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Dielectric properties of egg whites and whole eggs as influenced by thermal treatments

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ABSTRACT

Effects of cooking on dielectric properties of liquid whole eggs and liquid egg whites were studied in connection with radio frequency and microwave heating processes to preserve shelf-stable products. Dielectric measurements were made using an open-ended coaxial probe method over a temperature range of 20 and 120 °C at radio frequencies 27 and 40 MHz, and microwave frequencies 915 and 1800 MHz. Thermal denaturation of liquid egg whites and whole eggs influenced the dielectric constants and dipole loss component of eggs, as reflected by changes in loss factors above 60 °C. In addition, loss factor of liquid whole eggs was generally smaller than that of egg whites and larger than the loss factor of egg yolk. Ionic conductivity was a dominant factor determining the dielectric loss behavior of egg products at radio frequencies, whereas dipole water molecules played an increasing role with an increase in microwave frequencies.

1. Introduction

Thermal processing is a common commercial preservation method to produce shelf-stable low acid ($pH > 4.6$) food products. To achieve commercial sterility, foods are hermetically packed in containers and thermally processed at high temperatures (up to 121 °C or above) to inactivate spores of toxin-producing and heat resistant microorganism, *Clostridium botulinum* type A and B (Mudgett, 1986). For foods, especially solid and semisolid, conventional retort processes are time-consuming due to the slow heat transfer within foods. During a conventional sterilization process, the surface of the packaged food is exposed to high temperature much longer than the inner part, resulting in overcooking of the food. Dielectric heating, including radio frequency (RF) and microwave heating, can potentially reduce processing time and improve heating uniformity because the heat is volumetrically generated inside the food by conversion of alternating electromagnetic (EM) energy to thermal energy (Cathcart, Parker, & Beattie, 1947; Kenyon, Westcott, Case, & Gould, 1971; Kinn, 1947). But engineering design of dielectric heating is hindered by a lack of information about the dielectric properties of selected foods as functions of food composition, temperature, and EM wave frequencies (Zhao, Flugstad, Kolbe, Park, & Wells, 2000). This knowledge is needed in analyzing electromagnetic field distributions in microwave or RF sterilization systems.

The dielectric properties of a food describe its ability to store and dissipate electrical energy in response to an alternating EM field (Mudgett, 1986). Dielectric properties are normally described by complex permittivity, ε_c:

$$\varepsilon_c = \varepsilon' - j\varepsilon'' = \varepsilon_0\left(\varepsilon_r' - j\varepsilon_r''\right) \tag{1}$$

where $j = \sqrt{-1}$. In above equation, the real part ε', referred to as dielectric constant, describes material's ability to store electric energy in an alternating field, while the imaginary part ε'', referred to as loss factor, determines the property of the material to convert electric energy to thermal energy; ε_0 is the permittivity of free space ($=8.854 \times 10^{-12}$ F/m), $\varepsilon_r{}'$ and $\varepsilon_r{}''$ are the relative dielectric constant and the relative loss factor (relative to free space) (Lorrain, Corson, & Lorrain, 1988; Nyfors & Vainikainen, 1989).

The dielectric constant of a polar solution can be expressed as (Debye, 1929):

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (2\pi f)^2\tau^2} \tag{2}$$

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where optical permittivity, ε_∞, represents the dielectric constant when the molecules do not have adequate time to follow the alternating of external electric field to polarize; ε_s represents the static dielectric constant; f is frequency of EM wave, and τ is relaxation time which is a measure of time taken by the molecules to reach random orientation after the external electric field is switched off (Gabriel, Gabriel, Grant, Halstead, & Mingos, 1998). The frequency corresponding to the relaxation time, f_c, is referred to as the critical frequency. The value of the critical frequency of a polar solution increases with temperature but decreases with molecular weight of the polar molecules (Tang, 2005). At very low and very high frequencies, the dielectric constant approaches the value of ε_s and ε_∞, respectively. At intermediate frequencies, the dielectric constant decreases sharply with the increased frequency and the frequency region is designated as the region of dispersion or relaxation. Dipole molecules such as water only have detectable values of loss factor in this dispersion reason, with its peak at the critical frequency.

Many studies determine the dielectric properties of food materials in RF and microwave frequency ranges, including vegetables, fruits, meat, pasta, and others (Bircan & Barringer, 2002; Guan, Cheng, Wang, & Tang, 2004; Nelson, 1992; Sipahioglu & Barringer, 2003; Tinga & Nelson, 1973; Tong & Lentz, 1993; Tran & Stuchly, 1987; Wang, Wig, Tang, & Hallberg, 2003). However, there is a lack of systematic studies on the dielectric properties of whole eggs and egg whites at RF from 27 to 1800 MHz over temperatures from 20 to 120 °C. Knowledge of dielectric properties is important to the research of RF and microwave heating in applications for pasteurization and sterilization of egg products.

The objectives of this study were to: 1) determine the dielectric properties of liquid and pre-cooked egg whites and whole eggs at 27, 40, 915, and 1800 MHz over a temperature range between 20 and 120 °C; and 2) investigate the influence of temperature and frequency on the dielectric properties of egg whites and whole eggs; and 3) study the influence of heat treatment on the dielectric properties of the eggs.

2. Materials and methods

2.1. Dielectric properties measuring equipment

The open-ended coaxial probe method is an effective broadband measuring technique that has minimum disturbance to samples. It does not require the solid and semisolid samples to be in a particular precise geometry except for a flat contacting surface with coaxial probe (Sheen & Woodhead, 1999). As such, this is the most common method used to determine dielectric properties in the food research community (Herve, Tang, Luedecke, & Feng, 1998; Seaman & Seals, 1991). The open-ended coaxial probe method was also chosen in this study to determine the dielectric properties of egg products.

