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Dielectric Properties of Fruits and Insect Pests as related to Radio Frequency and Microwave Treatments

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Information on dielectric properties of commodities and insect pests is needed in developing thermal treatments for postharvest insect control based on radio frequency (RF) and microwave energy. Dielectric properties of six commodities along with four associated insect pests were measured between 1 and 1800 MHz using an open-ended coaxial-line probe technique and at temperatures between 20 and 60°C. The dielectric loss factor of fresh fruits and insects decreased with increasing frequency at constant temperatures. The loss factor of fresh fruits and insects increased almost linearly with increasing temperature at 27 MHz radio frequency, but remained nearly constant at 915 MHz microwave frequency. Both dielectric constant and loss factor of nuts were very low compared to those of fresh fruits and insects. The temperature effect on dielectric properties of nuts was not significant at 27 MHz. The large difference in the loss factor between insects and nuts at 27 MHz suggests possible differential heating of insects in nuts when treated at the same time in a RF system.

1. Introduction

There has been an increasing interest in using radio frequency (RF) and microwave energies as a new thermal treatment method for postharvest insect control in agricultural commodities (Tang *et al.*, 2000). The electromagnetic energy directly interacts with commodities to raise the interior temperature and significantly reduce treatment times as compared to conventional hot-water immersion and heated air methods. Thermal treatments for insect control using RF and microwave systems leave no chemical residues on products, have acceptable quality and have minimal impacts on the environment. Many studies have been reported to explore the possibility of using electromagnetic energy to disinfest insect pests (Headlee & Burdette, 1929; Frings, 1952; Nelson & Payne, 1982). Andreuccetti *et al.* (1994) reported on the possibility of using 2450 MHz microwaves to kill woodworms by heating the larvae to 52–53°C in less than 3 min. Hallman and Sharp (1994) and Nelson (1996) summarised research on the application of RF and microwave treatments to kill selected pests in many postharvest crops. Recently, treatments were developed using microwaves to control codling moths in cherries (Ikediala *et al.*, 1999), and RF energy to control the codling moth (Wang *et al.*, 2001a) and navel orangeworm (Wang *et al.*, 2002) in in-shell walnuts, all with acceptable product quality. These reports showed the potential of using electromagnetic energy to control insects in different commodities. Knowledge of dielectric properties of insects and commodities is necessary in guiding further development, improvement and scaling-up of RF and microwave treatment protocols.

Permittivity describes dielectric properties that influence reflection of electromagnetic waves at interfaces and the attenuation of the wave energy within materials. The complex relative permittivity ε^* of a material can be expressed in the following complex form:

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

The real part ε' is referred to as the dielectric constant and represents stored energy when the material is exposed to an electric field, while the dielectric loss factor ε'', which is the imaginary part, influences energy absorption and attenuation, and $j = \sqrt{-1}$. Mechanisms that contribute to the dielectric loss in heterogeneous mixtures include polar, electronic, atomic and Maxwell–Wagner responses (Metaxas & Meredith, 1993). At RF and microwave frequencies of practical importance and currently used for applications in food processing (RF of 1–50 MHz and microwave frequencies of 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; σ is the ionic conductivity in S m^{-1} of a material, ω is the angular frequency in rad s^{-1} and ε_0 is the permittivity of free space or vacuum ($8{\cdot}854 \times 10^{-12}$ F m^{-1}). Dielectric materials, such as most agricultural products, convert electric energy at RF and microwave frequencies into heat. The increase in temperature of a material due to dielectric heating can be calculated from (Nelson, 1996):

$$\rho C_p \frac{\Delta T}{\Delta t} = 5{\cdot}563 \times 10^{-11} f\, E^2\, \varepsilon'' \qquad (3)$$

where: C_p is the specific heat of the material in $Jkg^{-1}{}^\circ C^{-1}$, ρ is the density of the material in kg/m^{-3}, E is the electric field intensity in Vm^{-1}, f is the frequency in Hz, Δt is the time duration in s and ΔT is the temperature rise in the material in °C. It is clear from Eqn (3) that the rise in temperature is proportional to material's dielectric loss factor, in addition to electric field intensity, frequency and treatment time.

The three most popular methods for measuring dielectric properties of foods and commodities are: open-ended coaxial probe, transmission line and resonant cavity method (Ohlsson, 1980). The probe method is based on a coaxial line ending abruptly at the tip that is in contact with the material being tested. This method offers broadband measurements while minimising sample disturbance. The measured reflection coefficient is related to the sample permittivity (Sheen & Woodhead, 1999). The probe method is the easiest to use because it does not require a particular sample shape or special containers. The transmission line method involves placing a sample inside an enclosed transmission line. The cross-section of the transmission line must be precisely filled with sample. This method is usually more accurate and sensitive than the probe method, but it is difficult to use and time consuming. The resonant cavity method uses a single-mode cavity. Once a sample of known geometry is placed in the cavity, the changes in reflected power of the cavity and the frequency of resonance are used to compute the dielectric property of the sample. The cavity method can be accurate and is especially suited for samples with a very low dielectric loss factor, however, this method provides dielectric properties at only one fixed frequency (Engelder & Buffler, 1991).

Frequency, temperature, salt content, moisture content and the state of moisture (frozen, free or bound) are the major factors that influence dielectric properties of agricultural and biological materials. Many studies on dielectric properties have been reported for different frequency ranges, temperatures and moisture contents (Tran *et al.*, 1984; Engelder & Buffler, 1991; Seaman & Seals, 1991; Herve *et al.*, 1998; Berbert *et al.*, 2001; Garcia *et al.*, 2001; Feng *et al.*, 2002). Several comprehensive reviews on dielectric properties provide good sources of useful experimental data from many foods and agricultural products (Nelson, 1973; Mohsenin, 1984; Mudgett, 1986; Kent, 1987; Foster & Schwan, 1989; Ryynänen, 1995). Dielectric properties at room temperature were also reported for apples from 0·2 to 20 GHz (Nelson *et al.*, 1994), for apples and oranges from 0·15 to 6·4 GHz (Seaman & Seals, 1991) and for grape juice from 0·2 to 3 GHz (Garcia *et al.*, 2001). Limited reports are available on dielectric properties of insects such as grain weevils (Nelson & Payne, 1982), potato beetles (Colpitts *et al.*, 1992), and woodworms (Andreuccetti *et al.*, 1994). Recently, Ikediala *et al.* (2000) reported dielectric properties of four apple cultivars and codling moth larvae in a relatively high-frequency range (30–3000 MHz). A Hewlett Packard network analyser and an open-ended coaxial probe used in that study failed to yield reliable values of dielectric properties when the frequency was close to or lower than 30 MHz due to observable noise. Previous studies have reported the possibility of preferential heating of codling moth in selected commodities at low frequencies (Tang *et al.*, 2000; Wang *et al.*, 2001a; Ikediala *et al.*, 2002). However, no data have been reported on the dielectric properties of the important insect pests such as the Indianmeal moth, the Mexican fruit fly and the navel orangeworm and those of typical host commodities such as cherry, walnut and grapefruit. Reliable dielectric property data for those insects and agricultural commodities over a temperature between 20 and 60°C will be very helpful in developing effective pest control treatment methods based on electromagnetic energy.

