DIELECTRIC PROPERTIES OF APPLE CULTIVARS AND CODLING MOTH LARVAE

J. N. Ikediala, J. Tang, S. R. Drake, L. G. Neven

ABSTRACT. *Dielectric properties of four apple cultivars and third and fifth instars codling moth (Cydia pomonella) were measured between 30 MHz and 3000 MHz at 5°C to 55°C, using the open-ended coaxial-line probe technique. Dielectric constant of apples decreased with frequency and decreased slightly with increasing temperature. The dielectric loss factor increased linearly with temperature in the radio frequency range but was nearly constant at the microwave frequencies. Minimum dielectric loss factor of apples was observed at about 915 MHz. Dielectric constant and loss factor were not influenced by cultivar, pulp section or degree of ripeness of apples. Firmness and titratable acidity in apples decreased, while soluble solids content increased significantly due to ripeness. But these properties were not correlated with the dielectric properties. Dielectric constant and loss factor of codling moth larvae followed a similar pattern of variation with frequency and temperature as for the apples. The dielectric properties of third instars codling moth were higher than those of the fifth instars in the radio frequency region. Dielectric constant and loss factor of the insect were much higher than that of the apples at frequencies lower than 2450 MHz, suggesting that differential heating may be untenable at 2450 MHz or higher frequency for codling moth larvae in the apple host.*
Keywords. *Dielectric properties, Radio frequency, Microwaves, Apples, Codling moth.*

The dielectric properties of biological materials are important in the research on microwave processing of foods and agricultural materials, and the destruction of insect pests of postharvest and stored products. Dielectric properties, among other parameters, are required to provide insight into the interaction between materials and microwave and radio frequency (RF) energy during microwave and RF heating. For example, the dielectric properties of apples are required in modeling microwave and RF heating for the development of a thermal alternative quarantine treatment against codling moth.

Permittivity is a complex quantity commonly used to describe the electrical properties that influence reflection of electromagnetic waves at interfaces and the attenuation of the wave energy within materials. Relative permittivity describes permittivity related to free space. The real part is expressed in terms of the dielectric constant (energy stored) which influences the electric field distribution and the phase of waves traveling through the material. Dielectric loss factor, which is the imaginary part, mainly influences energy absorption and attenuation. The equation for relative permittivity is:

$$\varepsilon = \varepsilon' - j\varepsilon'' \qquad (1)$$

where ε is the relative permittivity, ε' is the dielectric constant, ε'' is the dielectric loss factor, and $j = \sqrt{-1}$. The mechanisms that contribute to the dielectric loss in heterogeneous mixtures include polar, electronic, atomic and Maxwell-Wagner responses (Metaxas and Meredith, 1993). At the RF and microwave frequency of practical importance and current applications in food processing (RF – 1 to 50 MHz and microwave –915 and 2450 MHz), ionic conduction and dipole rotation are dominant loss mechanisms (Ryynänen, 1995):

$$\varepsilon'' = \varepsilon''_d + \varepsilon''_\sigma = \varepsilon''_d + \frac{\sigma}{\varepsilon_0 \omega} \qquad (2)$$

where subscripts "d" and "σ" stand for contributions due to dipole rotation and ionic conduction, respectively, and σ is the ionic conductivity (S/m), ω is the angular frequency ($= 2\pi f$), ε_o is the permittivity of free space or vacuum ($\approx 8.854 \times 10^{-12}$ F/m), and f is the frequency (Hz). The conversion of RF or microwave energy into thermal energy in a dielectric (lossy) material is proportional to it's loss factor at a given frequency and electric field:

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

where P_{abs} is the absorbed power (W/m^3), and E is the electric field intensity (V/m).

The relative permittivity values of agricultural and biological materials are generally influenced by frequency, temperature, density, salt content, moisture content and the

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state of moisture (frozen, free or bound), as well as the size and arrangement of the cell structure. Dielectric properties of many foods and other biomaterials are summarized in several reviews (Nelson, 1973; Tinga and Nelson, 1973; Stuchly and Stuchly, 1980a; Mohsenin, 1984; Mudgett, 1986; Foster and Schwan, 1989; Kent, 1987; Ryynänen, 1995). Some of these authors have reported on the dielectric properties of fresh fruits and vegetables at selected frequencies and temperatures, and on the measurement techniques (Thompson and Zachariah, 1971; Kraszewski et al., 1983a; Tran et al., 1984; Seaman and Seals, 1991; Engelder and Buffler, 1991; Nelson et al., 1994). Engelder and Buffler (1991) described several currently used measurement methods and noted the open-ended coaxial-line probe technique as the easiest to use. They have also listed the advantages and limitations of this method compared with the other methods.

Microwave dielectric properties of selected fruits and vegetables, measured with the open-ended coaxial-line probes and network analyzers, have been reported by Tran et al. (1984) from 0.1 to 10 GHz and by Seaman and Seals (1991) from 0.15 to 6.4 GHz. Seaman and Seals (1991) compared the permittivities of the pulp and skin of pome fruits (‘Red Delicious’ and ‘Golden Delicious’ apples), stone fruit (peaches), citrus fruits (tangelos and oranges) and bananas at room temperature. Significant differences were found between the dielectric constants and loss factors for the pulp and skin. Nelson et al. (1994) measured the permittivities of 23 fruits and vegetables, including ‘Red Delicious’, ‘Golden Delicious’ and ‘Granny Smith’ apples, using the open-ended coaxial-line and probe technique in frequency range of 0.2 to 20 GHz at room temperature. Reports by these authors did not, however, discuss the effects of temperature and storage time or degree of ripeness on dielectric properties.