The dielectric property measurement system described in detail by Wang et al. (2005), consists of an Agilent 4291B impedance analyzer (Agilent Technologies, Palo Alto, CA), a custom-built test cell (Wang, Wig, et al., 2003), a VWR Model 1157 programmable temperature control circulation system (VWR Science Products, West Chester, PA), a high-temperature coaxial cable, and a dielectric probe included in the Hewlett Packard 85070B dielectric probe kit. The custom-built test cell was made with two coaxial stainless steel tubes with 11 and 19 mm radii, respectively. Two tubes were welded to two ferrules with 22 mm radii at both ends. The dielectric probe was fixed by an end-cap and sealed with an o-ring to the ferrule by a clamp. A thermocouple was mounted through the bottom cap to monitor the sample temperature inside the cell. A stainless steel spring and piston provided constant pressure to maintain tight contact between the sample and dielectric probe. A temperature-controlled liquid (90 ml/100 ml ethylene glycol and 10 ml/100 ml water) was pumped through the space between the two stainless steel tubes of the test cell to control the temperature (from 10 to 130 °C) of the sample inside the inner stainless steel tube. The impedance analyzer was connected through an IEEE-488 (GPIB) bus to a computer equipped with custom-designed software DMS 85070 (Innovative Measurement Solutions) to control the impedance analyzer and log the recorded data. The system was used to measure the dielectric properties of samples over frequencies from 1 to 1800 MHz and temperatures from 10 to 120 °C. Wang, Wig, et al. (2003) provides a detailed description of the dielectric property measurement system.

2.2. Materials

Commercially available frozen pasteurized liquid whole eggs for food services were purchased from M.G. Waldbaum Company (Wakefield, NE, USA). The frozen whole eggs were stored below −18 °C and placed at room temperature for at least 24 h before measurement. The pasteurized liquid egg whites were obtained from Beatrice Foods (Downers Grove, IL) and stored in a refrigerator at 4 °C for less than two weeks.

Whole eggs were comprised of egg white and yolk and contained 73.7 g/100 g water, 12.9 g/100 g protein, 11.5 g/100 g fat, and 1.9 g/100 g other components such as carbohydrate and ash. Egg whites consisted of 85 g/100 g water, 10 g/100 g protein, and 5 g/100 g other components such as lipid, carbohydrate, and ash (Stadelman & Cotterill, 1977). The protein compositions in egg whites are 54 g/100 g ovalbumin, 13 g/100 g conalbumin, 11 g/100 g ovomucoid, and 22 g/100 g others (Parkinson, 1966).

To prepare pre-cooked whole eggs and egg whites, defrosted whole egg or refrigerated liquid egg white was whisked and poured in 100 ml beakers. The beakers were then covered with plastic film and heated in an 80 °C water bath for 10 min. The cooked solid was then cut to the shape of a cylinder (radius = 11 mm, height = 70 mm) and placed into the test cell for measurement.

2.3. Experimental procedures

Before measuring dielectric properties, the impedance analyzer was turned on and allowed to warm up for at least 30 min. Following the manufacturer's recommendations, a 4219 B kit that included four calibration standards (an open circuit, a short circuit, a 50 Ω load, and a low-loss capacitor) was used to calibrate the impedance analyzer. The testing probe was then connected to the impedance analyzer and further calibrated using an 85070B dielectric probe kit that included a short circuit, an open circuit, and a selected standard load (deionized water at room temperature) (Wang, Tang, et al., 2003).

After calibration, an egg sample was placed and sealed in the custom-built test cell. The dielectric properties of the sample were determined over a 1–1800 MHz frequency range. Measurements for liquid and pre-cooked whole eggs were made from 20 to 120 °C in steps of 10 °C, and for the liquid and pre-cooked egg whites at 20, 40, 60, 70, 80, 100, and 120 °C. 10–15-min intervals were used to increase egg sample temperatures by 10 and 20 °C, respectively, and achieve a uniform temperature distribution inside the egg samples. All the measurements were conducted at least four replicates.

Electric conductivity of liquid egg whites and whole eggs at room temperature was measured in four replicates using a conductivity meter (CON-500, Cole-Parmer Instrument Co., Vernon 124 Hills, Ill., USA) equipped with a platinum/epoxy conductivity probe and a built-in temperature sensor.

The Federal Communications Commission allocates 13.56, 27.12, and 40.68 MHz to the RF range, and 915 and 2450 MHz to the microwave frequency range for industrial, scientific, and medical (ISM) applications. In this study, the dielectric properties of eggs were measured at 27 and 40 MHz RF frequencies and 915 and 1800 MHz microwave frequencies. The 1800 MHz was the upper limit of the measurement system and the closest frequency to 2450 MHz.

Regression analyses were used to assess the influence of temperature on dielectric properties of egg products. *T*-test was used to assess the effect of denaturization on dielectric properties of egg products, i.e., whether a significant difference existed on dielectric properties between those of liquid and pre-cooked egg products.

3. Results and discussion

3.1. Dielectric properties of egg whites

The dielectric properties of egg whites are primarily dependent on water, electrolytes, and proteins such as ovalbumin and conalbumin (Bircan & Barringer, 2002; Ragni, Al-Shami, Mikhaylenko, & Tang, 2007). Previous research reports that the protein denaturation temperature of liquid egg whites is in the range of 58–62 °C, ovalbumin at around 84 °C, and conalbumin in the range of 65–70 °C (Bircan & Barringer, 2002; Donovan, Mapes, Davis, & Garibaldi, 1975; Payawal, Lowe, & Stewart, 1946). This information is relevant to the discussion of influence of temperature on dielectric properties of different components of egg white.

The measured dielectric properties of egg whites at selected frequencies and temperatures are listed in Table 1.

Table 1
Dielectric properties (mean ± standard deviation) of liquid and pre-cooked egg whites (5 replicates).