The objectives of this research were: (1) to measure dielectric properties of four important insect pests (codling moth, Indianmeal moth, Mexican fruit fly and navel orangeworm) and six commodities (apple, cherry, almond, walnut, orange and grapefruit); (2) to determine the effects of frequency (1–1800 MHz) and temperature (20–60°C) on these properties; and (3) to determine the penetration depth of electromagnetic energy into those commodities at 27, 915 and 1800 MHz frequencies commonly used in dielectric heating applications.

2. Materials and methods

2.1. *Fruit and insect samples*

Apple cultivars including 'Red Delicious' (RD) and 'Golden Delicious' (GD), and 'Bing' sweet cherries used in this study were obtained from the commercial cherry orchards in Wenatchee, WA. Walnut (*Juglans regia* L., *cv* Hartley) and almond (Nonpareil) were obtained from commercial processors in California, and shipped to Washington State University (WSU). The initial moisture contents of RD, GD apple samples and cherries were 87, 86 and 88% w.b., respectively. Navel orange (*Citrus sinensis* L. Osbeck) and grapefruit (*Citrus paradisi* Macfad.) were obtained from USDA-ARS Crop Quality and Research Laboratory, Weslaco, TX, with the initial moisture content of 88% w.b. Fruit flesh (pulp) and nut kernels were used for dielectric property measurements. An electric blender was used to break the fruit flesh into paste and the nut kernels into powder. The initial moisture content of nut kernels was 3% w.b. Samples were held at room temperature shortly before tests.

Fifth-instar codling moth larvae, *Cydia pomonella* (L.) were reared at USDA-ARS, Yakima Agricultural Research Laboratory in Wapato, WA. Fifth-instar larvae of Indianmeal moth, *Plodia interpunctella* (Hübner) and navel orangeworm *Amyelois transitella* (Walker) were reared at the USDA-ARS Horticultural Crops Research Laboratory (HCRL), Parlier, CA. Third-instar Mexican fruit flies, *Anastrepha ludens* (*Loew*) were reared at USDA-ARS Crop Quality and Research Laboratory, Weslaco, TX. All larvae were packed in insulated shipping cartons, and shipped via overnight delivery to WSU. Based on our previous study (Ikediala *et al*., 2000), both the dielectric constant and loss factor of compacted codling moths had no significant differences from that of live larvae. Before recording dielectric property measurements, insect larvae were extracted from artificial diet and live larvae were blended into slurry. The initial moisture content of insect slurry was about 74% w.b. About 30 cm^3 of slurry was used for each sample to avoid electromagnetic field perturbation by the sample holder. Tests with insect larvae were conducted immediately after blending to minimise degradation of the haemolymph and other constituents.

2.2. *Measurement system*

It is highly desirable to measure dielectric properties of biomaterials over the temperature range commonly experienced in insect controls (Herve *et al*., 1998; Ikediala *et al*., 2000; Nelson & Bartley, 2000). As thermal treatments for controlling insects in commodities are between 20 and 60°C, this temperature range was used for the measurement of dielectric properties over a frequency range from 1 to 1800 MHz using the open-ended coaxial probe technique (*Fig. 1*). A test cell (20 mm in inner diameter and 94 mm in height) made of stainless steel was developed to control and maintain the sample temperature during the measurements. The coaxial probe was connected to an impedance analyser

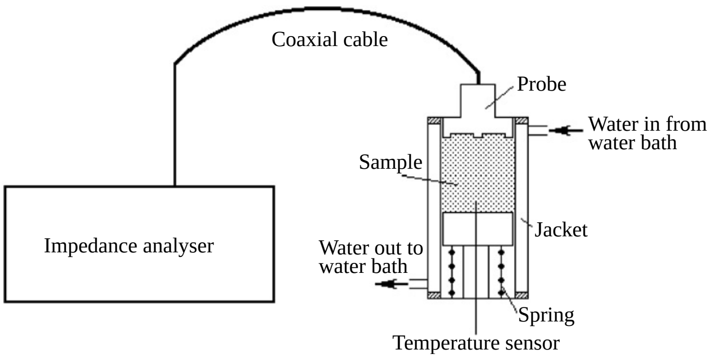

Fig. 1. Schematic view of the dielectric property measurement system and the sample size is 20 mm in diameter and 25 mm in height

(Model 4291B, Innovative Measurement Solutions Inc., Santa Clara, CA). The sample was confined in a sample cell with a pressure spring to ensure a close contact between the tip of the coaxial probe and the sample during the measurements. The sample temperature was controlled by circulating water ($15\,l\,min^{-1}$) from a water bath (Model 1157, VWR Scientific Products, Niles, IL, USA) into the jacket of the test cell. A 10% water and 90% ethylene glycol solution was used as a heat transfer medium. A type T thermocouple (0·8 mm diameter and 0·8 s response time) was used to monitor the sample temperature.

Before measurements, the impedance analyser (Hewlett Packard Corp., Santa Clara, CA) was calibrated with open air, a short (a metal block to provide a short to the coaxial tip), and a 50 Ω load and a low-loss capacitor. The coaxial probe was calibrated with a standard air-short-triple deionised water calibration procedure. Typical error of the system was about 5% after following the standard calibration process. To verify the calibration results and the sample size effect on the dielectric property, butyl alcohol in the cell was measured at room temperature because its dielectric property is well known and its loss factor has a peak value near 250 MHz (Garg & Smyth, 1965). Dielectric property results for butyl alcohol obtained by the impedance analyser were compared with those obtained by a network analyser measurement system (Model 85070B, Hewlett Packard Corp., Santa Clara, CA) to determine the measurement accuracy of two systems. Dielectric properties obtained by the latter system were reliable and accurate within a frequency range from 30 to 3000 MHz (Ikediala *et al.*, 2000). To further check the reliability of the impedance analyser, dielectric properties of butyl alcohol at 20°C were also compared with literature values reported by Garg and Smyth (1965).

2.3. *Measurement procedure*

Dielectric properties of insect slurry and selected commodities were measured by the impedance analyser. Before and after each measurement, the probe and the sample cell were cleaned with deionised water and wiped dry. Dielectric properties of each sample were measured at 200 discrete frequencies between 1 and 1800 MHz at 20, 30, 40, 50 and 60°C. Each frequency sweep took about 2 min. After each measurement, the water bath was adjusted to the next temperature level, with sample temperatures reaching the desired level in about 10 min. Dielectric property data for insects and fruits were determined in duplicate. Mean values and standard deviations were calculated from two replicates.

