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Analysis of bread dielectric properties using mixture equations

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ABSTRACT

Breads are prone to rapid microbial spoilage, particularly mold growth. In order to develop in-package pasteurization treatments based on radio frequency or microwave energy, a combined open-ended coaxial probe and mixture equation method was used to obtain bread dielectric properties over the frequency range of 1-1800 MHz and the temperature range of 25 °C–85 °C. Influences of frequency, moisture content and temperature on bread dielectric properties were analyzed. The Lichtenecker Equation (LE) was suited for calculating dielectric constant, and the Landau and Lifshitz, Looyenga Equation (LLLE) for dielectric loss factor of bread. Penetrations of both RF and microwave energies decrease with increasing temperature and moisture content. Overall, RF energy has several times the penetration in white bread than microwave energy.

1. Introduction

Intermediate and high moisture bakery products are prone to rapid microbial spoilage, particularly mold growth, which greatly limits their shelf life. Thus methods to control microbial spoilage are of great importance to the bakery industry (Smith et al., 2004). Microwave (MW) and radio frequency (RF) heating have been studied as a means to control mold growth and extend shelf life of finished bakery products (Cathcart et al., 1947; Bartholomew et al., 1947; Olsen, 1965; Zhao et al., 1999; Piyasena et al., 2003; Tang et al., 2005; Lakins et al., 2008). In order to obtain desired heating performance in microwave and RF heating treatment, relevant properties of foods must be obtained, among which dielectric properties are the most important.

Dielectric properties of a material are described by the complex relative permittivity (ε, relative to that of free space) (Von Hippel, 1954a,b):

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

where $j = \sqrt{-1}$.

Dielectric properties of a given food are influenced by various factors, including frequency, temperature, moisture content and other food compositions, in particular salt and fat contents (Calay et al., 1995; Sun et al., 1995; Tang et al., 2002; Tang, 2005; Venkatesh and Raghavan, 2004). Dielectric properties of foods have great influence on the temperature distribution during microwave sterilization and pasteurization processes (Ohlsson and Bengtsson, 1975; Wang et al., 2003).

Limited studies on dielectric properties of bakery products can be found in the literature, in particular, in the radio frequency range (10–100 MHz). Most of the reported measurements were performed on products at MW frequencies. Goedeken et al. (1997) reported that the dielectric constant of pregelatinized bread dough was independent of salt content, while dielectric loss factor increased with salt. In addition, the dielectric constant increased with temperature from 25 to 60 °C and then became constant from 60 to 95 °C, while dielectric loss factor increased linearly from 25 to 95 °C for samples containing 1% salt and decreased linearly for samples without salt. Dielectric properties of breads and cakes baked in microwave, microwave-jet impingement and microwave-infrared ovens were shown to be dependent on formulation, baking time and temperature. Both dielectric constant and loss factor decreased sharply within the first 2–3 min of baking and then remained constant (Sumnu et al., 2006; Keskin et al., 2007; Sakiyan et al., 2007). All above measurements were made at the microwave frequency of 2450 MHz.

Among the commonly used measurement methods for dielectric properties, the transmission line technique was reported to be most suitable for porous materials (Goedeken et al., 1997). The open-ended coaxial probe method, on the other hand, is easy to use, has a large bandwidth, and has been commonly used within the food research community (Nelson and Kraszewski, 1990; Engelder and Buffler, 1991; Nelson, 1999; Tang et al., 2002; Venkatesh and Raghavan, 2005). But according to several studies, when dielectric properties of bread were measured using open-ended coaxial probe method (Sumnu et al., 2006; Keskin et al., 2007; Sakiyan et al., 2007), the repeatability of the measurement was very poor. This was attributed to uncontrollable contact pressure and non-homogenous structure of bread caused by different pore sizes and uneven pore distribution. It is preferable that a homogenous

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Nomenclature

e	porosity
v	volume fraction
f	frequency, Hz or MHz
M	moisture content,% wet basis
T	temperature, °C
d_p	power penetration depth, cm or m
c	the speed of light in free space, 3×10^8 m/s
Greek symbols	
ε	complex relative permittivity
ε'	dielectric constant
ε''	dielectric loss factor
ρ	density, g/cm^3
Subscripts	
ap	apparent
m	material

structure of bread samples be obtained in order to use open-ended coaxial probe method to provide reliable dielectric property values of bread.

Dielectric mixture equations can be used to estimate the dielectric properties of an air-particle mixture (Lal and Parshad, 1973a,b; Sihvola and Kong, 1988; Nelson, 1991; Nelson and Datta, 2001). It is possible to use those equations in calculating dielectric properties of original porous bread as long as we obtain dielectric data for homogenous and truly dense bread materials.

The goal of the study was to obtain reliable dielectric property information in support of the development of in-package pasteurization process using radio frequency or microwave energy to control bread molds. *Penicillium* spp. and *Aspergillus* spp. are common molds observed in bread (Jenkins, 1975; Smith et al., 2004). These two mold species were chosen as the target microorganisms in our effort to extend shelf-life of white breads. Olsen (1965) reported that directly exposing bread to heating at 68–71 °C for about 20 min could completely control *Aspergillus* and *Penicillium*. In our studies we selected a temperature range from 25 to 85 °C with a 15 °C interval for measuring the dielectric properties.