	T (°C)	27 MHz	40 MHz	915 MHz	1800 MHz
Liquid					
ε'	20	84.6 ± 5.7	76.6 ± 6.2	64.0 ± 5.5	62.5 ± 5.3
	40	79.6 ± 5.8	69.8 ± 5.7	56.8 ± 6.0	54.5 ± 5.0
	60	81.3 ± 5.0	68.0 ± 5.4	51.5 ± 4.4	50.4 ± 4.6
	70	88.2 ± 4.4	71.3 ± 4.5	50.2 ± 4.1	49.9 ± 4.1
	80	98.3 ± 4.4	77.6 ± 4.9	50.5 ± 3.6	50.2 ± 2.8
	100	118.1 ± 3.1	88.9 ± 3.0	53.3 ± 2.8	52.5 ± 1.3
	120	135.1 ± 6.5	96.9 ± 3.8	53.2 ± 2.7	51.2 ± 0.5
ε''	20	427.0 ± 46.7	256.4 ± 21.5	18.7 ± 1.9	14.7 ± 1.7
	40	553.6 ± 94.8	320.0 ± 35.8	21.1 ± 2.3	13.8 ± 2.6
	60	646.4 ± 89.4	427.7 ± 52.4	25.3 ± 2.8	15.5 ± 2.1
	70	751.7 ± 87.6	493.4 ± 44.7	28.4 ± 2.3	16.7 ± 1.7
	80	866.5 ± 93.9	569.6 ± 45.9	33.3 ± 2.8	18.1 ± 1.7
	100	1242.3 ± 54.6	784.3 ± 19.2	44.9 ± 1.1	24.0 ± 0.8
	120	1665.8 ± 77.1	997.5 ± 24.5	56.9 ± 2.4	28.8 ± 1.2
Pre-cooked					
ε'	20	89.3 ± 2.8	81.9 ± 2.1	64.5 ± 1.9	63.5 ± 1.9
	40	89.8 ± 3.3	81.2 ± 3.5	59.7 ± 2.1	58.5 ± 1.6
	60	92.5 ± 2.7	82.3 ± 6.4	55.7 ± 2.2	54.3 ± 1.5
	70	95.3 ± 2.9	83.7 ± 6.5	54.2 ± 2.4	52.7 ± 1.5
	80	99.5 ± 1.7	85.5 ± 7.2	53.0 ± 2.4	51.3 ± 1.5
	100	106.8 ± 2.6	88.2 ± 7.2	50.3 ± 3.0	48.4 ± 1.8
	120	124.4 ± 4.7	97.8 ± 7.8	50.1 ± 1.6	48.5 ± 1.5
ε''	20	411.8 ± 18.6	256.3 ± 13.1	18.9 ± 0.7	14.7 ± 0.3
	40	562.2 ± 25.4	353.1 ± 17.2	22.8 ± 0.9	15.0 ± 0.5
	60	732.1 ± 26.7	460.0 ± 17.0	28.1 ± 0.8	17.0 ± 0.6
	70	830.4 ± 27.7	520.1 ± 18.0	31.4 ± 1.0	18.2 ± 0.5
	80	937.1 ± 27.5	582.3 ± 18.8	34.6 ± 0.7	20.0 ± 0.5
	100	1145.0 ± 21.6	698.9 ± 8.4	41.4 ± 1.2	23.0 ± 0.7
	120	1480.5 ± 89.9	879.8 ± 50.8	52.2 ± 2.4	28.1 ± 0.9

3.1.1. Dielectric constants of pre-cooked egg whites and liquid egg whites

Fig. 1A and B shows that the dielectric constants of pre-cooked egg whites decreased in the microwave range (i.e., 915 and 1800 MHz) with increasing temperatures (up to 100 °C), but increased in the RF range (i.e., 27 and 40 MHz). Over the entire selected measured frequency spectrum between 10 and 1800 MHz, the switch of the trend occurred about 90 MHz (Fig. 2A) for pre-cooked egg whites. That is, for a given frequency greater than 90 MHz, dielectric constants of egg whites decreased with increasing temperature. Below 90 MHz, the dielectric constant increased with increasing temperature. Similar trends were observed for liquid egg whites (Fig. 2B), although the frequency at which the trend switched was not as clear as that for pre-cooked egg whites.

The dielectric constants of liquid egg whites at four selected frequencies as influenced by temperature are presented in Fig. 1C and D. The dielectric property values of un-cooked liquid egg white at room temperature agree with the dielectric properties reported by Ragni et al. (2007). At 915 and 1800 MHz microwave frequencies, the dielectric constant of liquid egg whites decreased with increasing temperature until about 60–65 °C, then increased slightly from 65 to 100 °C, and remained constant between 100 and 120 °C (Fig. 1C). The initial reduction in the dielectric constants at microwave frequencies when temperature increased from 20 to 60 °C was mainly a result of the influence of water solution, a trend discussed in detailed in Tang (2005). Similar changes of dielectric constants with temperature are reported in Wang, Wig, et al. (2003) for whey protein gels, liquid whey protein mixture, macaroni noodles, and cheese sauce at 915 and 1800 MHz; in Guan et al. (2004) for mashed potatoes at 915 and 1800 MHz; and in Bircan, Barringer, and Mangino (2001) for whey protein solution at microwave frequencies (300–2450 MHz).

Egg whites solidify at about 60 °C which changed the trend discussed above. At 60–100 °C, the dielectric constants increased with increasing temperature, following a trend similar to that reported by Bircan and Barringer (2002). The smallest dielectric constants were observed at 60–65 °C in this study, whereas the minimum dielectric constant was reported at 70 °C in Bircan and Barringer (2002). The difference may be attributed to the triethyl citrate added in egg whites by the supplier to improve the foamability of egg whites as a whipping agent. Triethyl citrate acts as a denaturing agent (Meyer & Potter, 1975; Nakamura, 1964) and reduces denaturation temperature.

At 100–120 °C, the dielectric constant of egg whites at 915 and 1800 MHz microwave frequencies do not show a significant change ($p \leq 0.05$) (Fig. 1C), similar to observations made with pre-cooked eggs (Fig. 1A). The 915 and 1800 MHz microwave frequencies are at the lower end of the region for dispersion or relaxation for free water. We speculate that the increase of temperature increases the mobility of water molecules. But when fully cooked, water molecules became less mobile that counter plays the influence of increasing temperature on dielectric constant.

At 27 and 40 MHz RF, the dielectric constant of liquid egg whites decreased slightly from 20 to 65 °C, and then increased from 65 to 120 °C (Fig. 1D). From 20 to 65 °C, the dielectric constants of liquid egg whites were close to the dielectric constants of the water solutions reported by Barber (1983), Ohlsson, Bengtsson, and Risman (1974), and Mudgett (1986), indicating that the dielectric constants of liquid egg whites had a corollary dependence on water solutions.

Overall, changes in dielectric constants of liquid egg whites at microwave and RF frequencies as influenced by temperature differ from the dielectric constants of the pre-cooked solidified egg whites. For liquid egg whites, the dielectric behaviors resemble that of free water below about 60 °C, and there is a distinctive influence