2.4. *Penetration depth*

Penetration depth of microwave and RF power is defined as the depth where the power is reduced to $1/e$ ($e = 2{\cdot}718$) of the power entering the surface. Generally, RF energy penetrates further into fresh fruits and nuts than microwaves because of the much longer wavelength of RF waves. Selection of the appropriate thickness of a material bed in a commercial treatment line relies on the penetration depth of electromagnetic waves in this material. The penetration depth d_p in m of RF and microwave energy in a high loss material can be calculated by (von Hippel, 1954):

$$d_p = \frac{c}{2\pi f\sqrt{2\varepsilon'\left[\sqrt{1+\left(\varepsilon''/\varepsilon'\right)^2}-1\right]}} \tag{4}$$

where: c is the speed of light in free space ($3\times10^8\,m\,s^{-1}$). After obtaining the dielectric properties, the penetration depths into the selected commodities were calculated by the linear interpolation at 27, 915 and 1800 MHz.

3. Results and analyses

3.1. *Precision of the dielectric property measurement system*

Figure 2 shows a good overlap of the dielectric constant ε' and loss factor ε'' for butyl alcohol at 20°C measured with the network analyser and with the impedance analyser. Two systems gave similar shape and values of dielectric properties at frequency bands between 50 and 1800 MHz. The impedance analyser provided reliable values at frequencies between 10 and 1800 MHz, while the network analyser provided reliable values at frequencies between 30 and 3000 MHz. *Fig. 3* shows the dielectric constant ε' and the loss factor ε'' of butyl alcohol at 20°C using the transmission line method obtained by Garg and Smyth (1965) and those obtained in this study by the impedance analyser. A similar dielectric property curve and a peak in the loss factor at about 250 MHz were observed in both studies. Below 10 MHz, the values of ε' and ε'' were nearly 17 and 0, respectively, for both studies. Measurement results in this study agreed well with previously published data, with the largest relative difference between these two studies being 18·7 and 18·3% for the dielectric constant and the loss factor (at 250 MHz), respectively. The comparison results showed that the measurement results obtained by the impedance analyser were reliable and the sample size in the cell was adequate for the dielectric property measurements.

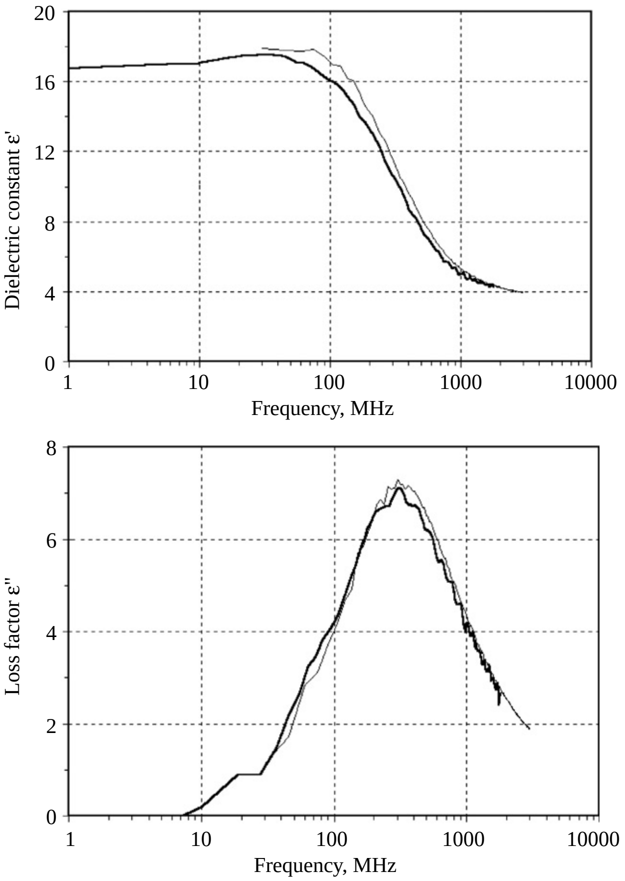

Fig. 2. Dielectric constant and loss factor of butyl alcohol at 20°C measured by the network (——) and impedance (——) analysers

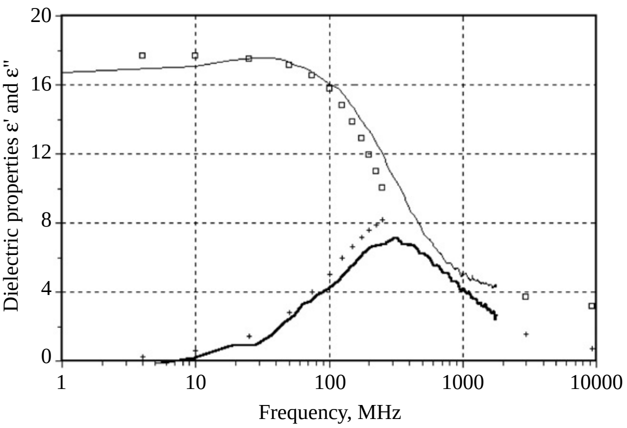

Fig. 3. Dielectric constant (ε′:□) and loss factor (ε″:+) of butyl alcohol at 20°C obtained by Garg and Smyth (1965) and ε′ (——) and ε″ (——) in this study

3.2. *Frequency-dependent dielectric property*

Dielectric properties of insects and commodities at four frequencies and five temperatures as determined by duplicate measurements using the impedance analyser are listed in Tables 1 and 2 for references of postharvest treatments using electromagnetic energy. The following discussion is focused only on trends with regard to temperature and frequency.

Mean values of the dielectric constant and the loss factor of 'Golden Delicious' (GD), 'Red Delicious' (RD) apples, and 'Bing' sweet cherry at 20°C are shown in *Fig. 4*. From 27 to 1800 MHz, the dielectric constant of apples ranged from about 74 to 67, and that of cherry changed from 91 to 71. The loss factors of apples and cherries decreased with increasing frequency to reach minimum values of about 8·5–16·4 at 915 MHz. The loss factor of cherry ranged from 293 to 16 in the frequency range of 27–1800 MHz and was higher than that of apples (from about 120 to 10). In this study, the mean values at 915 MHz for GD apples, RD apples and cherries were 74·3, 77·0 and 73·7, respectively, for the dielectric constant, and 8·5, 10·0 and 16·4, respectively, for the loss factor. These compare to the corresponding values obtained by Ikediala *et al.* (2000, 2002) of 56·5, 57·9 and 69·7 for the dielectric constant and 9·2, 9·5 and 14·3 for the loss factor. It should be pointed out that the dielectric constant curves of the golden and red delicious apples exhibited a local maximum at a frequency range of 200–900 MHz. It was probably due to some artefact of the measurement system as Feng *et al.* (2002) mentioned.

Mean values of the dielectric constant and the loss factor of grapefruit and orange at 20°C are shown in *Fig. 5*. Dielectric properties of grapefruit and orange had a similar trend and decreased with increasing frequency. In general, the dielectric constant and the loss factor for grapefruit and orange were very close at frequencies above 100 MHz. In the RF region (< 50 MHz), the dielectric constant of grapefruit was larger than that of orange, while the reverse was true for loss factors.

