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Physical properties of egg whites and whole eggs relevant to microwave pasteurization

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ABSTRACT

Microwave pasteurization is a novel thermal processing technology in which non-uniform heating may be a major challenge. In this study, the suitability of using egg whites (EWs) and whole eggs (WEs) as model foods to evaluate the heating uniformity and to determine the cold and hot spots during microwave pasteurization was investigated. The samples were prepared from mixtures of water with commercial EW or WE powders at different solid concentrations (20%, 25%, 27.5%, and 30%) and salt contents (0, 50, 100, and 200 mM). Critical physical properties for desirable model food systems include appropriate dielectric properties, gelation temperatures, gel strengths, and water holding capacities (WHCs). The gelation temperature of liquid EW and WE were 70 and 80 °C; both fell in the pasteurization temperature range. At 915 MHz, the dielectric constants of liquid EW and WE samples and their heat induced gels decreased with solid concentration while the loss factor was not affected. Loss factors of liquid EW and WE samples increased linearly with salt addition, which could be explained by the linear increase of electrical conductivities by adding salt. The strength and WHC of heat induced EW and WE gels increased linearly with solid concentration, while salt addition had no significant effect. The results demonstrated the suitability of using EW and WE as model foods to determine the heating uniformity during microwave pasteurization process.

1. Introduction

Microwave-assisted thermal processing is a novel thermal processing technology that provides rapid volumetric heating (Ohlsson, 1991). It overcomes the slow heating in conventional thermal processes, so that better product quality could be retained. In October 2009, a process for mashed potatoes (homogeneous food) based on the 915 MHz microwave assisted thermal sterilization (MATS) system developed at Washington State University (WSU) was accepted by the US. Food and Drug Administration (FDA), followed by a second FDA acceptance for microwave assisted sterilization of salmon fillets in Alfredo sauce (non-homogeneous food) in December 2010. Similar to microwave sterilization, microwave assisted pasteurization (MAP) also utilizes the microwave energy to quickly raise product temperatures to desired levels to inactivate viable pathogens in foods. A 915 MHz MAP system is currently under development at WSU for cold-storage prepacked foods.

A major challenge for developing microwave-assisted thermal processes is possible non-uniform heating patterns caused by the factors influencing the electromagnetic field, such as food properties, package geometry, and location of the product inside the microwave applicators (Keefer and Ball, 1992; Stanford, 1990). In the development of MATS processes, whey protein gels (WPGs) with chemical marker precursors were found useful to map the heating patterns using a computer vision method (Pandit et al., 2007; Wang et al., 2009b). However, WPGs are not suitable for microwave pasteurization due to their high gelling temperature at around 90 °C. It is thus essential to develop new model food systems for MAP processes.

Natural egg components including egg white and whole egg can form heat-induced gels. Their gelation temperatures vary from 42 to 78 °C at different pH, salt, and sugar levels (Raikos et al., 2007), which are all in the pasteurization temperature range. Powdered eggs (produced by drying, mostly spray-drying, from the liquid eggs) in homogeneous form have an extended shelf life, and can be easily and consistently reconstituted into the liquid form with different solid concentrations. Thus, EW and WE can be conveniently used to form model foods.

In microwave processing, heat is generated volumetrically inside the material by converting electromagnetic energy into thermal energy. The dielectric properties of the model foods dictate how the microwave energy is absorbed, transmitted, reflected, or concentrated. They are of great importance for understanding the behavior of model foods during microwave heating (Datta and

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Ananthesweran, 2001). The dielectric properties of foods include the dielectric constant ε_r' and the dielectric loss factor ε_r'', which are the real and imaginary parts of the relative complex permittivity ε_r:

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \quad (1)$$

where $j = \sqrt{-1}$, ε_r' indicates the ability of a material to store electric energy, and ε_r'' reflects the ability of the material to dissipate electromagnetic energy into heat (Nelson and Datta, 2001). The rate of energy generation per unit volume (Q) in the material can be calculated from (Dibben, 2001):

$$Q = 2\pi f\ \varepsilon_0 \varepsilon_r'' E^2 \quad (2)$$

where E is the strength of electric field, ε_0 (8.8542×10^{-12} F/m) is the permittivity of free space, and f is the frequency.

The dielectric properties of natural hen egg components have been investigated by many researchers for storage studies, protein denaturation determinations, or effect of thermal treatment investigation (Bircan and Barringer, 1998; Ragni et al., 2007; Dev et al., 2008; Wang et al., 2009a). However, there was no study on the effects of solid concentration or salt content on the dielectric properties of the egg proteins. One of our objectives was to explore the possibility of generating a wide range of dielectric property values of egg proteins by changing solid and salt contents to match potential foods to be processed by MAP.