There is no data in the literature for bread dielectric properties over a broad frequency range and a lack of information on the relationship between dielectric properties and influencing factors. The objectives of this study were to (1) determine dielectric properties and penetration depth of sliced white breads using combined open-ended coaxial probe and mixture equation method at the frequency range of 1–1800 MHz and the temperature range of 25 °C–85 °C, and (2) study the relationships between bread dielectric properties and different influencing factors, including frequency, temperature and moisture content.

2. Materials and methods

2.1. Sample preparation

Sliced white breads (Oven Joy White Enriched Bread made by Lucerne Foods, Inc.) were purchased from a local grocery store in Pullman, WA, USA and refrigerated at 4 °C for less than one week before testing. The ingredients of the bread are shown in Table 1, among which ash content (AOAC, 2000a), moisture content (AOAC, 2000b) and porosity (Rahman, 1995, 2005) were measured in our laboratory and the others were based on the label.

In order to adjust sample moisture content, bread slices were either covered with a wetted paper towel to obtain higher moisture contents or laid in air to let go of some water to obtain lower moisture contents. Moistened and slightly dehydrated bread slices were packaged in ziploc bags and refrigerated at 4 °C for 48 h to obtain moisture equilibrium and then placed at room temperature for 12 h to equilibrate before measurement.

Bread samples were compressed to the shape of a cylinder (diameter = 21 mm, height = 41 mm) to remove air voids before measurements, the weight of each bread sample was measured using an Analytical Plus electronic balance (OHAUS Corporation, Florham Park, New Jersey).

2.2. Moisture content

Moisture content of the bread on wet basis was calculated from the difference in weight after vacuum-drying at 98–100 °C for about 5 h (AOAC, 2000b).

2.3. Density and porosity

The apparent density of the bread crumb was determined by measuring the mass and volume, while material density of the bread crumb was measured with a pycnometer Accupyc 1330 (Micromeritics, USA) using toluene as the displacement fluid. Porosity was given by Rahman (1995, 2005):

$$e = 1 - \frac{\rho_{ap}}{\rho_m} \quad (2)$$

2.4. Dielectric properties measurement

US Federal Communications Commission (FCC) have allocated five frequencies for industrial, scientific, and medical (ISM) applications, namely 13.56, 27.12, and 40.68 MHz in radio frequency range and 915, and 2450 MHz in microwave range. But because 1800 MHz is the upper limit of the measurement system at Washington State University, we substituted it for 2450 MHz.

In this study, dielectric properties of bread were measured between 1 MHz and 1800 MHz using the open-ended coaxial probe technique. The measurement system consisted of an Agilent 4291B impedance analyzer with a calibration kit (Agilent technologies, Palo Alto, CA), a custom-built test cell, a high-temperature coaxial cable, and a Hewlett Packard 85070B dielectric probe kit (Fig. 1). Open-ended coaxial probe method is most commonly used in broad band dielectric property measurement. The typical accuracy of the system is ±8% for dielectric property measurement (Agilent Technologies, 2006) following standard calibration procedure as described in Wang et al. (2003).

Before measurements, the samples were loaded into the test cell (21 mm diameter), slightly compressed by the probe to the fixed height of 38 mm. The sample diameter and thickness are 4.4 and 13.6 times the outer diameter (4.8 mm) and the inner diameter (2.8 mm) of the outer coaxial conductor, respectively. Thus the sample satisfied the requirement for accurate dielectric property measurement using the open-ended coaxial probe method. A detailed discussion of this requirement is provided in Feng et al. (2002).

Table 1
Proximate analysis of the white bread samples (mean of three replicates).

Product	Protein (%, wet basis)	Ash (%, wet basis)	Fat (%, wet basis)	Carbohydrate (%, wet basis)	Moisture content (%, wet basis)	Porosity
White bread	6.90	2.89 ± 0.02	1.72	51.72	37.10 ± 0.17	0.8 ± 0.0

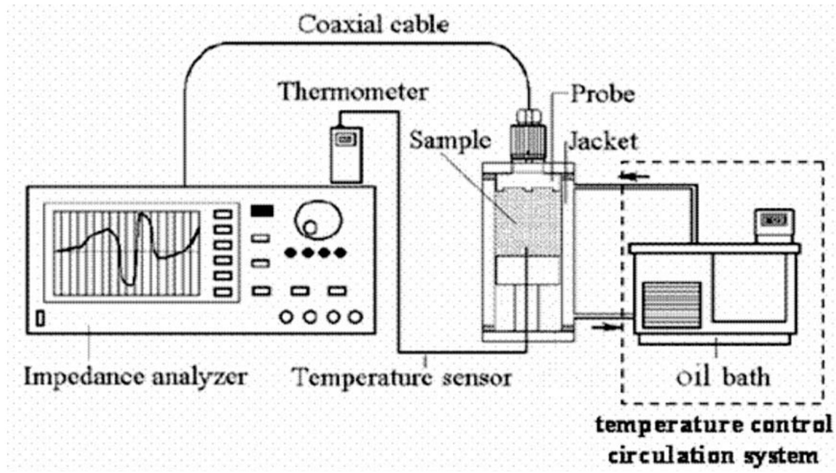

Fig. 1. Schematic diagram of the dielectric properties measurement system (Wang et al., 2005).