Mean values of the dielectric constant and the loss factor of almond and walnut at 20°C are shown in *Fig. 6*. Dielectric properties of almond and walnuts were below 7. This is because these nut kernels had a low moisture content (3% w.b.) and high oil content (about 50%). This was comparable with the values of the dielectric constant (2·7) and loss factor (0·3) for walnuts at 2000–3000 MHz obtained by Olmi *et al.* (2000). A similar trend was observed for the dielectric constant and loss factor for the two nuts. There was a peak value for loss factors at about 590 MHz at 20°C. This might have been the result of bound water. Harvey and Hoekstra (1972) also found that the bound water in lysozyme caused a peak value (3–5) of the dielectric loss factor at about 300 MHz at 25°C.

Table 1
Dielectric properties (mean ± STD of two replicates) of fruits and nuts at five temperatures and four frequencies

Material	*Temp.*,°C	*Dielectric constant*				*Loss factor*			
		Frequency, MHz				*Frequency, MHz*			
		27	*40*	*915*	*1800*	*27*	*40*	*915*	*1800*
Apple (GD*)	20	72·5 ± 0·6	72·6 ± 0·7	74·3 ± 0·8	67·4 ± 0·9	120·4 ± 2·1	80·5 ± 1·5	8·5 ± 0·8	9·9 ± 0·1
	30	71·3 ± 0·8	71·3 ± 0·8	72·3 ± 0·7	66·0 ± 0·9	143·9 ± 2·0	96·4 ± 1·4	8·5 ± 1·1	8·7 ± 0·0
	40	69·7 ± 0.8	69·7 ± 0·8	70·0 ± 0·8	64·1 ± 0·9	171·8 ± 2·6	115·3 ± 1·7	8·2 ± 0·9	7·6 ± 0·0
	50	68·1 ± 0·8	67·9 ± 0·8	67·8 ± 1·0	62·1 ± 1·0	202·2 ± 3·3	135·8 ± 2·2	8·3 ± 0·6	6·9 ± 0·1
	60	66.5 ± 0.8	66·4 ± 0·9	65·6 ± 1·0	60·1 ± 1·0	234·1 ± 4·3	157·4 ± 2·7	8·7 ± 0·3	6·7 ± 0·1
Apple (RD)	20	74·6 ± 0·6	74·7 ± 0·5	77·0 ± 0·0	70·4 ± 0·5	92·0 ± 0·9	61·1 ± 0·8	10·0 ± 1·4	10·8 ± 0·2
	30	72·7 ± 0·8	72·8 ± 0·7	74·5 ± 0·2	68·3 ± 0·4	109·1 ± 0·6	72·8 ± 0·6	9·4 ± 1·8	9·4 ± 0·7
	40	70·6 ± 0·8	70·8 ± 0·8	71·5 ± 0·1	66·1 ± 0·5	130·7 ± 1·1	87·5 ± 0·8	10·0 ± 2·5	8·3 ± 0·7
	50	68·7 ± 0·9	68·7 ± 0·8	68·9 ± 0·2	64·0 ± 0·5	153·8 ± 1·6	103·1 ± 1·3	9·8 ± 2·8	7·4 ± 0·8
	60	66·8 ± 1·0	66·8 ± 0·8	67·1 ± 0·5	62·0 ± 0·8	178·6 ± 2·3	119·9 ± 1·6	8·9 ± 1·9	6·7 ± 0·7
Almond	20	5·9 ± 0·1	5·9 ± 0·1	1·7 ± 0·9	5.8 ± 0.2	1·2 ± 0·2	1·5 ± 0·2	5·7 ± 0·5	2·9 ± 0·8
	30	5·7 ± 1·7	5·9 ± 1·8	3·2 ± 2·3	3·4 ± 2·3	0·6 ± 0·2	1·1 ± 0·6	6·4 ± 1·8	3·4 ± 0·9
	40	5·8 ± 1·6	6·1 ± 1·9	3·3 ± 2·0	3·6 ± 2·1	0·6 ± 0·1	1·0 ± 0·5	6·0 ± 1·3	3·5 ± 0·7
	50	5·8 ± 1·6	6·2 ± 1·8	3·4 ± 0·5	4·2 ± 1·6	0·6 ± 0·3	1·1 ± 0·6	5·7 ± 0·1	3·4 ± 0·2
	60	6·0 ± 1·5	6·3 ± 1·8	3·1 ± 1·4	3·9 ± 2·3	0·7 ± 0·1	1·1 ± 0·4	6·4 ± 1·3	3·0 ± 1·2
Cherry	20	91·2 ± 0·1	85·0 ± 0·4	73·7 ± 0·1	70·9 ± 0·1	293·0 ± 4·3	198·5 ± 2·9	16·4 ± 0·0	16·0 ± 0·2
	30	91·4 ± 0·9	84·0 ± 0·8	72·0 ± 0·3	69·7 ± 0·3	363·1 ± 11·2	245·7 ± 7·6	17·2 ± 0·5	15·1 ± 0·6
	40	91·0 ± 2·0	82·4 ± 1·6	69·6 ± 0·7	67·8 ± 0·6	44·01 ± 26·6	297·5 ± 18·0	18·3 ± 1·0	14·6 ± 0·9
	50	89·6 ± 3·6	79·9 ± 2·7	66·7 ± 1·6	65·2 ± 1·5	501·9 ± 37·2	338·9 ± 25·1	19·3 ± 1·4	14·2 ± 1·1
	60	89·8 ± 5·5	78·5 ± 3·8	64·1 ± 1·8	62·8 ± 1·6	565·4 ± 54·0	381·8 ± 36·6	20·4 ± 1·9	14·1 ± 1·4
Grape-fruit	20	89·0 ± 5·1	82·7 ± 1·8	72·7 ± 2·5	72·1 ± 1·2	202·4 ± 9·3	137·8 ± 7·0	12·1 ± 0·0	12·6 ± 0·1
	30	90·3 ± 6·8	81·9 ± 2·7	70·8 ± 2·3	70·2 ± 1·1	242·6 ± 8·9	165·2 ± 6·9	12·5 ± 0·2	11·5 ± 0·2
	40	91·9 ± 9·2	81·4 ± 4·0	68·5 ± 2·1	68·2 ± 1·1	291·4 ± 9·0	198·4 ± 7·3	13·3 ± 0·4	10·9 ± 0·2
	50	93·8 ± 11·3	80·9 ± 5·2	66·1 ± 2·1	66·0 ± 0·9	345·3 ± 7·8	235·2 ± 6·9	14·2 ± 0·3	10·7 ± 0·2
	60	96·5 ± 14·0	80·8 ± 6·6	63·7 ± 2·0	63·7 ± 0·8	401·1 ± 5·8	273·3 ± 5·8	15·5 ± 0·3	10·7 ± 0·2
Orange	20	84·0 ± 0·1	81·0 ± 0·1	72·9 ± 1·9	72·5 ± 0·1	223·3 ± 0·6	151·6 ± 0·3	16·5 ± 2·8	14·8 ± 0·5
	30	82·2 ± 0·3	78·5 ± 0·3	70·6 ± 1·8	70·7 ± 0·3	267·9 ± 1·8	181·6 ± 1·1	17·8 ± 2·7	13·9 ± 0·5
	40	80·2 ± 0·7	75·7 ± 0·6	68.0 ± 2.1	68·6 ± 0·4	318·0 ± 5·3	215·3 ± 3·4	18·7 ± 3·0	13·1 ± 0·5
	50	78·0 ± 0·5	72·7 ± 0·4	66·1 ± 0·6	65·6 ± 0·2	367·7 ± 5·0	248·6 ± 3·4	17·5 ± 1·2	12·3 ± 0·2
	60	75·8 ± 0·9	69·9 ± 0·6	63·2 ± 0·7	62·7 ± 0·3	418·4 ± 6·5	282·8 ± 4·3	18·4 ± 1·2	12·2 ± 0·2
Walnut	20	4·9 ± 0·0	4·8 ± 0·0	2·2 ± 1·6	2·1 ± 0·7	0·6 ± 0·0	0·7 ± 0·1	2·9 ± 0·1	1·8 ± 0·2
	30	5·0 ± 0·1	4·9 ± 0·1	2·1 ± 0·3	2·7 ± 0·2	0·5 ± 0·1	0·6 ± 0·1	2·6 ± 0·1	1·6 ± 0·2
	40	5·1 ± 0·1	5·1 ± 0·1	3·0 ± 0·1	3·2 ± 0·0	0·4 ± 0·0	0·6 ± 0·1	2·3 ± 0·1	1·3 ± 0·2
	50	5·2 ± 0·1	5·1 ± 0·0	3·4 ± 0·0	3·5 ± 0·0	0·3 ± 0·1	0·5 ± 0·1	2·0 ± 0·0	1·1 ± 0·1
	60	5·3 ± 0·0	5·2 ± 0·0	3·8 ± 0·0	3·7 ± 0·0	0.4 ± 0.1	0·5 ± 0·0	1·8 ± 0·0	1·0 ± 0·1

