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Dielectric properties of bentonite water pastes used for stable loads in microwave thermal processing systems

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ABSTRACT

The dielectric properties of bentonite water pastes relevant to microwave thermal processing were measured over 300–3000 MHz and 22–120 °C. Effects of bentonite content (7.5–25%, wb), salt (NaCl) content (0.3–1.2%, wb), vegetable oil content (5–15%, wb) and sucrose content (30%, wb) on dielectric properties were investigated. Regression equations were developed to reveal the influences of temperature and different ingredients on the dielectric properties of bentonite pastes at 915 and 2450 MHz. Results illustrated that dielectric properties of bentonite pastes could be adjusted with different ingredients to match those of a wide range of food materials with similar response to increasing temperature. Vegetable oil and salt were good additives to reduce dielectric constant and increase loss factor, respectively. Adding sucrose reduced both dielectric constant and loss factor. Derived from the regression equations, the influence factor of each ingredient was calculated to reveal its influence on the changing rate of dielectric properties with increasing temperature. The bentonite pastes can be formulated with stable dielectric properties and be used as dummy loads for evaluating performance of industrial microwave assisted thermal processing systems.

1. Introduction

Microwave thermal processing is a novel technology that has potential to produce high quality shelf stable food products (Guan et al., 2002, 2003; Ohlsson, 1992) due to its unique volumetric heating. A single model 915 MHz microwave assisted thermal sterilization (MATS) system was developed at Washington State University (WSU) with the ultimate goal aimed toward industrial implementation (Tang et al., 2006). In 2009, a microwave sterilization process based on the MATS system for mashed potatoes packaged in polymeric trays was accepted by the FDA (Food and Drug Administration). Several additional filings were accepted by FDA and USDA FSIS (United States Department of Agriculture Food Safety and Inspection Service) between 2010 and 2013. Those successful filings pave the path for commercial application of the new technology.

In microwave heating, the dielectric properties of materials are the principal parameters. They determine how materials interact with electromagnetic energy. Dielectric properties have two components: dielectric constant (ε') and loss factor (ε'') which describe the ability of a material to store and dissipate microwave energy, respectively, in response to applied electric field. In a microwave system, microwave power is delivered through waveguides from a generator to the microwave heating cavity. During operation, portion of the energy may be reflected back from the heating cavity. The reflected power level is affected by the waveguide elements, possible misalignment and the size, geometry and dielectric properties of the loads (Meredith, 1998). For microwave system development, calibration loads with known dielectric properties are often used in power delivery tests. Once a good power delivery system is installed and calibrated; the process schedule can then be developed for a specific product. To verify system stability, periodical test runs may need to be performed with full load. It is difficult to use food materials for such tests because dielectric properties of food materials vary with ingredients and their preheating conditions (Ryyannen, 1995; Sakai et al., 2005; Wang et al., 2008). Their dielectric properties are also altered during thermal treatments. Thus, each batch of food samples can only be used once. This would lead to a large amount of waste especially for an industrial system with a high production capacity.

Model foods with consistent and predictable dielectric properties can be used as dummy loads. In previous studies, agar gel (Padua, 1993a, b), whey protein gel (Lau et al., 2003; Wang et al., 2009) and egg white gel (Zhang et al., 2013) have been used to create model foods used in microwave heating research. However, the ingredients of those model foods have low thermal stability. Water was also used as load in a previous study

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(Housova and Hoke, 2002). But the convention heat transfer in water is much faster than that in most foods.

The material used for dummy loads should have the following features: low cost, thermal stability for reuse, homogeneous ingredients, easy to prepare, and having comparable dielectric and thermal properties to match different categories of foods. In traditional thermal processing, bentonite water pastes have been widely used as stable dummy loads to evaluate performance of retort systems (Hayakawa, 1974; Unklesbay et al., 1981, 1980; Peterson and Adams, 1983). Compared with other models, bentonite water pastes are inexpensive, easy to prepare and reusable.

Tong and Lentz (1993) measured the dielectric properties of 8% and 10% (bentonite powder concentration, wb) bentonite water pastes at 2450 MHz over a temperature range of −25 to 90 °C. It was reported that bentonite pastes could be good model foods because they had similar dielectric properties to most food materials. However, there was a lack of data at temperatures above 90 °C and at another allocated frequency of 915 MHz for industrial applications.