The heat induced gelation of egg proteins is a transition from a fluid-like to a solid-like viscoelastic structure (Montejano et al., 1984). Physical properties such as gelation temperature, gel strength, and water holding capacity (WHC) are also important for evaluating the suitability of EW and WE as model foods. The gelation temperature (the onset temperature at which the gelation occurs) determines whether the liquid EW and WE can solidify at the pasteurization temperatures to form solid model foods. It can be affected by the protein concentration, ion concentration, pH, and possible interaction between protein and other components (Yasuda et al., 1986). Gel strength indicates if the model food has a proper texture to hold its shape, and if it is proper for cutting and post-process evaluation. WHC is the ability of a gel to hold water in its network structure, indicating the ability of the model food to retain its geometry and size during and after the process.

The objectives of this study were to investigate the effects of solid concentration and salt content on physical properties (including dielectric properties, electrical conductivity, gelation temperature, gel strength, and WHC) of liquid egg white and whole egg samples and their heat induced gels, in order to evaluate their suitability as model foods for microwave pasteurization. The data can also be used as reference for processing of egg products using microwave pasteurization.

2. Materials and methods

2.1. Sample preparation

Commercial "Just Whites" all natural egg white powder (0% total fat, 2% sodium; Deb-El Foods Corporation, Elizabeth, NJ, USA) and "Honeyville Farms" whole egg powder (8% total fat, 3% sodium; Honeyville Food Products, Brigham City, UT, USA) were used to produce homogeneous liquid EW and WE samples. To study the effect of solid concentration on the physical properties, EW and WE were prepared with solid concentrations of 20%, 25%, 27.5%, and 30% (wb). Salted EW and WE samples were prepared by adding salt of 0, 50, 100, and 200 mM into liquid EW and WE samples with solid concentration of 25%. In the preparation of the liquid samples, a pre-determined amount of EW or WE powder was reconstituted using 35 °C double deionized (DDI) water and mixed for 3 min using a magnetic stir. Pre-determined amounts of table salt were added to the mixtures and further stirred for 15 min. The mixtures were held in a water bath at 35 °C for 20 min, and the n kept at room temperature overnight before use. Part of the liquid mixtures was then used for the determination of dielectric properties, electrical conductivities, and gelation temperature. Separate samples were filled into glass bottles (diameter = 40 mm; height = 30 mm), heated in a water bath at 85 °C for 30 min, and cooled in tap water for 20 min to form gels. The gels were used for the determination of gel strength and WHC. For each physical property measurement, duplicate sets of samples were prepared.

2.2. Dielectric properties

An HP 8752 C network analyzer (frequency range: 300–3000 MHz) and 85070B open-end coaxial dielectric probe (Agilent Technologies, Santa Clara, CA, USA) were used for the dielectric properties measurement (Fig. 1). After the instrument was warmed up and calibrated, liquid EW and WE samples were filled into the custom-built stainless steel test cell (20 mm inner diameter, 94 mm height). The test cell was connected to a circulating oil bath (Ethylene: water = 9:1) with programmable circulator (1157, VWR Science Products, Radnor, PA, USA) for temperature control. The liquid in the oil bath was pumped into the space between the two walls of the test cell to heat the sample from 22 to 100 °C. A thermocouple was inserted into the sample from the lower end of the test cell to monitor the temperature. The measurement was triggered at every 10 °C temperature increment. A stainless steel spring and piston inside the test cell compresses the sample tightly to the dielectric probe after heat-induced gelation in order to ensure the contact between the probe and the sample. 201 points were recorded through the whole frequency range of 300-3000 MHz. After each measurement, the test cell was dipped into ice to cool down. A more detailed description of the system and measurement procedure was described by Guan et al. (2004). All measurements were conducted in duplicate.

2.3. Penetration depth

Penetration depth (D_p) of microwave power in a dielectric material is the depth where the incident power decreases to $1/e$ ($e = 2.718$) of its original value at the material surface. D_p can be calculated from:

$$D_p = \frac{c}{2\pi f\sqrt{2\varepsilon'\left[\sqrt{\left(\frac{\varepsilon''}{\varepsilon'}\right)^2 + 1} - 1\right]}}\ (\mathrm{m}) \quad (3)$$

where c is the speed of light in free space as 3×10^8 m/s, f is the frequency (Hz) (Buffler, 1993), which is 915 MHz in this study.

2.4. Electrical conductivity

A CON-500 Electrical Conductivity meter (Cole-Parmer Instrument Co., Vernon Hills, IL, USA) was used for the electrical conductivity measurements of liquid EW and WE samples (25% solid concentration, wb) at room temperature. The probe was kept immersed in the solutions and the readings were recorded after the temperatures reached equilibrium. All measurements were made in triplicate.