*GD, Golden Delicious; RD, Red Delicious.

Values of dielectric constant and loss factor of codling moth, Indianmeal moth, Mexican fruit fly and navel orangeworm larvae at 20°C are shown in *Fig. 7*. Both the dielectric constant and loss factor decreased with increasing frequency. Mexican fruit fly had the maximum loss factor value among the four insects, followed by navel orangeworm, codling moth and Indianmeal moth. Differences in moisture, fat and haemolymph content among those four insects might have resulted in the differences in the dielectric properties (Ryynänen, 1995; Ikediala *et al.*, 2000).

Mean dielectric loss factors of a representative insect (codling moth) at 20°C are shown in *Fig. 8* to compare with the loss factor of the selected commodities such as GD apple, cherry, grapefruit and walnut. The dielectric loss factor of codling moth larvae was larger than that of all the host materials, except for cherry, particularly in the RF range. As shown in Eqn (3), a larger ε'' value resulted in more generation of thermal energy at a given frequency when subjected to the same electromagnetic field. Therefore, codling moth might absorb more energy than apples and grapefruits, and much more than walnuts.

3.3. *Temperature dependent dielectric property*

Figure 9 shows an example of the loss factor of codling moths and walnuts as a function of temperature over the measured frequency range between 1 and

Table 2
Dielectric properties (mean ± STD of two replicates) of four insect larvae at five temperatures and four frequencies

Material	*Temp.,*°C	*Dielectric constant*				*Loss factor*			
		Frequency, MHz				*Frequency, MHz*			
		27	*40*	*915*	*1800*	*27*	*40*	*915*	*1800*
Codling moth	20	71·5 ± 0·9	64·9 ± 0·9	47·9 ± 0·2	44·5 ± 0·1	238·1 ± 0·1	163·3 ± 0·4	11·7 ± 0·1	12·0 ± 0·2
	30	71·5 ± 0·1	63·9 ± 0·2	45·9 ± 0·9	42·9 ± 0·9	277·8 ± 8·5	190·2 ± 5·4	12·5 ± 0·4	11·7 ± 0·3
	40	73·8 ± 0·1	64·5 ± 0·1	44·6 ± 0·6	41·6 ± 0·4	332·4 ± 16·3	227·5 ± 10·5	13·9 ± 0·5	11·9 ± 0·3
	50	79·3 ± 1·1	68·5 ± 1·6	45·6 ± 1·5	42·7 ± 1·5	422·5 ± 5·9	288·6 ± 4·4	16·5 ± 0·3	13·2 ± 0·3
	60	84·5 ± 2·5	71·5 ± 2·9	45·0 ± 2·4	41·9 ± 2·2	511·3 ± 26·6	349·1 ± 18·3	19·1 ± 1·0	14·2 ± 0·7
Indian-meal moth	20	81·3 ± 1·9	69·1 ± 0·9	39·9 ± 0·4	37·5 ± 0·5	210·9 ± 4·8	149·0 ± 3·7	13·4 ± 1·4	10·6 ± 0·6
	30	85·8 ± 2·7	72·0 ± 1·4	39·2 ± 0·0	36·9 ± 0·1	244·1 ± 3·7	172·4 ± 3·0	14·3 ± 1·4	10·6 ± 0·8
	40	94·4 ± 1·5	77·3 ± 0·9	37·6 ± 0·8	35·5 ± 0·9	268·7 ± 25·1	190·9 ± 16·9	15·2 ± 2·1	10·6 ± 1·2
	50	103·7 ± 0·8	83·7 ± 0·5	37·2 ± 1·3	35·3 ± 1·4	314·0 ± 42·8	223·1 ± 28·1	16·9 ± 2·4	11·4 ± 1·5
	60	113·0 ± 3·3	90·4 ± 2·2	37·8 ± 1·6	35·6 ± 1·7	397·4 ± 57·8	280·7 ± 37·9	19·9 ± 2·8	12·8 ± 1·7
Mexican fruit fly	20	90·3 ± 13·6	71·2 ± 0·3	48·5 ± 3·4	47·0 ± 0·7	343·9 ± 15·1	230·9 ± 5·9	17·5 ± 2·0	13·3 ± 1·7
	30	105·1 ± 21·5	87·2 ± 12·1	47·3 ± 3·5	45·5 ± 0·4	384·7 ± 15·2	272·2 ± 18·2	21·3 ± 3·9	13·9 ± 1·9
	40	117·4 ± 28·2	95·4 ± 16·6	46·4 ± 2·9	44·7 ± 0·8	446·1 ± 19·0	316·5 ± 22·4	24·2 ± 5·1	14·5 ± 2·2
	50	128·7 ± 33·6	102·9 ± 20·0	45·7 ± 2·3	44·1 ± 1·4	521·8 ± 32·1	370·7 ± 33·0	26·8 ± 5·7	15·4 ± 2·5
	60	141·2 ± 37·5	111·5 ± 22·8	44·5 ± 2·0	43·0 ± 1·6	582·2 ± 28·1	414·5 ± 31·7	29·4 ± 5·9	16·5 ± 2·7
Navel orange worm	20	80·2 ± 0·3	68·6 ± 0·4	44·5 ± 1·3	42·2 ± 1·4	307·8 ± 4·9	212·6 ± 3·1	16·1 ± 0·1	12·7 ± 0·0
	30	83·6 ± 1·5	70·4 ± 1·0	43·6 ± 0·4	41·5 ± 0·7	359·7 ± 10·5	248·0 ± 7·5	17·5 ± 0·6	12·9 ± 0·4
	40	87·7 ± 2·1	72·7 ± 1·6	42·8 ± 0·1	40·7 ± 0·1	419·4 ± 17·3	288·8 ± 12·0	19·2 ± 0·9	13·4 ± 0·6
	50	92·8 ± 1·6	75·9 ± 1·2	42·3 ± 0·4	40·2 ± 0·1	480·3 ± 24·5	330·8 ± 16·5	21·2 ± 1·0	14·1 ± 0·6
	60	99·4 ± 0·0	80·1 ± 0·0	42·2 ± 0·1	40·0 ± 0·0	562·7 ± 3·3	386·7 ± 2·2	24·0 ± 0·1	15·5 ± 0·0

