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Dielectric properties of rice model food systems relevant to microwave sterilization process

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ABSTRACT

Model foods as chemical marker carriers are needed to evaluate the heating patterns and location of hot and cold spots in developing microwave assisted thermal sterilization (MATS) processes. Previous research on model food development has been conducted for high moisture foods, with limited data on medium moisture foods (20–60% water). This research aimed to determine the dielectric properties (dielectric constants and loss factors) and penetration depths of rice grain (RG) and rice flour gel (RFG) model foods with moisture contents between 50 to 60% (wet basis) and of cooked rice (CR) over a frequency range of 300–3000 MHz at temperatures from 20 to 121 °C. The dielectric properties of rice models with 0% salt and 0.5% D-ribose closely matched the properties of CR; this indicated that rice model foods could be used to emulate CR for heating pattern and cold/hot spot detection in the development of MATS processes at 915 MHz and 2450 MHz.

Therefore, rice model foods developed in this research could be useful in the future for the food companies, in order to visualizing the heating pattern and determining the location of cold and hot spots during MATS process of medium moisture foods, such as rice, pasta or macaroni used as main ingredient in ready-to-eat meal products.

1. Introduction

Rice is a main staple food in Thailand and many other Asian countries (Srichamnong, Thiyajai, & Charoenkiatkul, 2016). World rice production and consumption in 2016 considerably increased by 1.4% to 497.9 million tonnes (milled basis) and by 1.2% to 501.2 million tonnes (milled basis), respectively (World Food Situation, 2016). Jasmine rice (*Oryza sativa* L.) is one of the most popular varieties of rice in Thailand due to its excellent quality; it has a unique aromatic fragrance, a white color like the jasmine flower, a soft and tender texture, and a good taste. Jasmine rice is the primary rice cultivar for domestic consumption and a major export commodity for Thailand's economic growth (Leelayuthsoontorn & Thipayarat, 2006; Phanchaisri et al., 2007). With the increasing popularity of ready-to-eat (RTE) meals, Jasmine rice is often selected to produce rice-based products, including shelf-stable, chilled, and frozen products. Commercially sterilized RTE rice can be produced using retort (canning) (Byun et al., 2010).

Microwave heating, as an alternative conventional heating method, has drawn great attention in the food processing industry (Tang, 2015). Due to the rapid and internal direct interaction between microwaves and food products, the volumetric microwave heating can overcome the drawback of slow rates of heat transfer in conventional thermal processes. Therefore, the heating time can be significantly reduced to retain superior product quality (Pandit, Tang, Mikhaylenko, & Liu, 2006; Zhang, Tang, Liu, Bohnet, & Tang, 2014). Food companies in Europe and Japan commercially produce a range of RTE meals sterilized using microwave systems for retail markets; these companies include Tops Foods (Olen, Belgium), Otsuka Chemical Co. (Osaka, Japan) and Gustosi (Italy) (Tang, 2015). More recently the microwave-assisted thermal sterilization (MATS) technology developed at Washington State University (WSU) was accepted by the U.S. Food and Drug Administration (FDA) and received a non-objection notice from the U.S. Department of Agriculture Food Safety and Inspection Service (USDA-FSIS) for commercial sterilization of pre-packaged foods (Tang, 2015).

For effective development of commercial microwave sterilization processes that ensure the processed foods are safe for consumption, it is necessary to determine the location of cold and hot spots in packaged foods (Pandit, Tang, Liu, & Mikhaylenko, 2007; Wang, Lau, Tang, & Mao, 2004). However, it is difficult to assess the temperature distribution and to identify hot and cold spots within packaged foods

Abbreviations: RG, rice grains; RFG, rice flour gel; CR, cooked Jasmine rice

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during microwave sterilization. The dielectric heating by microwaves relies on direct interactions between complicated electromagnetic fields and the food; it is different from conventional heating that has been well defined (Lau et al., 2003). Moreover, direct temperature measurement devices such as thermocouples, fiber optic temperature sensors and infrared sensors have major limitations in dielectric heating (Wang et al., 2004).

A chemical marker method developed at the U.S. Army Natick Soldier Research Center provides a possible means to determine the heating pattern and locate the hot and cold spots in a food system during thermal sterilization processes (Kim & Taub, 1993). This method is based on the development of brown color in chemical markers through the Maillard browning reaction between amino acids and reducing sugars such as D-ribose. D-Ribose, as a chemical marker precursor, has been added into the model foods. Three chemical markers—M-1 (2,3-dihydro-3,5-dihydroxy-6-methyl-4(H)-pyran-4-one), M-2 (4-hydroxy-5-methyl-3(2H)-furanone), and M-3 (5-hydroxymethylfurfural)—have been used as time-temperature indicators with strong correlations to thermal lethality (Tang, 2015; Pandit, Tang, Liu, & Pitts, 2007; Pandit et al., 2006; Zhang et al., 2014).

Using the chemical marker technique in real foods is problematical, as real foods are mostly non-homogenous, which can lead to inaccurate heating pattern detection (Wang et al., 2004). Therefore, various model foods were developed to simulate real foods in order to accurately predict the location of cold and hot spots in microwave-processed foods (Zhang et al., 2015). For the purpose of heating pattern and cold/hot spot detection, the model foods should be developed to have similar dielectric properties to those of the real foods (Wang et al., 2009). The dielectric properties (electric permittivity) are the major characteristics of foods to determine the ability of the foods to store and dissipate electrical energy during dielectric heating (Mudgett, 1986). Dielectric properties are described by complex permittivity, ε^* as shown in Eq. (1):

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \tag{1}$$

where $j = \sqrt{-1}$, the dielectric constant (ε') expresses a material's ability to store electromagnetic energy, and the dielectric loss factor (ε'') measures a material's ability to convert microwave energy into thermal energy (Tang, 2015). The frequency of the electromagnetic waves as well as the temperature, moisture content, free and bound water content, salt content, sugar content, nature, and constituents of food materials can affect the dielectric properties and the resultant dielectric heating (Ahmed, Ramaswamy, & Raghavan, 2007; Guan, Cheng, Wang, & Tang, 2004).

