistically, there was a significant difference between the dielectric constants (ε′) and the loss factors (ε″) ($P < 0.05$) measured with two different supporting blocks

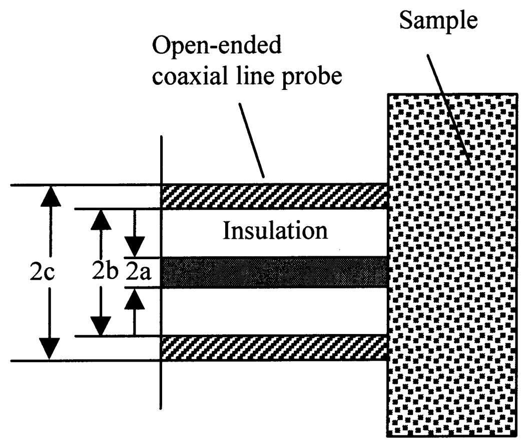

Figure 1. The open–ended coaxial line probe configuration (a = 0.45 mm, b = 1.4 mm, and c = 2.4 mm).

Table 1. Comparison between dielectric property measurements of apple piece supported with a foam block or a metal block.

Frequency (MHz)	Dielectric Properties	Foam Block Support (mean)	Metal Block Support (mean)	Relative Error (%)
2450	ε′	1.62 ±0.02	1.79 ±0.03	5
	ε″	0.12 ±0.01	0.14 ±0.01	17

(foam or metal). However, the difference was only 5% for the dielectric constant and 17% for the loss factor in the two extreme test conditions. We expect better measurement accuracy with samples at higher than 6% moisture content, with samples of large apple pieces, or using an apple block as the support (see the following section).

Dielectric Properties Measurement

Dielectric measurements were made as follows for samples with different moisture levels and geometry:

Fresh samples (87.5% moisture content): Apples were cut into halves, and a flat surface of the cut apple was placed against the probe during measurement. Five samples were measured.

Sliced apples (23.8% to 80.7%) that were dried from fresh apples: Five slices were used at each moisture content. Dielectric properties were measured by placing the probe against the flat surface of a slice. Five readings were taken from each slice. Dehydrated slices had a thickness of 8.0 to 11.5 mm. Therefore, the effect of thickness was considered negligible. During dielectric measurements, a small amount of pressure was applied manually to eliminate air gaps and ensure good contact of the sample with the probe.

Diced apples (3.8% to 22.4%): Measurements were made on a single apple piece (3.3 mm thick). During the measurement, the apple piece was supported by an apple slab about 11 mm thick. The support slab was compressed from diced and dried apple pieces using a Carver Laboratory Press (Fred S. Carver, Inc., Summit, N.J.). At low moisture contents, two surfaces of diced apple were gently trimmed with a sharp blade to provide good contact with the probe. For each moisture content, 13 to 16 pieces were measured. Dehydrated diced apples had a size of 9.2 (±1.0) × 5.8 (±0.9) × 3.3 (±0.7) mm. The contact surface area with the probe was large enough to cover the tip of the probe (∼4.8 mm). The thickness of a single piece plus the slab was 13.1 to 15.5 mm and was much greater than 2c = 4.8 mm. Hence, the errors attributable to sample size were assumed to be negligible.

Results and Discussion

Frequency and Temperature Effects

Dielectric relaxation spectrum (DRS) analysis is useful in studying the properties of water in food products by elucidating the function of different dispersion and loss mechanisms. This analysis has been used to study the hydration of foods and food components (Tsoubel et al., 1995; Lu et al., 1998). By considering the effects of moisture and temperature on both the magnitude and the shifting in the location of an absorption peak, DRS analysis can also be used to analyze the moisture and temperature response of dielectric properties.

Figure 2 shows dielectric properties of Red Delicious apples as a function of frequency at three selected moisture contents and two measured temperatures. At a high moisture content (~70%), ε′ decreased with increasing frequency, while ε″ decreased to a minimum value and then increased with frequency (figs. 2a and 2d). This agrees with reported results for fresh fruits and vegetables (Seaman and Seals, 1991; Nelson et al., 1994; Ikediala et al., 2000). The gradual reduction in ε′ of high moisture content samples with increasing frequency was likely caused by the dispersion of water molecules. In a single dispersion system (e.g., pure water), this transition take place in a narrow frequency range and follows the Debye equation. In multidispersion food systems, the transition is gradual because of the combined effects of different relaxations and the contribution of ionic conduction. The U–shape frequency response in ε″ was mainly due to the superposition of ionic conduction and free water dispersion (fig. 3).

