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Research Paper

Dielectric properties of peanut kernels associated with microwave and radio frequency drying

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To develop advanced drying methods based on microwave (MW) and radio frequency (RF) heating, knowledge of dielectric properties is essential for understanding the interaction between electromagnetic fields and peanuts. In this study, dielectric properties of peanut kernels were measured between 10 and 4500 MHz using an open-ended coaxial-line probe and network analyser at temperatures between 25 and 85 °C and moisture contents between 10% and 30% on a wet basis (w.b.). The results showed that both dielectric constant and loss factor of peanut kernels decreased sharply with increasing frequency over RF range (10–300 MHz), but gradually over the MW range (300–4500 MHz). Both dielectric constant and loss factor increased with increasing moisture content and temperature. The rate of increase was greater at higher temperature and moisture levels than at their lower levels. Penetration depth decreased with increasing frequency, moisture constant, and temperature. The measured dielectric properties were finally applied to determine the temperature profiles of RF heated samples under three moisture levels using experiment and simulation. This study on dielectric properties may provide useful guidelines in developing effective dielectric drying methods with a suitable drying thickness for peanuts.

1. Introduction

Peanuts (Arachis hypogea L.) are a widespread leguminous crop, mainly distributed in tropical and subtropical regions, including Africa, Asia and America. The world peanut production was about 45 Mt in 2013, and China is the country producing the most peanuts with about 17 Mt accounting for 37.8% of the total world production (FAOSTAT, 2013). Peanuts have a high nutritive value, and are a rich source of oils (44–56%), proteins (22–30%), minerals (phosphorus, calcium, magnesium and potassium), and vitamins (Asibuo et al., 2008). Adequate postharvest treatments may ensure the required good quality and storage stability of peanuts.

Drying is one of the most significant steps of post-harvest handling and storage of peanuts. The moisture content of peanut kernels at the time of harvesting is 30–50% on a wet basis (w.b.), and should be reduced to 10.5% or below for safe storage (Krzyzanowski, West, Neto, & de Barros, 2006). Usually, sun and hot air drying methods are commonly used for

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peanut drying (Yan, Nu, Hu, Xie, & Wang, 2012). The slow sun-drying rate is further influenced by the local solar intensity and ambient relative humidity (Bader, Adkins, & Butts, 1996) and sometimes results in poor product quality under rain (Yan, Nu, Zhi-Chao, Xie, & Wang, 2012). Hot air drying also takes a long time (e.g. 11 h at 40 °C) with low heating efficiency (Javare Gowda, Shivaprasad, & Ramaiah, 2012) and sometimes causes product quality degradation (Krzyzanowski et al., 2006). Therefore, it is of great significance to develop an advanced and efficient technology to replace the traditional drying methods.

Radio frequency (RF) and microwave (MW) treatments provide fast and volumetric heating due to internal heat generation throughout agricultural products via dipole rotation and ionic conductance. The dielectric heating results in short drying time and uniform drying rate in the products, and acceptable product quality, suggesting it may be able to replace the conventional drying methods. The RF and MW heating has been studied as potential advanced drying methods for several agricultural products, such as apricots (Albanese, Cinquanta, Cuccurullo, & Di Matteo, 2013), green peas (Zielinkska, Zapotoczny, Alves-Filho, Eikevik, Blaszczak, 2013), macadamia nuts (Wang et al., 2014), and wood (Leuca et al., 2014). Especially for RF drying, self-balancing effect of moisture level has been observed in various agricultural products due to less RF energy absorbed at locations with low moistures (Ling, Guo, Hou, Li, & Wang, 2015a; Wang, Zhang, Gao, Tang, & Wang, 2013). Therefore, having a good knowledge of dielectric properties of peanuts is essential to design an effective drying process for peanuts using RF or MW energy (Goyette, Chahine, Bose, Akyel, & Bosisio, 1990; Sosa-Morales, Valerio-Junco, López-Malo, & García, 2010).

Dielectric properties of materials determine how much electromagnetic energy can be stored and dissipated when they are exposed to RF or MW heating, and are commonly expressed as the complex permittivity, $\varepsilon = \varepsilon' - j\varepsilon''$. The real part, ε', is the dielectric constant, and represents a material's ability to store the electric field energy. The imaginary part, ε'', is the dielectric loss factor, and refers to the dissipation of electric field energy in the form of heat (Guo, Nelson, Trabelsi, & Kays, 2007).

Many studies on dielectric properties of food and agricultural product have been reported over different frequency, temperature and moisture ranges for drying (Wang et al., 2013), pest control (Ling, Tiwari, & Wang, 2015b; Wang et al., 2005), and pasteurization (Wang, Wig, Tang, & Hallberg, 2003; Zhu, Guo, & Wu, 2012a). Several studies on dielectric properties of nuts are available. Wang et al. (2003b) studied dielectric properties of almond and walnut kernels over the frequency range from 1 to 1800 MHz and temperature between 20 and 60 °C with moisture content 3% w.b. using the open-ended coaxial probe method. Ling et al. (2015a) developed quadratic polynomial equations for non-salted pistachio kernel samples to explain the relationship between moisture content, temperature and dielectric properties at four specific frequencies (27, 40, 915, and 2450 MHz). Zhu, Guo, Wu, and Wang (2012b) reported that the dielectric properties of chestnut flour decreased with increasing frequency and increased with increasing moisture content and temperature. Boldor, Sanders, and Simunovic (2004) studied dielectric properties of shelled and in-shell peanuts at several densities, moisture contents, and temperatures in the range of 300–3000 MHz. Dielectric properties of peanuts over different bulk density and moisture content at 23 °C between 2 and 18 GHz using a free-space-transmission technique were also reported by Trabelsi and Nelson (2004). However, there are few data for dielectric properties of peanuts over different temperatures and moisture contents at radio frequencies.