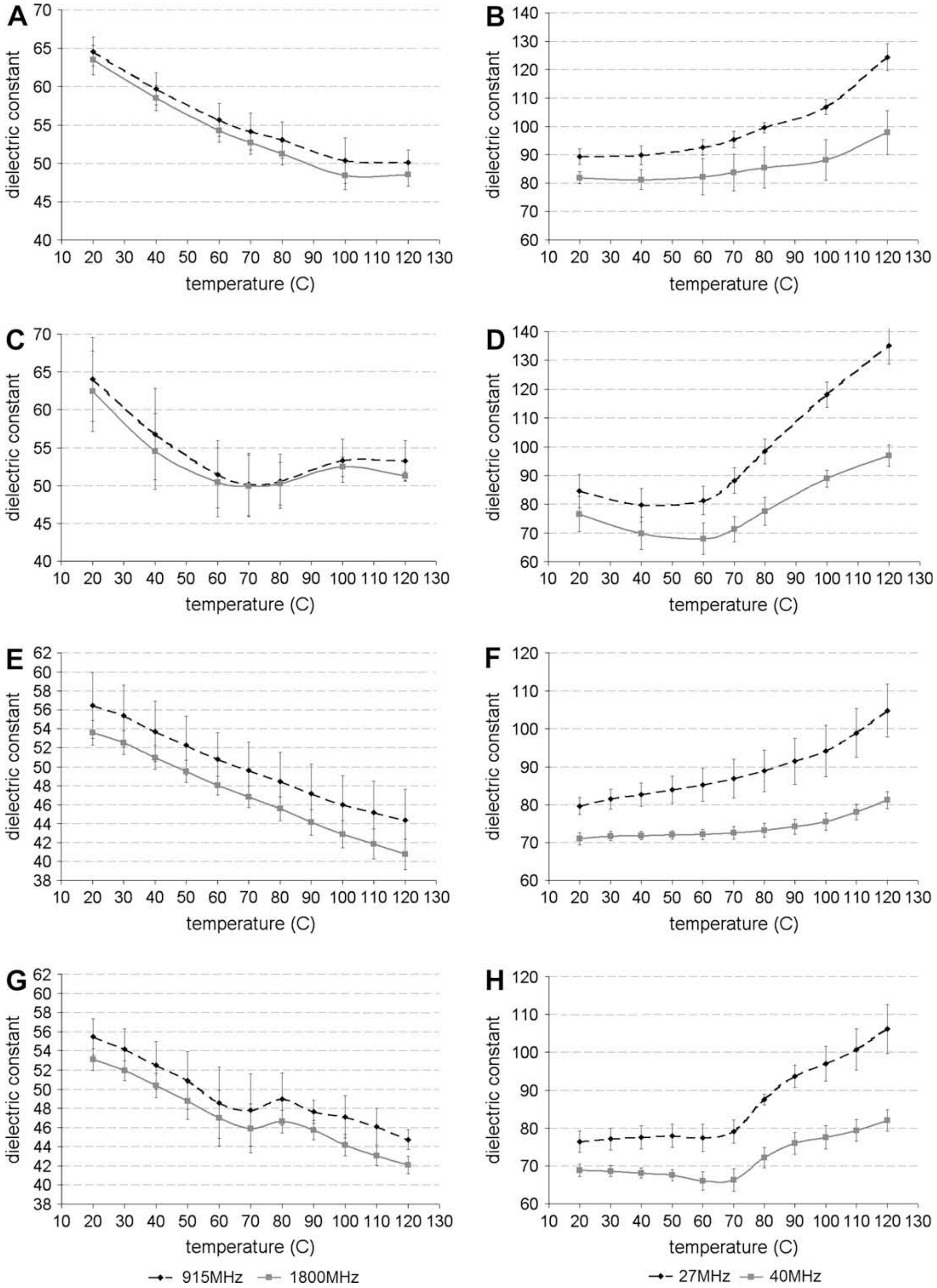

Fig. 1. Dielectric constants of (A) pre-cooked egg whites at microwave frequencies, (B) pre-cooked egg whites at radio frequencies, (C) liquid egg whites at microwave frequencies, (D) liquid egg whites at radio frequencies, (E) pre-cooked whole eggs at microwave frequencies, (F) pre-cooked whole eggs at radio frequencies, (G) liquid whole eggs at microwave frequencies, and (H) liquid whole eggs at radio frequencies.

of gelation at about 60 °C at which protein begins to denature; protein, water and other components form a continuous three-dimensional network by intermolecular interactions (Goldsmith & Toledo, 1985; Shimada & Matsushita, 1980). In cooked samples the protein networks reduce mobility of water molecules and reduce the dielectric constants (Bircan & Barringer, 2002; Shimada & Matsushita, 1980). But increase in temperature enhances the mobility of net free charges and water molecules, the dielectric constants of pre-cooked egg whites in the RF range increase in the temperature range of 65–120 °C.

When linearly correlating dielectric constants of pre-cooked eggs with temperature, the standardized residuals were larger than 2, indicating that a higher order regression analysis was necessary. The regression analysis results for the dielectric constants of pre-cooked and liquid egg whites for selected frequencies are summarized in Table 2. The R^2 for quadratic regression of the liquid

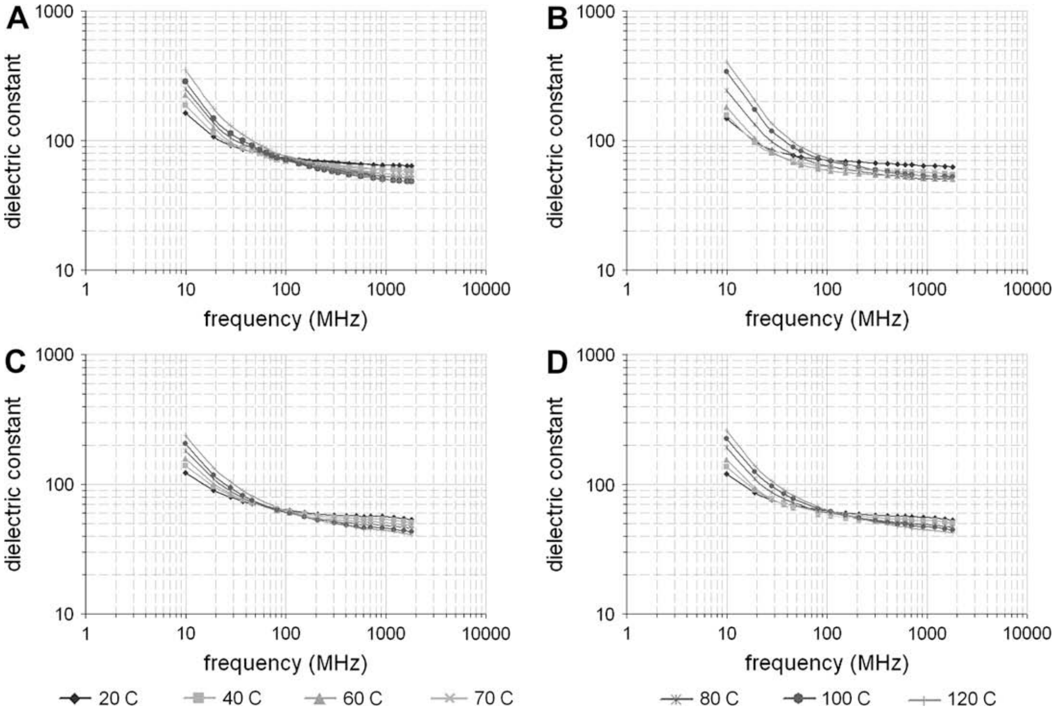

Fig. 2. Dielectric constant of (A) pre-cooked egg whites, (B) liquid egg whites, (C) pre-cooked whole eggs, and (D) liquid whole eggs at different temperatures.

egg white dielectric constants with temperature was smaller than 50% and there was a clear pattern in residual distribution that indicated a larger order relationship. It is, therefore, appropriate to use cubic regression to analyze the dielectric constant–temperature relationship to obtain the function with $R^2 \geq 0.80$ and standardized residual < 2.0.