Nelson et al. (1994) measured dielectric properties of three apple cultivars at 23°C and observed a minimum value for ε″ at about 1000 MHz. Ikediala et al. (2000) presented a curve for Red Delicious apple tissue with the minimum ε″ value also at 800 to 1000 MHz. In our study, a minimum ε″ was observed at 1000 MHz (10^9 Hz) (fig. 2a) at 22°C. The frequency corresponding to the minimum ε″ shifted to about 2000 MHz at 60°C (fig. 2d). This shift can be related to the temperature response of both the free water dispersion and ionic conduction. For Debye relaxation, the relaxation time (τ) and the viscosity of the water can be related by (Von Hippel, 1954):

$$\tau = V\frac{3\nu}{kT} \tag{1}$$

where

V = volume of molecule
ν = kinematic viscosity
k = a constant
T = temperature in K.

The viscosity also decreases with temperature according to an Arrhenius relation (Macosko, 1994):

$$\nu \propto e^{\frac{E_a}{RT}} \tag{2}$$

where E_a is activation energy, and R is universal gas constant. According to equations 1 and 2, increasing temperature reduces viscosity and relaxation time. As a result, the relaxation frequency ($f_c = 1/\tau$) increases with temperature. The dipole relaxation frequency, hence, moves to a higher frequency range (fig. 3) as temperature increases. Dielectric losses resulting from ionic conduction also increase with temperature, again as a result of a reduction in viscosity that leads to increased ionic conductivity. The combination of these two effects resulted in the shift of the minimum ε″ to a higher frequency in samples of high moisture content (fig. 2a and 2d).

The value of ε′ also decreased with increasing frequency at medium moisture content of ∼23% (figs. 2b and 2e). The U–shape for ε″, however, was not present at this moisture level. It is likely that the free water relaxation peak was depressed due to reduced amount of free water at 23% moisture content. A gradual decrease in ε″ with frequency was most likely due to the greater influence of ionic conduction than in samples of high moisture contents. This trend continued at low moisture content 4% (figs. 2c and 2f). At this moisture content, bound water accounts for dielectric