The objectives of this study were (1) to study frequency (10–4500 MHz), moisture content (10–30% w.b.) and temperature (25–85 °C) dependent dielectric properties of peanut kernels, (2) to provide the empirical equations describing peanut kernel's dielectric properties as function of moisture content and temperature at interested frequencies (27, 40, 915, and 2450 MHz), (3) to determine the penetration depth of electromagnetic energy into peanut kernels at four frequencies (27.12, 40.86, 915, and 2450 MHz) that refer to the industrial RF and MW applications, and (4) to confirm the RF heating rate of peanuts at three different moisture content (10%, 20%, and 30% w.b.) using experiment and simulation.

2. Materials and methods

2.1. *Materials*

The variety of shelled peanuts used in this study was "Huayu 20", which was purchased from a local farm market in Yangling, Shaanxi, China. The peanuts were stored in polyethylene bags at 4 °C until conducting tests. The chemical compositions of the peanuts determined with standard methods are summarised in Table 1 (AOAC., 2005).

2.2. *Moisture content measurements*

Moisture content of the peanuts was determined by the AOAC Official Method 925.40. Peanut samples were ground into powder. About 4–5 g peanut kernel flour was placed in an aluminium disk and dried to a constant weight at 95–100 °C under pressure ≤0.1 kPa in a vacuum oven. Then, the peanut kernel flour was cooled in a desiccator before weighing. The weight change was used to estimate the moisture content of the peanuts. Each measurement was conducted in triplicate and used to calculate the average moisture content.

2.3. *Sample preparation and true density measurement*

Based on the original moisture content (7.887% w.b.) of the peanut samples, 200 g peanuts in 5 prepared plastic bottles were sprayed with a predetermined amount of distilled water to obtain samples with 5 needed moisture content levels (10,

Table 1 – Chemical compositions of the peanuts.

Compositions	Content (g 100 g^{-1})	Methods
Moisture	7.89	AOAC 925.40
Fat	54.25	AOAC 948.22
Protein	24.54	AOAC 950.48
Total soluble solids	10.00	AOAC 950.50

15, 20, 25, and 30% w.b.). Then, the bottles were sealed and placed in the refrigerator at 4 °C for 7 days, and shaken three times a day to ensure the uniformity of moisture distribution.

To prepare peanut samples for dielectric properties measurement, it is necessary to determine the true density of peanut kernels. The true density of peanut kernels at different moisture content was determined by the liquid displacement method. Toluene (C_7H_8) was used as the displacement liquid to avoid absorption by peanut samples. Detailed measurement procedures can be found in Guo, Tang, Wang, and Tiwari (2008) and Ling et al. (2015a). The results showed that when the moisture content of the peanut kernels increased from 10% to 30% w.b., the true density was within 1.054–1.078 g cm^{-3} (Table 2). Because the changes in peanut kernel density were negligible, the density effect of dielectric properties of the peanut kernels was not considered in this study.

The open-ended coaxial probe technique is a popular method for measuring dielectric properties and is usually used to measure dielectric properties of liquid or semi-solid materials over a broad frequency range due to ease of handling and high accuracy. When using the open-ended coaxial probe method to measure dielectric properties of peanuts, the samples can not make close contact with the flat tip of the probe because of the irregular kernel shape. To solve this problem, peanut samples were ground into powder and compressed into cylindrical samples with flat surface to match the true density of peanuts. This method has been used for dielectric properties measurement of many products, such as legumes (chickpea, green pea, lentil, and soybean) (Guo, Wang, Tiwari, Johnson, & Tang, 2010), almonds (Wang et al., 2003b), chestnuts (Zhu et al., 2012b), macadamia nuts (Wang et al., 2013), and pistachios (Ling et al., 2015a).

2.4. *Dielectric properties measurement*

Dielectric properties measurement system consisted of an Agilent 85070E open-ended coaxial probe, an Agilent E5071C vector network analyser (Agilent technologies, Penang, Malaysia), a 85070E dielectric probe kit software (Agilent technologies, America), a computer, and a DK-98-1 constant temperature water bath (Tianjin Taisite Instrument Co., Ltd, Tianjin, China). The samples were put in a stainless steel cylindrical holder (23 mm in diameter and 25 mm in height) welded on a stainless steel plate. The plate was placed in the water bath, and the stainless steel cylindrical holder was immersed in the water bath to allow the samples to reach the selected temperatures (25, 45, 65, and 85 °C) before each measurement. The selection of this temperature range was based on the maximum permissible temperature for peanut drying (Javare Gowda et al., 2012). Measurements of peanut dielectric properties were conducted in three replicates at each selected temperature. Dielectric properties of the samples were calculated by a dielectric probe kit software. Before the measurement, the network analyser was turned on for about 1 h to warm up, and then calibrated with open, short, and 50 Ω load in sequence. The open-ended coaxial probe was then attached to the system, and further calibrated using air, short circuit, and 25 °C deionised water.

Table 2 – The true densities of peanuts at five moisture contents.