2.5. Gelation temperature

The gelation temperature can be studied by different methods, including Differential Scanning Calorimetry (DSC) (Ahmed et al., 2007) and rheological methods such as small amplitude oscillatory shear (SAOS) (Ould Eleya and Gunasekaran, 2002; Croguennec

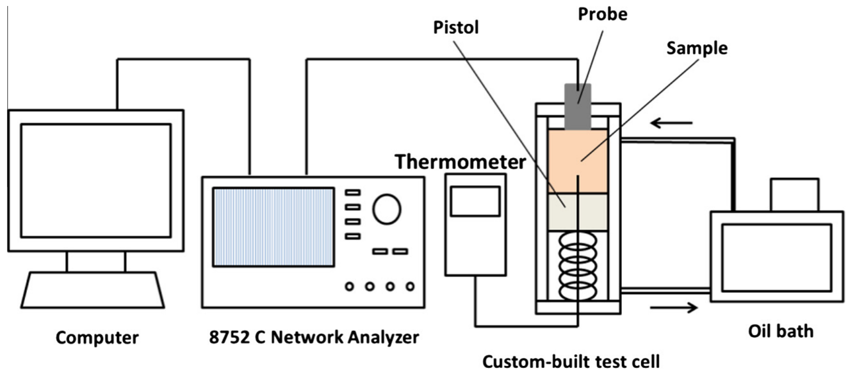

Fig. 1. Schematic diagram of the DP measurement system (adapted from Guan et al., 2004).

et al., 2002; Raikos et al., 2007). Since the SAOS method avoids the fracture of the formed protein network during measurement, it was chosen in this study as a more sensitive and accurate method.

An AR 2000 rheometer (TA Instruments, New Castle, DE, USA) was used to monitor the gelation temperature of liquid EW and WE samples using SAOS mode. For each measurement, approximately 1.26 mL sample was loaded between the 40 mm parallel plate geometry with a gap of 1.00 mm. In order to maintain a water saturated atmosphere to prevent evaporation of the sample during heating, the well in the upper plate was filled with distilled water and covered with a solvent trap cover. Once loaded, the sample was equilibrated to 30 °C for 1 min, and heated by a Peltier-plate temperature-controlling system to 90 °C at a heating rate of 5 °C/min. During heating, the SAOS test was carried out with a strain of 0.01 at a frequency of 1 Hz. Each measurement was carried out in duplicate.

Different approaches were used to extract the gelation temperature information from the rheological data for heat induced protein and polysaccharide gels. These include using the cross over point between the values of storage modulus (G') and loss modulus (G'') (Clark, 1991; Sun and Arntfield, 2011), the maximum G'' point (Stading and Hermansson, 1990), the temperature where G' becomes larger than the background noise (Ross-Murphy, 1995; Gunasekaran and Ak, 2000; Ould Eleya and Gunasekaran, 2002), and extrapolating the rapid increase of G' during the initial heating phase to intercept the temperature axis (Hsieh et al., 1993; Steventon et al., 1991; Tang et al., 1997). In our study, the method of extrapolating the rapid increase of G' during the initial heating phase to intercept the temperature axis was chosen to determine the gelation temperature.

2.6. Gel strength

A TA-XT2i Texture Analyzer (Texture Technologies Corp, Scarsdale, NY, USA) equipped with a 25 kg load cell and 40 mm plate probe was used to conduct the uniaxial compression tests for gel strength determination. The gel samples were cut into cylindrical specimens (diameter = 21 mm, height = 20 mm) using a stainless steel tube with sharp edges. The cross-head of the texture analyzer was set to move at a speed of 1 mm/s till 40% deformation, and return to the original position at a speed of 2 mm/s after the compression. The gel strength was represented by the maximum force indicated on the deformation curve. Each measurement was carried out in triplicate.

2.7. Water holding capacity (WHC)

The WHC of gels was determined following the method reported by Barbut (1995). The gel samples were cut into cylindrical specimens (diameter = 21 mm, height = 10 mm). The weight of a weighing plate with two pieces of 90-mm-dia Whatman filter paper # 541, was measured as W_0. A piece of gel specimen weighing W_s was placed between the two pieces of filter paper for a compression test using TA-XT2i Texture Analyzer. The compression test was set at 40% deformation and 30 s holding time. After compression, the weight of the plate and the wet filter paper were measured as W_1. The WHC value was calculated as:

$$\mathrm{WHC} = [1 - (W_1 - W_0)/W_s] \times 100\% \quad (4)$$

All measurements were carried out in triplicate.

2.8. Data analysis

Test data was analyzed using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA) to calculate the mean values and standard deviations. Linear regression tests and statistical difference determinations ($p = 0.05$) were conducted with Minitab (Minitab Inc., State College, PA, USA).

