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Analysis of bread loss factor using modified Debye equations

Yanhong Liu [a], Juming Tang [b,*], Zhihuai Mao [a]

[a] College of Engineering, China Agricultural University, Beijing 100083, China
[b] Department of Biological Systems Engineering, Washington State University, 213 L.J. Smith Hall, Pullman, WA 99164-6120, USA

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ABSTRACT

A modified Debye equation method was developed to analyze the frequency dependent behavior of bread loss factor over the moisture content range of 34.0–38.6% and temperature range of 25–85 °C. Moisture sorption isotherm of the bread was used to estimate monolayer and multilayer bound water contents. The overall contribution of bound water to loss factor was small. The calculated free water contribution to the dipole loss decreased with increasing temperature, while it increased with increasing moisture content. Over the studied frequency range, ionic conduction played the dominant role, while the importance of dipole relaxation of free water was very small at low frequencies and moderate at high frequencies. The effective ionic conductivity in breads increased with moisture content and temperature which explains the effect of these two parameters on changes to the ionic component of loss factor.

1. Introduction

Shelf life of fresh breads is limited due to growth of molds. New mold control methods that do not rely on chemical preservatives are of great interest to the bakery industry. Post-baking treatments of packaged bakery products using microwave (MW) and radio frequency (RF) energy hold good potential (Zhao et al., 1999; Piyasena et al., 2003; Koral, 2004; Lakins et al., 2008). In order to design effective MW or RF treatments that provide a good balance between mold control and retention of product quality, it is desirable to gain a better understanding of the dielectric properties of bread products.

Dielectric properties of foods are influenced by many factors, including moisture content, temperature and frequency (Calay et al., 1995; Sun et al., 1995; Tang et al., 2002; Tang, 2005; Venkatesh and Raghavan, 2004). An increase in moisture content increases the amount of polar molecules in food systems, thus increasing the overall dielectric properties (Ohlsson, 1989; Nelson, 1978, 1991; Tang et al., 2002; Venkatesh and Raghavan, 2004; Datta et al., 2005). Higher temperature increases the mobility of polar molecules and charged ions in foods. This is reflected in increased contribution of ionic conduction to the dielectric loss factor in the radio frequency region of the electromagnetic spectrum (10–300 MHz) and a shifting of the relaxation frequency (referred to as critical frequency) of free water molecules towards the higher end of microwave frequency range between 10 and 50 GHz (Tang, 2005). For pure water with no free ions, the loss factor either increases or decreases with increasing temperature depending on whether the operating frequency is lower or higher than the critical frequency, while the dielectric constant increases with increasing temperature over the entire dispersion region (Nelson, 1978, 1991; Venkatesh and Raghavan, 2004). The influences of different factors on dielectric constant are predictable, but the frequency dependent behavior, along with the temperature effect of loss factor, is much more complicated (Nelson, 1978; Datta et al., 2005).

In radio frequency (RF) and microwave (MW) frequency range (10 MHz–30 GHz) of practical importance to industrial heating applications, dipole rotation of water and ionic conduction due to water containing ions are the two major loss mechanisms in general food systems (Loor and Meijboom, 1966; Harvey and Hoekstra, 1972; Engelder and Buffler, 1991; Mudgett, 1995; Ryynänen, 1995; Kim et al., 1998; Tang, 2005):

$$\varepsilon'' = \varepsilon''_d + \varepsilon''_\sigma \tag{1}$$

For pure polar solutions, the Debye model (Decareau, 1985) is usually used to describe the general frequency dependent behavior. But for bakery foods that have intermediate moisture contents and contain ionic substances, no universal model is available to describe the frequency dependent behavior of loss factor. Yet, this parameter is considered one of the most important factors that influence the conversion of electromagnetic energy into thermal energy during RF or MW heating. Therefore, a better understanding of loss mechanisms is helpful in obtaining desired RF and MW heating performance. The objective of this paper was to analyze frequency dependent behavior of the loss factor of white bread as influenced by moisture content and temperature.

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* Corresponding author. Tel.: +1 509 335 2140; fax: +1 509 335 2722.
E-mail addresses: jtang@wsu.edu, jtang@mail.wsu.edu (J. Tang).