1800 MHz. The loss factor of fresh fruits and all tested insects had a similar trend as that of codling moths. The loss factor of almonds had a similar trend as that of walnuts with respect to temperature changes. For insects and fresh fruits (*Fig. 9a*), increasing temperature resulted in increasing loss factor at a fixed frequency, especially in the RF range. This may be due to the predominant ionic dispersion at low frequencies. Ionic conductivity generally increases with temperature due to reduced viscosity (Tang *et al.*, 2002). For almonds and walnuts, however, a broad peak was observed in the loss factor at all temperatures. The peak value of the loss factor decreased from 3·6 to 1·9 with increasing temperature from 20 to 60°C. The frequency corresponding to the peak value shifted from 590 to 890 MHz as the temperature increased from 20 to 60°C. This shift of the peak frequency was likely due to increased mobility of molecularly bound water at higher temperatures. A similar shift of a peak for dielectric loss factor can be found for free water but at frequencies over 16 GHz (Tang *et al.*, 2002). The large difference of dielectric loss factor between insects and walnuts at RF frequencies (< 100 MHz) should lead to preferential heating of insects in nuts.

Mean values of the dielectric constant and the loss factor of GD, RD apples and cherry as a function of temperature at 27 and 915 MHz are summarised in Table 1. The dielectric constant of cherry at 27 MHz was significantly higher than that at 915 MHz and than that of apples at all temperatures. The loss factor of apples and cherries increased with increasing temperature at 27 MHz and remained nearly constant at 915 MHz. The loss factor of cherry increased more rapidly as the temperature increased than that of apples at 27 MHz.

Mean values of the dielectric constant and the loss factor of grapefruit and orange as a function of temperature at 27 and 915 MHz are shown in Table 1. The dielectric constant of grapefruit increased slightly with increasing temperature while that of orange decreased slightly at 27 MHz. The values at 915 MHz decreased slightly with increasing temperature and were lower than those at 27 MHz for both grapefruits and oranges. Loss factors of grapefruit and oranges increased with increasing temperature at 27 MHz but remained almost constant at 915 MHz.

Mean values of the dielectric constant and the loss factor of almond and walnut as a function of temperatures at 27 and 915 MHz are also shown in Table 1. The temperature effect on dielectric properties of almond and walnut was not important. The dielectric constant at 27 MHz was higher than that at 915 while the loss factor had a reverse situation for both nuts.

Mean values of the dielectric constant and the loss factor of the targeted insect larvae as a function of temperatures at 27 and 915 MHz are listed in Table 2. Both the dielectric constant and the loss factor for

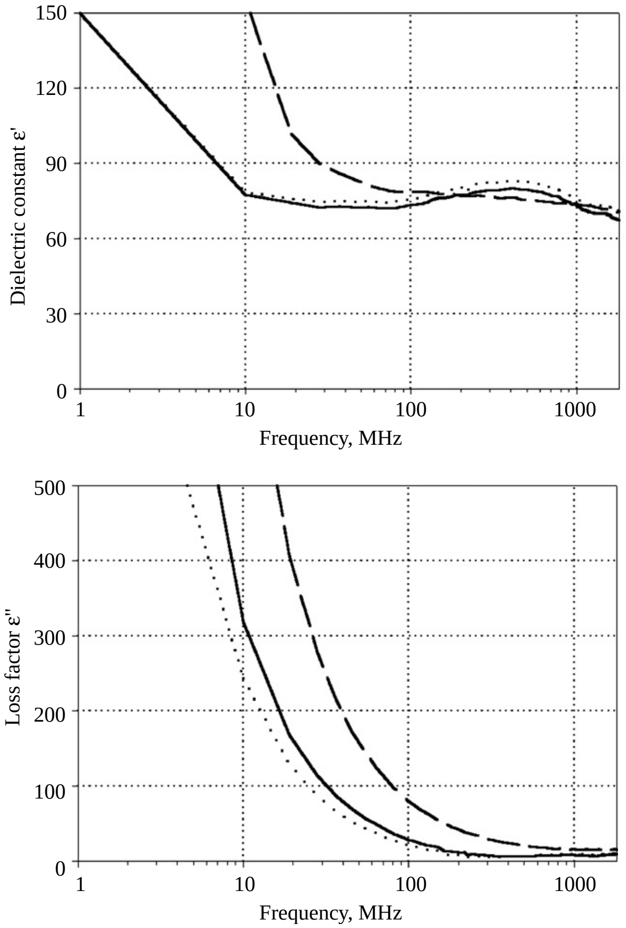

Fig. 4. Dielectric constant (ε′) and loss factor (ε″) of 'Golden Delicious' (GD) apple (——), 'Red Delicious' (RD) apple (······) and cherry (– – –) at 20°C