3. Results and discussion

3.1. Dielectric properties

3.1.1. Effect of frequency and temperature

The dielectric constant of both liquid EW and WE samples (25% solid concentration, wb) decreased with increasing frequency from 300 to 3000 MHz (Fig. 2a and c). The result agreed with the influence of microwave frequency on other food materials such as egg albumen and yolk (Ragni et al., 2007), liquid and precooked egg whites and whole eggs (Wang et al., 2009a), mashed potatoes (Guan et al., 2004), and whey protein gels (Nelson and Bartley, 2002). The dielectric loss factors of EW and WE also decreased with increasing frequency in the tested frequency range (Fig. 2b and d). The result confirmed earlier reports that the dielectric loss factor of most foods tended to decrease with increasing frequency (Calay et al., 1995), and that the loss factor of many foods was reduced almost by a half with the increase of frequency from 900 to 2800 MHz (Ohlsson and Bengtsson, 1975).

Effects of temperature (22–100 °C) on the dielectric properties of EW and WE can also be seen in Fig. 2. Calay et al. (1995) stated that the influence of temperature on the dielectric properties depended on the operating frequency, the bound-water and free-water content ratio, and the ionic conductivity of the material. For EW samples at frequencies higher than 500 MHz (Fig. 2a) and WE samples at higher than 400 MHz (Fig. 2c), the dielectric constants decreased as temperature increased from 22 to 100 °C. However, at lower frequencies, the change of dielectric constant with temperature was not consistent. It was reported that the dielectric constant increased with temperature for liquid and pre-cooked

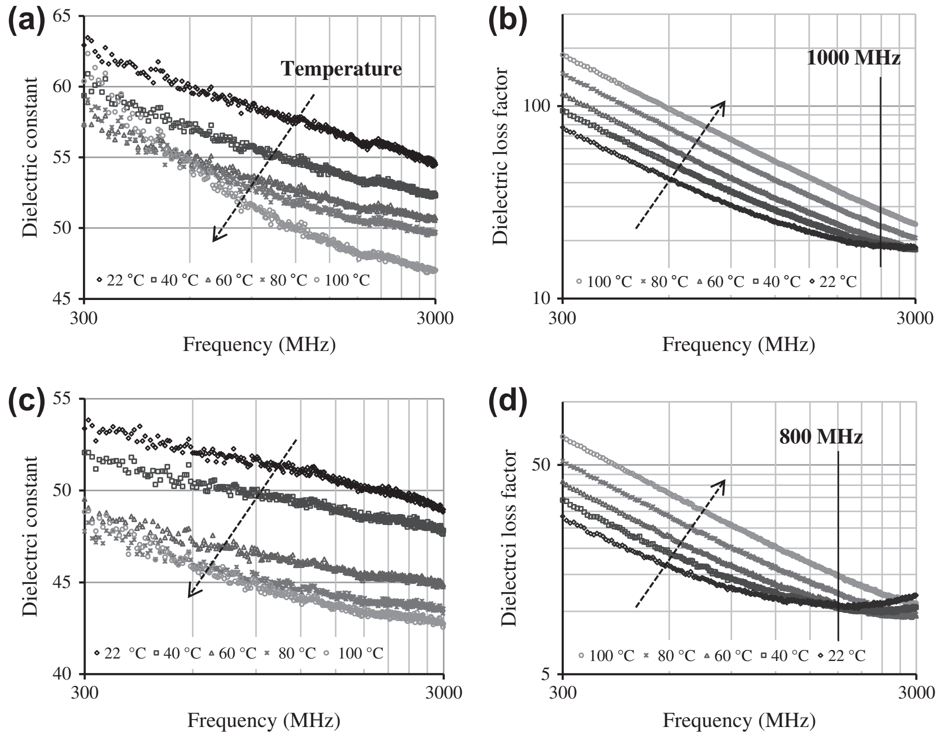

Fig. 2. Effects of frequency and temperature on the dielectric properties of liquid egg white (EW) and whole egg (WE) samples (25% solid concentration, wb): (a) Dielectric constant of egg white; (b) Dielectric loss factor of egg white; (c) Dielectric constant of whole egg; (d) Dielectric loss factor of whole egg.

natural egg white and whole eggs (Wang et al., 2009a) and whey protein gel (Wang et al., 2003) at 27 and 40 MHz. The dielectric constants of some biological tissues or agricultural products were even higher than 80 (Wang et al., 2003; Stuchly et al., 1982). Some authors attributed the high dielectric constant values to the poorly conditioned calibration at low frequencies (Sheen and Woodhead, 1999). However, the lowest frequency used in our study was 300 MHz, much higher than the ones in the former reports. We have no clear explanation for the different trends of dielectric constant with temperature at frequency range of 300–500 MHz for EW and 300–400 MHz for WE samples.