Dielectric properties were measured at four moisture contents (34.0–38.6% on wet basis) and three densities (0.9–1.2 g/cm^3). Measurement at each moisture content and density was made in three replicates.

2.5. Dielectric mixture equations

Several dielectric mixture equations have been used in the literature to estimate the dielectric properties of an air-particle mixture (Lal and Parshad, 1973a, 1973b; Sihvola and Kong, 1988; Nelson, 1991; Nelson and Datta, 2001). Four equations were proven to be applicable to experimental data in our prescreening analyses. These equations are Complex Refractive Index mixture equation (CRIME):

$$\varepsilon^{\frac{1}{2}} = v_1(\varepsilon_1)^{\frac{1}{2}} + v_2(\varepsilon_2)^{\frac{1}{2}} \quad (3)$$

Landau and Lifshitz, Looyenga equation (LLLE):

$$\varepsilon^{\frac{1}{3}} = v_1(\varepsilon_1)^{\frac{1}{3}} + v_2(\varepsilon_2)^{\frac{1}{3}} \quad (4)$$

Bottcher equation (BE):

$$\frac{\varepsilon - \varepsilon_1}{3\varepsilon} = v_2\frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon} \quad (5)$$

and Lichtenecker equation (LE):

$$\ln\varepsilon = v_1 \ln\varepsilon_1 + v_2 \ln\varepsilon_2 \quad (6)$$

where ε represents the complex permittivity of the mixture, ε_1 is the complex permittivity of the medium in which particles of complex permittivity ε_2 are dispersed, and v_1, v_2 are the volume fraction of the respective components, and $v_1 + v_2 = 1$.

Bread was considered as a mixture of solid bread material and air voids. In the above equations, the complex permittivity of air, ε_1, is $1 - j0$, the corresponding v_1 is the value of bread porosity e; while ε_2 is the complex permittivity of solid bread material. It was difficult to obtain the complex permittivity of truly dense bread material (without air voids) directly, ε_2 was therefore estimated by extrapolation from directly measured dielectric properties of the bread samples that had been compressed to three different densities.

3. Results and discussion

3.1. Selection of mixture equation

Based on our preliminary study, relationships between dielectric constant (ε'), loss factor (ε'') and frequency (f, MHz) can be described by

$$\varepsilon' = A + \frac{B}{f} \quad (7)$$

$$\varepsilon'' = C + \frac{D}{f} \quad (8)$$

where A, B, C, and D are constants, and Eq. (8) was found to be consistent with findings reported by Tanaka et al. (2004).

Dielectric properties for compressed bread samples of 37.1% moisture content at three densities and room temperature (23 °C) are shown in Figs. 2 and 3. The corresponding constants of Eqs. (7) and (8) are listed in Table 2. The constants, A, B, C, D in Table 2 are linearly related to sample density, ρ, as follows:

$$A = 30.087\rho - 19.494 \quad R^2 = 0.985 \quad (9)$$

$$B = 1697.7\rho - 1415.2 \quad R^2 = 0.979 \quad (10)$$

$$C = 11.286\rho - 7.5253 \quad R^2 = 0.981 \quad (11)$$

$$D = 3406.7\rho - 2778.3 \quad R^2 = 0.979 \quad (12)$$

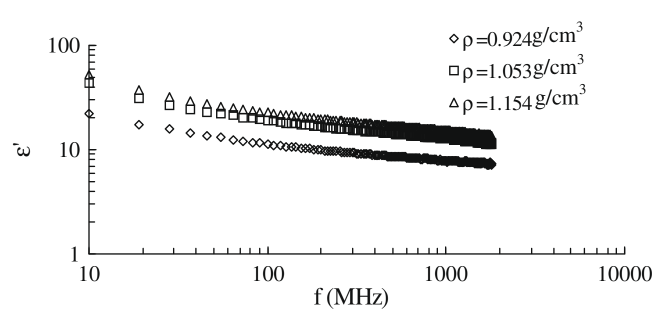

Fig. 2. Dielectric constants of compressed white bread samples with 37.1% moisture content at three densities and 23 °C.

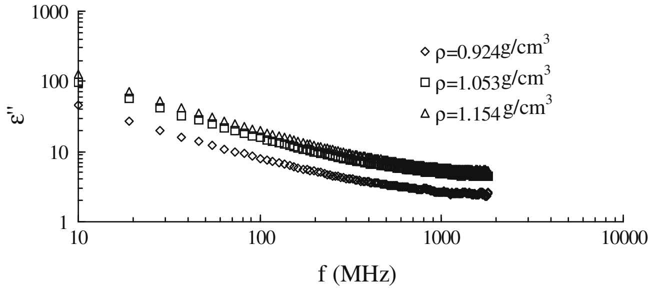

Fig. 3. Dielectric loss factors of compressed white bread samples with 37.1% moisture content at three densities and 23 °C.

Table 2
Constants along with R^2 values in frequency dependency Eqs. (7) and (8) of ε' and ε'' for white bread samples with 37.1% moisture content at three densities and 23 °C.