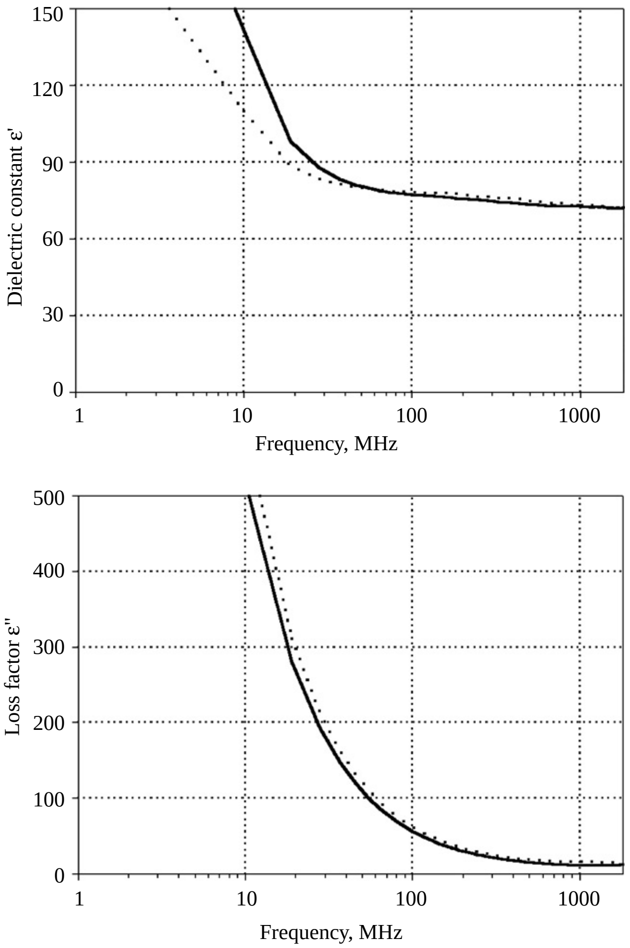

Fig. 5. Dielectric constant (ε′) and loss factor (ε″) of grapefruit (——) and orange (······) at 20°C

insects increased with increasing temperature at 27 MHz, but remained almost constant at 915 MHz. The loss factor of insects at 27 MHz decreased in order at all temperatures: Mexican fruit fly, navel orangeworm, codling moth and Indianmeal moth.

3.4. *Penetration depth*

Penetration depths of fruits and nuts at 20°C were calculated from the measured dielectric properties at 27, 915 and 1800 MHz (Table 3). The penetration depth decreased with increasing frequency. Penetration depths in RD apples were 18·9 and 4·6 cm at 27 and 915 MHz, respectively. These data compared well with the values of 20·0 and 4·4 cm reported by Ikediala *et al.* (2000) for the same material and frequencies. Penetration depths for cherries were 8·5 and 2·8 cm at 27 and 915 MHz, which were close to 9·8 and 3·1 cm obtained by Ikediala *et al.* (2000) for cherries at the two frequencies. Penetration depths in almonds and walnuts at 27 MHz reached 538 and 654 cm due to their low moisture contents. Deep penetration depths in nuts at 27 MHz might make it possible to design a continuous operation with conveyor belts transporting multi-layer products through two RF plate electrodes. Microwaves at 915 and 2450 MHz, however, might not be able to treat more than two-layer nuts, because of the smaller penetration depths (2–3 cm). Limited penetration depths led to non-uniform heating in large fruits, especially in the microwave frequency region. This might in part explain the disappointing results reported by Seo *et al.* (1970) and Hayes (1984) when using 2450 MHz microwaves to treat mangoes and papaya.

4. Discussion

Temperature effects on the dielectric property of a material are complicated because free water dispersion,

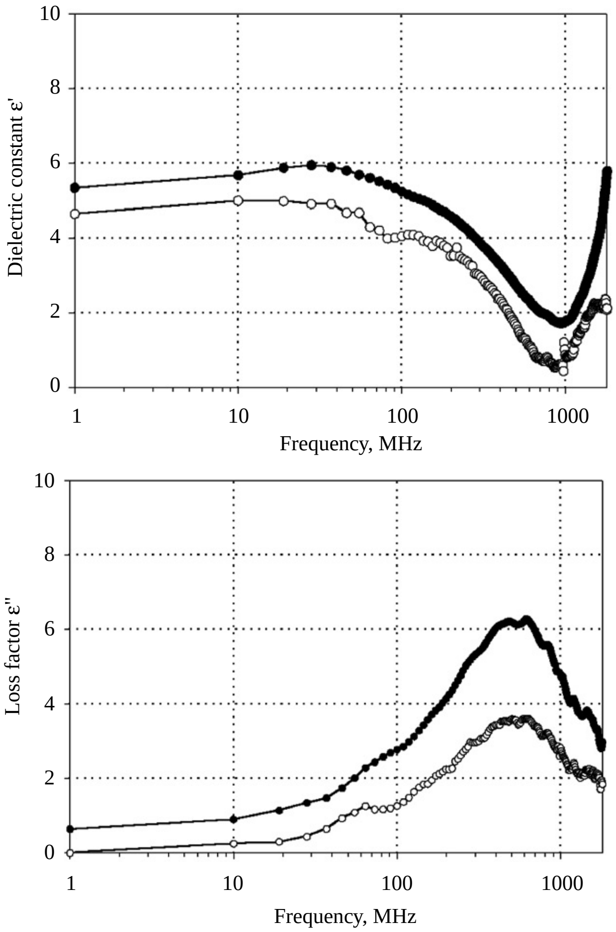

Fig. 6. Dielectric constant (ε′) and loss factor (ε″) of almond (●) and walnut (○) at 20°C

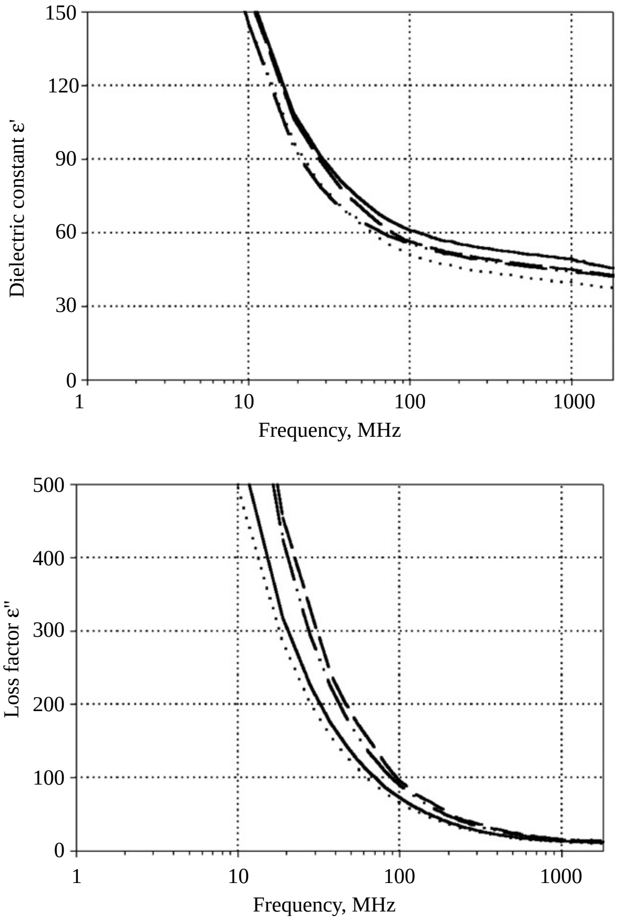

Fig. 7. Dielectric constant (ε′) and loss factor (ε″) of codling moth (——), Indianmeal moth (······), Mexican fruit fly (– – –) and navel orangeworm (–••–) at 20°C

bound water dispersion, and ionic conduction determine the response within a broad frequency range (Perkin, 1979; Feng *et al.*, 2002). At 27 MHz, ionic dispersion was predominant for fresh fruits and insects. The loss factor of insects and fruits at this frequency always increased with increasing temperature because of an increased ionic conductivity as a result of reduced viscosity at high temperatures (Tang *et al.*, 2002). This may cause an undesirable thermal run away effect during dielectric heating. This effect serves as a positive-feedback in which any difference in temperature tends to accelerate heating in warmer regions and results in greater temperature differences. It is important that the fruits to be heated should have a fairly uniform initial temperature and be exposed to uniform electromagnetic field if a uniform heating is desired. For nuts, however, the dielectric loss factor at 27 MHz reduces as temperature increases. This may help reduce uneven heating caused by possible non-uniform electric field distribution.