Previous model foods for microwave processing applications include whey protein gel (Lau et al., 2003), mashed potato with xanthan gum (Pandit et al., 2006), low-acyl gellan gel (Zhang et al., 2015), mashed potato with gellan gum (Bornhorst, Tang, Sablani, & Barbosa-Cánovas, 2017), egg white gel (Zhang, Liu, Nindo, & Tang, 2013), and agar gel (Sakai, Mao, Koshima, & Watanabe, 2005). The model foods have been used to emulate real foods, such as mashed potato, macaroni and cheese (Wang, Wig, Tang, & Hallberg, 2003), salmon fillets (Wang et al., 2009), sliced beef in gravy (Tang et al., 2008) and sea cucumbers (Cong, Liu, Tang, & Xue, 2012). It has been proven that using model foods that match the dielectric properties of real foods is a good solution for heating pattern and cold/hot spot determination.

All previous research on model food development focused on high moisture foods. Salt and sugar were used to adjust the dielectric properties of high moisture model foods (Guan et al., 2004; Sakai et al., 2005; Wang et al., 2009; Zhang et al., 2015) and food materials (Ahmed et al., 2007; Peng, Tang, Jiao, Bohnet, & Barrett, 2013). However, there are no existing model foods that could be used to simulate medium moisture food products, such as rice or pasta. In particular, there is a lack of research on the influence of salt and D-ribose on the dielectric properties of rice model food systems and cooked Jasmine rice (CR) at 300–3000 MHz over temperatures from 20 to 120 °C. Knowledge of such properties is needed for the development of the microwave pasteurization and sterilization of medium moisture foods, such as rice-based products. The objectives of this research were: 1) to determine the dielectric properties of rice model food systems containing various salt and D-ribose contents at 300–3000 MHz and 2) to develop appropriate rice model foods to emulate CR in microwave heating at 915 MHz and 2450 MHz which are the frequencies allocated by the Federal Communication Commission for industrial, scientific, and medical applications.

2. Materials and methods

2.1. Preparation of rice model food systems

Two types of rice-based model food systems were used in this study: rice grains (RG) and rice flour gel (RFG) model foods. Salt (sodium chloride) (J.T. Baker, NJ, USA) and D-ribose (Sigma-Aldrich, St. Louis, MO, USA) were added to both RG and RFG model foods in order to adjust the dielectric properties and to facilitate brown color formation from the Maillard reaction, respectively.

For the RG model food system, 100 g of Jasmine rice grains with 120 g of distilled water (rice to water ratio of 1:1.2) were cooked in a water bath for 40 min at 95 °C. The formulations of the RG model foods with different concentrations of salt and D-ribose are presented in Table 1.

The rice flour used in this study was made from milled dry Thai Jasmine rice (*Oryza sativa*, CP. Intertrade, Thailand) using a Vitamix blender (G-series, Vitamix, OH, USA), followed by sieving through a U.S. standard mesh#100 (Advantech, WI, USA). Rice flour, tapioca starch (Walong Marketing Inc., CA, USA), xanthan gum (Sigma-Aldrich, St. Louis, MO, USA), sodium chloride and D-ribose according to Table 2 were mixed with distilled water (solid to water ratio of 1:1.2) in order to make each RFG model food. The suspension was mixed continuously for 3 h at room temperature (22 °C) using magnetic stirring to achieve homogeneity. The mixture was heated at 95 °C in a water bath for 40 min to set the gel.

2.2. Dielectric properties measurement

The dielectric properties of the RFG, RG, and CR samples were measured using an HP 8752 C Network Analyzer and 85070B Open-End Coaxial Dielectric Probe (Agilent Technologies, Santa Clara, CA, USA) over a temperature range of 20–121 °C and a frequency range of 300–3000 MHz. Before measurement, the system was calibrated using a calibration kit which included an open circuit (air), a short circuit

Table 1
Nine formulations (% wet basis) of the rice grain (RG) model foods.

Ingredients	1	2	3	4	5	6	7	8	9
Salt	0.0	0.5	1.0	1.5	2.0	3.0	0.3	0.3	0.3
D-Ribose	0.5	0.5	0.5	0.5	0.5	0.5	0.2	0.5	1.0
Water	54.3	54.0	53.7	53.4	53.2	52.6	54.3	54.1	53.8
Rice grains	45.2	45.0	44.8	44.6	44.3	43.9	45.2	45.1	44.9

Table 2
Nine formulations (% wet basis) of the rice flour gel (RFG) model foods.