The objective of this study was to measure the dielectric properties of bentonite pastes with different ingredients and to study the feasibility of using bentonite pastes as stable dummy loads for potential industrial microwave power delivery and system stability tests.

In this study, dielectric properties of bentonite pastes were measured over 300–3000 MHz and 22–120 °C. Additives were used to adjust the dielectric properties of bentonite pastes to broaden the application range for different categories of foods. Salt (NaCl) is a good additive for adjusting loss factors of model foods (Sakai et al., 2005; Wang et al., 2009); it was used to raise the loss factor of bentonite paste. Vegetable oil which has a very low dielectric constant (Ryynanen, 1995) was used to reduce dielectric constant of bentonite pastes. Although the molecules of vegetable oil are hydrophobic, the large basal surface structure of bentonite can act as an emulsion stabilizer for oil and water (Clem and Doehler, 1961). Furthermore, sucrose has been used to reduce the dielectric constant of model foods (Sakai et al., 2005; Padua, 1993a,b; Zhang et al., 2013). High concentrations of sucrose significantly reduced the moisture of model food which may change the response of dielectric constant to increasing temperature. In this study, high concentration of sucrose (30%, wb) was used to reduce dielectric constant of the paste samples. A comparison measurement was carried out to compare the effect of sucrose and oil on dielectric properties of bentonite paste. Regression equations were developed to describe the dielectric properties of bentonite pastes affected by ingredients and temperature at 915 MHz and 2450 MHz.

2. Material and methods

2.1. Bentonite powder

Bentonite powder consists of two main basic elements, alumina octahedral and silica tetrahedral. Both silica tetrahedral and alumina octahedral exist with a sheet formation (Fig. 1). A bentonite unit has two silica tetrahedral sheets, and between them is one alumina octahedral sheet. Bentonite is negative in charge balanced by cations such as sodium and calcium. Bentonite flakes are superposed loosely in such a way as to make bentonite similar to books of sheets or bundles of needles (Clem and Doehler, 1961). The length and width of these flakes are 10–100 times the thickness. With this structure water molecules can easily enter and separate bentonite flakes and give rise to a great basal surface increase as well as total volume expansion. Water molecules are adsorbed or bounded on the flat basal surface and aligned regularly. These molecules have properties more like bounded water other than free water. When the amount of water is relatively large and bentonite has adsorbed its maximum of water molecules, the additional water takes effects as lubricant.

The two major compositions of bentonite, silica and alumina, are both diamagnetic material. Similar to water and fatty substance, this type of material has no magnetic energy absorbed (Kirschvink et al., 1992) when applied to an electromagnetic field.

2.2. Preparation of bentonite water pastes

Bentonite powder (MP Biomedicals LLC, Solon, OH, USA) was mixed with distilled water to obtain uniform pastes. Pastes with bentonite concentrations of 7.5%, 15%, 20% and 25% (wb) were prepared. Beyond this concentration range, the pastes were either too dilute as liquid solution or too dry to mix uniformly.

A paste with 20% bentonite concentration was used to study the effect of additives. The concentration of water was reduced with the addition of additives to keep the bentonite concentration constant. Four concentration levels of salt (NaCl) were prepared: 0.3%, 0.6%, 0.9%, and 1.2% (wb). The salt was dissolved in distilled water first and then mixed with bentonite powder uniformly.

Bentonite pastes with three concentration levels of vegetable oil were prepared: 5%, 10% and 15% (wb). Vegetable oil was first mixed with bentonite powder before adding distilled water. Preliminary tests were performed to study the maximum absorption of vegetable oil for bentonite powder. Results showed that the ratio between oil and bentonite powder (wb/wb) should be less than 0.75. Otherwise the vegetable oil could not be totally absorbed by bentonite powder resulting in a non-uniform mixture.

To study the interaction effect between additives (i.e. salt and vegetable oil), 20% bentonite paste with 15% vegetable oil and 1.2% salt was prepared. Furthermore, 20% bentonite paste with 30% sucrose and 1.2% salt was also prepared to compare the effect of oil and sucrose on dielectric properties. Fig. 2 shows the appearance of 20% bentonite pastes with different additives.