Moisture content (%, w.b.)	Density ± SD (g cm^{-3})
10	1.054 ± 0.022
15	1.056 ± 0.007
20	1.058 ± 0.010
25	1.062 ± 0.009
30	1.078 ± 0.018

2.5. *Power penetration depth*

The penetration depth (d_p, m) is defined as the distance at which an incident electromagnetic power intensity is reduced to 1/e (e = 2.718) of its amplitude at the entry surface (Von Hippel, 1954). The penetration depth was calculated as follows:

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

where c is the speed of light in free space (3 × 10^8 m s^{-1}), and f is the frequency (Hz). The penetration depth in peanuts was calculated at selected frequencies, temperatures and moisture contents based on the measured dielectric properties.

2.6. *RF heating systems and temperature measurement*

To explain the relationship between dielectric properties and RF heating, the heating rate of peanuts was obtained both by experiment and simulation. A 6 kW, 27.12 MHz free-running oscillator RF system (SO6B, Strayfield International, Workingham, U.K.) was used to heat 2.5 kg peanuts in a plastic container (300 mm × 220 mm × 60 mm) (Fig. 1). The electrode gap of 120 mm and heating time of 4 min were selected for RF heating. The peanuts samples under three moisture levels (10%, 20%, and 30% w.b.) were vertically separated into three equal sections by two pieces of plastic foam board and placed at the centre of the bottom electrode. The sample temperature at the centre of each section was measured by a six-channel fibre optical temperature sensor system (HQ-FTS-D120, Heqi Technologies Inc., Xian, China) with an accuracy of ±0.5 °C.

A 3D geometric model was constructed using COMSOL (V4.3a COMSOL Multiphysics, CnTech Co., LTD., Wuhan, China) software based on the actual structure and size of the RF system in the simulation. All the metallic casings except the upper electrode were grounded (V = 0 V) with a constant upper electrical voltage (5810–6500 V) based on the measured anode current as described by Huang, Zhu, Yan, and Wang (2015). Electrical insulation $\vec{\nabla}\cdot\vec{E}=0$ was considered for the external walls of the RF cavity. The initial temperature of all domains in the system, including the air, plastic container, peanuts, upper and bottom electrodes was set at room temperature (20 °C). The convective heat transfer boundary conditions were assigned at the outer sample surfaces exposed to air with heat transfer coefficient of h = 20 W m^{-2} K^{-1}. The measured dielectric properties of peanuts were entered into the Joule heating module to solve the coupled quasi-static

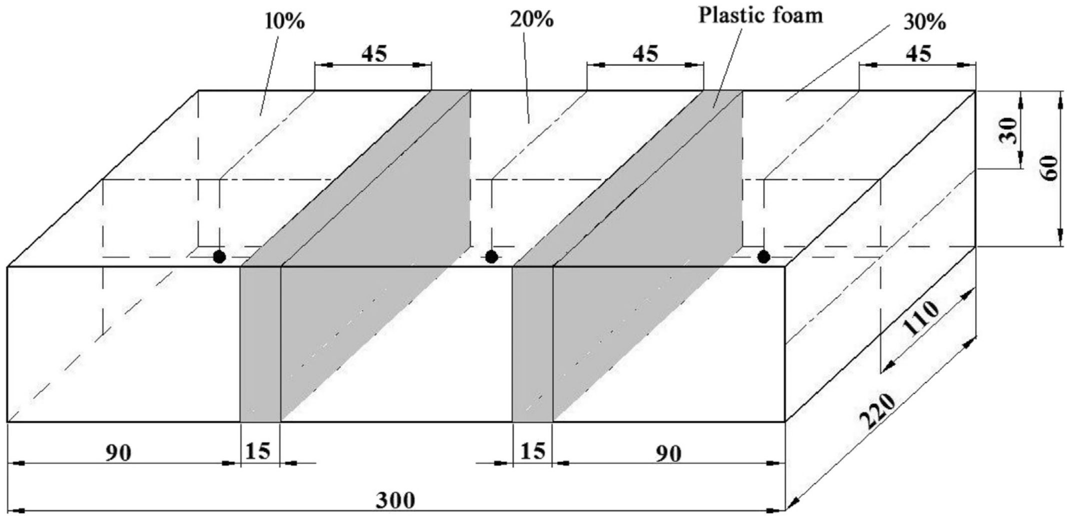

Fig. 1 – Rectangular plastic container separated into three sections with three moisture contents of RF heated peanut kernels for measuring temperatures at the three positions (all dimensions are in mm).

electromagnetic and heat transfer equations. All computer simulations were performed on a Dell workstation with an Intel® Core™ i5-2400, 3.10-GHz processor and 8 GB RAM running a Windows 8.1 64-bit operating system. The direct linear system solver (UMFPACK) was used with a relative tolerance and absolute tolerance of 0.01 and 0.001, respectively, with the initial and maximum time steps of 0.001 s and 0.1 s. The simulated sample temperature was further used to confirm the experimental data.

3. Results and discussion

3.1. *Frequency-dependent dielectric properties*

Figures 2 and 3 show the dielectric constant and loss factor of peanuts as a function of frequency with moisture contents of 10% w.b. and 30% w.b. at temperatures range from 25 to 85 °C. Both the dielectric constant and loss factor were significantly influenced by frequency. The dielectric constant decreased monotonically with increasing frequency at the given temperatures. The decrease of dielectric constant was more pronounced at lower frequencies, especially at higher temperatures. For example, when the frequency increased from 10 to 300 MHz, the dielectric constant of peanut samples with 30% w.b. moisture content decreased from 34.94 to 17.25 at 25 °C, and from 55.19 to 22.31 at 85 °C (Fig. 2b). However, it decreased less at high frequencies than at low frequencies for each temperature. Moreover, the effect of frequency on dielectric constant was greater at higher moisture contents. For example, when the frequency increased from 10 to 300 MHz at 45 °C, the dielectric constant decreased by 1.68 at 10% w.b. and by 20.13 at 30% w.b. moisture content (Fig. 2b).