The changes of dielectric loss factor of EW and WE with temperature are shown in Fig. 2b and d. For EW at frequencies lower than 1000 MHz and WE at frequencies lower than 800 MHz, the dielectric loss factor increased with temperature. However, with the increase of frequency, the trends started to switch. Similar observations were reported for samples such as mashed potato (Guan et al., 2004), egg white and whole eggs (Wang et al., 2009a), and whey proteins (Wang et al., 2003). According to Mudgett (1986), the dielectric loss factor can be expressed as:

$$\varepsilon'' = \varepsilon''_d + \varepsilon''_\sigma \tag{5}$$

where ε''_d is the loss component due to the dipole rotation, and ε''_σ is the loss component due to the displacement of charged ions (Mudgett, 1986). At lower frequencies, the loss factor was mainly contributed by the ionic loss component ε''_σ. With the increase in frequency, the contribution of dipole component ε''_d started to increase. However, the importance of the dipole loss component decreased with increasing temperature, which meant the switch of trend of loss factor for low temperatures started at a lower frequency than the high temperature samples. Wang et al. (2009b) explained this phenomena by the shift of dispersion region of free water to higher frequencies at higher temperatures.

3.1.2. Effect of solid concentration

Effect of solid concentration on the dielectric properties of liquid EW samples is shown in Fig. 3. The dielectric constant decreased with the increase of solid content (Fig. 3a). However, the differences among dielectric constants of samples with different solid contents decreased with the increase in temperature. At 100 °C, no significant difference among the dielectric constants was found for all samples ($p > 0.05$). Sun et al. (1995) reported that for food samples with moisture content of higher than 40%, water in free form was supposed to be the dominant component governing the dielectric properties of the material. In our study, the samples at lower temperatures were in liquid form. Therefore, the increase of solid content resulted in decrease of free water content, and caused the decrease of the dielectric constant. With the increase of temperature where the denaturation of egg proteins started to occur and combine with a large amount of water, the amount of free water decreased and resulted in a similar dielectric constant value for egg white samples with different solid contents. However, Guan et al. (2004) found that moisture content had no effect on the dielectric constants of mashed potatoes. The difference could be attributed to the smaller solid content differences used in their study (from 12.2% to 18.4%). The effect of solid concentration on the dielectric loss factor was not significant ($p > 0.05$) (Fig. 3b). The results confirmed the findings of Mudgett et al. (1980) that dielectric loss factor showed little dependence on moisture content.

3.1.3. Effect of salt content

As shown in Fig. 4, salt addition of up to 200 mM had no significant effect on the dielectric constant of liquid EW and WE samples (25% solid concentration, wb) at 915 MHz ($p > 0.05$). However, the dielectric loss factor of both samples increased significantly with the increase of salt addition ($p < 0.05$) (Fig. 5). The result agreed well with the reported effect of salt on dielectric properties of

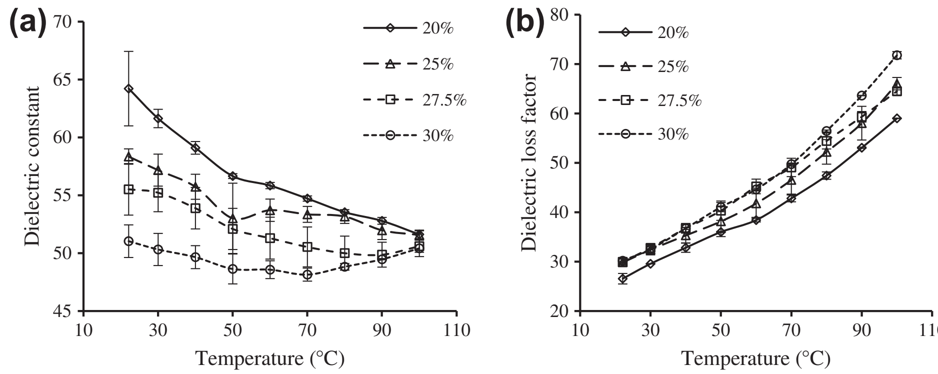

Fig. 3. Effect of solid concentration (wb) on the dielectric properties of liquid egg white (EW) samples at 915 MHz. (a) Dielectric constant and (b) dielectric loss factor.

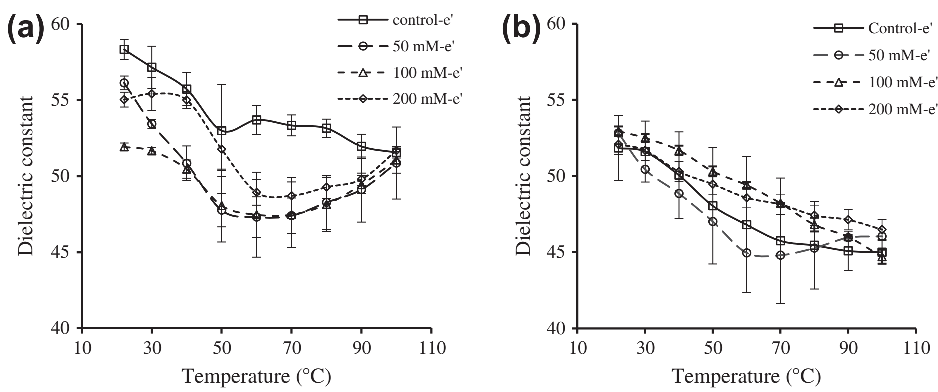

Fig. 4. Effect of salt content on the dielectric constant of liquid egg white (EW) (a) and whole egg (WE) (b) samples (25% solid concentration, wb) at 915 MHz.