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Nomenclature

e	porosity
M	moisture content, % wet basis
M_0	monolayer bound water content, % wet basis
a_w	water activity
f	frequency (Hz)
f_c	critical frequency (Hz)
T	temperature (°C)

Greeks

ε''	dielectric loss factor
ρ	density (kg/m^3)
ε	complex permittivity
σ	ionic conductivity (S/m)
ω	angular frequency (rad/s)
ε_0	permittivity of free space or vacuum (8.854×10^{-12} F/m)
ε_s	static dielectric constant
ε_∞	optical dielectric constant
τ	relaxation time (s)
σ_e	effective ionic conductivity (S/m)

Subscripts

d	contribution of dipole rotation
σ	contribution of ionic conduction
ap	apparent
m	material
b	bound water
f	free water

2. Materials and methods

2.1. Sample preparation

Sliced white breads (Oven Joy White Enriched Bread made by Lucerne Foods, Inc.) were acquired from a local grocery store in Pullman, WA, USA. Approximate compositions of the bread samples used are stated in Table 1. The ash content (AOAC, 2000a), moisture content (AOAC, 2000b) and porosity (Rahman, 1995, 2005) were measured in our laboratory while the other values were simply read off the label.

Bread samples containing different moisture contents were prepared by rewetting or dehydrating at room temperature, refrigerated for 48 h to equilibrate and conditioned at room temperature for 12 h before measurements.

2.2. Moisture content and water activity

The moisture content of bread was determined from the difference in weights before and after vacuum-drying at 98–100 °C for about 5 h (AOAC, 2000b).

The water activity at room temperature was measured using an AquaLab Series 3 water activity meter (Decagon Devices Inc., Pullman, WA, USA). Three replicates were conducted for each measurement.

2.3. Porosity

The apparent density of bread was calculated from measured mass and volume. The true density of bread was measured at room temperature with pycnometer Accupyc 1330 (Micromeritics, USA) by displacing toluene. The porosity was calculated from the following equation (Rahman, 1995, 2005):

$$e = 1 - \frac{\rho_{ap}}{\rho_m} \tag{2}$$

2.4. Bound water content

In biological systems, such as foods, water exists either in the bound or free states (Nagashima and Suzuki, 1981; Rahman, 1995; Al-Muhtaseb et al., 2002; Datta et al., 2005; Rizvi, 2005). Depending on the binding energy, bound water can be divided into monolayer and multilayer states (Al-Muhtaseb et al., 2002; Schmidt, 2007; Labuza and Altunakar, 2007).

2.4.1. Moisture sorption isotherm

Moisture sorption isotherm is the relationship between moisture content and water activity at a given temperature. The sorption isotherms for most processed foods are sigmoid shaped with two bending regions (Rahman, 1995; Al-Muhtaseb et al., 2002; Schmidt, 2007). Monolayer and multilayer bound water contents can be obtained from the intersection of three linear parts of the sorption isotherm (Rahman, 1995; Schmidt, 2007).

2.4.2. GAB equation method

Several moisture sorption isotherm models are commonly used to estimate monolayer bound water content in foods, such as BET equation, Halsey equation, Smith equation and GAB equation (Rahman, 1995; Al-Muhtaseb et al., 2002; Rizvi, 2005). Among those equations, the GAB equation has been suggested to be the most versatile sorption model known (Lim et al., 1995; Al-Muhtaseb et al., 2002; Quirijns et al., 2005; Labuza and Altunakar, 2007). Hence, this model was chosen to calculate the monolayer bound water content of bread. The GAB equation is written in the form:

$$M = \frac{M_0 C K a_w}{(1 - K a_w)(1 - K a_w + C K a_w)} \tag{3}$$

where C and K are constants, and a_w is in the range between 0.05 and 0.95.

For the isotherm tests, bread samples with 24 different moisture content levels (0.9–34.1%) were prepared and conditioned at room temperature for 48 h to equilibrate. The sample moisture contents and the corresponding water activities were measured in three replicates.