Limited literature reports exist on the permittivities of insects. Pioneering work was reported by Nelson and Charity (1972), Nelson (1976) and Nelson et al. (1997). These reports concentrated, however, on grains and grain weevils. Colpitts et al. (1992) reported dielectric data of the Colorado potato beetle in frequency ranging from 0.1 to 26.5 GHz, while Ondracek and Brunnhofer (1984) at 2375 MHz for *Tenebrio molitor* and *Pyrrhocoris apterus* (beetles) tissues. Andreuccetti et al. (1994) reported the dielectric properties of woodworms at 2450 MHz. Our preliminary investigations showed the use of 915 MHz microwave radiation to be promising for the control of codling moth larvae infestation of postharvest cherries (Ikediala et al., 1999). Thus, information on the dielectric properties of the codling moths and host fruits are needed to develop suitable quarantine treatment protocols.

The objectives of this research were to measure the dielectric properties of apple and to determine the effect of cultivars, degree of ripeness, temperature and frequency on these properties. The dielectric properties of codling moth instars were also measured and compared with those of apples in relation to RF and microwave heating potential.

MATERIALS AND METHODS

DIELECTRIC PROPERTY DETERMINATION

The dielectric properties were measured by the coaxial probe technique. The principles of the measurement, calibration, computations and sensitivity have been described by several authors (Stuchly and Stuchly, 1980b; Athey et al., 1982; Kraszewski et al., 1983a,b; Tran et al., 1984; Grant et al., 1989; Misra et al., 1990; Seaman and Seals, 1991; Colpitts et al., 1992; Nelson et al., 1994, 1997). The HP Dielectric Probe Kit (Model 85070B, Hewlett Packard Corp., Santa Clara, Calif.) consisted of an open-ended semi-rigid coaxial cable connected to the dielectric probe and to an Hewlett-Packard 8752C Network Analyzer (Hewlett-Packard Corp., Santa Clara, Calif.). The Dielectric Probe Kit software assisted in data acquisition and permittivity calculations. The probe system was calibrated with a standard calibration procedure (air-short-triple deionized water), with calibration refreshed up to three times daily during the course of the measurements. Measurements were made with a frequency sweep from 0.3 to 3000 MHz. Typical permittivity measurement accuracy is about 5% as specified by Hewlett-Packard.

APPLE AND CODLING MOTH LARVAE SAMPLES

Apple cultivars (‘Red Delicious’, ‘Golden Delicious’, ‘Granny Smith’, and ‘Fuji’) were procured from the USDA-ARS Fruit Quality Laboratory, Wenatchee, Washington. Freshly harvested apples (new apples) and apples of the previous season (old apples) that were initially in CA storage and later in normal cold storage (to represent two states of maturity or ripeness) were tested. Apples were kept in cold storage (2 to 4°C) for less than one week before being used. Dielectric properties of apple flesh (pulp) were measured on whole apples, close to the apple core and the surface, at mean sample temperatures of 5, 23, 40, and 55°C. Samples to be measured at 5°C were taken directly from cold storage while those for 23°C were first kept in room conditions overnight before dielectric property measurement. Those for higher temperatures were first kept at room conditions overnight, wrapped in aluminum foil to avoid water absorption, and conditioned in a water bath set at the target temperature. Dielectric property measurements at temperatures other than ambient were done by holding the foil-wrapped sample in a cup with water at the given temperature and then slicing open the pulp section for measurement. Sample temperature was taken as the mean temperatures at a 3 to 5 mm depth below the point where the probe was placed. Since the apples are generally large compared to the probe size, fringing electric fields were not expected to be affected by the foil.

Each apple was measured close to the surface by slicing off about 3 mm thickness of flesh/skin, and close to the core (probe placed axially in the inner radial half portion of apple) by slicing equatorially, using a sharp scalpel blade to obtain smooth horizontal surfaces. The sample surface was brought in close contact with the probe using a laboratory mini-support jack. The dielectric property measurement was triggered with the Network Analyzer’s remote switch. Each measurement took about 20 s. Care was taken to avoid undue pressure on the specimen which could lead to deformation of the surface and juice expression. The probe was cleaned with distilled and deionized water and wiped dry before and after each measurement. Measurements were repeated on four to five apples. Furthermore, moisture content, firmness, soluble solids content, and titratable acidity of the sample lots were also determined.

Codling moth instars reared at the USDA-ARS Insect Research Laboratory, Wapato, Yakima, Washington, were shipped to Washington State University, Pullman, Washington. The insect larvae were extracted from artificial diet (Toba and Howell, 1991) and cocoon and separated into second to third and fourth to fifth instars. Sufficient live or crushed larvae were placed in a vial (27 mm diameter) so as to obtain at least 25 mm thickness of samples when pressed down with the probe. This thickness was necessary in order to avoid possible electromagnetic field perturbation by the sample holder. The applied pressure served to reduce voids between the insects but to the extent that live larvae were not crushed. Duplicate larval dielectric property measurements were made at the same temperatures and test conditions as for the apples, except that the insects were conditioned to the appropriate temperatures while in the vial covered with rubber stopper. Tests with crushed (slurry) larvae were conducted as quickly as possible to minimize degradation of the hemolymph and other constituents. The results were compared with the tests on live larvae. The moisture content of the codling moth larvae were also determined.

Determination of Moisture Content and Other Properties

The moisture content of fruit and of codling moth larvae samples were obtained by drying in a vacuum oven at 70°C for 6 h (AOAC, 1996), as well as by freeze drying. For the freeze drying of the codling moths, one or several larvae were weighed and placed in 1.5 mL microcentrifuge tubes. The insects were quickly frozen for 5 min in a blast freezer at –80°C. The microcentrifuge tubes openings were then covered with parafilm and holes poked in it before placing in a freeze dryer. Sample weights were monitored over a period of 48 to 72 h until they reached constant values. Before each weighing, samples were first placed in a desiccator for about 1 h. Five replicate measurements were made for the apples and 10 for the insects.