The dielectric constant determines the electric field distribution when the loss factor is far smaller than the dielectric constant (when the sample moisture level is low). The best heating uniformity would be achieved when the dielectric constant of surrounding material is in a comparable range with that of the sample (Huang et al., 2015). For disinfestations

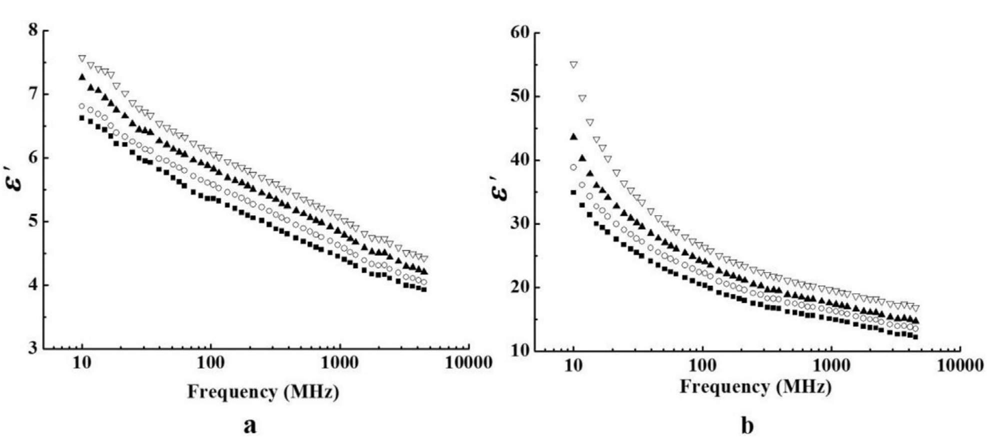

Fig. 2 – Frequency-dependent dielectric constant (ε') of peanuts at 25(■), 45(○), 65(▲) and 85 °C (▽) with moisture content of 10% (a) and 30% w.b. (b).

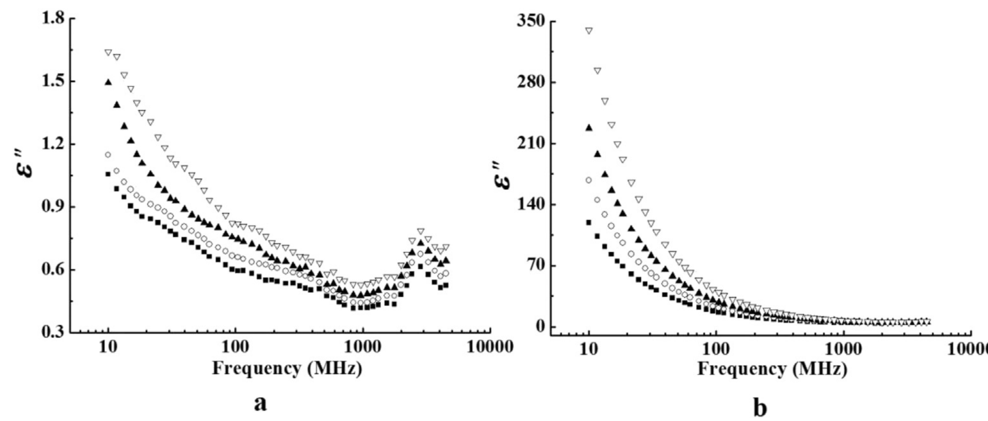

Fig. 3 – Frequency-dependent dielectric loss factor (ε'') of peanuts at 25(■), 45(○), 65(▲) and 85 °C (▽) with moisture content of 10% (a) and 30% w.b. (b).

and pasteurization of dried peanuts, the container material could be effectively selected based on the known dielectric constant of the sample.

At low moisture contents, the dielectric loss factor decreased with increasing frequency when the frequency was below 2000 MHz, and then increased above 2000 MHz (Fig. 3a). Moreover, the loss factor values peaked between 2450 and 4000 MHz at 10% w.b. moisture content and disappeared when the moisture content is higher than 10% w.b. The reason for this phenomenon may be lower ionic and greater bound water relaxation of peanut samples at MW frequencies (Wang et al., 2013). Similar trends have also been found in macadamia nut, walnuts and almonds (Wang, Tang, Cavalieri, & Davis, 2003a, 2003b, 2013). The dielectric loss factor decreased monotonically with increasing frequency when the moisture content was higher than 10% w.b. Temperature and moisture content had a significant effect on the frequency-dependent dielectric loss factor. High temperature and moisture content led more prominent depression of loss factor with increasing frequency especially at low frequencies.