ρ (g/cm^3)	A	B	R_1^2	C	D	R_2^2
0.924	8.088	138.943	0.993	2.807	340.073	0.998
1.053	12.683	405.580	0.998	4.570	875.882	1.000
1.154	14.953	525.378	0.998	5.378	1115.462	1.000

The density of truly compressed white breads was determined to be ρ_m = 1.4 g/cm^3 using toluene displacement method with a pycnometer. The dielectric properties of ε' and ε'' of the solid bread material (bread without air voids) at 37.1% moisture content and room temperature can then be calculated from Eqs. (7) and (8) by setting ρ = 1.4 g/cm^3 in Eqs. (9)–(12) as

$$\varepsilon'_m = 22.652 + \frac{962.95}{f(\text{MHz})} \tag{13}$$

$$\varepsilon''_m = 8.2839 + \frac{1993.85}{f(\text{MHz})} \tag{14}$$

With the estimated values of ε' and ε'' for the solid bread material, the mixture equations were used to calculate ε' and ε'' of the bread samples at different densities. Measured and calculated dielectric properties for bread samples of 37.1% moisture content at 23 °C are shown in Table 3.

As shown in Table 3, the dielectric constant data calculated from Lichtenecker Equation match with the measured values best, while dielectric loss factor data calculated from Landau and Lifshitz, Looyenga Equation match the measured values best.

The dielectric properties of compressed bread samples for four moisture contents (38.6%, 37.1%, 34.6% and 34.0%) at five different temperatures (25–85 °C) were obtained at 13.56, 27.12, 40.8, 915 and 1800 MHz. At each moisture content level, three different densities were tested. The dielectric properties of bread material without air voids were calculated according to the relationship between dielectric properties and bread density, and then Lichtenecker Equation was used to calculate dielectric constant, Landau and Lifshitz, Looyenga Equation was used to calculate loss factor of compressed bread.

Errors between calculated and measured dielectric properties were estimated according to Eq. (15):

$$\text{Error} = \frac{\text{Calculated value} - \text{measured value}}{\text{measured value}} \times 100\% \tag{15}$$

For all the measured dielectric property data, 80% of the error values fall into the range of ±30%, 97% fall into the range of ±40%, 100% fall into the range of ±50%. Most errors occurred at the high moisture content and temperatures. The errors seem to be relatively high. But considering the porosity of the bread is 0.8, that is, the bread material just makes up 20% of the original bread, the total error of dielectric properties of original bread samples were at most ±10%.

Therefore, Lichtenecker Equation is applicable to calculation of dielectric constant and Landau and Lifshitz, Looyenga Equation was applicable to calculation of dielectric loss factor of original bread from compressed bread samples.

3.2. Dielectric properties of white bread

The values of ε' and ε'' of original white breads (porosity = 0.8) were calculated from the measured data of compressed bread samples using the mixture equations for five frequencies (13.56 MHz, 27.12 MHz, 40.68 MHz, 915 MHz, and 1800 MHz), four moisture levels (38.6%, 37.1%, 34.6%, and 34.0%) and five different temperatures (25 °C, 40 °C, 55 °C, 70 °C, and 85 °C). These values are summarized in Table 4.

3.3. Frequency dependency

As shown in Figs. 4 and 5 for example, in the moisture content range between 34.0% and 38.6%, the dielectric constant and loss factor of white breads decreased sharply with the increase in frequency up to 100 MHz, and then gradual decreased above 100 MHz at any given temperature.

Table 3
Measured and calculated dielectric properties for white bread samples with 37.1% moisture content at 23 °C.

ρ (g/cm^3)	f (MHz)	ε'					ε''				
		Measured	Calculated				Measured	Calculated			
			CRIME	LLLE	BE	LE		CRIME	LLLE	BE	LE
0.924	13.56	21.98	57.96	48.68	59.33	28.59	46.33	93.99	71.26	101.81	23.76
	27.12	15.71	28.92	25.06	28.98	16.69	20.16	36.67	28.77	38.99	12.07
	40.68	14.49	24.91	21.71	24.87	14.77	16.31	28.84	22.82	30.50	10.07
	915	7.95	12.67	11.27	12.58	8.25	2.69	5.03	4.16	5.15	2.32
	1800	7.19	12.42	11.05	12.32	8.10	2.68	4.52	3.75	4.63	2.10
1.053	13.56	43.17	72.30	63.83	75.40	43.31	98.46	120.40	99.11	130.50	43.72
	27.12	26.95	35.60	32.10	36.50	23.75	41.31	46.70	39.30	50.00	20.55
	40.68	24.71	30.60	27.66	31.20	20.75	33.03	36.60	31.03	39.10	16.84
	915	13.03	15.30	14.04	15.50	11.00	5.04	6.30	5.51	6.60	3.55
	1800	11.47	15.00	13.76	15.20	10.79	4.49	5.70	4.96	5.90	3.21
1.154	13.56	52.13	84.70	77.60	88.00	59.17	126.09	143.30	125.30	152.90	69.53
	27.12	32.04	41.30	38.40	42.40	31.01	52.39	55.30	49.10	58.50	30.77
	40.68	29.33	35.40	33.00	36.30	26.86	41.75	43.40	38.60	45.80	24.88
	915	15.47	17.60	16.50	17.90	13.76	5.95	7.40	6.70	7.70	4.90
	1800	13.72	17.20	16.20	17.50	13.49	5.31	6.70	6.10	6.90	4.43

Table 4
Mean ± standard deviation (three replicates) of dielectric properties for white bread samples with different moisture levels at 25–85 °C.