2.5. Dielectric loss factor

As shown in Table 1, fresh bread samples had a moisture content of 37.1%. To evaluate the effect of moisture content on the dielectric properties over a broader range, samples at three other

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

moisture contents (namely, 38.6%, 34.6% and 34.0%) were also included in the measurements.

Fresh bread samples had a porosity of 0.8, corresponding to a density of 280 kg/m^3 at 37.1% moisture content. At this high porosity, it was difficult to ensure a consistent contact between bread sample surface and the small coaxial end (4.8 mm diameter) of the dielectric probe. Instead of undertaking measurements with porous samples, compressed bread samples were used in the dielectric property measurement.

Dielectric properties of compressed white bread samples were measured in three replicates at five different temperatures (25, 40, 55, 70 and 85 °C) between 1 and 1800 MHz using an open-ended coaxial probe system. This system consisted of an Agilent 4291B impedance analyzer (Agilent technologies, Palo Alto, CA), a custom-built test cell, and a Hewlett Packard 85070B dielectric probe kit. The test cell was designed to allow conditioning of samples at above ambient temperatures before each measurement. Detailed information on the test cell design has been provided by Wang et al. (2003b). The system was calibrated following the standard procedure described by Wang et al. (2003a).

Before measurement, the samples were loaded into the test cell (21 mm diameter) and compressed to a fixed height of 38 mm. The sample diameter was 4.4 times the outer diameter (4.8 mm) and the sample thickness was 13.6 times the inner diameter (2.8 mm) of the outer coaxial conductor of the open-ended dielectric property probe. Thus, the sample size and thickness 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).

For each moisture content, samples possessing three different density values (900–1200 kg/m^3) were measured. The measured dielectric property data were all relative to that of ambient air at room temperature.

Bread was considered to be a mixture of condensed bread material and air voids. The Landau & Lifshitz, Looyenga equation, shown as Eq. (4), was used to calculate dielectric loss factor (ε'') (Nelson, 1991; Nelson and Datta, 2001; Kim et al., 1998; Liu et al., 2009):

$$\varepsilon^{\frac{1}{3}} = e(\varepsilon_1)^{\frac{1}{3}} + (1-e)(\varepsilon_2)^{\frac{1}{3}} \tag{4}$$

where ε represents the complex permittivity of porous bread; $\varepsilon_1 = 1$ is the complex permittivity of air; and ε_2 is the complex permittivity of condensed bread material.

2.5.1. Ionic loss

Ionic loss mainly results from ionic conduction in food materials. It plays a major role at frequencies below 1 GHz (Ryynänen, 1995). For liquid foods (Mudgett, 1995; Tang, 2005):

$$\varepsilon''_\sigma = \frac{\sigma}{\varepsilon_0 \omega} = \frac{\sigma}{2\pi f \varepsilon_0} \tag{5}$$

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

Eq. (6) indicates that a log–log plot of the ionic contribution to dielectric loss factor and frequency for aqueous ionic solutions is linear with a slope of -1.

For solid materials, no general equation is available to describe the frequency dependent behavior of ionic loss. Provided the total loss factor is measured, and the loss factor due to polar relaxation estimated, the contribution of ionic loss can be obtained from Eq. (7):

$$\varepsilon''_\sigma = \varepsilon'' - \varepsilon''_d \tag{7}$$

2.5.2. Dipole loss

The dipolar polarization in moisture containing food materials is the most important of all the loss mechanisms at frequencies above 1 GHz (Ryynänen, 1995). Dipole loss mainly results from the relaxation of water molecules (Loor and Meijboom, 1966; Mudgett, 1995; Ryynänen, 1995). At constant temperature, the dielectric loss factor of water can be predicted as a function of frequency by the Debye model (Decareau, 1985; Mudgett, 1995):

$$\varepsilon''_d = \frac{(\varepsilon_s - \varepsilon_\infty)\frac{f}{f_c}}{1 + \left(\frac{f}{f_c}\right)^2} \tag{8}$$

where f_c is related to relaxation time τ as $f_c = \frac{1}{2\pi\tau}$ (Decareau, 1985; Mudgett, 1995).