2.3. Measurement of dielectric properties

The dielectric properties of prepared bentonite pastes were measured using an open ended coaxial-line probe connected to a network analyzer (HP 8752C, Hewlett Packard Corp., Santa Clara, CA, USA) with a setting frequency range of 300–3000 MHZ. This frequency range covers the two industrial application microwave frequencies of 915 MHz and 2450 MHz allocated by US Federal Communications Commission (FCC). Temperature of the sample was controlled by a custom-built test cell with one oil circulating heating system. The detailed information of this heating system can be found in Wang et al. (2003). Each measurement was performed at temperatures of 22, 30, 40, 50, 60, 70, 80, 90, 100, 110 and 120 °C with three replicates.

2.4. Data analysis

Dielectric properties of bentonite pastes at 915 MHz and 2450 MHz were plotted against temperatures. Regression equations based on the quadratic polynomial were developed to reveal the response of the dielectric properties to increasing temperatures and the concentration of each ingredient such as bentonite, salt and vegetable oil. The regression equations were fitted using Matlab (Mathworks, MA, USA). The parameters in the fitted equations (i.e. temperature, concentrations of bentonite, salt and vegetable oil) were normalized before regression to adjust their values within 0 and 1. After normalization, the coefficient of each parameter in the fitted equation represented the impact factor on

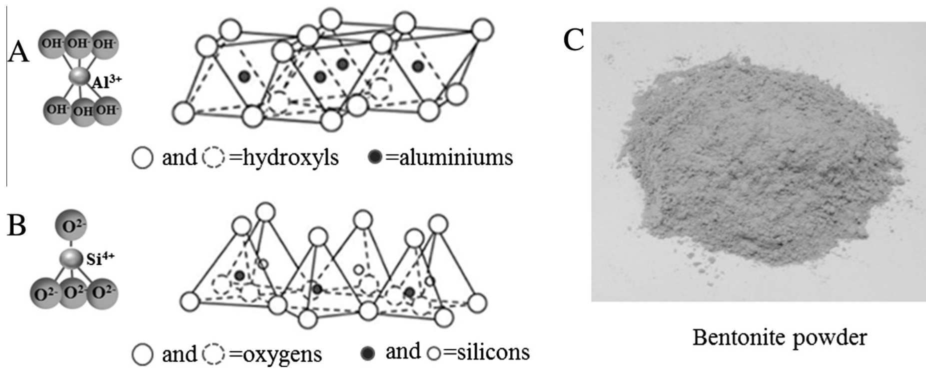

Fig. 1. Structure and appearance of Bentonite powder. (A) Alumina octahedral unit and section of sheet structure, (B) silica tetrahedral unit and section of sheet structure and (C) bentonite powder (Edited from Clem and Doehler, 1961).

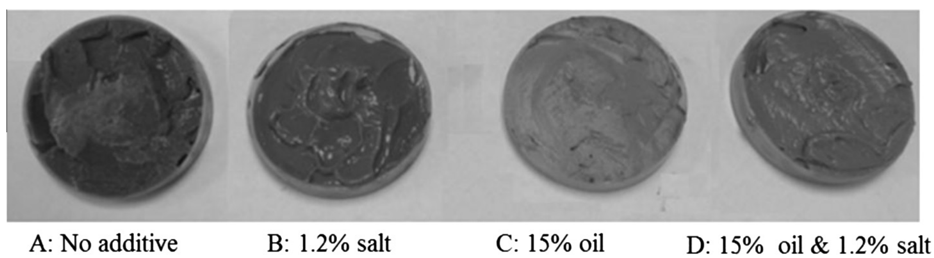

Fig. 2. 20% bentonite paste with different additives. A: no additive, B: 1.2% salt, C: 15% oil, D: 15% oil and 1.2% salt.

the dielectric properties. The formula for normalizing a parameter X is:

$$X_N = \frac{X - \min(X)}{\max(X) - \min(X)} \quad (1)$$

X_N is the normalized value of the parameter X, $\max(X)$ and $\min(X)$ are the maximum and minimum values of the parameter. As long as the upper and lower limits of a parameter were fixed, the original value and normalized value can be switched through Eq. (1).