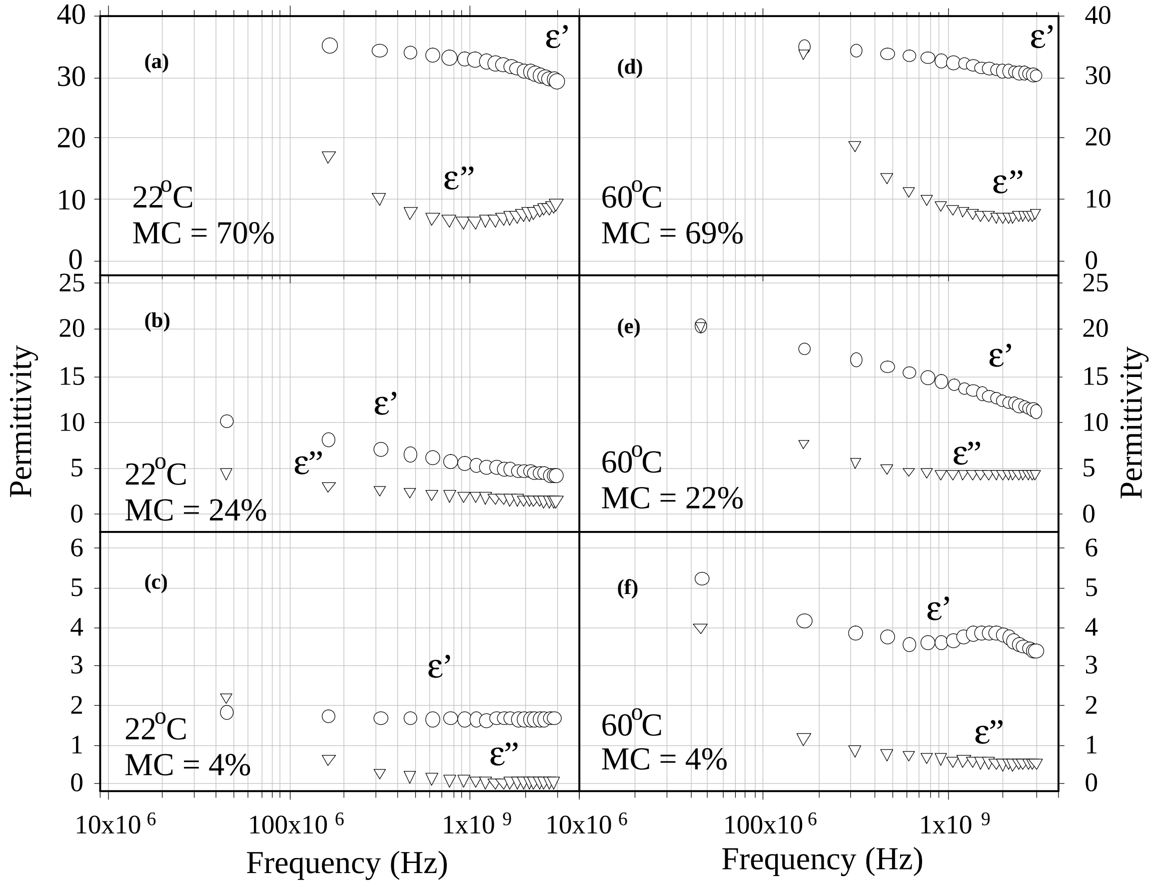

Figure 2. Dielectric properties of Red Delicious apples at three moisture contents and two temperatures.

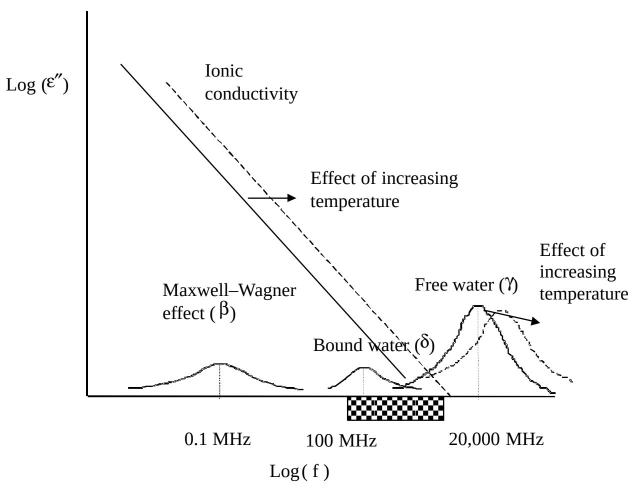

Figure 3. Contribution of different dispersion mechanisms in biological materials as affected by frequency and temperature (Tang et al., 2002; based on Roebuck and Goldblith, 1972; Harvey and Hoekstra, 1972; Metaxas and Meredith, 1993; Kuang and Nelson, 1997). The shaded range represents our measured frequency range.

dispersion. In figure 2f, the increase in ε′ with frequency (with a peak at 1.5 GHz) is most likely due to some artifact of the measurement system.

MOISTURE CONTENT EFFECT

Measured values of dielectric constant ε′ and loss factor ε″ at 915 MHz and 2450 MHz are listed in tables 2 and 3 and presented graphically in figure 4. In general, ε′ and ε″ decreased with decreasing moisture content. Water in apples can be divided, in descending mobility, into: (1) water held in intercellular space or capillaries that behaves like free water, (2) multilayer water, and (3) monolayer water that is tightly bound to the polar sites of apple tissues, e.g., in the form of H–bond (Okos et al., 1992). Therefore, as the drying progresses, water dipole becomes less mobile, resulting in reduced loss factor. Reduced moisture content during drying also reduces ionic conductivity, as little free water is available as solvent. In addition, air voids in the apple samples as a result of dehydration contributed to the low values of both ε′ and ε″.