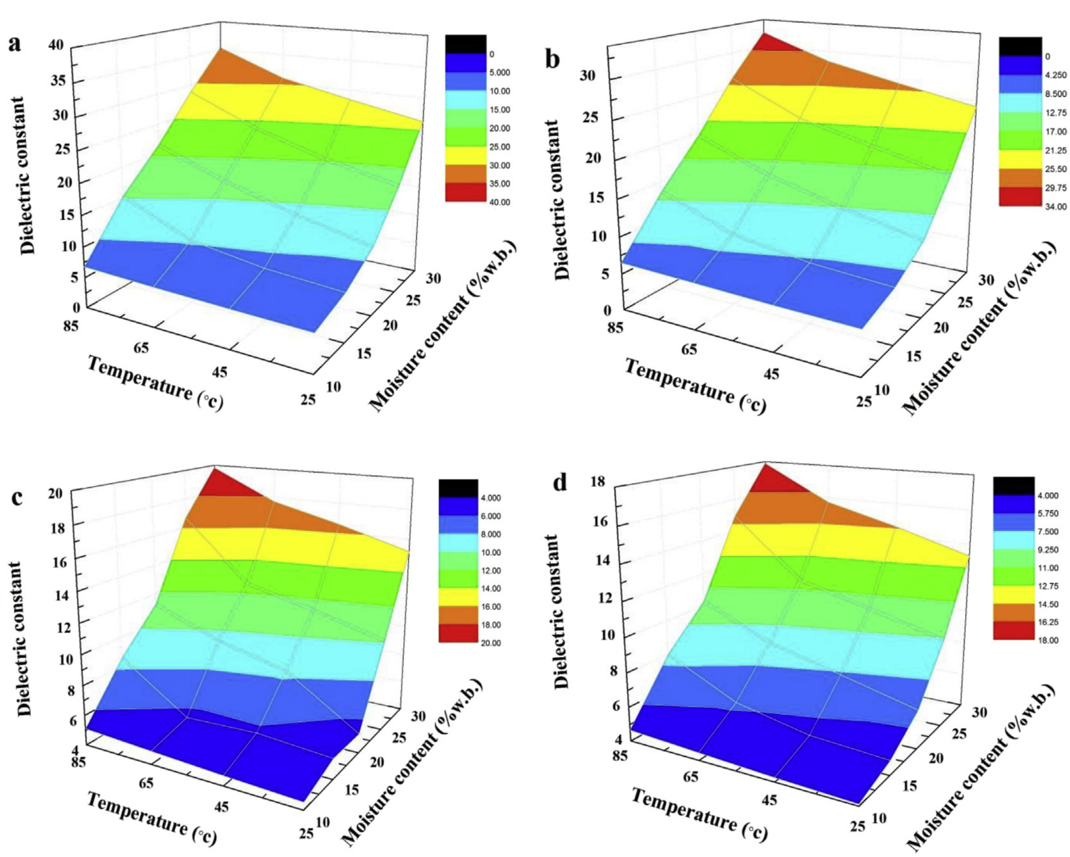

Fig. 4 – Moisture and temperature-dependent dielectric constant of peanuts at 27 (a), 40 (b), 915 (c), and 2450 MHz (d).

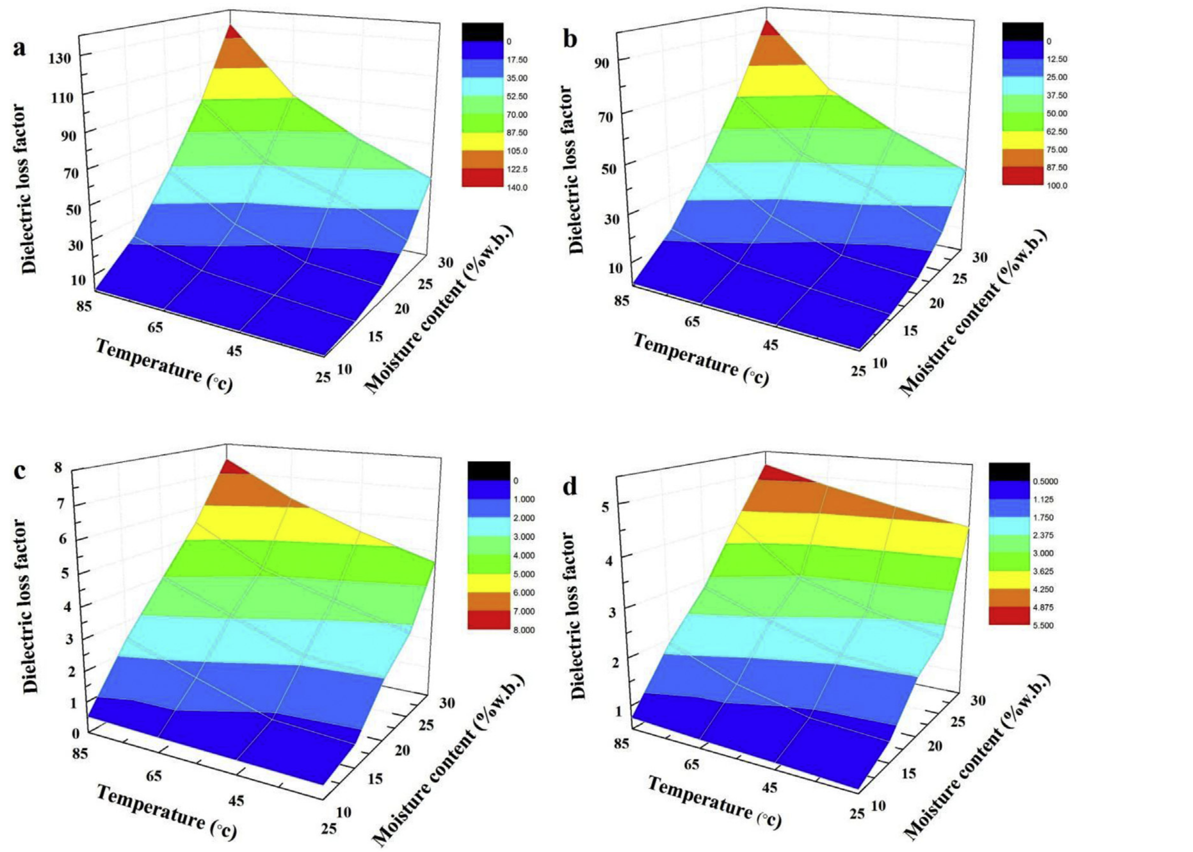

Fig. 5 – Moisture and temperature-dependent dielectric loss factor of peanuts at 27 (a), 40 (b), 915 (c), and 2450 MHz (d).