Firmness was measured using a Topping motorized penetrometer (Topping, 1981) fitted with an 11.1 mm (7/16 in.) tip. Soluble solids content (SSC) was measured with a refractometer (Reichert ABBE Mark II, Buffalo, N.Y.). After extracting 10 mL of juice from the apples, titratable acidity (TA) was measured using the Titraprocessor (Metrohm 672, Herisau, Switzerland) and expressed as percent malic acid equivalent. These tests were made in an attempt to correlate changes in dielectric with some mechanical and chemical property changes due to cultivar and ripening. Three replicate measurements were made for each property.

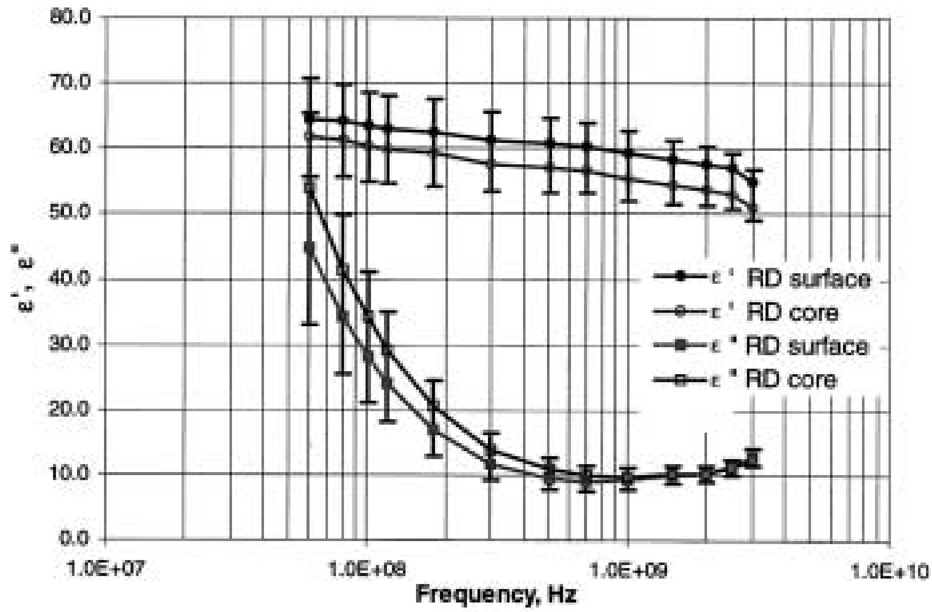
Results and Discussion

Dielectric Properties of Apple Cultivars

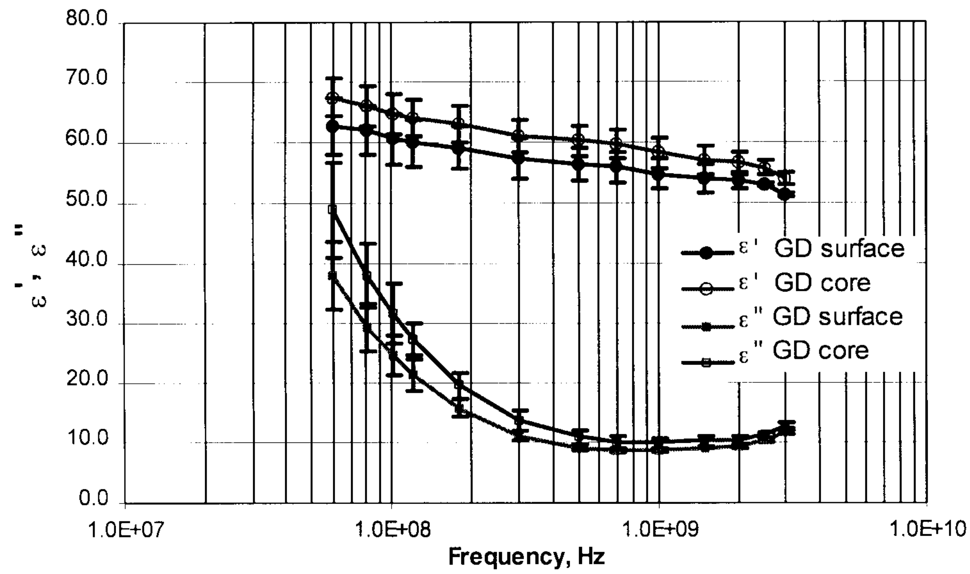
Dielectric constant (ε′) and loss factor (ε″) data of old ‘Red Delicious’ (RD) and ‘Golden Delicious’ (GD) apple flesh, close to the surface and core sections, are shown in figure 1. The two plots show typical variation within the surface and core sections of the apple cultivars for the measured dielectric properties. Old crop apples appear to show observable visual difference between the surface and core section, probably due to ripeness and other physiological changes. The ε′ of RD apple pulp, close to the surface, appeared to be slightly higher than the core while the ε″ close to the core appeared higher than that close to the surface, especially at the RF and lower microwave frequency region (fig. 1a). This trend was, however, not shown by the GD apple (fig. 1b). Furthermore, there was more variability in the data for the RD apples than the GD apples. From the standard deviations associated with the mean values of the replicates for old crop RD and GD surface and core apples sections, there appeared to be no true difference between the dielectric property values related to the portion of the fruit. Seaman and Seals (1991) obtained a large difference between the pulp and skin dielectric properties of GD apples. However, our study considered the pulp just below the skin. This approach was thought to be of more practical importance since the skin of an apple is too thin compared to the whole fruit pulp to be of any significance in absorbing microwave energy. In addition, the microwave heating of apples gives a core region-focused heating instead of a surface heating. Thus, apple shape and size, as opposed to difference in the loss factors between the core and the surface, may account for the center-focused heating effect observed during microwave treatment (Ikediala et al., 1999).