For intermediate moisture content and porous products, such as breads, we modified the Debye model to estimate the contribution of bound water and free water to loss factor:

$$\varepsilon''_b = M_b(1-e)\frac{(\varepsilon_{sb} - \varepsilon_{\infty b})\frac{f}{f_{cb}}}{1 + \left(\frac{f}{f_{cb}}\right)^2} \tag{9}$$

$$\varepsilon''_f = (M - M_b)(1-e)\frac{(\varepsilon_{sf} - \varepsilon_{\infty f})\frac{f}{f_{cf}}}{1 + \left(\frac{f}{f_{cf}}\right)^2} \tag{10}$$

$$\text{And} \qquad \varepsilon''_d = \varepsilon''_b + \varepsilon''_f \tag{11}$$

In the above equations, $M_b(1-e)$ reflects the amount of bound water within a unit volume of bread while the product $(M - M_b)$ $(1-e)$ indicates the amount of free water in the same volume.

3. Results and discussion

The dielectric constants and loss factors of white breads at four different moisture contents between 34.0% and 38.6% and five temperatures from 25 to 85 °C are reported elsewhere (Liu et al., 2009). In this paper, we focus on analyzing the influence of frequency, temperature and moisture content on the dielectric loss factor which is more directly related to conversion of electromagnetic energy to thermal energy during dielectric heating.

3.1. Parameters for Eqs. (9) and (10)

3.1.1. Bound water content

Moisture sorption isotherm of white bread sample is shown in Fig. 1, where Regions I, II and III refer to monolayer bound water, multilayer bound water and free water, respectively (Rahman, 1995; Schmidt, 2007). Moisture content and water activity at the two intersections, Points A and B, are 5.8%, 12.2% and 0.23, 0.75, respectively. These values are consistent with Labuza and Altunakar's (2007) findings that water activity for the Region I–II transition is 0.25, for the Region II–III transition is 0.75 for most food materials. Monolayer bound water content and bound water content for bread samples in this study were:

$$M_0 = 5.8\% \tag{12}$$

$$M_b = 12.2\% \tag{13}$$

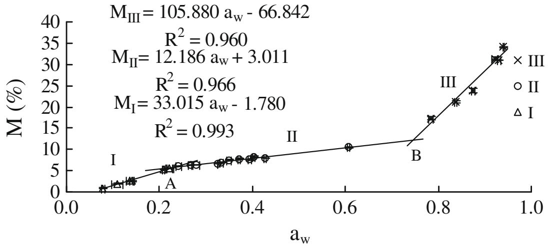

Fig. 1. Moisture sorption isotherm of white bread samples at 25 °C.

The data in Fig. 1 were also fitted to Eq. (3) using SYSTAT software (SYSTAT Software Inc., San Jose, CA, USA) to estimate the monolayer bound water content of bread, yielding:

$$M_0 = 4.5\% \qquad R^2 = 0.991 \tag{14}$$

Comparing Eq. (14) with Eq. (12), we can see a 1.3% difference in monolayer bound water content of bread obtained from moisture sorption isotherm curves and GAB equation. Labuza and Altunakar (2007) also reported a 1.5% difference between the moisture sorption isotherm bound water content and BET monolayer bound water content for native corn starch.

3.1.2. Static, optical dielectric constants and critical frequencies

The reported values of ε_{sb}, $\varepsilon_{\infty b}$ and f_{cb} in Eq. (9) for biomaterials were found to be 15 (Harvey and Hoekstra, 1972; Tang et al., 2002; Tang, 2005), 4 (Roebuck and Goldblith, 1972; Harvey and Hoekstra, 1972; Tang et al., 2002; Tang, 2005) and 200 MHz (Harvey and Hoekstra, 1972; Mashimo et al., 1987; Tang et al., 2002; Tang, 2005), respectively, at 25 °C. The values of ε_{sf}, $\varepsilon_{\infty f}$ and f_{cf} in Eq. (10) at different temperatures were obtained by regression of literature data (Collie et al., 1948; Hill, 1970; Decareau, 1985; Kaatze, 1989; Nelson, 1991; Mudgett, 1995; Ryynänen, 1995; Venkatesh and Raghavan, 2004; Datta et al., 2005; Trabelsi and Nelson, 2006). These values are summarized in Table 2. In Eq. (10), the frequency f is in the range 1–1800 MHz, while the critical frequency for free water, f_{cf}, is between 19,000 and 58,000 MHz (see Table 2). Thus, when $1+(\frac{f}{f_{cf}})^2 \to 1$, Eq. (10) can be reduced to:

$$\varepsilon''_f = (M - M_b)(1-e)\frac{(\varepsilon_{sf} - \varepsilon_{\infty f})}{f_{cf}} f \tag{15}$$

The coefficient of frequency in Eq. (15) contains three different terms: (1) $(M - M_b)$ is the moisture content corresponding to the free water; (2) $(1 - e)$ reflects the proportion of solid bread material; and (3) $\frac{(\varepsilon_{sf}-\varepsilon_{\infty f})}{f_{cf}}$ gives temperature effect. For a given moisture content and temperature, $\frac{(M-M_b)(1-e)(\varepsilon_{sf}-\varepsilon_{\infty f})}{f_{cf}}$ is a constant, therefore, a linear relationship exists between free water contribution to dipole loss and frequency.

3.2. Components of bread loss factor

The contributions of bound water, free water and ionic conduction to the overall loss factor of bread were separately calculated using Eqs. (9), (10) and (7). Experimentally obtained loss factor of bread of 38.6% moisture content at 25 °C and each calculated element of the loss factor are illustrated in Fig. 2. From Fig. 2 we can see that ionic loss dominates in the frequency range studied, while free water contribution plays an important role above 1000 MHz. This is consistent with the findings reported by Ryynänen (1995) and Tang (2005) that ionic loss plays a major role at frequencies below 1 GHz, while both ionic conduction and the dipole rotation of free water are important at MW frequencies.

Bound water contribution, however, accounts for a small proportion, 12% at most at 300 MHz (near to the critical frequency corresponding to the bound water, see Fig. 2) for bread with 38.6% moisture content at 25 °C. The peak value of dipole loss factor of bound water has been reported to be decreasing with increase in temperature (Wang et al., 2003). In the moisture range 34.0–38.6%, the amount of bound water in white bread samples should be the same. That is, moisture change has no effect on bound water contribution to dipole loss. Therefore, subsequent analysis will only be focused on ionic loss and free water contribution to dipole loss. Bound water contribution will be neglected.

Table 2
Static, optical dielectric constant and critical frequency of free water at five temperatures.

T (°C)	ε_{sf}[a]	$\varepsilon_{\infty f}$[b]	f_{cf}[c] (GHz)
25	78.4	5.4	19
40	73.2	4.2	27
55	68.0	4.1	36
70	62.7	4.0	47
85	57.4	3.9	58

[a] Data generated based on Collie et al. (1948), Hill (1970), Decareau (1985), Kaatze (1989), Nelson (1991), Ryynänen (1995), Venkatesh and Raghavan (2004), and Datta et al. (2005), Trabelsi and Nelson (2006).

[b] Data generated based on Hill (1970), Kaatze (1989), Mudgett (1995), Ryynänen (1995), Venkatesh and Raghavan (2004), Datta et al. (2005), and Trabelsi and Nelson (2006).

[c] Data generated based on Collie et al. (1948), Decareau (1985), Kaatze (1989), Nelson (1991), Mudgett (1995), Venkatesh and Raghavan (2004), and Datta et al. (2005).

3.3. Influence of moisture content

Frequency dependency of bread loss factor at 25 °C and 34.0% moisture content is shown in Fig. 3. A comparison between Figs. 2 and 3 reveals that free water dipole loss increases slightly with moisture content, while ionic loss increases sharply.