Similar trends of frequency-dependent dielectric properties of peanuts have been reported for wheat, beans, fruits and vegetables (Berbert, Queiroz, & Melo, 2002; Jiao, Johnson, Tang, Tiwari, & Wang, 2011; Nelson, 2003; Nelson & Trabelsi, 2006). Dipolar rotation and ionic conduction are the main mechanisms that affect the dielectric properties of agricultural food materials (Ryynänen, 1995; Venkatesh & Raghavan, 2004). Ionic conduction plays a dominant effect on dielectric properties at low frequencies and high moisture contents (Guo & Zhu, 2014; Wang et al., 2013).

3.2. *Moisture and temperature-dependent dielectric properties*

The measured mean values of moisture and temperature-dependent dielectric properties of peanut samples at 27, 40, 915, and 2450 MHz over a moisture content range from 10% to 30% w.b. and temperature range from 25 to 85 °C are shown in Figs. 4 and 5. It was observed that both the dielectric constant and loss factor increased with increasing temperature and moisture content at a certain frequency. For example, at 27 MHz for RF drying, when the temperature increased from 25 to 85 °C, the dielectric constant increased from 6.00 to 6.78, from 13.61 to 31.36, and from 26.10 to 35.33 with moisture content of 10%, 20% and 30% w.b., and the dielectric loss factor increased from 0.82 to 1.32, from 7.86 to 50.41, and from 48.84 to 131.26, respectively. At 915 MHz for MW drying, the dielectric constant and loss factor were clearly reduced at the same moisture and temperature levels as compared to RF drying. Similar trends have also been found in red pepper powder and chestnut flour (Guo & Zhu, 2014; Zhu et al., 2012b).

In food materials, the dipole most responsible for dielectric heating is water (Guan, Cheng, Wang, & Tang, 2004). The moisture-dependent dielectric properties are mainly influenced by the free and bound water contents in food materials (Calay, Newborough, Probert, & Calay, 1994). The dielectric polarization caused by free water is much larger than that of bound water (Guo & Zhu, 2014; Ling et al., 2015a). In low moisture content samples, the water molecules are bound to proteins or starch in peanuts, resulting in less dielectric polarization and thus low dielectric properties of peanut samples. With the increase of moisture content, free water contributes much more than bound water, leading to the increase of dielectric properties. The increased temperature causes the decrease in viscosity of biomaterials, thus improves ionic mobility and ionic conduction (Tang, Hao, & Ming, 2002). Therefore, the dielectric constant and loss factor increased with increasing temperature.

The increase of dielectric loss factor with increasing moisture content in materials at RF frequencies may lead to the potentially advantageous phenomenon “moisture levelling” (Feng, Tang, & Cavalieri, 2002; Mexatas & Meredity, 1983). During the dielectric heating process, the portion with higher moisture content has larger dielectric loss factor, thus may be heated preferentially and absorb more electromagnetic energy than that with lower moisture content. It contributes to the uniformity of product heating in dielectric drying. Moreover, the portion with lower moisture content has low temperature, which would be beneficial to the quality of food materials after heating. However, the increase of dielectric loss factor with increasing temperature may lead to “thermal run away” (Zhao, Flugstad, Kolbe, Park, & Wells, 2000). The portion with higher temperature has larger dielectric loss factor, resulting in more dielectric heating. But this phenomenon may be reduced by the moisture levelling effect (Ling et al., 2015a; Wang et al., 2013).

3.3. *Regression models for dielectric properties of peanuts*

The regression models for dielectric properties of peanut samples as function of moisture content and temperature are shown in Tables 3 and 4. The regression equations at different temperature and moisture are given at 27, 40, 915 and 2450 MHz, respectively. Eqs. (2)–(5) were regression models for dielectric constant, and cubic polynomials were best fit for dielectric constant at 27, 40 and 2450 MHz, while quadratic polynomial was the best for 915 MHz. Eqs. (6)–(9) were regression models for dielectric loss factor, only Eq. (9) was cubic polynomial, others were quadratic polynomials.

Analysis of variance (ANOVA) was carried out to determine whether the dielectric properties of peanuts were significantly influenced by temperature and moisture content. Tables 5 and 6 show the ANOVA results for Eqs. (2)–(5) and Eqs. (6)–(9), respectively. The linear term and quadratic term of M had very strong effect on these models ($p < 0.001$). All the equations provided a good fit to the experimental data at the significance level of 0.0001 ($p < 0.0001$) and with a coefficient of determination of greater than 0.980. It suggested that these models were able to precisely predict the dielectric constant and loss factor for peanuts at any given moisture content between 10% and 30% w.b. and temperature range from 25 to 85 °C at the four specific frequencies (27, 40, 915 and 2450 MHz). These models could also be used to estimate moisture and temperature-dependent dielectric properties in computer simulation.

Table 3 – Regression equations of peanuts dielectric constant as a function of moisture content (10%–30% w.b.) and temperature (25–85 °C).