Ingredients	1	2	3	4	5	6	7	8	9
Salt	0.0	0.5	1.0	1.5	2.0	3.0	0.3	0.3	0.3
D-Ribose	0.5	0.5	0.5	0.5	0.5	0.5	0.2	0.5	1.0
Water	55.9	55.4	54.9	54.4	53.9	52.9	55.9	55.6	50.1
Rice flour	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	35.0
Tapioca starch	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
Xanthan gum	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

(gold-plated precision shorting block), and a known load (25 °C distilled water). After the calibration of the analyzer and the probe, the sample was added and tightly sealed in the test cell for measurement (Wang et al., 2003). The measurements for each type of sample were performed in triplicate. The effects of the sodium chloride (NaCl) and D-ribose concentrations on the dielectric properties of the rice model systems were examined by adding 0, 0.3, 0.5, 1, 1.5, 2 and 3% of NaCl and 0.2, 0.5 and 1% of D-ribose into rice model systems. RFG was cut into a cylindrical shape using a custom-made stainless steel tube in order to fit into the custom-designed, temperature-controlled test cell connected to an oil bath containing ethylene glycol (PolyScience Products, Niles, IL, USA). The RG model food was directly added and tightly compressed into the test cell for measurement. Preparation of CR involved cooking a mixture of 100 g Jasmine rice grains and 120 g distilled water (rice to water ratio of 1:1.2) in a 95 °C water bath for 40 min. The temperature of the CR was equilibrated to room temperature prior to filling the sample into the test cell for measurement. A stainless steel spring installed on the bottom inside the test cell maintained close contact between the food sample and the probe throughout the measurement process.

2.3. Determination of microwave penetration depth

Microwave penetration depth is an important parameter in characterizing the temperature distribution in microwave-heated foods and is generally used to predict the distance that microwave energy can penetrate into a food. Penetration depth (D_p) is defined as the depth where the power is reduced to 1/e (e = 2.718) of the power entering the surface (Ahmed et al., 2007; Tang, 2015). Eq. (2) was used to determine D_p (Ahmed et al., 2007):

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

where ε′ is the dielectric constant, ε″ is the dielectric loss factor, c is the speed of light in free space (3×10^8 m/s), and f is the frequency (Hz).

2.4. Data analysis

Statistical and regression analyses of the data were performed using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA) and values were shown as the mean ± standard deviation. The p-value for significance was < 5% ($p < 0.05$).

3. Results and discussion

3.1. Dielectric property data

Dielectric properties are critical criteria for selecting appropriate model foods for microwave-heating process development (Zhang et al., 2015). The dielectric constant and loss factor data of RFG, RG and CR at 915 MHz and 2450 MHz are presented in Figs. 1 and 2, respectively. The dielectric constants and the loss factors of CR as well as RFG and RG with 0.5% D-ribose and no added salt decreased with increasing temperature. In moist foods with less salt, dielectric properties are governed by water. Increasing sample temperature increases Brownian movement of water molecules resulting in decreased dielectric constants (Tang, 2005). In addition, increased sample temperature shifts free water relaxation peak away from 915 or 2450 MHz and depresses relaxation peak, leading to reduced dielectric loss factor for samples with 0% salt (Feng, Tang, & Cavalieri, 2002; Guan et al., 2004; Sumnu & Sahin, 2005; Tang, 2005; Wang et al., 2003). Similar trends were observed with whey protein gel, liquid whey protein mixture and cheese sauce (Wang et al., 2003), and mashed potatoes without salt (Guan et al., 2004). Ahmed et al. (2007) offered an additional explanation to the decrease in both the dielectric constant and loss factor of 20% Basmatic rice flour slurry with the temperature increase; they suggested that this trend might also be influenced by amylose leaching out of the rice flour granules during heating, which would contribute to the increase in the water soluble components at high temperatures. Various mathematical models were tried to fit the dielectric property parameters with temperature at 915 MHz and 2450 MHz. The best fit was with second order polynomial equations for the dielectric property