3.1.2. *Loss factor of pre-cooked egg whites and liquid egg whites*

The loss factors of pre-cooked egg whites as influenced by temperature at two RF frequencies and two microwave frequencies are presented in Fig. 3A and B. From 20 to 120 °C, the loss factor increased with increasing temperature at the four selected frequencies. But the loss factor increased more rapidly with the increase of temperature at the RF frequencies compared to at the two microwave frequencies. For example, at microwave frequencies of 915 and 1800 MHz, the loss factor at 120 °C was two to three times the loss factor at 20 °C (Fig. 3A), whereas, at RF frequencies of 27 and 40 MHz, the loss factor at 120 °C was about four times the loss factor at 20 °C (Fig. 3B). Similar trends were observed for the loss factor of liquid egg white as shown in Table 1.

The faster increase in the loss factor at the RF frequencies can be explained by the two mechanisms that contribute to the loss factor of aqueous ionic solutions, as shown by the following equation (Mudgett, 1986):

$$\varepsilon'' = \varepsilon''_d + \varepsilon''_\sigma \tag{3}$$

In above, the dipole loss component, ε''_d, is due to the dipole rotation; the ionic loss component, ε''_σ, results from displacement of charged ions, which can be further expressed as (Metaxas & Meredith, 1983):

$$\varepsilon''_\sigma = \frac{\sigma}{2\pi f \varepsilon_0} \tag{4}$$

where σ is ionic conductivity of the solution, it increases with temperature T; f is frequency of the EM wave. Taking the log value on both sides of Eq. (4) yields (Guan et al., 2004):

$$\log \varepsilon''_\sigma = -\log f + \log[\sigma(T)] + C \tag{5}$$

where constant $C = -\log 2\pi - \log \varepsilon_0$.

According to Eq. (5), when the ionic loss component dominates the influence on the loss factor of material, there should be a linear relationship between loss factors and frequency on a log–log graph. Measured electric conductivities due to charged ions in eggs are summarized in Table 3. The electric conductivities of liquid egg

Table 2

Regression analysis for dielectric constants of pre-cooked and liquid egg whites and whole eggs at four frequencies.

Frequency (MHz)		
Pre-cooked egg whites		
27	$\varepsilon' = 94.22 - 0.31\,T + 4.58 \times 10^{-3}\,T^2$	0.94
40	$\varepsilon' = 83.87 - 0.11\,T + 2.22 \times 10^{-3}\,T^2$	0.74
915	$\varepsilon' = 70.56 - 0.32\,T + 1.26 \times 10^{-3}\,T^2$	0.85
1800	$\varepsilon' = 69.98 - 0.345\,T + 1.36 \times 10^{-3}\,T^2$	0.92
Liquid egg whites		
27	$\varepsilon' = 91.33 - 0.59\,T + 0.0081\,T^2$	0.93
40	$\varepsilon' = 84.08 - 0.56\,T + 0.0057\,T^2$	0.80
915	$\varepsilon' = 80.17 - 0.81\,T + 7.46 \times 10^{-3}\,T^2 - 2.12 \times 10^{-5}\,T^3$	0.82
1800	$\varepsilon' = 80.79 - 1.0\,T + 0.013\,T^2 - 4.27 \times 10^{-5}\,T^3$	0.89
Pre-cooked whole eggs		
27	$\varepsilon' = 81.42 - 7.41 \times 10^{-2}\,T + 2.15 \times 10^{-3}\,T^2$	0.74
40	$\varepsilon' = 73.62 - 0.12\,T + 1.44 \times 10^{-3}\,T^2$	0.80
915	$\varepsilon' = 58.98 - 0.18\,T + 3.67 \times 10^{-4}\,T^2$	0.98
1800	$\varepsilon' = 57.39 - 0.17\,T + 2.40 \times 10^{-4}\,T^2$	0.94
Liquid whole eggs		
27	$\varepsilon' = 79.31 - 0.22\,T + 3.79 \times 10^{-3}\,T^2$	0.88
40	$\varepsilon' = 72.65 - 0.24\,T + 2.77 \times 10^{-3}\,T^2$	0.80
915	$\varepsilon' = 61.25 - 0.22\,T + 7.60 \times 10^{-4}\,T^2$	0.76
1800	$\varepsilon' = 56.62 - 0.142\,T + 1.8 \times 10^{-4}\,T^2$	0.80