3. Results and discussion

3.1. Effect of frequency

The dielectric properties of 20% bentonite pastes changing with frequency at three temperatures are shown in Fig. 3. Both the dielectric constant and loss factor decreased with frequency. This agrees with the previous observations of food or model food materials such as mashed potatoes (Guan et al., 2004), Salmon fillet (Wang et al., 2008) and whey protein gel (Wang et al., 2009). It is interesting that the dielectric constant increased with increasing temperature below 480 MHz. Above this frequency, dielectric constant decreased with increasing temperature. A similar phenomenon was observed for mashed potatoes (Guan et al., 2004) and whey protein gel (Nelson and Bartley, 2002).

3.2. Effect of bentonite concentration

The dielectric properties of bentonite pastes changing with bentonite powder concentration and temperature at frequencies of 915 and 2450 MHz are shown in Fig. 4. The dielectric constant of bentonite pastes decreased with increasing bentonite concentration. This decrease was due to the reduction in water content of the paste. Similar to food materials, higher moisture content results

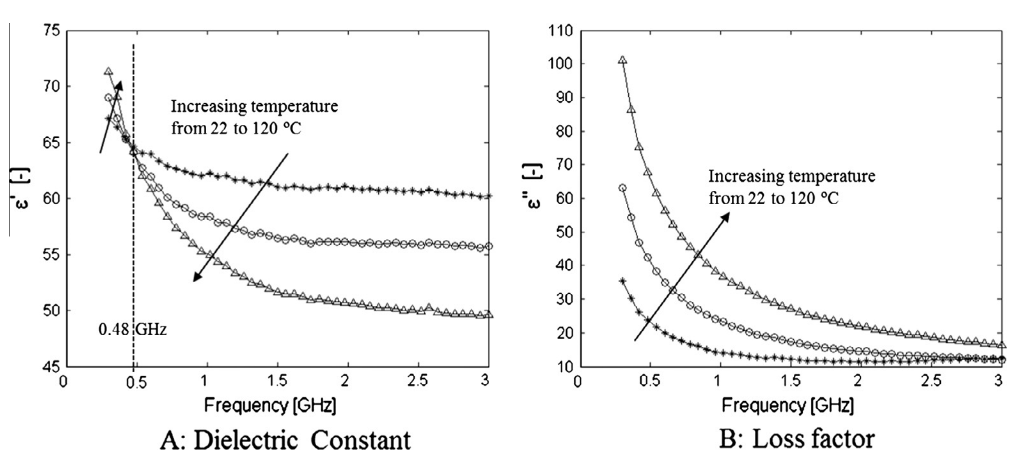

Fig. 3. Dielectric properties of 20% bentonite paste changing with frequency at three temperature levels (—✳— 22 °C, —○— 70 °C, —△— 120 °C). A: dielectric constant, B: loss factor.