3.3.1. Ionic loss

The frequency dependency of ionic loss at four moisture contents and 25 °C is illustrated in Fig. 4. A log–log plot of ionic loss (ε''_σ) and frequency (f, Hz) is linear with a slope of $-b$ over the frequency range between 1 and 1800 MHz:

$$\log \varepsilon''_\sigma = a - b \log f \tag{16}$$

where a, b are constants whose values for white bread samples at four moisture contents and 25 °C are listed in Table 3. We can see from Fig. 4 and Table 3, that the higher moisture content corresponds to steeper slope (greater b value), consistent with findings of Wang et al. (2005) who reported 0.958 and 0.938 as the b value

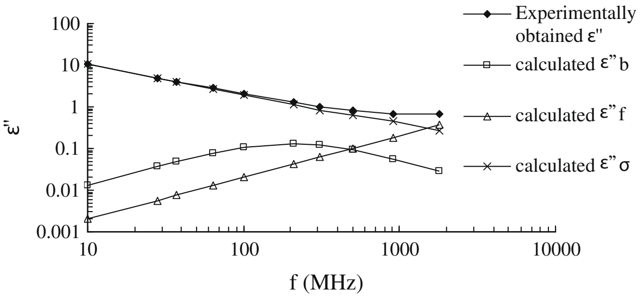

Fig. 2. Frequency dependency of bread loss factor at 25 °C and 38.6% moisture content.

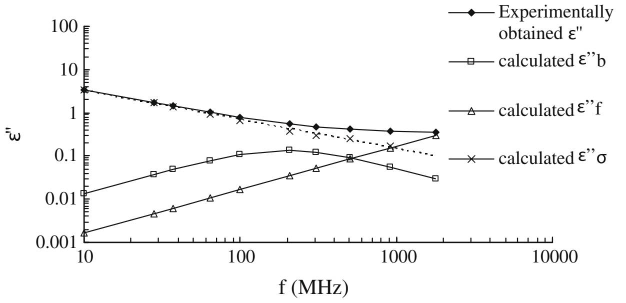

Fig. 3. Frequency dependency of bread loss factor at 25 °C and 34.0% moisture content.

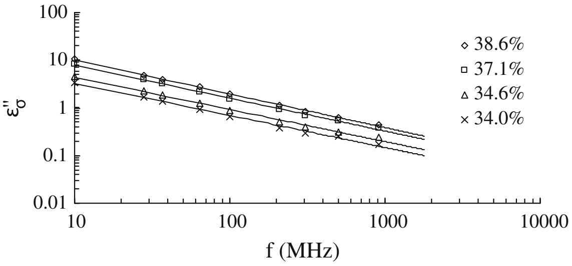

Fig. 4. Ionic loss of white bread samples at four moisture contents and 25 °C.

Table 3
Constants along with R^2 values in Eqs. (16) and (19) for white bread samples.

M (%)	*T* (°C)	*a*	σ_e (S/m)	*b*	R^2
34.0	25	5.221	9.254×10^{-6}	0.673	0.995
34.6	25	5.367	12.951×10^{-6}	0.675	0.994
37.1	25	5.718	29.062×10^{-6}	0.689	0.998
38.6	25	5.964	51.206×10^{-6}	0.709	0.998
38.6	40	6.120	73.328×10^{-6}	0.717	0.999
38.6	55	6.290	108.390×10^{-6}	0.724	0.998
38.6	70	6.470	164.323×10^{-6}	0.733	0.999
38.6	85	6.674	262.323×10^{-6}	0.746	0.999

for avocado and passion fruit, respectively, with moisture contents of 75% to 87%. In general, for liquid or high moisture foods, *b* value should be or close to 1, as in the cases of mashed potato (Guan et al., 2004), eggs (Wang et al., 2009) and salmon fillets (Wang et al., 2008).

For white breads with intermediate moisture contents between 34.0% and 38.6%, the *b* value varies between 0.673 and 0.709. This suggests that Eq. (6) cannot be directly applied to such foods and, most likely, to low moisture contents in general. Therefore, we modified Eq. (6) into the following form:

$$\log \varepsilon''_\sigma = \log \frac{\sigma_e}{2\pi\varepsilon_0} - b \log f \tag{17}$$