Frequency (MHz)	Dielectric constant (ε')
27	$\varepsilon' = 21.814 - 0.254T - 2.576M + 0.041TM - 2.40 \times 10^{-3}T^2 + 0.102M^2 + 2.46 \times 10^{-5}T^2M - 9.21 \times 10^{-4}TM^2 + 1.92 \times 10^{-5}T^3 - 4.68 \times 10^{-4}M^3$ (2)
40	$\varepsilon' = 72.436 - 0.182T - 6.766M - 0.036TM - 2.94 \times 10^{-3}T^2 + 0.097M^2 + 1.96 \times 10^{-5}T^2M - 8.02 \times 10^{-4}TM^2 + 2.20 \times 10^{-5}T^3 - 5.01 \times 10^{-4}M^3$ (3)
915	$\varepsilon' = 7.280 - 0.075T - 0.488M - 0.036TM + 6.24 \times 10^{-4}T^2 + 0.023M^2 + 3.65 \times 10^{-3}T^2M$ (4)
2450	$\varepsilon' = 8.127 + 0.033T - 0.885M + 0.013TM - 3.21 \times 10^{-3}T^2 + 0.032M^2 + 2.85 \times 10^{-5}T^2M - 3.13 \times 10^{-4}TM^2 + 2.04 \times 10^{-5}T^3 + 2.89 \times 10^{-5}M^3$ (5)

Table 4 – Regression equations of peanuts dielectric loss factor as a function of moisture content (10%–30% w.b.) and temperature (25–85 °C).

Frequency (MHz)	Dielectric loss factor (ε'')
27	$\varepsilon'' = 72.436 - 6.766M - 1.604T + 0.069MT + 0.178M^2 + 8.23\times10^{-3}T^2$ (6)
40	$\varepsilon'' = 48.922 - 4.546M - 1.125T + 0.048\,MT + 0.123M^2 + 5.85 \times 10^{-3}T^2$ (7)
915	$\varepsilon'' = 0.656 - 0.048M - 0.044T + 2.09 \times 10^{-3}MT + 5.10 \times 10^{-3}M^2 + 3.07 \times 10^{-4}T^2$ (8)
2450	$\varepsilon'' = 0.205 + 0.234M - 0.046T + 5.49 \times 10^{-3}MT - 1.07 \times 10^{-4}T^2 - 0.019M^2 + 5.05 \times 10^{-6}T^2M - 1.32 \times 10^{-6}T^3 + 5.36 \times 10^{-4}M^3$ (9)

Table 5 – Significance of probability of regressed models of Eqs. (2)–(5) for peanuts at four frequencies of interest.

Variance and R^2	27 MHz (Eq. 2)	40 MHz (Eq. 3)	915 MHz (Eq. 4)	2450 MHz (Eq. 5)
M	<0.0001	<0.0001	<0.0001	<0.0001
T	<0.0001	<0.0001	<0.0001	0.0016
MT	<0.0001	<0.0001	0.0074	<0.0001
M^2	<0.0001	<0.0001	0.0001	<0.0001
T^2	0.0008	0.0005	0.1975	0.0050
M^2T	<0.0001	<0.0001	–	0.0044
MT^2	0.5266	0.5306	–	0.3389
M^3	0.3722	0.2408	–	0.9405
T^3	0.3549	0.1962	–	0.2023
Model	<0.0001	<0.0001	<0.0001	<0.0001
R^2	0.9986	0.9989	0.9800	0.9964

Table 6 – Significance of probability of regressed models of Eqs. (6)–(9) for peanuts at four frequencies of interest.

Variance and R^2	27 MHz (Eq. 6)	40 MHz (Eq. 7)	915 MHz (Eq. 8)	2450 MHz (Eq. 9)
M	<0.0001	<0.0001	<0.0001	<0.0001
T	<0.0001	<0.0001	<0.0001	0.0119
MT	<0.0001	<0.0001	<0.0001	0.0129
M^2	<0.0001	<0.0001	0.0008	0.0002
T^2	0.0007	0.0006	0.0269	0.0816
M^2T	–	–	–	0.0187
MT^2	–	–	–	0.7495
M^3	–	–	–	0.0258
T^3	–	–	–	0.8743
Model	<0.0001	<0.0001	<0.0001	<0.0001
R^2	0.994	0.994	0.992	0.991

3.4. *Penetration depth*

The penetration depths calculated from the obtained dielectric constants and loss factors of peanut samples at four specific frequencies, five moisture levels, and four temperatures are listed in Table 7. The penetration depth decreased with increasing frequency, moisture content, and temperature. For example, when the frequency increased from 27 to 2450 MHz, the penetration depth decreased from 94.01 cm to 4.39 cm for peanut samples at 45 °C with moisture content of 15% w.b. When the moisture content of peanut samples increased from 10% to 30% w.b., the penetration depth

Table 7 – Penetration depth of peanuts at five moisture contents and four temperatures.