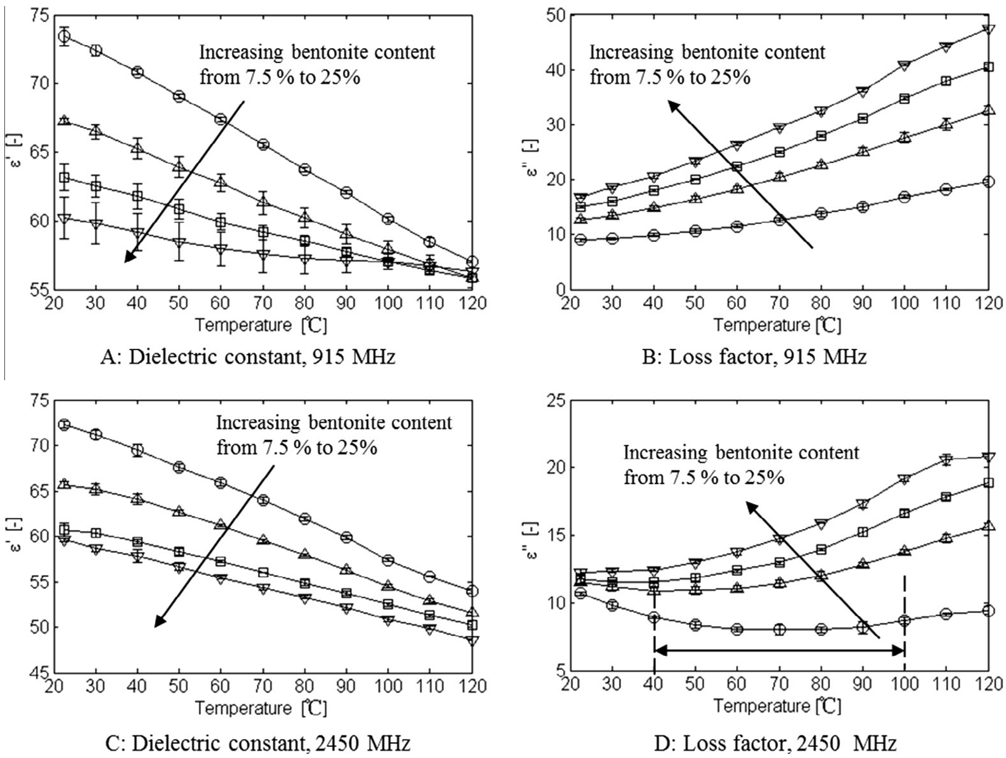

Fig. 4. Dielectric properties of bentonite paste changing with bentonite concentration (○ 7.5%, △ 15%, □ 20%, ▽ 25%) and temperature A: dielectric constant at 915 MHz B: loss factor at 915 MHz, C: dielectric constant at 2450 MHz, D: loss factor at 2450 MHz.

in higher dielectric constant. However, the dielectric loss factor increased with increasing bentonite concentration. It was reasonable that higher concentration of bentonite brought higher ion (cation) concentration and increased the loss factor.

At 2450 MHz, although there was a general trend that loss factor increased with increasing temperature, there was a broad valley around the temperature 40–100 °C (Fig. 4D). This was more obvious for pastes with lower bentonite concentrations (7.5%). Similar curves were reported for 8% and 10% bentonite pastes by Tong (1993). This type of valley curve may be caused by the two different loss mechanisms of loss factor: dipole loss (ε''_d) from dipole rotation and ionic loss (ε''_σ) from ionic conductivity. It can be mathematically expressed as (Ryynanen, 1995):

$$\varepsilon'' = \varepsilon''_d + \varepsilon''_\sigma \quad (2)$$

with

$$\varepsilon''_\sigma = \frac{\sigma}{2\pi f \varepsilon_0} \quad (3)$$

whereσ is the electric conductivity of the material; ε_0 is the permittivity of free space (8.854×10^{12} F/m) and f is the frequency of the electromagnetic waves.

The two mechanisms have different responses to temperature changes (Roebuck and Goldblith, 1972). The dipole loss contributed by dipole rotation of free water decreases with the increase of temperature while ionic loss caused by ionic conductivity increases with increasing temperatures. If one of the two loss mechanisms dominated the contribution, the overall loss factor will have similar trend to the dominant loss in response to increasing temperature. However, if the two mechanisms had parallel contributions to the loss factor, the trend may show a valley curve as observed in Fig. 4D. Such type of curve could also be found for many food materials containing salt (To et al., 1974).

The dielectric properties of bentonite pastes with different contents of bentonite powder have similar curves to that of food varying with temperatures (To et al., 1974; Ryynanen, 1995; Sakai et al., 2005). However, the trend of dielectric properties changing with bentonite concentration is fixed. A higher bentonite concentration resulted in a lower dielectric constant and a higher loss factor. Pastes with higher dielectric constants and higher loss factors or low dielectric constants and low loss factors could not be obtained by adjusting the bentonite concentrations. Additives are required to obtain a paste with such dielectric properties.

3.3. Effect of salt

Fig. 5 summarizes the effects of salt on the dielectric properties of 20% bentonite paste changing with temperature. At 915 MHz and 2450 MHz, the dielectric properties had similar responses to increasing salt concentration. The dielectric constant increased slightly with the increasing salt content. A possible explanation was that salt increased the concentration of cations (Na^+) in the paste and reduced the binding effect of bentonite to water molecules (Grim, 1978). The reduction in bound water and increase in free water resulted in a slightly increase in the dielectric constant. The addition of salt sharply increased the dielectric loss factor at both 915 and 2450 MHz.