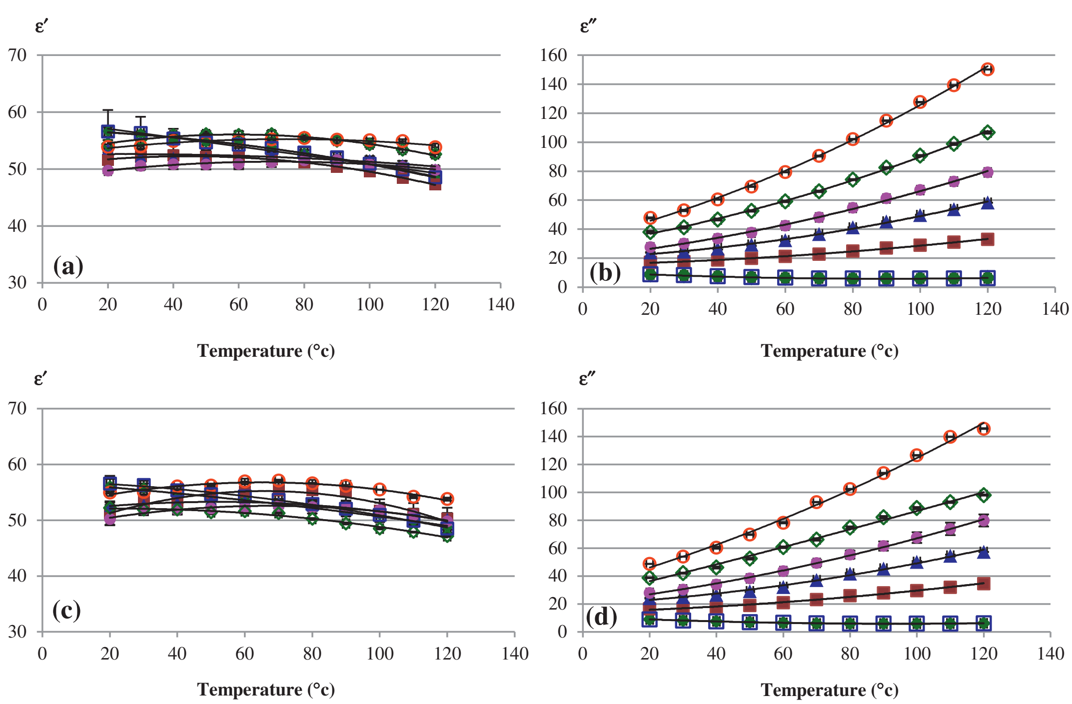

Fig. 1. Effect of salt content (0% (◆), 0.5% (■), 1% (▲), 1.5% (●), 2% (◇) and 3% (○)) on the dielectric constant of rice flour gel (RFG) (a) and rice grains (RG) (c) as well as the dielectric loss factor of rice flour gel (RFG) (b) and rice grains (RG) (d) at 915 MHz between 20 and 121 °C with 95% confidence internals (3 replicates). The dielectric properties of cooked rice (CR) (□) are shown for comparison with the model food systems. Second-order polynomial correlations for data are also shown in (—).

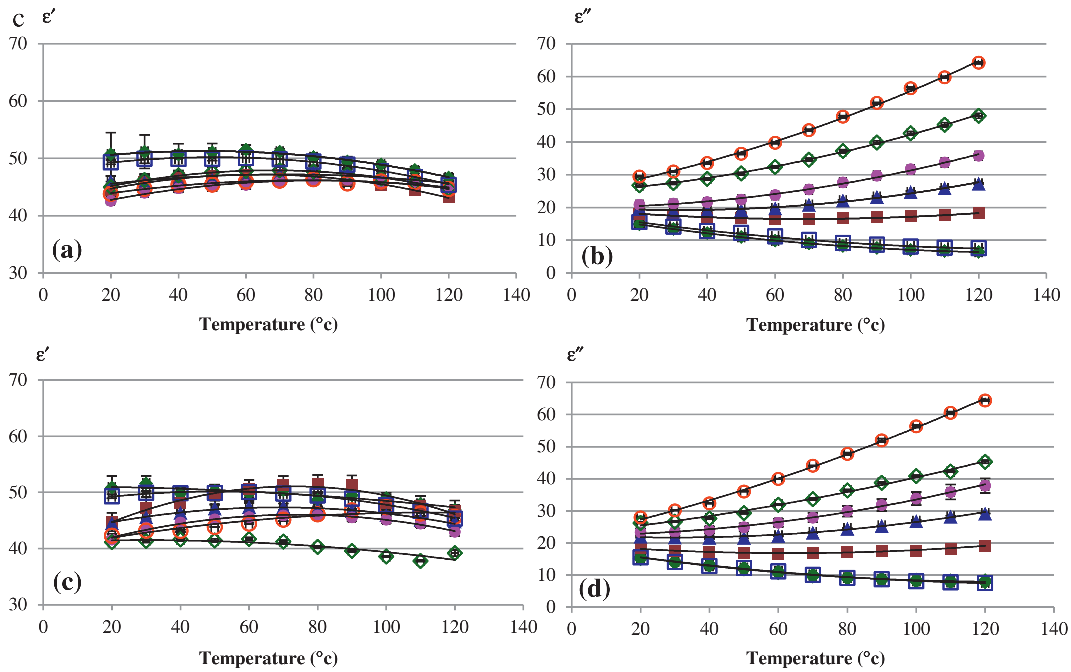

Fig. 2. Effect of salt content (0% (◆), 0.5% (■), 1% (▲), 1.5% (●), 2% (◇) and 3% (○)) on the dielectric constant of rice flour gel (RFG) (a) and rice grains (RG) (c) as well as the dielectric loss factor of rice flour gel (RFG) (b) and rice grains (RG) (d) at 2450 MHz between 20 and 121 °C with 95% confidence internals (3 replicates). The dielectric properties of cooked rice (CR) (□) are shown for comparison with the model food systems. Second order polynomial correlations for data are also shown in (—).

Table 3
Relationship of the dielectric constant (ε′) and dielectric loss factor (ε″) with temperature at 915 MHz for the rice flour gel (RFG) and rice grain (RG) model food systems with no added salt and 0.5% added D-ribose as well as for the cooked Jasmine rice (CR) (n = 3).

Sample	Dielectric properties (ε′, ε″) correlation with temperature (T in °C)	R^2
RG	$\varepsilon' = -0.0002T^2 - 0.0434T + 56.842$	0.98
	$\varepsilon'' = 0.0006T^2 - 0.1097T + 10.94$	0.99
RFG	$\varepsilon' = -0.0004T^2 - 0.0161T + 56.908$	0.99
	$\varepsilon'' = 0.0006T^2 - 0.1073T + 10.691$	0.99
CR	$\varepsilon' = -0.0004T^2 - 0.0213T + 57.061$	0.99
	$\varepsilon'' = 0.0005T^2 - 0.1036T + 10.819$	0.99

Table 4
Relationship of the dielectric constant (ε′) and dielectric loss factor (ε″) with temperature at 2450 MHz for the rice flour gel (RFG) and rice grain (RG) model food systems with no added salt and 0.5% added D-ribose as well as for the cooked Jasmine rice (CR) (n = 3).