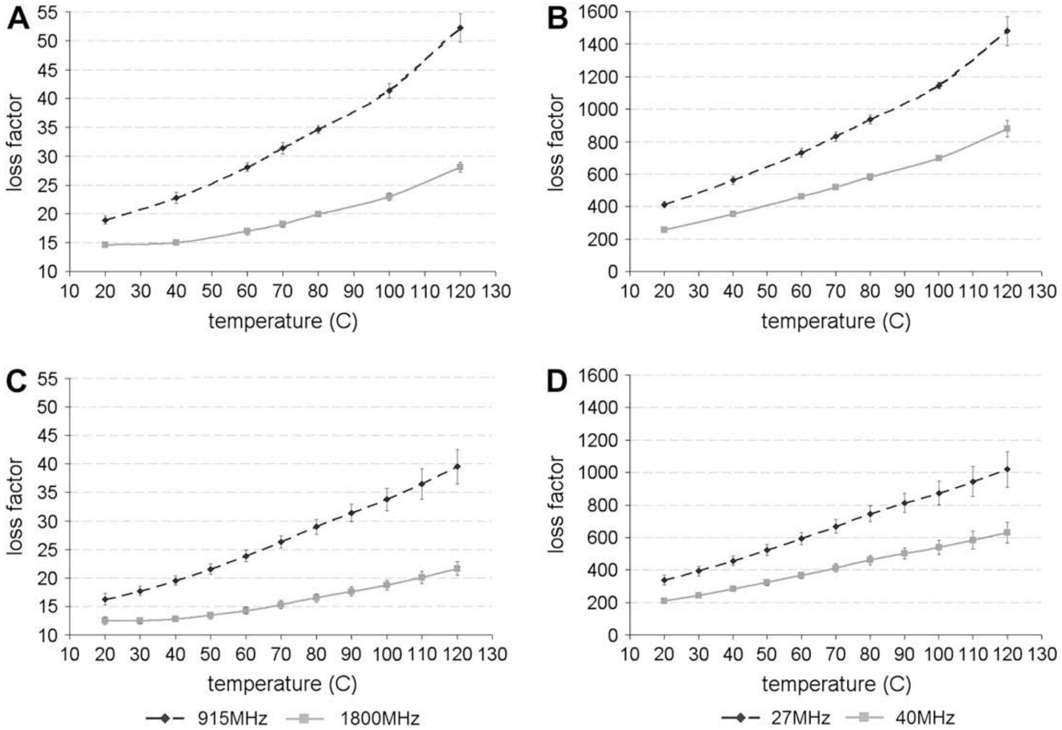

Fig. 3. Loss factors of (A) pre-cooked egg whites at microwave frequencies, (B) pre-cooked egg whites at radio frequencies, (C) pre-cooked whole eggs at microwave frequencies, and (D) pre-cooked whole eggs at radio frequencies.

whites and liquid whole eggs were determined by a conductivity meter at 20 °C in four replicates. The electric conductivities of pre-cooked eggs at all temperatures and liquid eggs at elevated temperatures were calculated from the measured loss factor at 19 MHz according to Eq. (4), assuming $\varepsilon_d'' = 0$.

Total measured loss factors and the calculated ionic loss components for pre-cooked and liquid egg whites at selected temperatures as influenced by frequency are presented in Fig. 4A and B. The close match between the curve for the ionic loss component (calculated from measured electric conductivity) at 20 °C and that of the experimentally determined total dielectric loss factor over 10–100 MHz clearly indicated that the loss factors of pre-cooked and liquid egg whites were mainly contributed by the ionic loss components in the indicate frequency range. The dipole loss component contributed by free water became increasingly important at higher frequencies beyond 100 MHz. But increasing temperature reduced the importance of the dipole loss component at microwave frequencies (Mudgett, 1986; Tang, 2005). Similar observation was reported by Guan et al. (2004) for mashed potatoes and Wang et al. (2005) for tropical fruits. This is the result of shifting of the dispersion region for free water to high frequencies at elevated temperatures. For example, the critical frequency of free water is about 19,0000 MHz at 25C. This frequency shifts to 58,000 MHz at 85C (Liu, Tang & Mao, 2009). Results from regression analyses for the loss factors of pre-cooked and liquid egg whites at selected frequencies are summarized in Table 4. With R^2 larger than 0.96, the loss factors of pre-cooked and liquid egg whites have a quadratic relationship with temperature.

3.2. *Dielectric properties of whole eggs*

The dielectric properties of whole eggs at selected frequencies and temperatures are listed in Table 5.

3.2.1. *Dielectric constants of pre-cooked and liquid whole eggs*

The dielectric constants of pre-cooked and liquid whole eggs as influenced by temperature are presented in Fig. 1E–H, respectively. Once again, we observed significant differences ($p \leq 0.05$) between the dielectric constants of pre-cooked and liquid whole eggs at 27 and 40 MHz from 40 to 70 °C (Fig. 1F and H), revealing the influence of denaturation on the dielectric constants of whole eggs in the RF range. However, the difference was not significant at 27 and 40 MHz for other temperatures. Although statistically no difference was observed for pre-cooked and liquid whole eggs at 915 and 1800 MHz over 20–120 °C, a change of trend was observed at temperatures between 60 and 80C for liquid eggs (Fig. 1G).

In general, the dielectric constants of whole eggs (containing egg white and yolk) were smaller than the dielectric constants of egg whites, but larger than that of egg yolk reported by Bircan and Barringer (2002) at microwave frequencies and by Ragni et al.

Table 3
Summary of electric conductivities (S/m) of egg whites and whole eggs (mean ± stand deviation) for four replicates.

Temperature (°C)	Liquid egg whites	Pre-cooked egg whites	Liquid whole eggs	Pre-cooked whole eggs
20	0.71 ± 0.07[a]	0.69 ± 0.09	0.52 ± 0.04[a]	0.53 ± 0.05
60	1.01 ± 0.17	1.14 ± 0.12	0.95 ± 0.05	0.92 ± 0.06
100	1.90 ± 0.10	1.74 ± 0.10	1.48 ± 0.07	1.35 ± 0.10

Conductivities were calculated based on Eqs. (3) and (4) through the loss factor of egg products at 19 MHz, except liquid egg whites and whole eggs at 20 °C.

[a] Measured with a conductivity meter.