In the above equation, a new term has been introduced: effective ionic conductivity (σ_e). In liquid or high moisture foods, electrical conductivities can be directly measured using conductivity probes (Guan et al., 2004; Wang et al., 2008, 2009). But for foods with intermediate or low moisture content, discontinuities in zones of free water as solvent for charged ions within food structures do not allow accurate measurement of ionic conductivity. Yet, the effect of ionic conduction in the loss factor of white bread is evident from the log linear relationship between loss factor and frequency (Fig. 4). It is our hypothesis that the charged ions in bread migrate in an oscillating mode in localized regions of free water and, to a certain degree, in bound water at RF frequencies. The effective ionic conductivity is a good indicator of this effect. From Eqs. (16) and (17), we obtain:

$$a = \log \frac{\sigma_e}{2\pi\varepsilon_0} \tag{18}$$

Effective ionic conductivity can then be calculated from Eq. (18):

$$\sigma_e = 2\pi\varepsilon_0 10^a \tag{19}$$

The calculated effective ionic conductivity at 25 °C in Table 3 increases with moisture content according to the following relationship:

$$\sigma_e = 1.686 \times 10^{-6} M^2 - 1.136 \times 10^{-4} M + 1.923 \times 10^{-3} \quad R^2 = 0.997 \tag{20}$$

The effective ionic conductivity of white bread samples obtained from this study is about 3–5 orders of magnitude smaller than that in high moisture vegetables, fruits and NaCl solutions (Wang and Sastry, 1993; Ikediala et al., 2002; Castro et al., 2003; Guan et al., 2004; Wang et al., 2005; Sastry, 2005). This is reasonable considering the lower moisture content of the bread which limits the mobility of charged ions.

3.3.2. Free water contribution to dipole loss

In Eq. (15), at a given temperature, $(1-e)\frac{(\varepsilon_{sf}-\varepsilon_{\infty f})}{f_{cf}} = c_1$ is a constant, thus:

$$\varepsilon''_f = c_1 (M - M_b) f \tag{21}$$

In the above equation, free water contribution to dipole loss increases with increasing frequency. This is evident in Fig. 5. The term c_1 $(M - M_b)$ in Eq. (21) represents the slope of ε''_f *vs*. *f* plot. The higher moisture content, i.e. greater amount of free water, corresponds to a steeper gradient.

3.4. Influence of temperature

Frequency dependency of bread loss factor at 85 °C and 38.6% moisture content is shown in Fig. 6. Comparing Fig. 6 with Fig. 2 reveals that ionic loss increases sharply with temperature, while free water dipole loss decreases with increasing temperature. This can be explained by a shift of the critical frequency from 19 GHz at 25 °C to 58 GHz at 85 °C (see Table 2). Because ionic loss dominates in the frequency range studied, the overall bread loss factor increases with increasing temperature.

3.4.1. Ionic loss

With increase in temperature, ionic loss increases as shown in Fig. 7. Effective ionic conductivities of white bread samples at five temperatures and 38.6% moisture content were calculated using

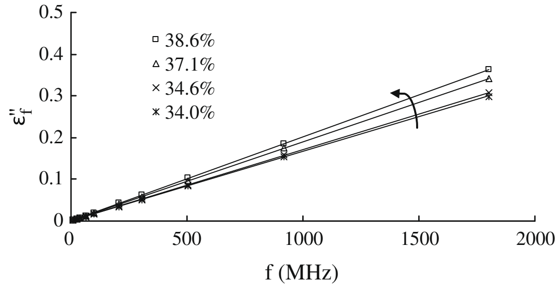

Fig. 5. Free water contribution to bread loss factor at various moisture contents and 25 °C.

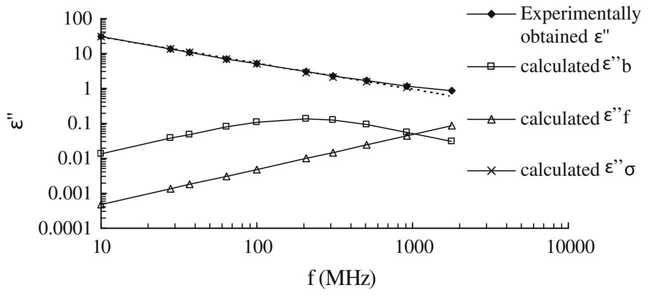

Fig. 6. Frequency dependency of bread loss factor at 85 °C and 38.6% moisture content.