In Fig. 5D, the dielectric loss factor steadily increased with increasing temperatures. This result revealed that at a higher salt content level, ionic loss was the dominant loss mechanism. The increase in ionic loss response to increasing temperature balanced the decrease in dipole loss at the low temperature range. This could also be verified by the relationship between ε''_σ and the frequency. By taking a logarithm of both side of Eq. (3), one obtains:

$$\log \varepsilon''_\sigma = -\log f + \log \frac{\sigma}{2\pi\varepsilon_0} \quad (4)$$

Bases on Eq. (4), there should be a linear relationship between dielectric loss factor due to electric conductivity (ε''_σ) and frequency

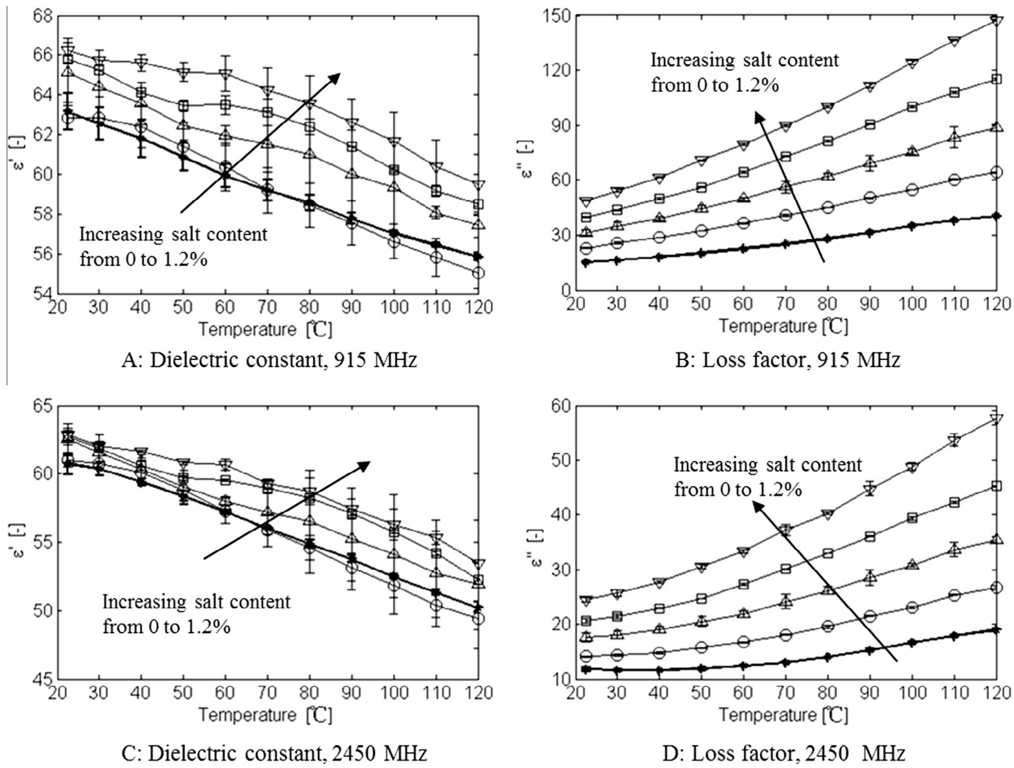

Fig. 5. Dielectric properties of 20% bentonite paste changing with salt contents (0, 0.3%, 0.6%, 0.9%, 1.2%) and temperatures. A: dielectric constant at 915 MHz, B: loss factor at 915 MHz, C: dielectric constant at 2450 MHz, D: loss factor at 2450 MHz.

in a log–log graph, if ionic loss (ε''_σ) dominates the overall loss factor. The log–log plots of total loss factor and frequency for bentonite pastes with different salt contents are shown in Fig. 6. At 22 °C (Fig. 6A), dielectric loss factor decreased linearly with increasing frequency only to 1 GHz with 0% added salt, and to 2 GHz for samples with 1.2% salt. It is evident that at lower frequency, ε''_σ was the dominant contributor of the overall loss factor. However, at higher frequency, increasing ε''_d weakened the linearity. The deviation from the linearity was severer for low salt samples.

At 120 °C (Fig. 6B), dielectric loss factor decreased linearly with increasing frequency over the whole measured frequency range of 0.3–3 GHz. Thus ε''_σ was the major contributor to the overall loss factor at this temperature. Overall values of loss factor for bentonite pastes steadily increased with salt contents increasing from 0, 0.3% to 1.2% and temperature from 22 to 120 °C. This because the electric conductive in Eq. (3) (σ) increases with increasing salt content and temperature (Guan et al., 2004; Peng et al., 2013).