Figure 2 shows the variation of the dielectric properties among the cultivars. Values plotted are the mean for both surface and center for new apples. The mean ε′ and ε″ within the investigated frequency region ranged from about 64 to 50 and 47 to 7.5, respectively. Results of ε′ and ε″ for different measurements were fairly variable as was seen in figure 1, particularly at the radio frequency (RF) region. Data within the RF range of 0.3 MHz to about 30 MHz had observable noise with calculated error sensitivity up to 19% and were adjudged not to be reliable, thus they have not been reported for brevity. Many authors have also reported this type of variability which may be due to the nonhomogeneity associated with biological samples such as apples, as well as the measurement instrument sensitivity at the lower frequencies (Seaman and Seals, 1991; Colpitts et al., 1992; Nelson et al., 1997). For all apple cultivars, ε′ decreased continuously with increasing frequency. However, ε″ decreased sharply to a minimum around 915 MHz and then increased slightly with increasing frequency. These results agree with those of Tran et al. (1984), Seaman and Seals (1991) and Nelson et al. (1994) both in trend and value for the equivalent frequencies. It is well known that the dielectric properties of agricultural products vary with frequency. Lawrence et al. (1992) noted that ε′ may remain constant or decrease with frequency while ε″ either increases or decreases depending on the dielectric relaxation process. Our result suggested that ionic polarization was dominant at the RF and lower microwave frequencies (<~915 MHz), while water dipole response may have been predominant at higher microwave frequencies (>~915 MHz). It appeared that ε″ for the new crop of Granny Smith (GS) apple was slightly higher than that of the other cultivars at the RF region, but this was apparently not unique. There was also no significant difference in the dielectric properties data among the apple cultivars’ freshly harvested fruits.

Table 1 shows a summary of the moisture content, firmness, soluble solids content, titratable acidity, and the variation of ε′ and ε″ as a function of frequency at 23°C,



(a)



(b)

Figure 1–Dielectric constant (ε′) and loss factor (ε″) of old (a) 'Red Delicious' (RD) and (b) 'Golden Delicious' (GD) apples close to the surface and core pulp section. Error bars are standard deviations from replicates. ε′ = dielectric constant; ε″ = loss factor.

for the old and new crop of the apple cultivars investigated. The table also shows the properties for codling moth instars. It is notable that although the moisture content, firmness, soluble solids content, and titratable acidity of old and new GD apples were different, and these properties differed also among cultivars to some degree, the dielectric properties could not be correlated with any of these properties. There was no significant variation among old and new apple crops other than that due to experimental and statistical randomness.

During the dielectric measurement at 55°C, the apples appeared to be cooked after the long duration needed to heat the core from the surface to the set point temperature. RD and GD apples were much softened compared to the 'Granny Smith' (GS) and 'Fuji' apples. Thus, GD and 'Fuji' were chosen to show the representative variation of permittivity values with temperature. It should be noted that apple cultivar differences have already been shown to have little or no effect on the dielectric properties of apples. The effect of temperature on the dielectric properties of apples is shown for GD and 'Fuji' apples in figure 3. In general, the ε′ tended to decrease as the temperature increased in both the RF and microwave frequency regions, although this decrease seemed less noticeable at 2450 MHz with the GD apples. On the other hand, ε″ increased almost linearly as the temperature increased at 100 MHz, remained almost constant when at 915, and tended to decrease at 2450 MHz. Both the GD and 'Fuji' apples

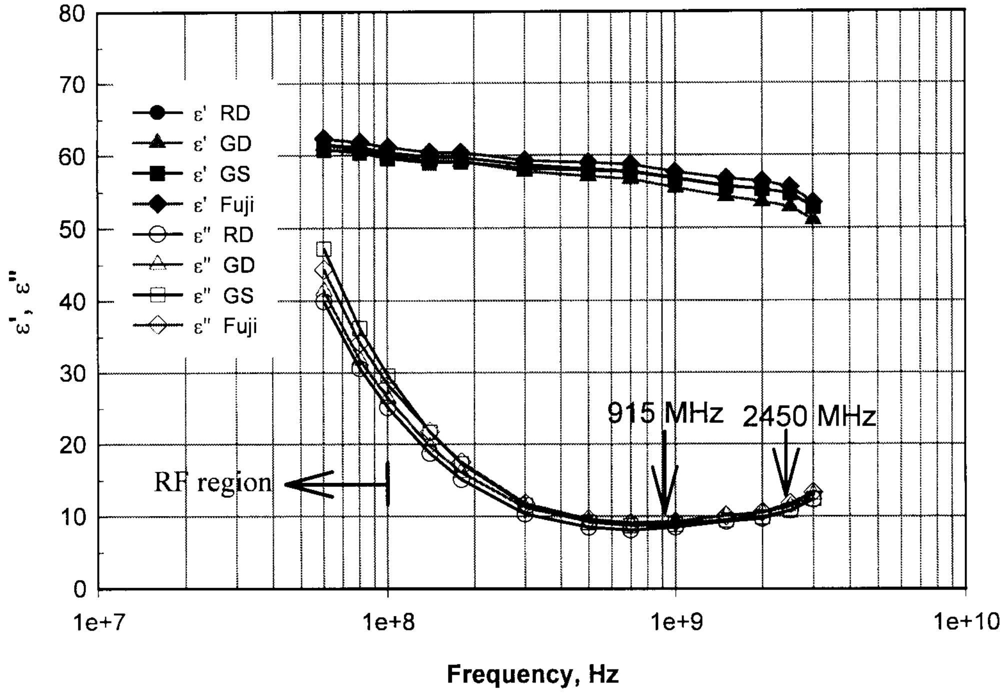


Figure 2–Plot of mean dielectric constant (ε′) and dielectric loss factor (ε″) for four apple cultivars at 23°C. Data plotted are the mean of surface and core sections of new apples.