Sample	Dielectric properties (ε′, ε″) correlation with temperature (T in °C)	R^2
RG	$\varepsilon' = -0.0003T^2 + 0.0005T + 51.059$	0.83
	$\varepsilon'' = 0.0007T^2 - 0.1708T + 18.618$	0.99
RFG	$\varepsilon' = -0.0009T^2 + 0.0829T + 49.239$	0.97
	$\varepsilon'' = 0.0006T^2 - 0.1742T + 18.068$	0.99
CR	$\varepsilon' = -0.0001T^2 + 0.1003T + 47.638$	0.99
	$\varepsilon'' = 0.0007T^2 - 0.1708T + 18.618$	0.99

results of the CR and the rice model food systems (RG and RFG) without added salt for ease of using the data in future work (Tables 3 and 4).

3.2. Effect of salt concentration

When salt was added to the RFG and RG model foods, the dielectric loss factor increased with increasing temperature (Figs. 1 and 2). This was expected, as dissolved salt ions increased the ionic conductivity, and electrophoretic migration of dissolved ions yielded an increased loss factor (Ahmed et al., 2007; Peng et al., 2013). Dielectric constant was not much influenced by the salt content. Similar dielectric property trends were reported for rice slurry (Ahmed et al., 2007), salt-starch (Bircan & Barringer, 1998), tomato tissues (Peng et al., 2013), agar gel (Sakai et al., 2005), whey protein gel (Wang et al., 2009), mashed potatoes (Guan et al., 2004), and low-acyl gellan gel (Zhang et al., 2015). The current results showed that the intensity of salt significantly influenced the loss factor, but did not have a major effect on the dielectric constant. The same conclusion was also reported by Guan et al. (2004) for mashed potato model foods.

3.3. Effect of D-ribose concentration

Varying the D-ribose concentration (0.2, 0.5, and 1.0%) did not significantly affect the dielectric constant or loss factor of RFG and RG at 915 MHz and 2450 MHz (Figs. 3 and 4), possibly due to the fact that D-ribose has much larger and less polar molecules than water. Several researchers also reported only minor effects of sugars on dielectric properties of model foods (Sakai et al., 2005; Wang et al., 2009).

3.4. Effect of frequency and temperature

The dielectric constant of the RFG and RG model foods with 0.5% D-ribose and 0% salt decreased with increasing frequency and temperature (Fig. 5). A similar result was reported for whey protein gel, liquid whey protein mixture, macaroni and cheese (Wang et al., 2003), mashed potatoes (Guan et al., 2004), salmon fillet (Wang et al., 2009), and tomato tissues (Peng et al., 2013). The loss factor of the RFG and RG model foods initially decreased at low frequencies followed by an increase with increasing frequency. A similar phenomenon was also found in basmati rice flour slurry (Ahmed et al., 2007), mashed potatoes (Guan et al., 2004), and low-acyl gellan gel (Zhang et al., 2015). At higher frequencies, dipole rotation of free water is the dominant contribution to loss factor, whereas at lower frequencies (lower than 1000 MHz), ionic conductivity plays a more predominant role (Peng et al., 2013: Zhang et al., 2015). In generally, the loss factor increases

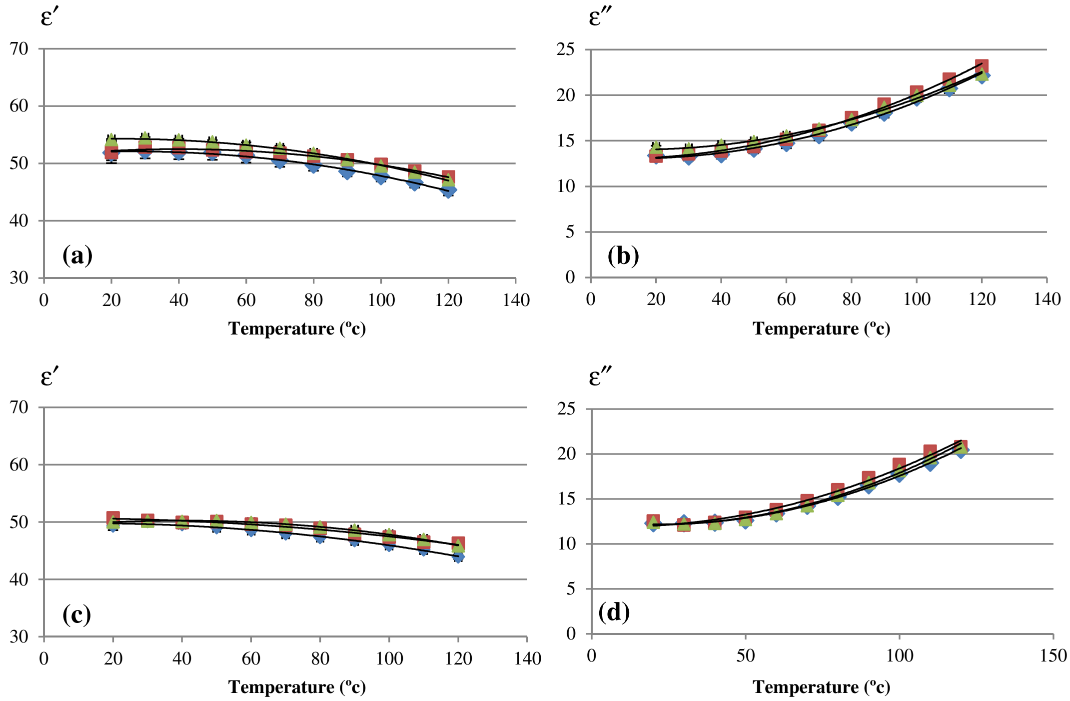

Fig. 3. Effect of D-ribose content (0.2% (◆), 0.5% (■) and 1% (▲)) on the dielectric constant of rice flour gel (RFG) (a) and rice grains (RG) (c) as well as the dielectric loss factor of rice flour gel (RFG) (b) and rice grains (RG) (d) at 915 MHz between 20 and 121 °C with 95% confidence internals. Second-order polynomial correlations for data are shown in (—).

with increasing temperature at low frequencies due to the increased ionic conductivity and decreases with increasing temperature at high frequencies due to the shift of free water dispersion (Zhang et al., 2013, 2015) and negative temperature coefficient of free water in the high microwave frequencies (Calay, Newborough, Probert, & Calay, 1995).