M (%)	f (MHz)		T (°C) 25	40	55	70	85
38.6	13.56	ε′	3.37 ± 0.10	3.56 ± 0.16	3.80 ± 0.29	4.06 ± 0.32	4.32 ± 0.37
		ε″	10.41 ± 0.59	13.11 ± 0.42	17.33 ± 0.77	22.89 ± 0.84	29.66 ± 2.09
	27.12	ε′	2.83 ± 0.06	2.97 ± 0.10	3.15 ± 0.19	3.35 ± 0.26	3.55 ± 0.26
		ε″	4.95 ± 0.25	6.15 ± 0.16	8.00 ± 0.57	10.39 ± 0.30	13.26 ± 0.52
	40.68	ε′	2.71 ± 0.05	2.84 ± 0.09	3.00 ± 0.17	3.19 ± 0.23	3.37 ± 0.23
		ε″	4.07 ± 0.19	5.03 ± 0.13	6.52 ± 0.40	8.43 ± 0.34	10.72 ± 0.35
	915	ε′	2.08 ± 0.03	2.12 ± 0.03	2.17 ± 0.06	2.21 ± 0.10	2.26 ± 0.13
		ε″	0.69 ± 0.03	0.72 ± 0.04	0.83 ± 0.01	0.98 ± 0.05	1.15 ± 0.03
	1800	ε′	2.01 ± 0.03	2.05 ± 0.03	2.10 ± 0.05	2.14 ± 0.08	2.18 ± 0.11
		ε″	0.66 ± 0.02	0.67 ± 0.03	0.72 ± 0.01	0.80 ± 0.01	0.85 ± 0.03
37.1	13.56	ε′	3.18 ± 0.03	3.36 ± 0.01	3.64 ± 0.03	3.95 ± 0.05	4.26 ± 0.08
		ε″	8.18 ± 0.02	10.33 ± 0.30	14.56 ± 0.19	20.53 ± 0.06	28.05 ± 0.47
	27.12	ε′	2.68 ± 0.02	2.81 ± 0.00	3.02 ± 0.02	3.26 ± 0.03	3.50 ± 0.05
		ε″	3.90 ± 0.00	4.86 ± 0.13	6.74 ± 0.09	9.34 ± 0.04	12.55 ± 0.18
	40.68	ε′	2.58 ± 0.02	2.70 ± 0.01	2.89 ± 0.01	3.10 ± 0.02	3.33 ± 0.05
		ε″	3.23 ± 0.01	4.00 ± 0.11	5.51 ± 0.07	7.60 ± 0.03	10.17 ± 0.14
	915	ε′	2.03 ± 0.01	2.07 ± 0.01	2.11 ± 0.01	2.17 ± 0.01	2.23 ± 0.02
		ε″	0.59 ± 0.01	0.67 ± 0.00	0.78 ± 0.00	0.93 ± 0.01	1.13 ± 0.00
	1800	ε′	2.00 ± 0.03	2.04 ± 0.03	2.08 ± 0.03	2.12 ± 0.03	2.17 ± 0.03
		ε″	0.57 ± 0.04	0.64 ± 0.02	0.70 ± 0.02	0.78 ± 0.02	0.80 ± 0.03
34.6	13.56	ε′	2.76 ± 0.15	2.94 ± 0.15	3.37 ± 0.21	3.81 ± 0.25	4.22 ± 0.27
		ε″	4.56 ± 0.38	6.07 ± 0.02	10.70 ± 0.11	17.62 ± 0.16	26.55 ± 0.33
	27.12	ε′	2.35 ± 0.11	2.49 ± 0.11	2.80 ± 0.15	3.14 ± 0.18	3.45 ± 0.19
		ε″	2.32 ± 0.20	3.00 ± 0.06	5.09 ± 0.06	8.14 ± 0.09	11.98 ± 0.14
	40.68	ε′	2.27 ± 0.10	2.39 ± 0.10	2.67 ± 0.14	2.98 ± 0.17	3.28 ± 0.18
		ε″	1.94 ± 0.17	2.49 ± 0.05	4.18 ± 0.06	6.64 ± 0.08	9.71 ± 0.12
	915	ε′	1.81 ± 0.06	1.86 ± 0.06	1.94 ± 0.07	2.03 ± 0.08	2.13 ± 0.08
		ε″	0.47 ± 0.01	0.52 ± 0.02	0.67 ± 0.02	0.89 ± 0.02	1.07 ± 0.01
	1800	ε′	1.75 ± 0.07	1.81 ± 0.07	1.89 ± 0.08	1.98 ± 0.09	2.07 ± 0.08
		ε″	0.47 ± 0.00	0.50 ± 0.01	0.59 ± 0.01	0.73 ± 0.01	0.76 ± 0.01
34	13.56	ε′	2.55 ± 0.01	2.68 ± 0.08	3.24 ± 0.25	3.77 ± 0.37	4.23 ± 0.41
		ε″	3.35 ± 0.20	4.21 ± 0.00	9.20 ± 0.27	16.90 ± 0.25	25.96 ± 1.96
	27.12	ε′	2.21 ± 0.00	2.31 ± 0.04	2.70 ± 0.16	3.10 ± 0.31	3.47 ± 0.29
		ε″	1.73 ± 0.10	2.10 ± 0.00	4.39 ± 0.43	7.82 ± 0.16	11.17 ± 0.21
	40.68	ε′	2.15 ± 0.00	2.24 ± 0.04	2.58 ± 0.15	2.95 ± 0.28	3.29 ± 0.27
		ε″	1.46 ± 0.09	1.76 ± 0.00	3.62 ± 0.35	6.39 ± 0.19	9.67 ± 0.12
	915	ε′	1.77 ± 0.01	1.82 ± 0.00	1.92 ± 0.05	2.04 ± 0.10	2.18 ± 0.14
		ε″	0.38 ± 0.02	0.39 ± 0.03	0.55 ± 0.00	0.84 ± 0.07	1.01 ± 0.03
	1800	ε′	1.75 ± 0.03	1.80 ± 0.02	1.89 ± 0.03	1.99 ± 0.08	2.10 ± 0.12
		ε″	0.36 ± 0.02	0.37 ± 0.02	0.46 ± 0.00	0.62 ± 0.01	0.72 ± 0.03