The maximum moisture content corresponding to the monolayer moisture in fruits ranges from 10% to 17%, depending upon the type of fruit (Lim et al., 1995). The very low dielectric loss factor at moisture contents between 3% and 20% and at room temperature (figs. 4b and 4d) are likely due to the fact that most water is tightly bound to solids with little mobility at room temperature to respond to alternating electromagnetic fields. Raising the temperature to 60°C increased the mobility of water molecules, as indicated by an increase in loss factor in samples with moisture content between 3% and 20% (figs. 4b and 4d).

In microwave drying, electric energy is converted to thermal energy in food materials according to (Goldblith, 1967):

$$P = 5.563 \times 10^{-11} f E^2 \varepsilon'' \qquad (3)$$

where

P = amount of thermal energy generated through dielectric dispersion per unit volume (W/m^3)
E = electric field intensity (V/m)
f = frequency (Hz).

Table 2. Dielectric properties of Red Delicious apple at 60°C and eight moisture contents.

MC (%)	915 MHz				2450 MHz			
	ε′	Std. Dev.	ε″	Std. Dev.	ε′	Std. Dev.	ε″	Std. Dev.
68.7	32.8	4.1	9.1	1.0	30.8	3.6	7.5	0.9
53.6	28.5	5.4	8.5	2.6	26.0	5.4	7.2	1.5
34.6	22.5	4.3	6.8	1.8	19.7	4.0	6.6	1.3
22.4	14.4	5.0	4.5	1.3	11.9	4.6	4.5	1.4
12.7	7.4	2.3	2.1	1.0	6.2	1.8	1.7	0.9
11.0	5.3	0.8	1.7	0.4	4.5	0.6	1.4	0.3
5.9	4.1	0.8	1.0	0.3	3.7	0.7	0.7	0.2
3.8	3.6	0.6	0.7	0.1	3.6	0.5	0.5	0.1

Table 3. Dielectric properties of Red Delicious apple at 22°C and fourteen moisture contents.

MC (%)	915 MHz				2450 MHz			
	ε′	Std. Dev.	ε″	Std. Dev.	ε′	Std. Dev.	ε″	Std. Dev.
87.5	56.0	0.9	8.0	0.4	54.5	1.2	11.2	0.5
80.7	43.0	5.0	7.0	1.0	41.0	4.8	9.3	1.2
79.6	38.2	3.9	6.1	0.9	36.3	3.8	8.6	0.9
78.0	39.0	6.6	6.3	1.1	37.1	6.2	8.5	1.4
69.7	33.0	3.7	6.7	1.1	30.3	3.4	8.5	1.1
55.1	26.9	2.4	6.9	0.9	23.1	2.1	8.5	0.9
46.6	22.2	2.0	6.7	1.0	18.4	1.8	7.8	0.8
36.4	16.2	2.6	6.1	0.9	12.3	2.1	6.2	1.1
30.3	14.4	5.9	6.0	1.0	10.7	1.6	5.5	1.0
23.8	5.7	0.5	2.1	0.3	4.5	0.4	1.6	0.2
19.0	3.7	0.3	0.8	0.1	3.3	0.3	0.7	0.1
14.1	2.8	0.2	0.3	0.1	2.6	0.2	0.3	0.04
9.2	2.2	0.2	0.2	0.03	2.2	0.2	0.1	0.03
3.8	1.7	0.2	0.1	0.04	1.7	0.2	0.07	0.04

The thermal energy is either used to evaporate water or raise product temperature. The values of ε″ in figure 4 suggest that, in general, the ability of dehydrated apples to absorb microwave energy decreases with decreasing moisture content at 915 MHz and 2450 MHz. This results in a phenomenon commonly referred to as "moisture leveling effect" (Metaxas and Meredith, 1993). That is, within a batch of diced apples in a relatively uniform microwave field, pieces with higher moisture content absorb more microwave energy because of their larger dielectric loss factor. Moist pieces should, thus, dry faster than pieces of lower moisture content. As a result, in properly designed microwave drying systems, the final product should have relatively uniform moisture content. This is one of the unique advantages of microwave drying compared to hot–air drying. Based on figure 4, the moisture leveling effect should be very strong in apples when dried from 50% to 4% at 60°C in 915 MHz or 2450 MHz microwave drying systems.