3.5. Microwave penetration depth

The microwave penetration depths in RG and RFG decreased with increasing salt concentration and decreased with increasing temperature (except for the samples with no salt addition) at both 915 MHz and

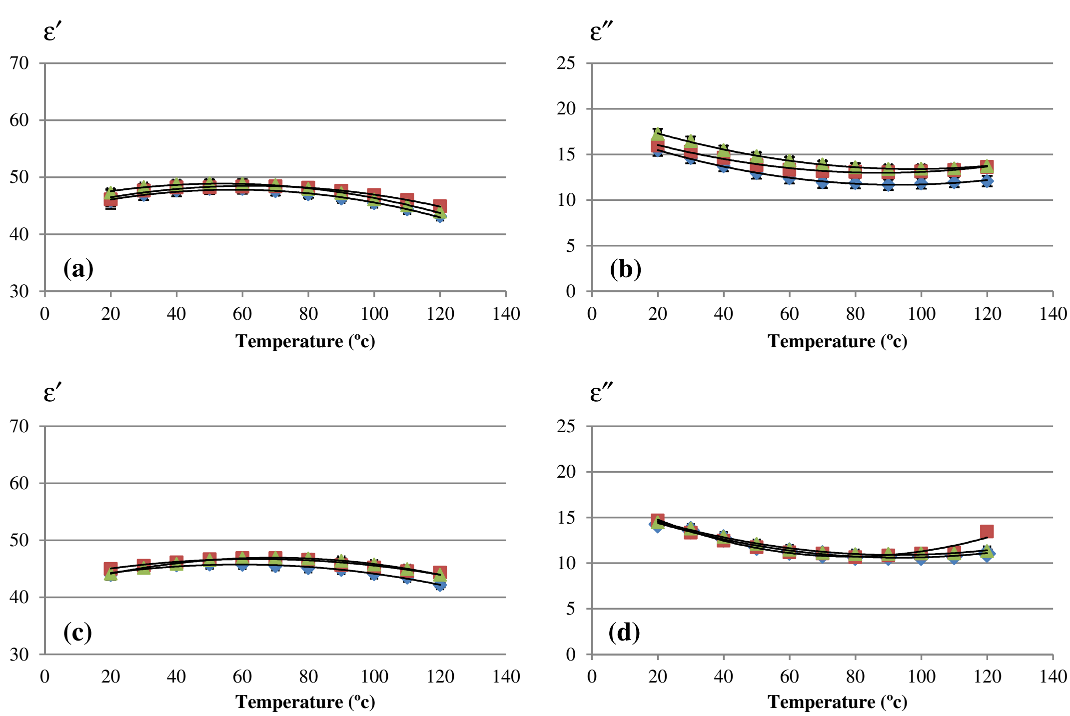

Fig. 4. Effect of D-ribose content (0.2% (◆), 0.5% (■) and 1% (▲)) on the dielectric constant of rice flour gel (RFG) (a) and rice grains (RG) (c) as well as the dielectric loss factor of rice flour gel (RFG) (b) and rice grains (RG) (d) at 2450 MHz between 20 and 121 °C with 95% confidence internals. Second-order polynomial correlations for data are shown in (—).