The trend for dielectric constant with frequency is consistent with findings reported by Nelson (1978) that dielectric constant either decreased or remained constant as frequency increased, provided all other conditions were held constant. Dipole rotation and ionic conduction are the two primary loss mechanisms for RF and MW absorption in food materials. Ionic conduction plays a major role at frequencies below 1 GHz (Ryynänen, 1995). Since the frequency range of this study is 1–1800 MHz, the dominant loss mechanism is ionic conduction.

The frequency dependent regression equations of dielectric properties for white bread samples at five temperatures and 37.1% moisture content are listed in Table 5.

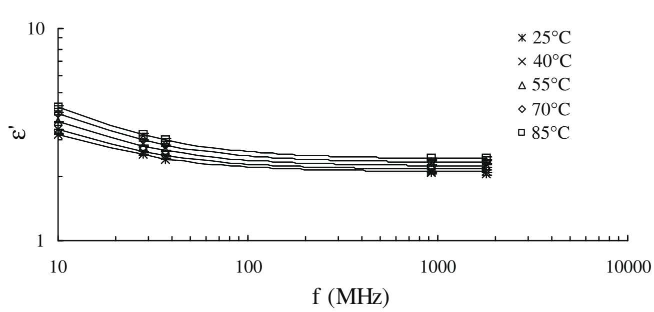

Fig. 4. Values of bread dielectric constant at five temperatures and 37.1% moisture content.

3.4. Moisture content dependency

At any given frequency, dielectric constant and loss factor increased linearly with the increase in moisture content within the temperature range of 25–85 °C. It could be attributed to the increased the amount of water molecules in breads at higher moisture contents (Datta et al., 2005). At RF frequencies ranging from 13.56 to 40.68 MHz, a sharper increase was observed in the loss factor with increasing moisture content as compared to the change in the dielectric constant, while at MW frequencies ranging from 915 to 1800 MHz, increase in loss factor is flatter. The higher frequency corresponded to the smaller influence of moisture content on dielectric constant and loss factor as illustrated in Figs. 6 and 7.

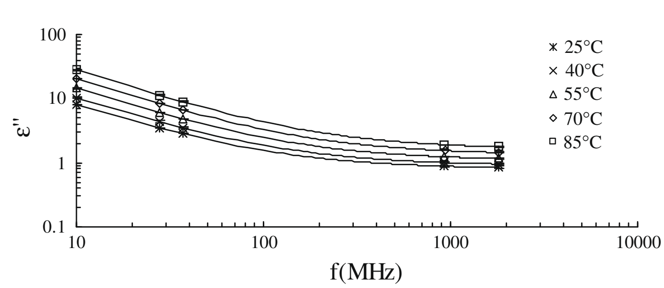

Fig. 5. Values of bread loss factor at five temperatures and 37.1% moisture content.

Table 5
Frequency, moisture content and temperature dependent regression equations of dielectric properties for white breads.