Table 1. Physico-chemical and dielectric properties of apple (old and new crop) cultivars and codling moth instars at 23°C

Material	Moisture Content (% w.b.)	Firmness (lb)	SSC (%)	TA (%)		Frequency (MHz) 50	100	500	1000	2000	2500	3000
						Apple						
RD: Old	87.3 ± 1.2	11.7 ± 1.6	12.7 ± 0.7	0.36 ± 0.06	ε′	64.4 ± 8.3	61.8 ± 7.3	59.0 ± 6.5	57.9 ± 6.2	55.8 ± 5.4	55.1 ± 5.1	53.1 ± 5.0
					ε″	73.5 ± 22	31.2 ± 9.5	10.2 ± 2.3	9.5 ± 1.5	10.3 ± 1.1	11.3 ± 1.1	12.8 ± 1.3
New	87.6 ± 0.8	13.0 ± 1.8	11.8 ± 0.5	0.41 ± 0.12	ε′	61.9 ± 6.0	60.4 ± 5.2	58.2 ± 4.7	56.9 ± 4.6	55.3 ± 4.7	54.7 ± 4.5	52.8 ± 4.2
					ε″	59.9 ± 15	25.1 ± 6.7	8.5 ± 1.7	8.5 ± 1.1	9.7 ± 1.0	10.8 ± 1.1	12.3 ± 1.2
GD: Old	81.7 ± 1.3	11.6 ± 1.2	14.0 ± 0.6	0.36 ± 0.07	ε′	67.2 ± 3.9	62.7 ± 3.6	58.3 ± 3.0	56.5 ± 2.9	55.1 ± 2.3	54.4 ± 1.9	52.7 ± 1.9
					ε″	63.6 ± 11	28.2 ± 4.7	10.0 ± 1.0	9.2 ± 0.8	9.9 ± 0.6	10.8 ± 0.6	12.3 ± 0.6
New	84.1 ± 1.6	13.3 ± 2.0	12.0 ± 0.7	0.63 ± 0.06	ε′	62.3 ± 4.2	60.0 ± 3.6	57.1 ± 3.0	55.5 ± 3.0	53.6 ± 3.1	52.9 ± 3.0	51.1 ± 2.8
					ε″	62.0 ± 3.5	26.4 ± 1.8	9.3 ± 0.8	9.3 ± 0.6	10.5 ± 0.8	11.4 ± 0.9	13.0 ± 1.1
GS: Old	85.4 ± 0.4	11.9 ± 0.6	12.6 ± 0.4	0.24 ± 0.02	ε′	59.2 ± 3.7	57.1 ± 3.6	55.5 ± 3.5	54.4 ± 3.5	53.1 ± 3.6	52.6 ± 3.5	50.9 ± 3.4
					ε″	50.2 ± 17	21.4 ± 7.4	7.3 ± 1.5	7.5 ± 0.5	8.7 ± 0.7	9.6 ± 1.0	11.1 ± 1.3
New	87.7 ± 1.2	16.0 ± 0.2	11.8 ± 0.1	0.78 ± 0.11	ε′	61.4 ± 3.3	59.6 ± 2.7	57.9 ± 2.2	56.8 ± 2.2	55.3 ± 2.1	54.7 ± 2.2	52.9 ± 2.1
					ε″	71.4 ± 24	29.6 ± 10	9.2 ± 2.3	8.9 ± 1.5	9.9 ± 1.2	10.8 ± 1.2	12.4 ± 1.3
Fuji: Old	86.9 ± 0.6	12.5 ± 2.6	13.4 ± 0.8	0.23 ± 0.03	ε′	62.6 ± 8.7	59.2 ± 6.9	54.8 ± 5.6	53.4 ± 5.2	52.1 ± 5.0	51.3 ± 5.0	49.7 ± 4.8
					ε″	49.7 ± 20	22.6 ± 9.3	7.9 ± 2.8	7.3 ± 2.0	9.1 ± 1.9	10.3 ± 1.9	11.2 ± 1.9
New	87.5 ± 0.7	16.6 ± 1.7	12.5 ± 0.7	0.52 ± 0.08	ε′	63.0 ± 5.3	61.1 ± 4.3	59.0 ± 4.0	57.7 ± 4.0	56.4 ± 4.0	55.6 ± 3.7	53.5 ± 3.4
					ε″	65.6 ± 25	28.3 ± 11	9.6 ± 2.7	9.3 ± 1.4	10.6 ± 0.8	11.8 ± 0.8	13.3 ± 0.7
						CM						
Fifth instar												
Whole	72.9 ± 3.3	-	-	-	ε′	84.6	65.4	54.6	51.8	49.4	48.2	46.8
					ε″	243.1	105.2	26.6	17.5	14.1	14.3	14.9
Slurry	73.7 ± 1.9	-	-	-	ε′	99.5 ± 0.8	75.1 ± 2.9	62.9 ± 3.5	59.8 ± 3.5	57.4 ± 3.3	56.1 ± 3.3	54.4 ± 3.1
					ε′	316.1 ± 44	135.2 ± 17	33.2 ± 3.4	21.3 ± 2.0	17.0 ± 1.3	16.6 ± 1.2	16.5 ± 1.1
Third instar												
Slurry	79.8 ± 1.1	-	-	-	ε′	107.3 ± 1.9	78.2 ± 2.0	63.5 ± 2.8	59.4 ± 2.7	57.4 ± 2.6	56.6 ± 2.5	54.4 ± 2.3
					ε″	359.4 ± 9.5	154.5 ± 3.1	37.3 ± 0.6	23 ± 0.6	18.1 ± 0.9	17.6 ± 1.0	17.1 ± 1.1

RD = ‘Red Delicious’; GD = ‘Golden Delicious’; GS = ‘Granny Smith’; CM = Codling Moth; SSC = Soluble Solids Content; TA = Titratable Acidity.