3.4. Effect of vegetable oil

Fig. 7 summaries the effects of vegetable oil on dielectric properties of 20% bentonite paste changing with temperature. At 915 and 2450 MHz, the dielectric constant was significantly reduced by increasing vegetable oil. This reduction was due to the reduced water content in the tested samples and the binding effect of bentonite to water molecules. The loss factor decreased slightly with an increasing concentration of oil. A possible explanation is that low water content and addition of oil reduced the migration rate of ions. Bentonite pastes with addition of oil had stable dielectric

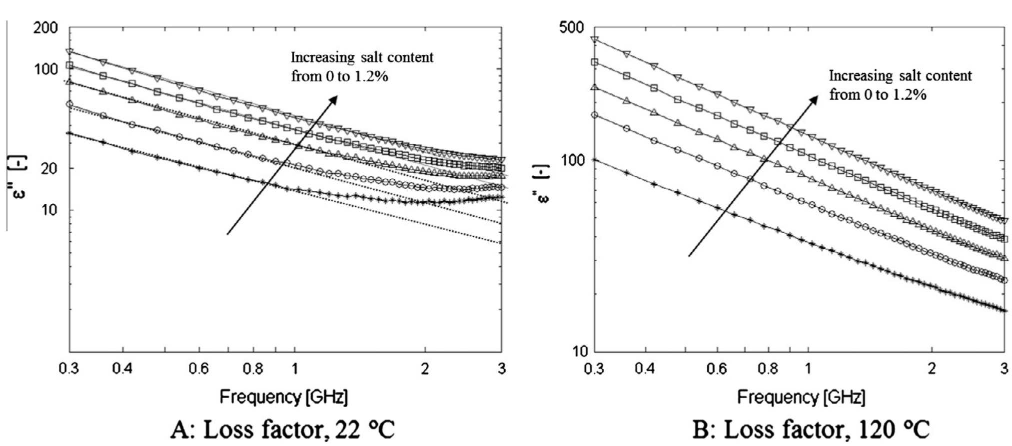

Fig. 6. Loss factors of 20% bentonite paste with different salt contents (0, 0.3%, 0.6%, 0.9%, 1.2%) changing with frequency in a log–log plot at two temperatures. A: 22 °C, the dash lines represent the ideal curve without the contribution of ε''_d, B: 120 °C.