		Dielectric constant	Loss factor
Frequency (f, MHz) dependent regression equations:			
M (%)	*T* (°C)	Dielectric constant	Loss factor
37.1	25	$\varepsilon' = 2.111 + \frac{11.659}{f} (R^2 = 0.997)$	$\varepsilon'' = 0.803 + \frac{76.088}{f} (R^2 = 0.995)$
	40	$\varepsilon' = 2.165 + \frac{13.015}{f} (R^2 = 0.997)$	$\varepsilon'' = 0.903 + \frac{97.254}{f} (R^2 = 0.995)$
	55	$\varepsilon' = 2.242 + \frac{15.396}{f} (R^2 = 0.996)$	$\varepsilon'' = 1.091 + \frac{138.862}{f} (R^2 = 0.995)$
	70	$\varepsilon' = 2.330 + \frac{18.017}{f} (R^2 = 0.994)$	$\varepsilon'' = 1.337 + \frac{197.650}{f} (R^2 = 0.995)$
	85	$\varepsilon' = 2.423 + \frac{20.544}{f} (R^2 = 0.992)$	$\varepsilon'' = 1.621 + \frac{271.783}{f} (R^2 = 0.995)$
Moisture content (M, %) dependent regression equations:			
T (°C)	*f* (MHz)		
25	13.56	$\varepsilon' = 0.173M - 3.286(R^2 = 0.983)$	$\varepsilon'' = 150.920M - 47.817(R^2 = 0.999)$
	27.12	$\varepsilon' = 0.131M - 2.221(R^2 = 0.987)$	$\varepsilon'' = 68.169M - 21.366(R^2 = 0.998)$
	40.68	$\varepsilon' = 0.122M - 1.964(R^2 = 0.987)$	$\varepsilon'' = 55.331M - 17.286(R^2 = 0.997)$
	915	$\varepsilon' = 0.071M - 0.650(R^2 = 0.979)$	$\varepsilon'' = 5.254M - 1.375(R^2 = 0.941)$
	1800	$\varepsilon' = 0.065M - 0.463(R^2 = 0.921)$	$\varepsilon'' = 5.197M - 1.371(R^2 = 0.921)$
Temperature (T, °C) dependent regression equations:			
f (MHz)	*M* (%)		
27.12	34.0	$\varepsilon' = 0.0001T^2 + 0.0060T + 1.9482(R^2 = 0.9918)$	$\varepsilon'' = 0.0023T^2 - 0.0896T + 2.3960(R^2 = 0.9989)$
	34.6	$\varepsilon' = 9 \times 10^{-5}T^2 + 0.0093T + 1.9973(R^2 = 0.9973)$	$\varepsilon'' = 0.0021T^2 - 0.0661T + 2.3147(R^2 = 0.9998)$
	37.1	$\varepsilon' = 8 \times 10^{-5}T^2 + 0.0050T + 2.5004(R^2 = 0.9985)$	$\varepsilon'' = 0.0017T^2 - 0.0373T + 3.7637(R^2 = 0.9998)$
	38.6	$\varepsilon' = 4 \times 10^{-5}T^2 + 0.0072T + 2.6158(R^2 = 0.9995)$	$\varepsilon'' = 0.0014T^2 - 0.0221T + 4.8613(R^2 = 0.9995)$

The dielectric constant (ε'), loss factor (ε'') and moisture content (M, %) of bread can be correlated using a linear relationship. The moisture content dependent regression equations of dielectric properties for white bread samples at five frequencies and 25 °C are listed in Table 5.

3.5. Temperature dependency

At RF and MW frequencies ranging from 1 to 1800 MHz, dielectric constant and loss factor gradually increase with temperature as illustrated in Figs. 4 and 5 and shown in Table 4. The observed trend in changes of dielectric constant with temperature is consistent with general observation reported in the literature for low moisture or intermediate moisture foods (Nelson, 1978; Feng et al., 2002). The bread samples had more than 2% ash content (Table 1). The dissolved ions (included as a part of the ash content), thus, should contribute significantly to the overall loss factor of the bread samples. It has been documented that over the tested frequencies in our study, the loss factor due to ionic polarization increases with increasing temperature (Sun et al., 1995; Venkatesh and Raghavan, 2004; Guan et al., 2004).

Based on preliminary study, dielectric constant (ε'), loss factor (ε'') and temperature (*T*, °C) can be correlated quadratically. The temperature dependent regression equations of dielectric properties for white bread samples at four moisture contents and 27.12 MHz are listed in Table 5. A sharper increase is observed in loss factor compared with dielectric constant. The higher moisture content corresponds to the smaller temperature influence on dielectric constant and loss factor.

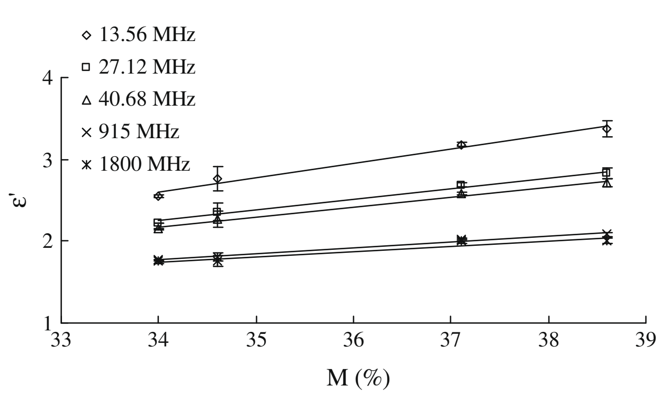

Fig. 6. Moisture content dependency of bread dielectric constant at five frequencies and 25 °C.

3.6. Power penetration depth

Power penetration depth is the distance over which the power intensity of electromagnetic waves is reduces to 36.79% of the original level. It was calculated according to (Von Hippel, 1954b):

$$d_p = \frac{c}{2\pi f \sqrt{2\varepsilon' \left[\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1 \right]}} \quad (16)$$

where *f* is in Hz and d_P in m.

Power penetration depth in bread decreases with increase in moisture content and frequency (Table 6). This is consistent with findings reported by Mudgett (1982) and Tang (2005). The value is 3–6 times that in vegetables, fruits and yogurt, 10 times that in cooked beef and 20 times that in cooked ham (Tang, 2005). This large difference is mainly due to the porous structure of the breads.