showed the same trend. Higher ε″ values at the lower frequencies at elevated temperatures may be the result of reduced solution viscosity which leads to increased mobility of ions and, thus, higher electrical conductivity (Herve et al., 1998). Ryynänen (1995) reported that at microwave frequencies only salty foods show an increase in ε″ with temperature, but at RF frequencies, ε″ increases in all foods. Since the dielectric loss factor, ε″, of apples

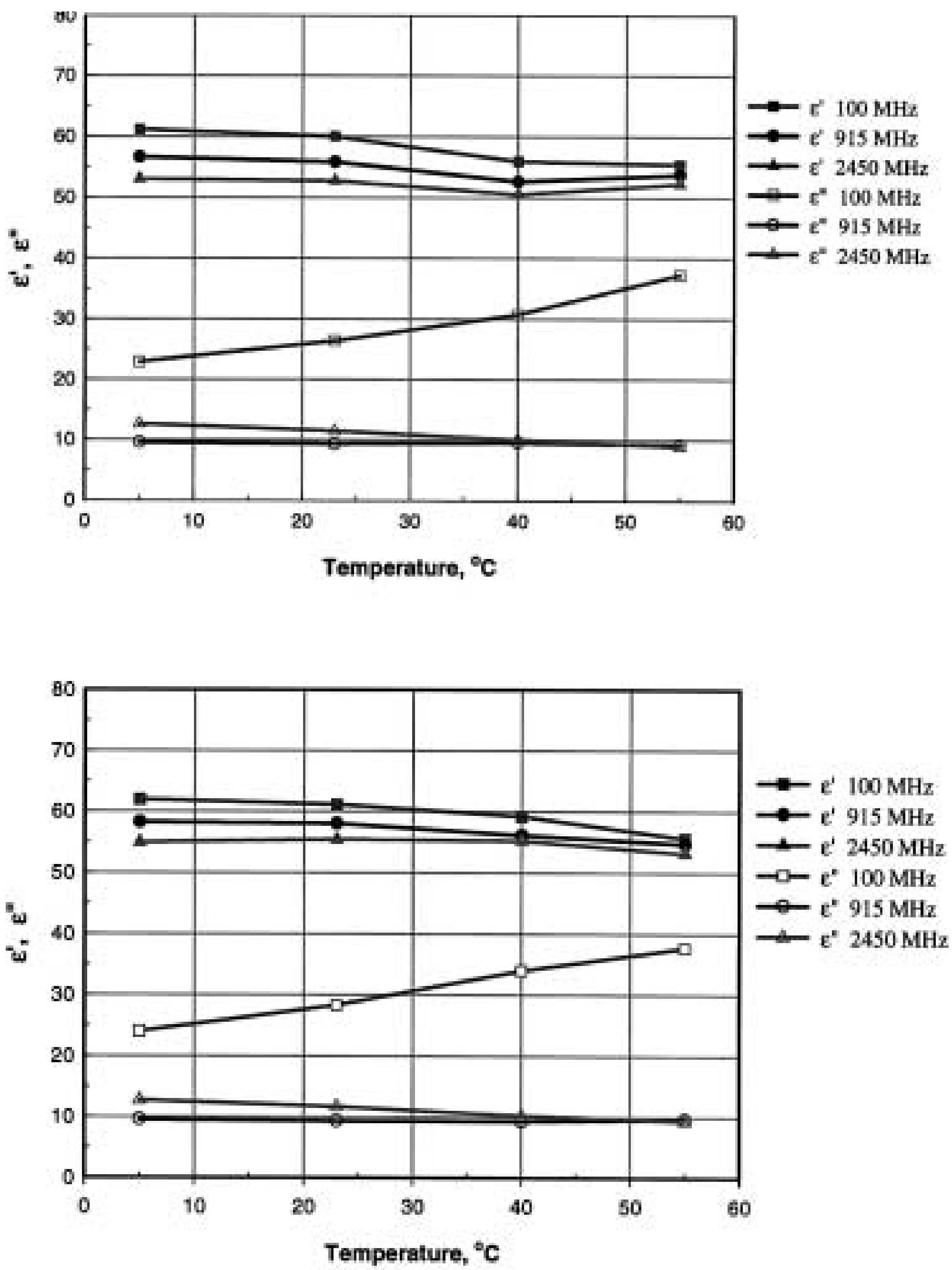


Figure 3–Effect of temperature at given frequencies on the dielectric properties of new (a) GD and (b) 'Fuji' apple pulp. Data plotted are the mean of surface and core sections.