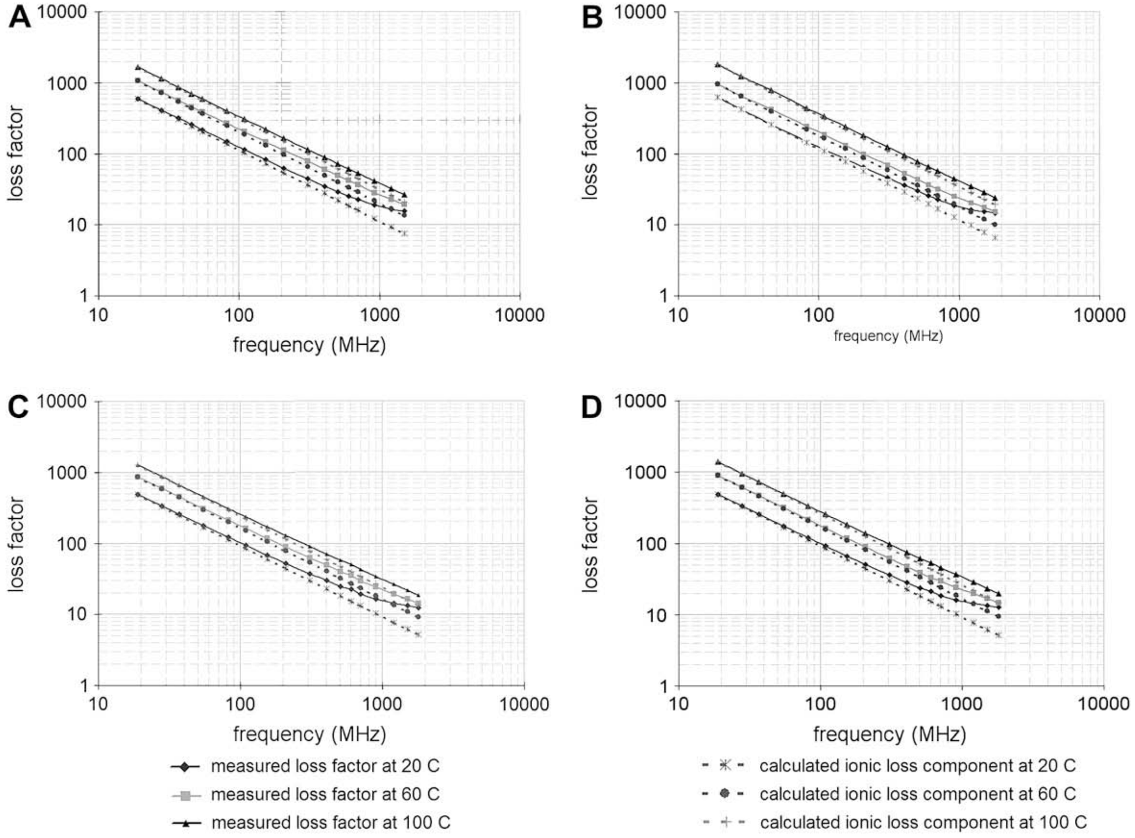

Fig. 4. Loss factors and calculated ionic loss components of (A) pre-cooked egg whites (B) liquid egg whites, (C) pre-cooked whole eggs, and (D) liquid whole eggs vs. frequency at selected temperatures.

(2007) at room temperature. Liquid egg yolk contains more than 30 g/100 g fat (Ragni et al., 2007; Stadelman & Cotterill, 1977), while egg white contains close to 0 g/100 g fat. This may result from the diluting effect of fat (Bircan & Barringer, 2002), as liquid whole eggs contain 11.5 g/100 g fat.

Table 4
Regression analysis for loss factors of pre-cooked and liquid egg whites and whole eggs.

Frequency (MHz)		R^2
Pre-cooked egg whites		
27	$\varepsilon'' = 324.71 + 3.85\,T + 4.69 \times 10^{-2}\,T^2$	0.99
40	$\varepsilon'' = 184.90 + 3.35\,T + 1.97 \times 10^{-2}\,T^2$	0.99
915	$\varepsilon'' = 16.70 + 8.20 \times 10^{-2}\,T + 1.75 \times 10^{-3}\,T^2$	0.99
1800	$\varepsilon'' = 14.87 - 3.99 \times 10^{-2}\,T + 1.25 \times 10^{-3}\,T^2$	0.98
Liquid egg whites		
27	$\varepsilon'' = 482.46 - 3.96\,T + 0.11\,T^2$	0.97
40	$\varepsilon'' = 239.96 + 0.11\,T + 5.14 \times 10^{-2}\,T^2$	0.98
915	$\varepsilon'' = 19.26 - 9.88 \times 10^{-2}\,T + 3.43 \times 10^{-3}\,T^2$	0.97
1800	$\varepsilon'' = 16.18 - 0.13\,T + 1.96 \times 10^{-3}\,T^2$	0.91
Pre-cooked whole eggs		
27	$\varepsilon'' = 199.19 + 6.43\,T + 3.51 \times 10^{-3}\,T^2$	0.94
40	$\varepsilon'' = 125.93 + 3.91\,T + 2.50 \times 10^{-3}\,T^2$	0.95
915	$\varepsilon'' = 12.76 + 0.15\,T + 6.12 \times 10^{-4}\,T^2$	0.96
1800	$\varepsilon'' = 11.98 - 1.79 \times 10^{-3}\,T + 6.93 \times 10^{-4}\,T^2$	0.95
Liquid whole eggs		
27	$\varepsilon'' = 195.82 + 6.42\,T + 1.17 \times 10^{-2}\,T^2$	0.99
40	$\varepsilon'' = 123.46 + 3.88\,T + 7.67 \times 10^{-3}\,T^2$	0.99
915	$\varepsilon'' = 11.86 + 0.16\,T + 7.85 \times 10^{-4}\,T^2$	0.97
1800	$\varepsilon'' = 12.30 - 8.07 \times 10^{-3}\,T + 8.43 \times 10^{-4}\,T^2$	0.88

The dielectric constants for pre-cooked and liquid whole egg over a frequency spectrum between 10 and 1800 MHz at the tested temperatures are presented in Fig. 2C and D. For whole eggs, the trend in changes of dielectric constants as influenced by temperature altered at 90–100 MHz. That is, at frequencies greater than 100 MHz, the dielectric constants decreased with increasing temperatures. At frequencies smaller than 90 MHz, the dielectric constants increased with increasing temperatures. This can be explained by the previously discussed dominate effect of ionic conductivity between 10 and 90 MHz (Fig. 4), as ionic conductivities increase sharply with temperature for egg whites.

The regression analysis for the dielectric constants of pre-cooked and liquid whole eggs for selected frequencies is summarized in Table 2. The R^2 for the quadratic regression of dielectric constants of pre-cooked whole eggs and liquid whole eggs with temperature was at generally larger than 0.74, demonstrated quadratic relationships.

3.2.2. *Loss factor of pre-cooked and liquid whole eggs*

Fig. 3C shows that the loss factors of pre-cooked whole eggs increase with increasing temperature. Similar trends were observed for liquid whole eggs. In general, the loss factors of whole eggs are smaller than the loss factors of egg whites but larger than the loss factors of egg yolk reported by Bircan and Barringer (2002) at microwave frequencies and by Ragni et al. (2007) at room temperature. The differences are attributed to the fact that egg white had larger electric conductivity (0.64–0.78 S/m at 20 °C) and higher water content (85 g/100 g) than that of whole eggs (0.48–0.56 S/m at 20 °C, and 73.7 g/100 g water), resulting mainly from the difference in fat content.

Table 5
Dielectric properties (mean ± standard deviation) of liquid and pre-cooked whole eggs (4 replicates).