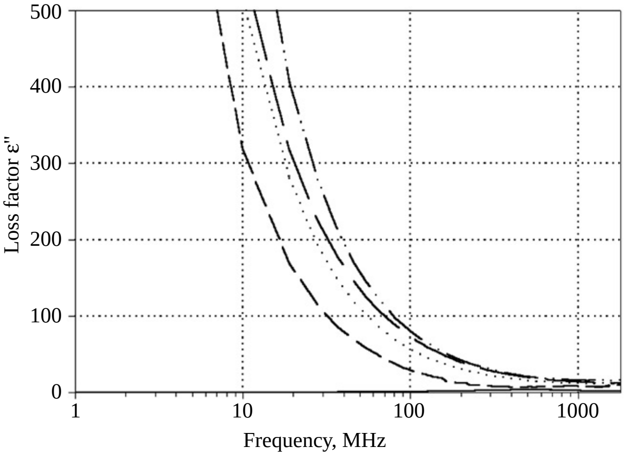

Fig. 8. Dielectric loss factor (ε″) of 'Golden Delicious' (GD) apple (– – –), cherry (–••–), grapefruit (. . .), walnut (——) and codling moth (— —) at 20°C

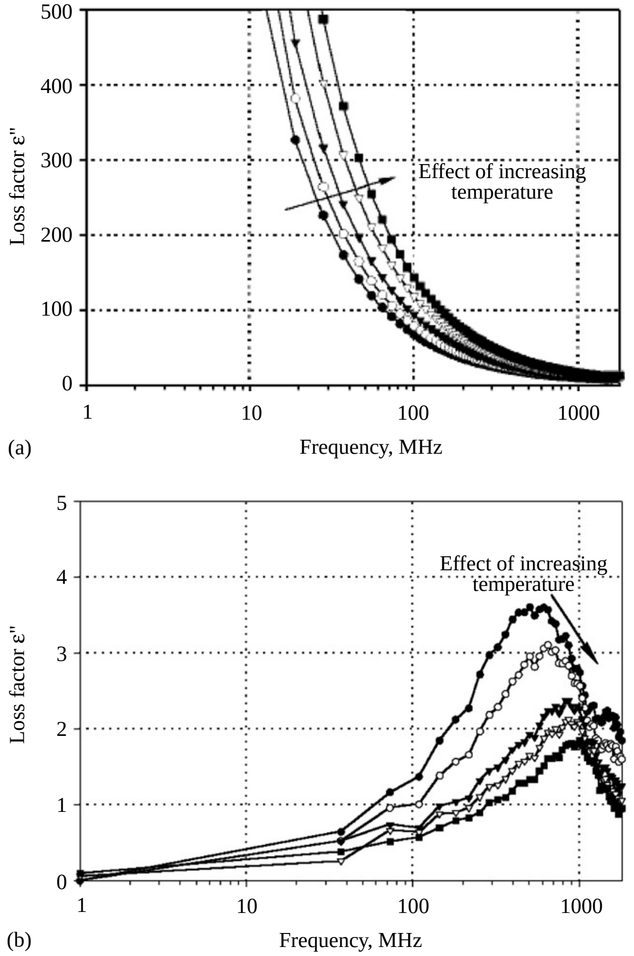

Fig. 9. Dielectric loss factor (ε'') of codling moth (a) and walnut (b) as a function of temperatures (20°C, ●; 30°C, ○; 40°C, ▼; 50°C, ∇; and 60°C, ■)

Table 3
Penetration depths (cm) calculated from the measured dielectric properties at 20°C

Fruits	*Penetration depth, cm*		
	Frequency, MHz 27	*915*	*1800*
GD* apple	15·2	5·3	2·2
RD apple	18·9	4.6	2.1
Almond	538·2	1·9	2·3
Cherry	8·5	2·8	1·4
Grapefruit	10·9	3·7	1·8
Orange	10·1	2·7	1·5
Walnut	653·6	3·1	2·3

*GD, Golden Delicious; RD, Red Delicious.

Radio frequency and microwaves rapidly heat fruits and nuts in pilot-scale systems (Ikediala *et al.*, 1999; Wang *et al.*, 2001a; 2001b). Fresh fruit subjected to RF energy may suffer heat damage at points of contact between fruit and between fruit and the container (Ikediala *et al.*, 2002). Bengtsson *et al.* (1970) used water immersion in RF pasteurisation of cured ham as a method of levelling out electric fields. Recently, Ikediala *et al.* (2002) developed a technique to use a saline solution to match the dielectric property of cherries and to ensure a uniform heating in a RF system. Full immersion of fruits in water may not only reduce the core focusing but also help even up the temperature distribution over whole fruit. Based on the dielectric property data of fruits at 27 MHz, the effective ionic conductivity can be obtained according to the second part of Eqn (2). By matching the ionic conductivity of saline water solution (0.05–2% NaCl) to the effective ionic conductivity of the commodity, it may be possible to raise the temperature uniformly in both core and surface of fruit. Use of immersion in water could also provide additional benefits for heat treatments of surface arthropods on fruits during RF and microwave treatments.

5. Conclusions

Dielectric properties of fruits and insects as affected by frequencies and temperatures can be determined efficiently by suitable temperature control system and the open-ended coaxial-line probe technique. The dielectric loss factor of fruits and insects decreased with increasing frequency. The loss factor of nuts was low in comparison with those of fruits and insects. The loss factor of fruits and insects increased almost linearly with increasing temperature but the temperature effect on nuts was not important at 27 MHz. However, the peak value of the loss factor of almonds and walnuts decreased from 3.6 to 1.9, with the corresponding frequency shifting from 590 to 890 MHz as the temperature increased from 20 to 60°C. This peak was probably the result of dispersion of bound water. The penetration depth in nuts was much larger than that in fruits at 27 MHz. The loss factor of insects was clearly larger than that of nuts in the RF range, suggesting possible differential heating of insects in nuts when treated in the same time in a RF system. But further experiments are needed to confirm the temperature difference between insects and nuts when subjected to the same RF field.

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