Comparison with Literature

Data on the dielectric properties of fruits and vegetables as a function of frequency at room temperature were reported by Tran et al. (1984), Seaman and Seals (1991), Nelson et al. (1994), and Kuang and Nelson (1997). Dielectric properties of fresh apples at temperatures up to 55°C were measured by Ikediala et al. (2000). Some early measurements were reported for fresh and cooked potatoes and carrots at elevated temperatures and at 2800 and 3000 MHz (Bengtsson and Risman, 1971; Ohlsson et al., 1974). No data, however, exist in the literature that relate dielectric properties of apples to moisture content.

Mudgett et al. (1980) studied the effect of moisture (3% to 80.3%) on dielectric behavior of freeze–dried potatoes at 3000 MHz (3 GHz) and 25°C with a standing–wave measurement system. The dielectric properties of freeze–dried potatoes followed a trend similar to that of dehydrated apples measured in our study with respect to changes in moisture content (fig. 5), but dehydrated potatoes had higher dielectric constant and loss factor values than dehydrated apples at comparable moisture contents. This difference may be attributed to the large difference between the intercellular air voids in fresh potatoes and apples. Apples have intercellular voids of 20% to 27% of total volume (Khan and Vincent, 1990), while potatoes have less than 1% air voids (Hudson, 1975). The air voids reduced the dielectric properties of fresh apples. The difference in composition also contributes to the differences between the dielectric properties of the two products.

Penetration Depth

Figure 6 shows the microwave penetration depth (dp) calculated from the measured dielectric properties by (Von Hippel, 1954):

$$dp = \frac{\lambda_o}{2\pi(2\varepsilon')^{0.5}}\left[\left(1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2\right)^{0.5}-1\right]^{-0.5} \qquad (4)$$

where λ_o is the free–space wavelength, λ_o = 122.4 m at 2450 MHz, and λ_o = 327.7 mm at 915 MHz.

The penetration depth of microwaves in deionized water at room temperature is 122.5 mm at 915 MHz and 16.8 mm