Moisture content (% w.b.)	T (°C)	Penetration depth (cm)			
		27 MHz	40 MHz	915 MHz	2450 MHz
10	25	524.85 ± 39.86	391.52 ± 17.06	26.97 ± 0.34	6.84 ± 0.13
	45	489.37 ± 23.13	366.02 ± 4.23	25.48 ± 0.05	6.36 ± 0.06
	65	448.25 ± 5.64	339.70 ± 2.54	24.13 ± 0.06	6.05 ± 0.04
	85	379.90 ± 4.21	284.07 ± 1.02	22.20 ± 0.07	5.70 ± 0.05
15	25	184.68 ± 2.38	136.69 ± 0.35	16.86 ± 0.09	4.66 ± 0.02
	45	94.01 ± 3.81	76.02 ± 3.79	14.66 ± 0.32	4.39 ± 0.03
	65	63.68 ± 0.52	52.02 ± 0.23	9.23 ± 0.82	2.94 ± 0.03
	85	38.42 ± 0.11	32.00 ± 0.08	6.45 ± 0.05	2.89 ± 0.02
20	25	77.05 ± 0.67	62.24 ± 0.32	6.18 ± 0.01	2.83 ± 0.01
	45	61.37 ± 0.14	50.28 ± 0.27	6.02 ± 0.03	2.85 ± 0.01
	65	33.43 ± 0.07	27.91 ± 0.06	5.37 ± 0.01	2.49 ± 0.01
	85	21.11 ± 0.07	17.91 ± 0.06	4.54 ± 0.01	2.24 ± 0.01
25	25	38.10 ± 0.08	32.09 ± 0.11	6.04 ± 0.02	2.77 ± 0.01
	45	24.18 ± 0.08	20.65 ± 0.09	5.20 ± 0.02	2.52 ± 0.01
	65	20.41 ± 0.06	17.32 ± 0.09	4.52 ± 0.13	2.25 ± 0.05
	85	15.49 ± 0.05	13.14 ± 0.05	3.99 ± 0.01	1.89 ± 0.01
30	25	22.51 ± 0.04	19.23 ± 0.03	4.50 ± 0.00	1.72 ± 0.01
	45	18.33 ± 0.03	15.68 ± 0.01	4.06 ± 0.01	1.68 ± 0.01
	65	15.28 ± 0.06	13.05 ± 0.06	3.61 ± 0.03	1.63 ± 0.01
	85	12.15 ± 0.01	10.35 ± 0.01	3.20 ± 0.01	1.61 ± 0.01

decreased from 448.25 cm to 15.28 cm at 65 °C and 27 MHz. When the temperature increased from 25 to 85 °C, the penetration depth decreased from 136.69 cm to 32.00 cm for peanut samples at 40 MHz with moisture content of 15%. Moreover, the penetration depth decreased sharply with increasing moisture content and temperature at RF frequencies (27 and 40 MHz), but decreased slightly at MW frequencies (915 and 2450 MHz). Similar trends of penetration depths as influenced by frequency, temperature, and moisture content have also been found by others (Guo et al., 2010; Wang et al., 2013). It is obvious that the penetration depths were much larger at RF frequencies than that at MW frequencies. Lower penetration depths at MW frequencies means more surface heating in peanuts. Large penetration depths at RF frequencies mean better heating uniformity in peanuts and higher throughputs for dielectric heating. When designing the drying bed, the appropriate sample thicknesses would be 24.3, 6.4 and 3.2 cm for effective dielectric drying at 27, 915 and 2450 MHz, respectively.

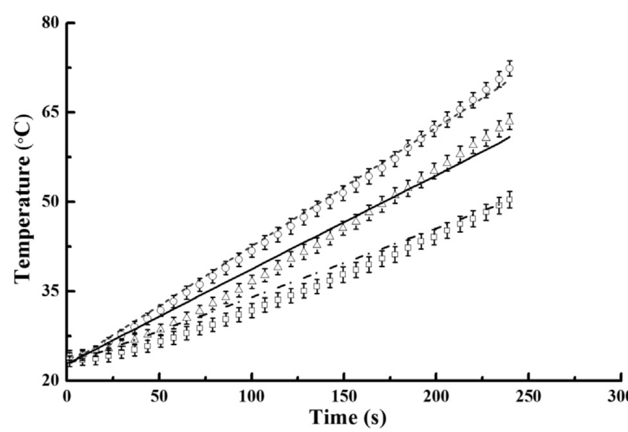

Fig. 6 – Experimental (exp with symbols) and simulated (sim with lines) temperature-time histories of peanut kernels with moisture content of 10% (□), 20% (○) and 30% w.b. (△) when subjected to RF heating for 4 min with electrode gap of 120 mm.

3.5. *RF heating rates of peanuts at three moisture contents*

Figure 6 shows the experimental and simulated temperature-time histories of peanut kernels with three moisture contents of 10%, 20%, and 30% w.b. when subjected to RF heating for 4 min with electrode gap of 120 mm. With the measured dielectric properties, the simulation results agreed well with the experimental data at three sections under three moisture levels. Both the simulated and experimental results revealed that the sample temperatures increased almost linearly with the RF heating time but the heating rates of peanut kernels were in the following order: 20% > 30% > 10% w.b. These observed phenomena were similar to those found by Huang et al. (2015), in which the increasing loss factor caused an initial increase and then a decrease in RF heating rates. The maximum heating rate can be obtained when $\varepsilon'' = \varepsilon' + d_m/d_0$ (d_m is the height of the sample, d_0 is the air gap between the top electrode and the upper surface of materials) (Jiao, Tang, Wang, & Koral, 2014). In this study, the maximum RF heating rate would be achieved when the moisture content of the sample was conditioned to 20.4% w.b. based on the measured dielectric properties at 45 °C.

4. Conclusions

Dielectric properties of peanut kernels were greatly influenced by frequency, moisture content, and temperature. Both dielectric constant and loss factor decreased with increasing frequency, and increased with increasing moisture content and temperature. The quadratic and cubic regression models were established to explain dielectric properties as influenced by moisture content and temperature at four specified frequencies. The maximum RF heating rate can be estimated based on the dielectric properties using the regression models at the four specified frequencies. The penetration depths were much larger at RF frequencies than those at MW frequencies, suggesting better uniformity in RF drying. The dielectric properties data could be useful to explore the RF and MW heating mechanisms and guide the development of effective treatment protocols.

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