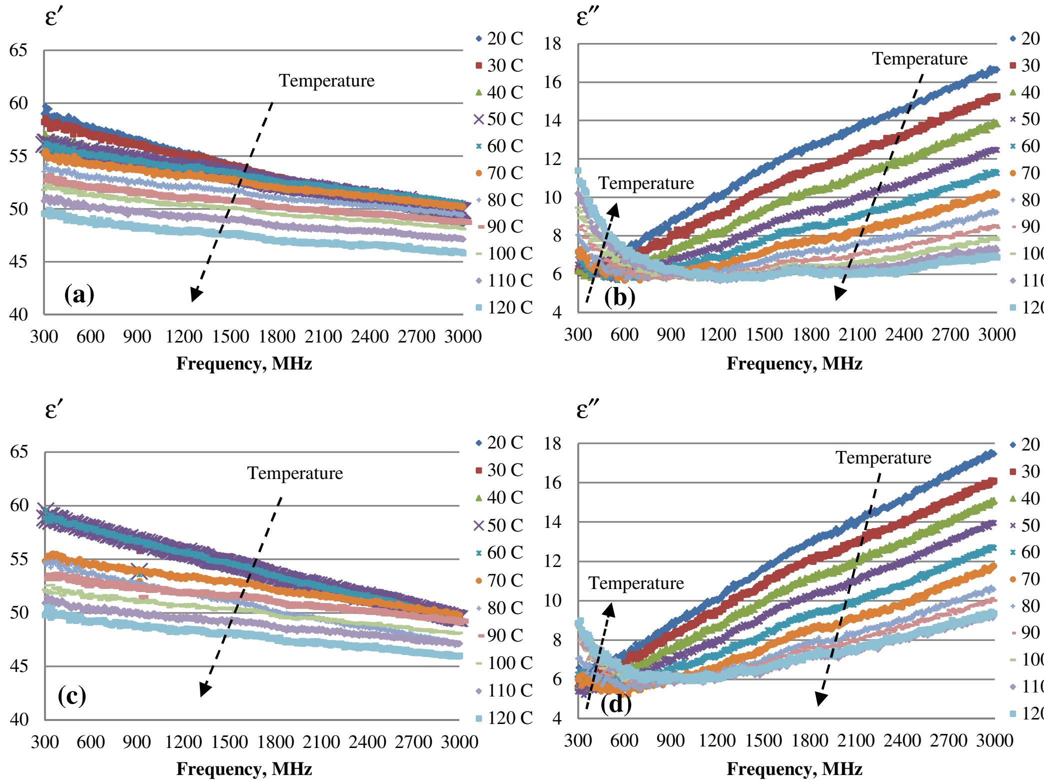

Fig. 5. Effect of frequency and temperature on the dielectric constant and loss factor of rice flour gel (RFG) (a and b) and rice grains (RG) (c and d) with 0.5% D-ribose and without added salt.

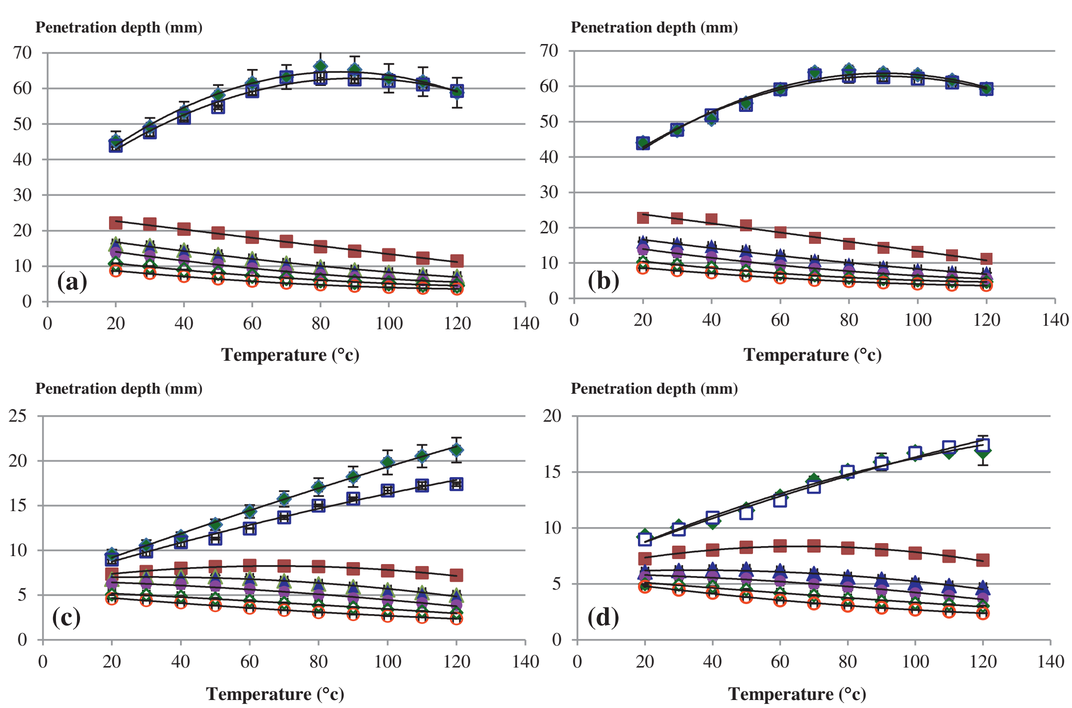

Fig. 6. Microwave penetration depths in rice flour gel (RFG) (a) and (c) and rice grains (RG) (b) and (d) with various salt contents (0% (◆), 0.5% (■), 1% (▲), 1.5% (●), 2% (◇) and 3% (○)) at 915 MHz (a and b) and 2450 MHz (c and d), respectively, between 20 and 121 °C with 95% confidence internals. The penetration depths in cooked rice (CR) (□) are shown for comparison with the model food systems. Second-order polynomial correlations for data are shown in (—).