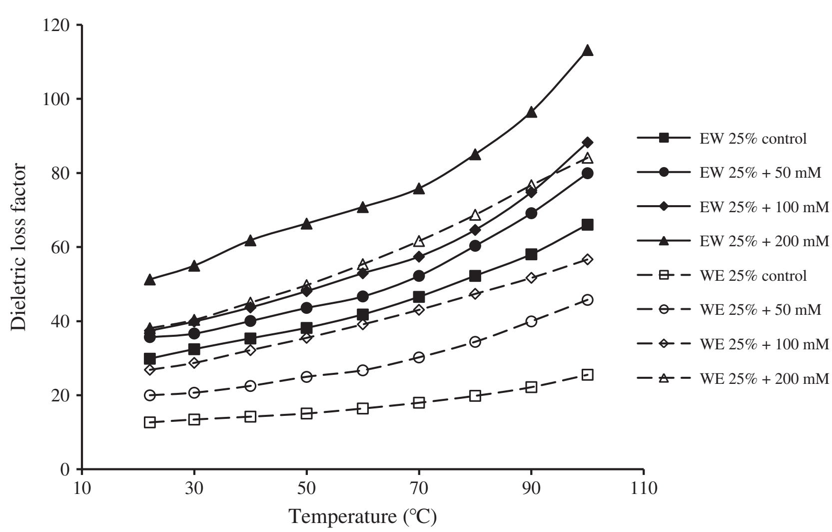

Fig. 5. Dielectric loss factor of liquid egg white (EW) and whole egg (WE) samples (25% solid concentration, wb) with different salt additions at 915 MHz.

mashed potatoes (Guan et al., 2004). This could be explained by the increased electrophoretic migration (Mudgett, 1986) achieved by adding salt. In Eq. (5), the ionic loss component (ε''_σ) due to the displacement of charged ions can be expressed as:

$$\varepsilon''_\sigma = \frac{\sigma}{2\pi f \varepsilon_0} \tag{6}$$

where σ is the electrical conductivity (S/m). The equation indicates that the ionic loss factor component increases linearly with electrical conductivity. As shown in Fig. 6, the electrical conductivity of liquid EW and WE samples (25% solid concentration, wb) increased linearly with salt addition at 22 °C. Therefore, a linear relationship between loss factor and salt addition can be deduced. From the experimental data, the relationship between loss factor and salt addition was developed as:

$$\varepsilon'' = a + bT + cS + dT^2 \tag{7}$$

where a, b, c, and d are constants, T is temperature (22∼100 °C), and S is salt content (0∼200 mM). The regression analysis results and

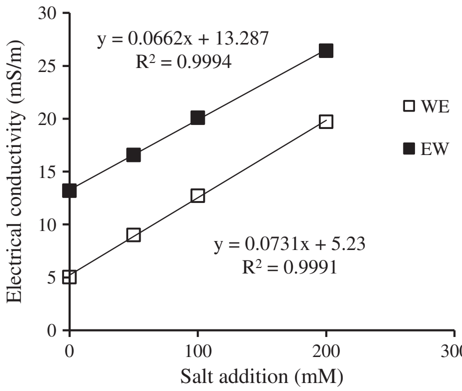

Fig. 6. Effect of salt addition on the electrical conductivities of liquid egg white (EW) and whole egg (WE) samples (25% solid concentration, wb) at 22 °C.

Table 1
Regression constants and coefficients of determination in Eq. (7) for dielectric loss factor of liquid egg white (EW) and whole egg (WE) samples (25% solid concentration, wb) at 915 MHz

	a	*b*	*c*	*d*	R^2
Egg white	26.68	−0.1444	0.1519	0.0060	0.97
Whole egg	−4.480	0.0575	0.1995	0.0025	0.94

the coefficients of determination R^2 for egg white and whole egg are shown in Table 1.

As shown in Fig. 5, higher electrical conductivity of EW sample partially contributed to the larger loss factors of EW than that of WE at the same solid and salt contents. In addition, the lower fat content of EW samples than that of WE was also part of the reason (Sun et al., 1995), which agreed well with the findings by Ragni et al. (2007), Dev et al. (2008), and Wang et al. (2009a). Therefore, a wide range of loss factors was provided by EW and WE with different salt contents. In our study, loss factor ranges of 12.7 ± 0.9 to 51.3 ± 0.4 at 22 °C and 25.5 ± 0.8 to 111.6 ± 0.3 at 100 °C were obtained. The regression results shown in Table 1 can be used to calculate the salt content of liquid EW and WE samples (solid concentration 25%, wb) so that desired loss factor could be obtained to model various foods at different temperatures.