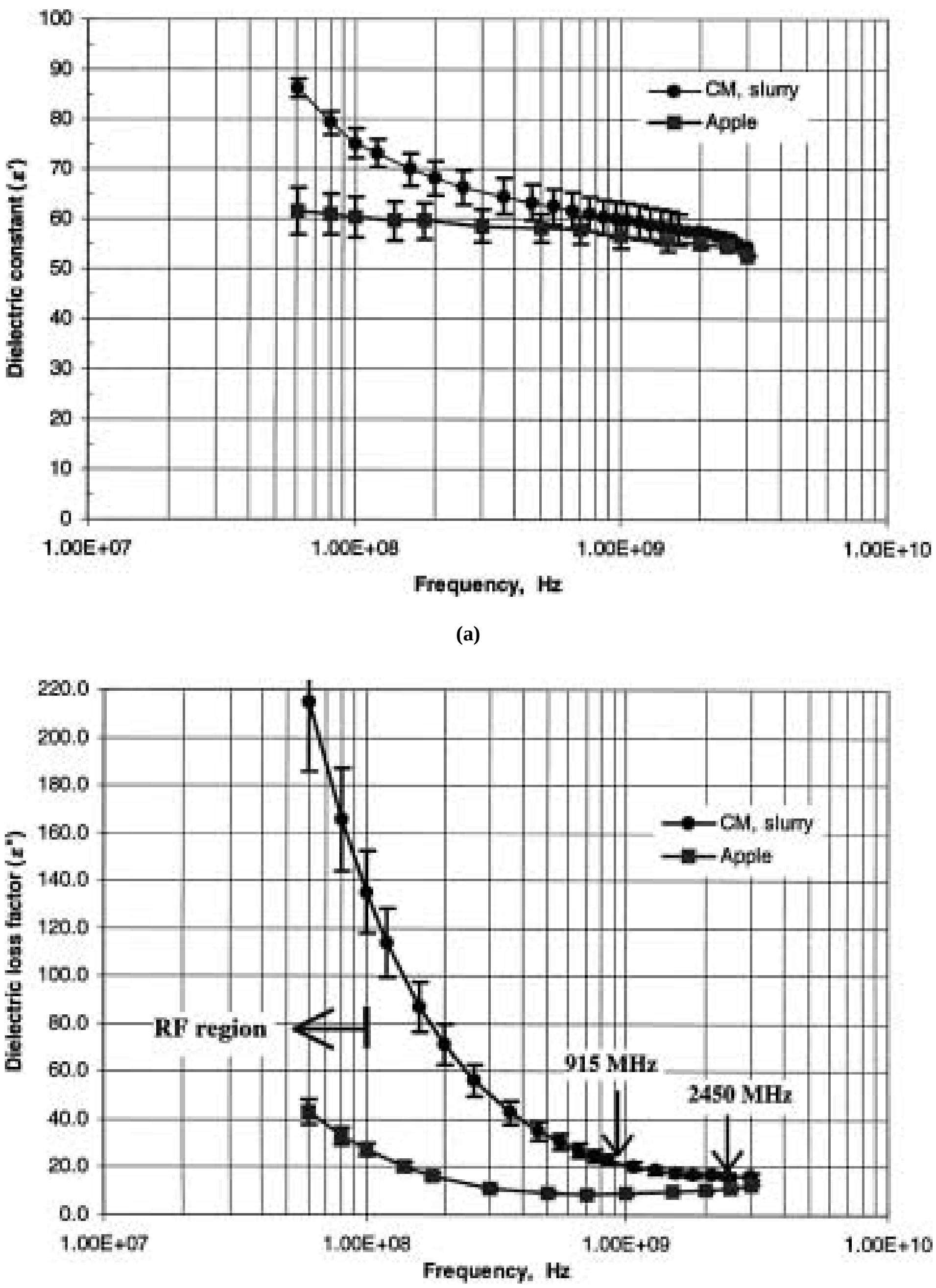
either remained constant or slightly decreased with increasing temperature at 915 MHz and 2450 MHz, thermal "runaway", a phenomenon where temperatures at hot spots keep increasing faster relative to other portions of food material during microwave or RF heating, is unlikely at 915 MHz and 2450 MHz, while it may be expected to pose a problem during RF heating.

Dielectric Properties of Codling Moth Larvae

Dielectric properties of crushed (slurry) fifth instars were significantly higher than for whole insects, particularly at the RF and lower microwave frequencies (table 1). This was expected and can be partly attributed to probable higher packing density of crushed insects compared to the whole insects, and liberation of the constituent ions from the damaged insect tissue. A much more marked difference (in the order of 10) between homogenized and whole grain beetle eggs was reported by Ondracek and Brunnhofer (1984) at 2375 MHz. Those authors suggested that the differences might have been due to the organization of the sample in the electric field. The difference in our result at 2450 MHz were eight and two units for ε′ and ε″, respectively. The insect we studied was, however, different from those of the above authors. The fourth through fifth instar codling moth larva is much larger, having softer and fattier tissues and higher moisture content than grain weevils. Thus, the difference between the slurry and whole insects in our study appeared reasonable.

Both ε′ and ε″ of third instars at the RF region were higher than those of the fifth instars (table 1). The fifth instars are known to possess a high amount of hemolymph (“blood”), a larger mass of cuticle, and fat-body (“fat”). No information on the proportion of fat-body in codling moth larvae could be found in the literature. It is inferred that the cuticle and fat-body both combine to lower the dielectric properties in the fifth instars. Ryynänen (1995) noted that bulky fat molecules have low dielectric properties while Herve et al. (1998) found that fat tends to suppress electrical properties in mixtures.

Figure 4 compares the dielectric properties of apple and codling moth fifth larvae. The ε′ of codling moth larvae exhibited similar pattern as for the apples, decreasing monotonically but more rapidly with increasing frequency. At the RF frequency region, the ε′ of the codling moth larvae was much higher than the apples, but was similar at 915 MHz and above. Differences between ε″ of codling moths and apples was more pronounced, the former being much higher than that of apples. Unlike the apples, the ε″ of codling moths did not exhibit a U-shape but continuously decreased from a value about five times that of the apple at 60 MHz to about the same value as for apples at 3000 MHz. Much higher ε″ of insects at the RF frequencies suggests the existence of a large amount of