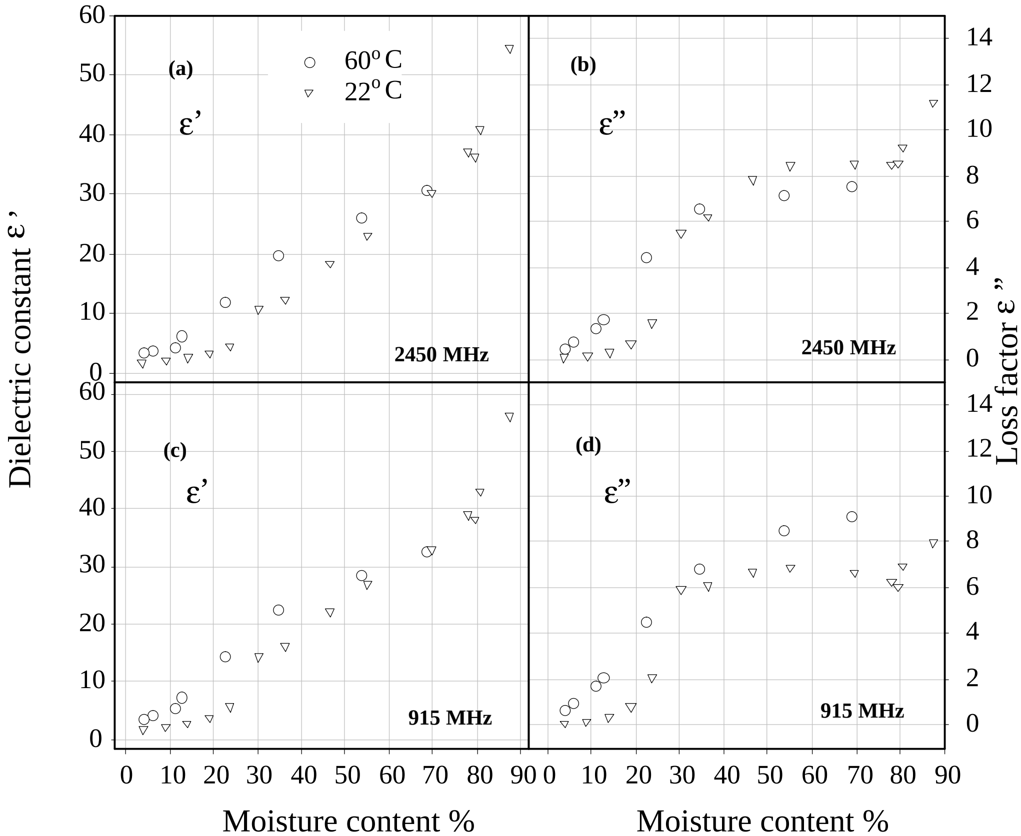

Figure 4. Dielectric properties of Red Delicious apples at 915 MHz and 2450 MHz as influenced by moisture content: (a) and (c) dielectric constant, (b) and (d) loss factor.

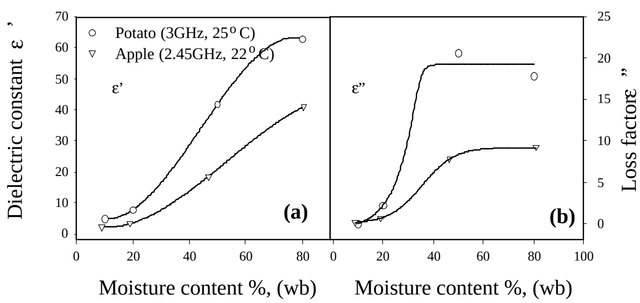

Figure 5. Comparison of dielectric properties of Red Delicious apples obtained in this study with those of potatoes reported by Mudgett et al. (1980).

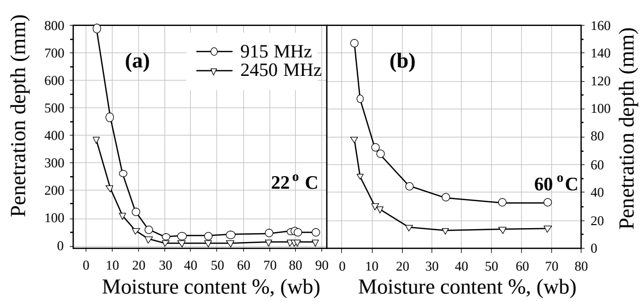

Figure 6. Penetration depth of microwaves in Red Delicious apples as a function of moisture content at two temperatures.

at 2450 MHz (Tang et al., 2002). The penetration depth of 915 MHz microwaves in fresh Red Delicious apples (87.5% moisture content) was smaller than in water (fig. 6). At high moisture contents, moisture had little effect on penetration depth until the moisture content was reduced to about 30%. Below 30% moisture content, microwave penetration depth increased sharply with decreasing moisture. This moisture content corresponded to the sharp change in ε″ in figure 4. A similar change in the penetration depth with moisture was reported by Goedeken et al. (1997) for pregelatinized bread. In general, penetration depth increased as both temperature and moisture decreased. As shown in figure 6, the penetration depth of microwaves would not impose a problem when drying diced apples using microwave energy in a fluidized bed.

Conclusions

Moisture has significant effects on the dielectric losses in apples. When moisture content was relatively high (>70%), both free water dispersion and ionic conduction contributed to the dielectric behavior. At an intermediate moisture content (∼23%), the ionic conduction determined the frequency response of the dielectric properties. At low moisture content (∼4%), the bound water accounted for any dispersion. Moisture removal in dehydration operations resulted in a decrease in dielectric constant and loss factor. A transition region was found in ε″ curves (with respect to moisture content) that corresponded to the transition from bound water to free water. We expect dehydrated apples to experience moisture leveling when dried to between 50% and 4% moisture content at elevated temperatures. An increase in temperature at low moisture contents resulted in increased dielectric properties. At high moisture contents, the dielectric responses to temperature were difficult to predict. The results of this study compared well with work of Mudgett et al. (1980). The penetration depth increased as moisture was removed from the sample.

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