3.1.4. Penetration depth (D_p)

The D_p of 915 MHz microwave in liquid EW and WE samples (25% solid concentration, wb) without added salt at 22 °C were 13.8 and 29.9 mm, respectively, which were comparable with that of egg white (19.4 mm), egg yolk (21.3 mm) (Dev et al., 2008), egg albumen (20 mm), and egg yolk (26 mm) (Guo et al., 2007). As shown in Fig. 7, the D_p of 915 MHz microwave in both EW and WE decreased linearly with temperature ($R^2 > 0.98$). This was caused by the increase of dielectric loss factor and slight decrease of dielectric constant with increasing temperature. Similar effects of temperature on D_p were reported for mashed potatoes (Guan et al., 2004) and whey protein gels (Wang et al., 2009b).

The addition of salt also caused decreasing of D_p in both liquid EW and WE samples due to the large influence on dielectric loss factor. However, water/solid concentration has no significant effect on D_p (Guan et al., 2004). It is, therefore, important to monitor the salt content of EW and WE to be used as model foods. It has been suggested that the thickness of a food material should not be more than two or three times that of the D_p for uniform pasteurization with dielectric heating (Schiffmann, 1995). Based on the results of the penetration depth, the maximum thickness of the model food using formulas in this study could range from approximately 30 mm for EW with 200 mM salt to 90 mm for WE without salt.

3.2. Gelation temperature

Plots of storage modulus (G') of liquid EW and WE samples (solid concentration 25%, wb) versus temperature are shown in Fig. 8. The initial gradual increase of G' was due to the denaturation of the less heat stable albumen protein, conalbumin (Montejano et al., 1984). When the temperature was further increased to around 70–74 °C, ovalbumin which is the major protein in egg whites (Powrie, 1977) started to denature and caused the rapid increase of rigidity, indicating the quick formation of three-dimensional gel network. In our study, the gelation temperature of liquid EW and WE samples determined by extrapolating the rapid increase of G' during the initial heating phase to intercept the temperature axis were 70 and 80 °C, respectively (Fig. 8). Both gelation temperatures were in the pasteurization temperature range, indicating that those gels could be formed during the microwave pasteurization process as model foods. The higher gelation temperature of WE was due to the higher thermostability of egg yolk than egg white proteins. The results were comparable with the reported gelation temperatures of natural EW and WE as 74.3 and 72.0 °C, respectively (Raikos et al., 2007). However, the lower gelation temperature of WE reported by Raikos et al. (2007) could be explained by the effect of protein concentration on gelation temperature.

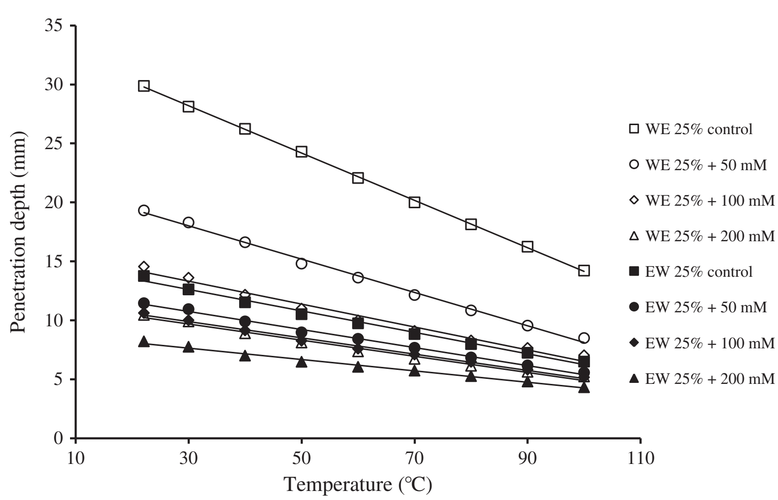

Fig. 7. Penetration depth of 915 MHz microwave in liquid egg white and whole egg samples (25% solid concentration, wb).

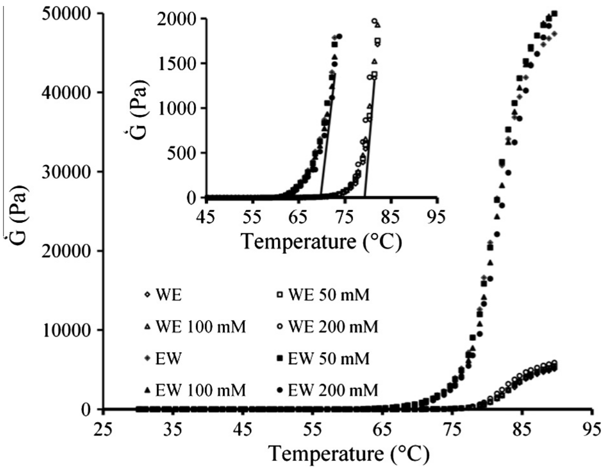

Fig. 8. Changes of storage modulus (G') of liquid egg white and whole egg samples (25% solid concentration, wb) with different salt additions during heating.