Since loss factor of air is zero, from Eq. (16) we can see that penetration depth in air is infinite. Therefore, porous materials like bread can be easily heated with RF and MW, which is the advantage of RF and MW heating over conventional heating in which low thermal conductivity in porous structure hinders heat flow.

The penetration depth decreases sharply with temperature at all the listed frequencies in Table 6. But even at the highest temperature studied (85 °C), the penetration depth of 1800 MHz or lower frequency electromagnetic waves can still penetrate more than 4 cm in white breads. Overall, electromagnetic energy at radio

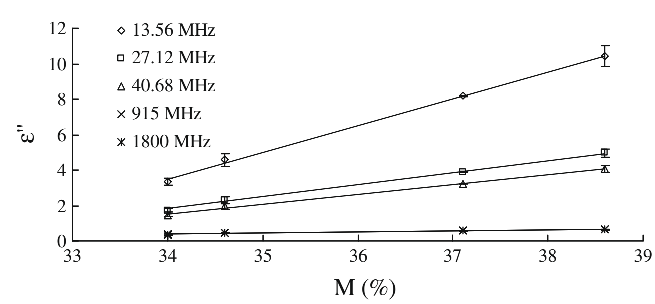

Fig. 7. Moisture content dependency of bread loss factor at five frequencies and 25 °C.

Table 6
Power penetration depth (cm) of RF and MW energy in white bread samples.

M (%)	f (MHz)	T (°C)				
		25	40	55	70	85
38.6	13.56	122.7 ± 4.0	106.7 ± 1.5	90.5 ± 1.7	77.1 ± 1.1	66.7 ± 2.3
	27.12	71.2 ± 2.3	61.4 ± 0.7	51.7 ± 1.9	43.9 ± 0.3	37.8 ± 0.6
	40.68	61.9 ± 1.9	53.3 ± 0.6	44.7 ± 1.4	37.8 ± 0.6	32.6 ± 0.3
	915	11.9 ± 0.4	10.7 ± 0.6	9.4 ± 0.0	8.1 ± 0.2	7.0 ± 0.0
	1800	6.3 ± 0.2	6.0 ± 0.2	5.6 ± 0.0	5.0 ± 0.0	4.4 ± 0.1
37.1	13.56	142.8 ± 0.0	123.3 ± 2.3	100.2 ± 0.7	82.0 ± 0.1	68.8 ± 0.6
	27.12	84.3 ± 0.2	72.1 ± 1.4	57.8 ± 0.5	46.9 ± 0.1	39.1 ± 0.3
	40.68	73.3 ± 0.1	62.6 ± 1.3	50.0 ± 0.4	40.4 ± 0.1	33.6 ± 0.2
	915	12.3 ± 0.2	11.3 ± 0.0	9.9 ± 0.0	8.4 ± 0.0	7.1 ± 0.0
	1800	6.3 ± 0.4	6.0 ± 0.1	5.6 ± 0.1	5.0 ± 0.1	4.5 ± 0.1
34.6	13.56	210.5 ± 10.5	173.2 ± 1.4	120.6 ± 0.3	89.6 ± 0.1	71.0 ± 0.1
	27.12	128.3 ± 7.1	105.4 ± 0.2	72.1 ± 0.2	52.9 ± 0.1	41.7 ± 0.0
	40.68	107.9 ± 6.4	88.6 ± 0.3	60.3 ± 0.2	44.0 ± 0.1	34.6 ± 0.0
	915	14.9 ± 0.1	13.8 ± 0.3	11.0 ± 0.1	8.6 ± 0.0	7.2 ± 0.1
	1800	7.6 ± 0.1	7.2 ± 0.0	6.2 ± 0.0	5.2 ± 0.1	4.7 ± 0.0
34.0	13.56	262.1 ± 8.6	222.1 ± 1.2	132.4 ± 0.7	91.8 ± 0.1	71.3 ± 1.7
	27.12	156.0 ± 5.9	133.9 ± 0.6	77.0 ± 3.2	53.1 ± 0.1	41.8 ± 0.0
	40.68	136.2 ± 5.2	117.2 ± 0.3	66.9 ± 2.8	45.2 ± 0.1	34.7 ± 0.1
	915	18.3 ± 0.7	18.3 ± 1.0	13.1 ± 0.1	9.0 ± 0.3	7.2 ± 0.0
	1800	9.8 ± 0.3	9.7 ± 0.4	8.0 ± 0.0	6.2 ± 0.0	4.8 ± 0.0

frequencies (13.56, 27.12, 40.68 MHz) has deeper penetrations in white breads as compared to microwave frequencies (915 and 1800 MHz). It is likely that RF energy provides more uniform heating.

4. Conclusions

The use of combined open-ended coaxial probe and mixture equation method enabled estimation of the dielectric properties of porous breads. Inverse, linear and quadratic relationship between dielectric properties and frequency, moisture content and temperature were observed in bread.

A significantly higher power penetration depth was estimated in bread than for other solid foods, which confirmed the advantage of RF and microwave heating over conventional heating for porous materials. Bread penetration depth values show RF heating to be a better choice than microwave heating for a whole package of bread.

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