	T (°C)	27 MHz	40 MHz	915 MHz	1800 MHz
Liquid					
ε'	20	76.3 ± 2.8	68.8 ± 1.6	55.5 ± 1.9	53.1 ± 1.1
	30	77.1 ± 2.9	68.6 ± 1.5	54.2 ± 2.1	51.9 ± 1.0
	40	77.5 ± 3.0	68.1 ± 1.4	52.5 ± 2.5	50.4 ± 1.3
	50	77.9 ± 3.1	67.5 ± 1.5	50.9 ± 3.0	48.8 ± 1.9
	60	77.4 ± 3.6	66.0 ± 2.5	48.6 ± 3.7	47.0 ± 2.9
	70	79.1 ± 3.1	66.3 ± 2.9	47.8 ± 3.8	45.9 ± 2.5
	80	87.5 ± 1.4	72.2 ± 2.7	48.9 ± 2.7	46.6 ± 1.2
	90	93.7 ± 2.9	75.9 ± 2.8	47.6 ± 1.2	45.7 ± 1.0
	100	96.9 ± 4.6	77.5 ± 3.1	47.1 ± 2.2	44.2 ± 1.1
	110	100.7 ± 5.4	79.3 ± 2.9	46.1 ± 1.9	43.0 ± 1.0
	120	106.1 ± 6.5	82.0 ± 2.8	44.7 ± 1.0	42.1 ± 0.9
ε''	20	335.9 ± 12.9	208.4 ± 7.8	15.8 ± 1.6	12.8 ± 1.3
	30	398.5 ± 13.8	246.8 ± 8.5	17.3 ± 1.6	12.7 ± 1.5
	40	467.8 ± 14.4	289.1 ± 9.0	19.2 ± 1.8	13.1 ± 1.5
	50	541.8 ± 21.6	334.2 ± 13.5	21.4 ± 2.0	13.8 ± 1.5
	60	612.0 ± 32.7	377.1 ± 19.9	23.9 ± 2.4	14.7 ± 1.7
	70	694.9 ± 28.7	427.8 ± 17.8	26.6 ± 2.5	15.7 ± 1.6
	80	801.8 ± 20.2	494.0 ± 12.5	30.5 ± 2.0	17.3 ± 1.3
	90	880.1 ± 28.4	542.9 ± 17.4	33.3 ± 1.0	19.0 ± 1.0
	100	956.4 ± 4.1	589.8 ± 26.9	35.7 ± 1.2	20.0 ± 1.2
	110	1035.1 ± 49.1	638.5 ± 29.6	38.4 ± 1.5	21.3 ± 1.5
	120	1132.7 ± 48.0	698.7 ± 28.8	42.3 ± 1.2	23.4 ± 1.3
Pre-cooked					
ε'	20	79.6 ± 2.2	71.0 ± 1.6	56.5 ± 3.5	53.6 ± 1.3
	30	81.5 ± 2.6	71.7 ± 1.2	55.4 ± 3.2	52.5 ± 1.2
	40	82.7 ± 3.0	71.8 ± 1.0	53.7 ± 3.2	51.0 ± 1.2
	50	83.9 ± 3.6	72.0 ± 1.1	52.3 ± 3.1	49.5 ± 1.2
	60	85.2 ± 4.4	72.1 ± 1.4	50.8 ± 2.8	48.0 ± 1.0
	70	86.9 ± 5.1	72.5 ± 1.7	49.6 ± 3.0	46.8 ± 1.2
	80	89.0 ± 5.5	73.2 ± 1.8	48.5 ± 3.0	45.6 ± 1.3
	90	91.4 ± 6.1	74.1 ± 2.0	47.2 ± 3.1	44.1 ± 1.4
	100	94.2 ± 6.8	75.4 ± 2.3	46.0 ± 3.1	42.9 ± 1.4
	110	99.0 ± 6.5	78.1 ± 2.0	45.2 ± 3.3	41.8 ± 1.6
	120	104.8 ± 7.0	81.2 ± 2.2	44.3 ± 3.3	40.7 ± 1.6
ε''	20	336.8 ± 29.2	209.5 ± 18.2	16.3 ± 1.0	12.5 ± 0.7
	30	393.1 ± 27.9	244.2 ± 16.9	17.7 ± 0.9	12.5 ± 0.6
	40	456.0 ± 28.4	282.8 ± 17.0	19.5 ± 0.8	12.8 ± 0.6
	50	522.0 ± 32.2	323.2 ± 19.0	21.5 ± 0.9	13.4 ± 0.6
	60	594.1 ± 36.6	367.4 ± 21.4	23.9 ± 1.0	14.3 ± 0.6
	70	667.8 ± 41.3	412.6 ± 24.0	26.3 ± 1.1	15.3 ± 0.7
	80	745.8 ± 48.5	460.5 ± 28.3	29.0 ± 1.3	16.5 ± 0.7
	90	813.0 ± 59.3	501.9 ± 34.7	31.4 ± 1.6	17.6 ± 0.8
	100	874.1 ± 73.0	539.5 ± 42.8	33.8 ± 1.9	18.7 ± 0.9
	110	944.5 ± 93.8	583.3 ± 55.6	36.5 ± 2.6	20.1 ± 1.1
	120	1020.0 ± 109.8	630.4 ± 65.0	39.5 ± 3.0	21.6 ± 1.2

The loss factors and calculated ionic loss components of pre-cooked and liquid whole eggs at the tested temperatures are presented in Fig. 4C and D. From 10 to 100 MHz, the loss factors were primarily affected by the ionic loss component, but at frequencies greater than 100 MHz, the dipole loss component exhibited an increasingly important contribution.

Regression analysis for the loss factors of pre-cooked and liquid whole eggs for selected frequencies is summarized in Table 4. With R^2 larger than 0.88, the loss factors of pre-cooked and liquid whole eggs exhibit a quadratic relationship with temperature.

4. Conclusions

Denaturation of egg products during heating exhibits significant influence on the dielectric constants of liquid egg whites and whole eggs. The dielectric constants of pre-cooked egg whites and whole eggs increased with increasing temperatures at radio frequencies, but decreased with increasing temperatures at the microwave frequencies.

The loss factors of liquid whole eggs, pre-cooked whole eggs, liquid egg whites, and pre-cooked egg whites increased with increasing temperatures at the selected RF and microwave frequencies. Denaturation of egg products did not exhibit significant effects on the ionic loss component of the loss factors, but influenced the dipole loss components of the loss factors at temperatures greater than 100 °C.

Ionic conductivity had a dominant influence on behavior of dielectric properties in the RF frequency range, whereas, polar water molecules played increasing role at higher frequencies. The differences between dielectric properties of egg white and whole eggs were attributed to the difference in ionic conductivity.

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