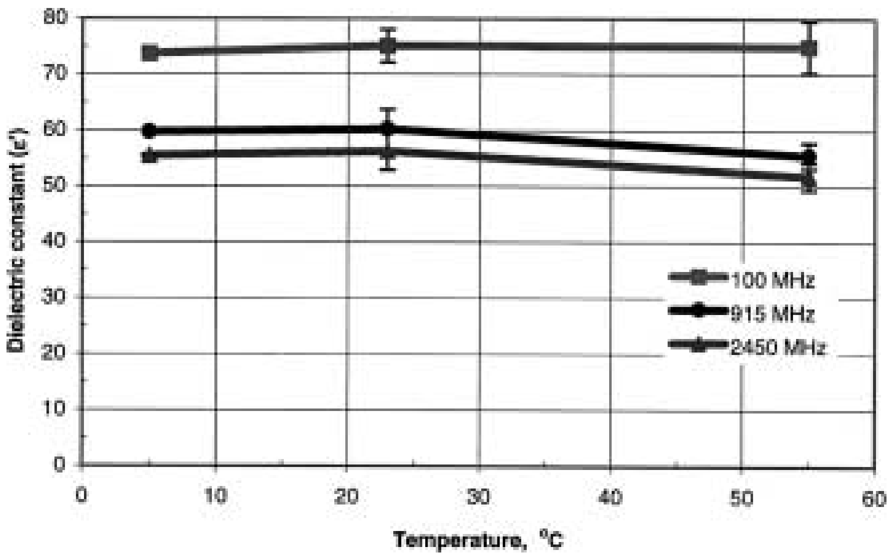


(b)

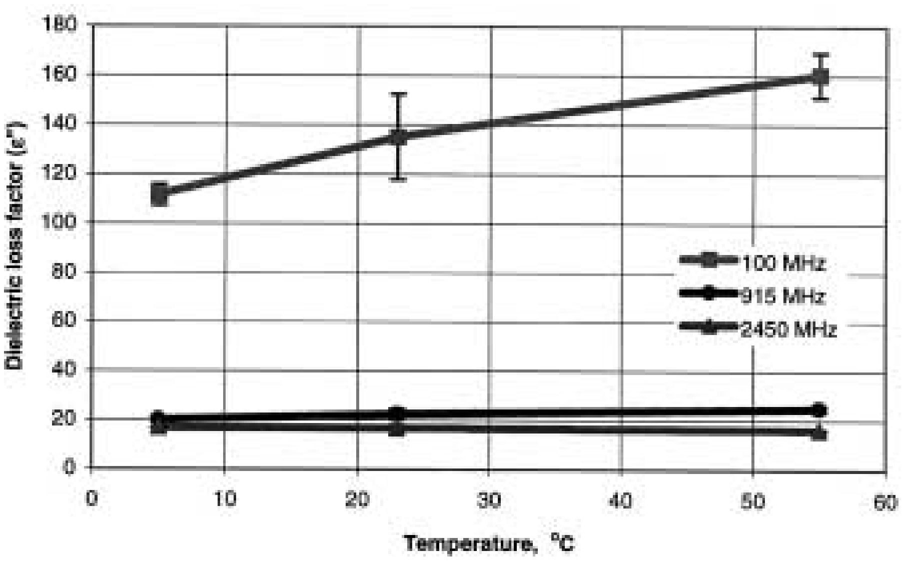
Figure 4–Dielectric properties of apple and codling moth (CM) larvae (a) dielectric constant (ε′) and (b) dielectric loss factor (ε″) at 23°C.

ionic constituents in the insect hemolymph, because ionic polarization mechanism dominates the loss contribution at those frequencies. On the other hand, sugar (fructose mainly), which constitutes soluble solids in the apple, is a large non-polar molecule which may not significantly influence ε″ (Herve et al., 1998). Nelson and Charity (1972) also reported that the dielectric properties of the adult rice weevil were higher than those of the host wheat within the frequency range employed in this study. However, results reported by Colpitts et al. (1992) for three anatomical parts of the Colorado potato beetle and potato plant host materials were opposite to the above two findings. At similar frequencies, dielectric property of codling moth larvae obtained in our study were slightly higher than those of Colpitts et al. (1992) for different anatomical parts of Colorado potato beetle, and Andreuccetti et al. (1994) for woodworms. The results reported by Nelson et al. (1997) for rice weevils (corrected for sample bulk density) were even much lower (particularly ε″ which was about half) than obtained in this study. The insects considered by those authors, however, were different from codling moth physiologically and anatomically. These insects also derived their food from different agricultural materials. From the foregoing and all things being equal, it appears that differential heating of the insects during electromagnetic heat treatment of codling moth infested apples would be most significant within the RF region, but only slightly in the lower microwaves range. It must be noted, however, that factors other than dielectric loss alone may also affect electromagnetic energy coupling and heating pattern of biological materials.

The effect of temperature on the dielectric properties of the codling moth larvae resembled that of the apples, although the values were higher for the codling moth



(a)



(b)

Figure 5–Effect of temperature on the dielectric properties of codling moth larvae at one RF (100 MHz) and two microwave frequencies (915 and 2450 MHz) at 23°C (a) dielectric constant (ε′) and (b) dielectric loss factor (ε″).

instars (fig. 5). Loss factor was highly dependent on temperature at the lower frequencies (RF), but showed little or no dependence at higher frequencies (microwave region). Ryynänen (1995) has also noted that typically, ionic loss contribution to the dielectric property of materials is strongly temperature dependent. These results further suggest that runaway heating of the codling moth larvae may further aid differential heating of infested apples at the RF region.

CONCLUSION

Dielectric constant of apples and codling moth instars generally decreased with increasing frequency and temperature. Dielectric loss factor showed a minimum at about 915 MHz microwave frequency for the apples, but decreased asymptotically for the codling moth instars within the frequency range investigated. There was no significant difference between the dielectric properties close to the surface or core of the apples. No difference was observed among apple cultivars or between the old and new apple crops. The dielectric properties of the codling moth third instars were generally higher than those of the fifth instars in the radio frequency (RF) range. The dielectric properties of codling moth larvae were higher than those of the host apple at the RF range and microwave frequencies below the 915 MHz, suggesting that differential heating may be obtainable at these regions. Furthermore, the dielectric loss factor changed very little with temperature at the microwave frequencies but markedly at the RF region, suggesting that runaway heating may supplement selective heating of insects in infested apples during postharvest quarantine treatment using RD energy. There was no clear correlation between firmness, soluble solids content, and titratable acidity with the dielectric properties of the apples.

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