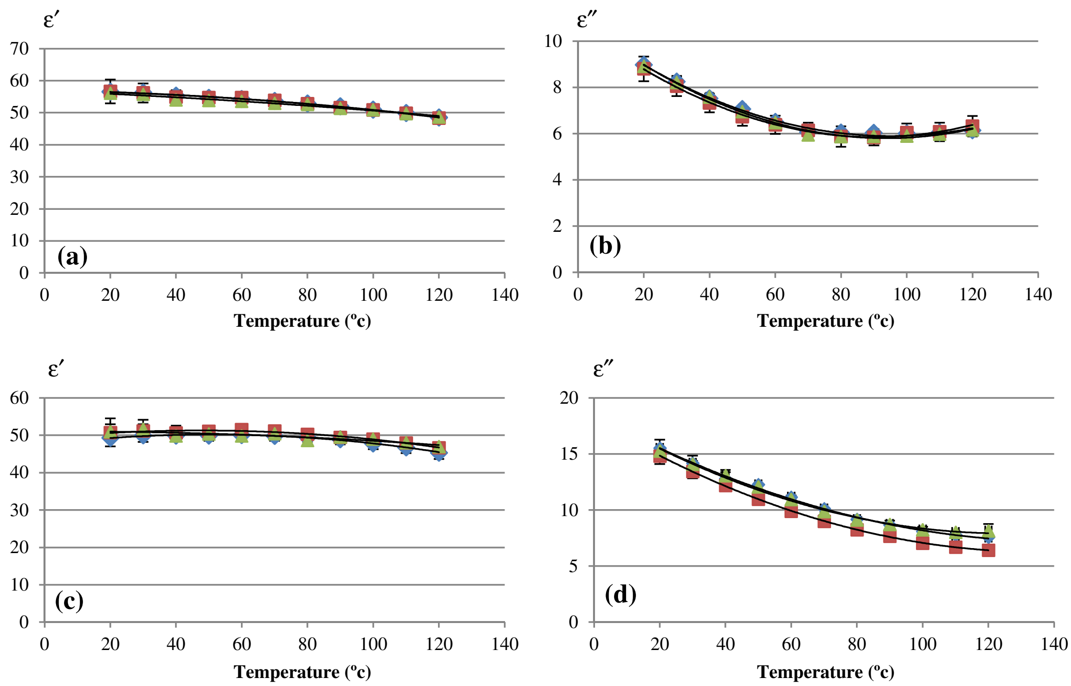

Fig. 7. Comparison of dielectric constants (a and c) and dielectric loss factors (b and d) of cooked rice (CR) (◆), rice flour gel (RFG) (■), and rice grain (RG) (▲) with 0.5% D-ribose and no added salt at 915 MHz (a and b) and 2450 MHz (c and d) between 20 and 121 °C with 95% confidence internals. Second-order polynomial correlations for data are shown in (—).

2450 MHz (Fig. 6). For example, at 915 MHz, the penetration depth in RG and RFG with 0.5% salt at 120 °C was 11.23 mm and 11.48 mm, respectively; increasing the salt concentration to 3%, the penetration depth in RG and RFG at 120 °C decreased to 3.66 mm and 3.59 mm, respectively. At 2450 MHz, the penetration depths in RG and RFG with 0.5% salt at 120 °C were 7.12 mm and 7.23 mm, respectively; increasing the salt concentration to 3%, the penetration depths in RG and RFG at 120 °C decreased to 2.39 mm and 2.38 mm, respectively. This was expected, as increased amount of dissolved salt ions increases the ionic conductivity leading to increased loss factor and reduced penetration depths (Ahmed et al., 2007; Peng et al., 2013). Additional explanations on the significant increase in the loss factor and the resultant decreased penetration depth with adding salt to samples were also made by Guan et al. (2004) and Zhang et al. (2015).

The changes in penetration depths with increasing temperature (Fig. 6) were opposite to those with the loss factors (Figs. 1 and 2). As described in Eq. (2), the penetration depth D_p is inversely related to the loss factor ε″ (Peng et al., 2013). A similar change in the penetration depth with changing temperature at 915 MHz was also reported for whey protein gel, macaroni and cheese (Wang et al., 2003), mashed potatoes (Guan et al., 2004), pink salmon fillets (Wang et al., 2009), tomatoes tissues (Peng et al., 2013), and low-acyl gellan gel (Zhang et al., 2015).

3.6. Comparison of dielectric properties and penetration depths between rice model food systems and real food

RFG and RG with 0.5% D-ribose and without added salt had dielectric constants and loss factors similar to those of CR at 915 MHz and 2450 MHz (Fig. 7). This was due to the fact that the moisture contents of both model systems—RFG (58.60%) and RG (58.31%)—were similar to that of CR (58.22%). At 915 MHz, the penetration depths in CR were 43.87 mm at 20 °C and 59.26 mm at 120 °C. The penetration depths in RG and RFG with 0.5% D-ribose and no added salt were similar to those in CR—44.01 mm at 20 °C and 59.21 mm at 120 °C in the RG model food and 45.23 mm at 20 °C and 58.81 mm at 120 °C in the RFG model food (Fig. 6a and b). At 2450 MHz, the penetration depths in CR were 8.98 mm at 20 °C and 17.39 mm at 120 °C. The penetration depths in RG and RFG with 0.5% D-ribose and no added salt were also similar to those in CR—9.20 mm at 20 °C and 16.92 mm at 120 °C in the RG model food and 9.53 mm at 20 °C and 21.20 mm at 120 °C in the RFG model food (Fig. 6c and d).

Based on the above discussion and considering the match in the dielectric properties and penetration depths, RFG and RG with 0.5% D-ribose and no added salt could be used as model food systems to simulate CR. The model food systems could be used for heating pattern and cold/hot spot detection in development of microwave-assisted thermal sterilization processes using microwaves at a frequency of 915 MHz or 2450 MHz.

4. Conclusion

Both the dielectric constants and the loss factors of non-salted rice food systems, rice flour gel (RFG), rice grains (RG), and cooked Jasmine rice (CR), decreased as the temperature increased. Altering the salt content had a significant impact on dielectric loss factors, whereas changing the D-ribose content did not have a significant effect on the dielectric properties. The microwave penetration depths in the samples with no added salt increased with increasing temperature, whereas those in the samples with salt additions (0.5% to 3%) decreased as the temperature and the salt content increased. RFG and RG samples with no added salt and 0.5% D-ribose matched CR with regard to the dielectric properties and therefore were selected as model food systems for CR. The selected rice model food systems could be used for heating patterns and cold/hot spot detection in the development of sterilization processes with microwaves at frequencies of 915 MHz and 2450 MHz for CR. Adjustment of the salt content in rice model food systems can alter the dielectric properties, thus providing adaptability as a model food for microwave sterilization process development.

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