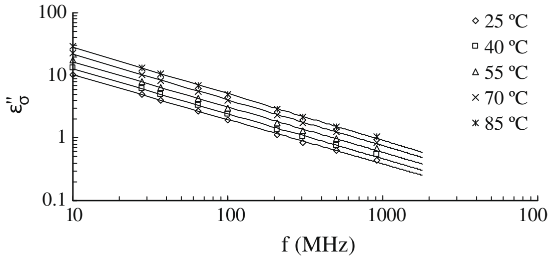

Fig. 7. Ionic loss of white bread samples at five temperatures and 38.6% moisture content.

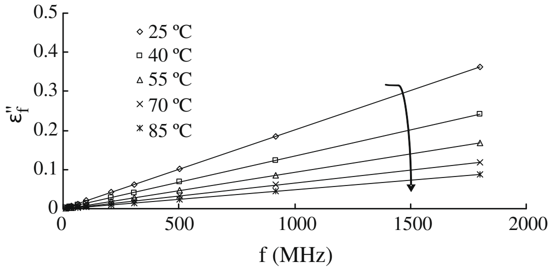

Fig. 8. Free water contribution to bread loss factor at different temperatures and 38.6% moisture content.

Eq. (19) and are listed in Table 3. It is clear from Table 3 that increasing temperature sharply increases the effective ionic conductivity. Higher temperatures reduce the viscosity of free water, making charged ions more mobile as compared to lower temperatures.

The effective ionic conductivity was related to product temperature using the following relationship:

$$\sigma_e = 5.480 \times 10^{-8}\mathrm{T}^2 - 2.607 \times 10^{-6}\mathrm{T} + 8.485 \times 10^{-5}$$
$$R^2 = 0.997 \tag{22}$$

Similar results were also reported for NaCl solutions (Stogryn, 1971), potato tissue (Wang and Sastry, 1993) and strawberry pulp (Castro et al., 2003).

3.4.2. Free water contribution to dipole loss

In Eq. (15), at any given moisture content, $(M - M_b)(1 - \mathrm{e}) = c_2$ is constant, thus:

$$\varepsilon''_f = c_2 \frac{\varepsilon_{\mathrm{sf}} - \varepsilon_{\infty\mathrm{f}}}{f_{\mathrm{cf}}} f \tag{23}$$

The above relationship suggests that free water contribution to dipole loss increases with frequency. In Eq. (23), $c_2 \frac{\varepsilon_{\mathrm{sf}} - \varepsilon_{\infty\mathrm{f}}}{f_{\mathrm{cf}}}$ represents the slope of the plot of ε''_f *vs*. *f*. An increase in sample temperature reduces the value of $\varepsilon_{\mathrm{sf}} - \varepsilon_{\infty\mathrm{f}}$ and shifts f_{cf} to a greater value (see Table 2). Thus the constant, $c_2 \frac{\varepsilon_{\mathrm{sf}} - \varepsilon_{\infty\mathrm{f}}}{f_{\mathrm{cf}}}$, decreases with temperature. As a results, the higher temperature corresponds to a lower slope (i.e. lower rate of increase), as shown in Fig. 8.

4. Summary

Influence of moisture content and temperature on dielectric loss factor of white breads with moisture content between 34.0% and 38.6% were studied by analyzing contributions of free water, bound water and ionic conduction over a frequency range between 10 and 1800 MHz. The bound water content of bread was obtained from moisture sorption isotherm and GAB equation, and a small difference was found between the monolayer bound water contents obtained using the two methods. For the bread samples considered in this work, the overall contribution of bound water to loss factor was small. Over the frequency range studied, the ionic conduction played the main role, while the importance of dipole relaxation of free water was insignificant at low frequencies but moderate at high frequencies.

The effective ionic conductivity increased with moisture content and temperature, which explains the effect of these two parameters on changes in the ionic component of loss factor. The free water loss component also increased with moisture content, but decreased sharply with temperature as a result of the critical frequency of free water moving further away from the frequency range selected in this study.

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