Ould Eleya and Gunasekaran (2002) revealed the decrease of gelation temperature with increasing protein content. The gelation temperature of EW with solid concentration of 10%, 15%, and 20% determined in their study were 78, 75, and 70 °C.

Salt has been reported to affect the heat-induced gelation of proteins by many researchers. Kohnhorst and Mangino (1985) suggested that low concentrations of salt could promote the solubilization of protein before heating. Arntfield et al. (1990) found that salt addition of 0.1–0.5 M (0.6–2.9%) had no effect on the denaturation temperature of EW. However, higher concentration of salt addition (6%) caused an increase of gelation temperature (Raikos et al., 2007), due to its inhibition of interactions between water and hydrophilic groups in protein (Danilenko et al., 1985), and the shielding effect on the repulsive forces between protein molecules (Raikos et al., 2007). In our study, salt addition of up to 200 mM (resulting in final salt content of 1.8% in EW and 2.0% in WE) had no significant ($p > 0.05$) effect on the gelation temperatures (Fig. 8).

3.3. Gel strength and water holding capacity (WHC)

Fig. 9 shows the linear increase in gel strength and WHC with solid concentration for EW and WE gels ($R^2 > 0.94$). The gel strength of EW was much higher than that of WE with the same solid concentration. This could be explained by the more compact network formed in EW gels due to higher protein content. However, solid concentrations of 20–25% for EW and 25–30% for WE should be used for model food preparation. We observed that other solid concentrations resulted in gels with either strong network structure that was difficult to cut, or low gel strength for handling. Salt addition (up to 200 mM) had no significant effect on gel strength of EW and WE ($p > 0.05$, results not shown). The result was different from the decreasing hardness of EW and WE gels caused by adding 6% salt (Raikos et al., 2007). The reason could be the lower salt and protein concentration ratio in our study, where less salt was added to more concentrated reconstituted liquid EW and WE samples. The WHC of WE was higher than that of EW with the same solid concentration, whereas both were high enough to retain gel form during and after the microwave processes. The effect of salt content on WHC of both EW and WE gels was also not significant ($p > 0.05$, results not shown).

4. Conclusions

The dielectric properties of liquid egg white and whole egg samples decreased with frequency from 300 to 3000 MHz. Dielectric constant decreased with solid concentration while loss factor was not affected. Salt addition caused significant increase in loss factor of both egg samples, resulting in a wide range of loss factor values so that various foods could be modeled following the regression equations obtained. Heat-induced gelation of egg whites and whole eggs with solid concentration of 25% occurred at 70 and 80 °C independent of the salt content in the tested range. Those temperature values suggest that egg white and whole eggs can form gel model foods during microwave pasteurization processes. The gel strength and water holding capacity of both gels increased linearly with solid concentration and was not affected by salt addition. The gel strength of both egg white and whole eggs under the tested concentrations are adequate for post-process evaluation. However, egg white with solid concentration of higher than 25% formed gels with very high strength, making them difficult to cut. The water holding capacities of both gels were high enough to retain the shape during and after the process. The results demonstrated that egg whites and whole eggs are suitable to model various foods in microwave pasteurization processes. In future studies, we will include chemical markers in the gel system to indicate the heating patterns in prepackaged foods during microwave pasteurization processes.

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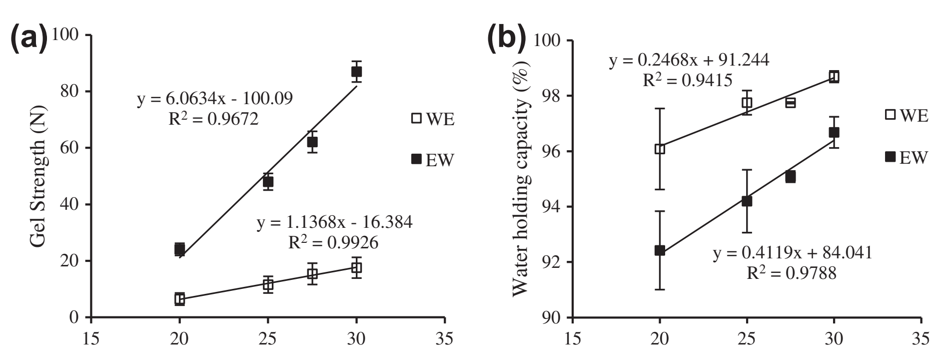

Fig. 9. Effect of solid concentration on the gel strength (a) and WHC (b) of egg white and whole egg gels without salt addition.

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