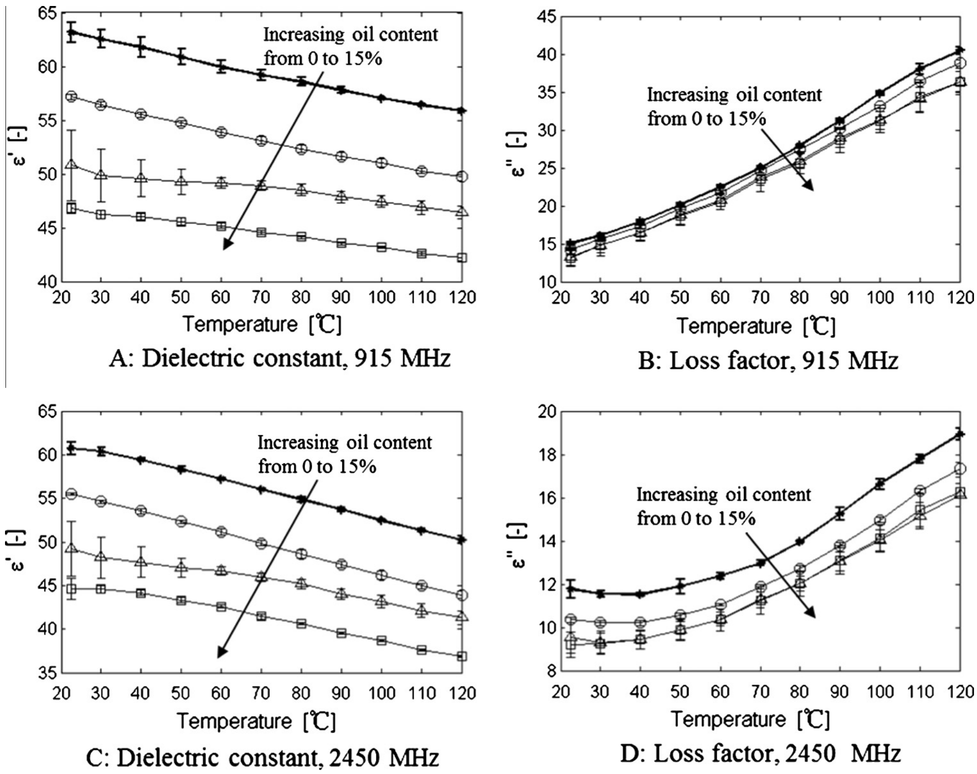

Fig. 7. Dielectric properties of 20% bentonite pastes changing with temperatures and oil contents (—✱— 0, —⊖— 5%, —△— 10%, —⊟— 15%). A: dielectric constant at 915 MHz, B: loss factor at 915 MHz, C: dielectric constant at 2450 MHz, D: loss factor at 2450 MHz.

properties (less than 5% variation) after six repeated heating tests in the MATS system within six months, roughly once per month.

3.5. Interaction effect between salt and vegetable oil

The addition of salt primarily affected the loss factor; the addition of oil mainly affected the dielectric constant. As a result, the desired dielectric properties could be obtained by adjusting the concentration of the two additives. However, there may be some interaction effect between them. The dielectric properties of 20% bentonite paste with high concentrations of both oil (15%) and salt (1.2%) were compared with the samples without additives and with only one additive (1.2% salt or 15% vegetable oil). The dielectric properties results at 915 MHz and 2450 MHz changing with temperature are shown in Fig. 8. Compared with samples without additive, the bentonite paste with 1.2% salt and 15% oil showed an obvious decrease in the dielectric constant and a great increase in the loss factor. However, compared with samples containing only one additive (15% oil or 1.2% salt), the addition of salt increased the dielectric constant slightly and the addition of vegetable oil reduced the loss factor slightly. With vegetable oil present, relatively higher salt concentration is required to obtain the same increase level in loss factor. Moreover, more vegetable oil content has to be applied to offset the influence of salt on the dielectric constant.

The dielectric properties of 20% bentonite paste with 30% sucrose and 1.2% salt are also shown in Fig. 8. At 915 MHz, the bentonite paste with 15% vegetable oil and 1.2% salt had a lower dielectric constant (Fig. 8A) and a much higher loss factor than the bentonite paste with 30% sucrose and 1.2% salt (Fig. 8B). Similar results were observed at 2450 MHz (Fig. 8C and D). This result proved that vegetable oil was more effective in reducing the dielectric constant of bentonite paste with less influence on dielectric loss factor. In addition, the dielectric constant of the paste with 30% sucrose increased slightly at lower temperature range and then decreased with increasing temperatures at 2450 MHz. That may be caused by the binding effect of high concentration of sucrose to water molecules. This type of trend was also reported for 1% agar gel with 30% sucrose (Sakai et al., 2005).

3.6. Regression equations

To relate the dielectric properties of bentonite pastes with temperature, regression equations of dielectric properties as functions of ingredients and temperatures were developed (Table 1). The value of each parameter (i.e. temperature, concentrations of bentonite powder, salt and vegetable oil) was normalized within 0 and 1 using Eq. (1) before regression equations were fitted. The influence of each parameter on dielectric properties was reflected by its coefficient in the regression equations. The coefficient of each parameter had a significance of $P < 0.01$. The non-significant parameter was not included in the equations. The adjusted coefficient of determination (r^2_{adj}) of each regression equation was greater than 0.95, which verified that the quadratic polynomial was good enough to fit to the profiles of dielectric properties.

Based on regression equations, one can find more details of dielectric properties as affected by ingredients and temperatures. When taking the derivation of a regression equation with respect to temperature, the changing rate of the response value (dielectric constant or loss factor) against temperature was revealed. For example, in Table 1 the regression equation of dielectric constant as a function of bentonite concentration and temperature at 915 MHz is:

$$\varepsilon' = 73.96 - 18.25T - 17.15B + 13.16B \times T + 1.312T^2 + 3.178B^2 \tag{5}$$

Taking the derivative with respect to temperature gives:

$$\frac{d\varepsilon'}{dT} = -18.25 + 13.16B + 2.624T \tag{6}$$

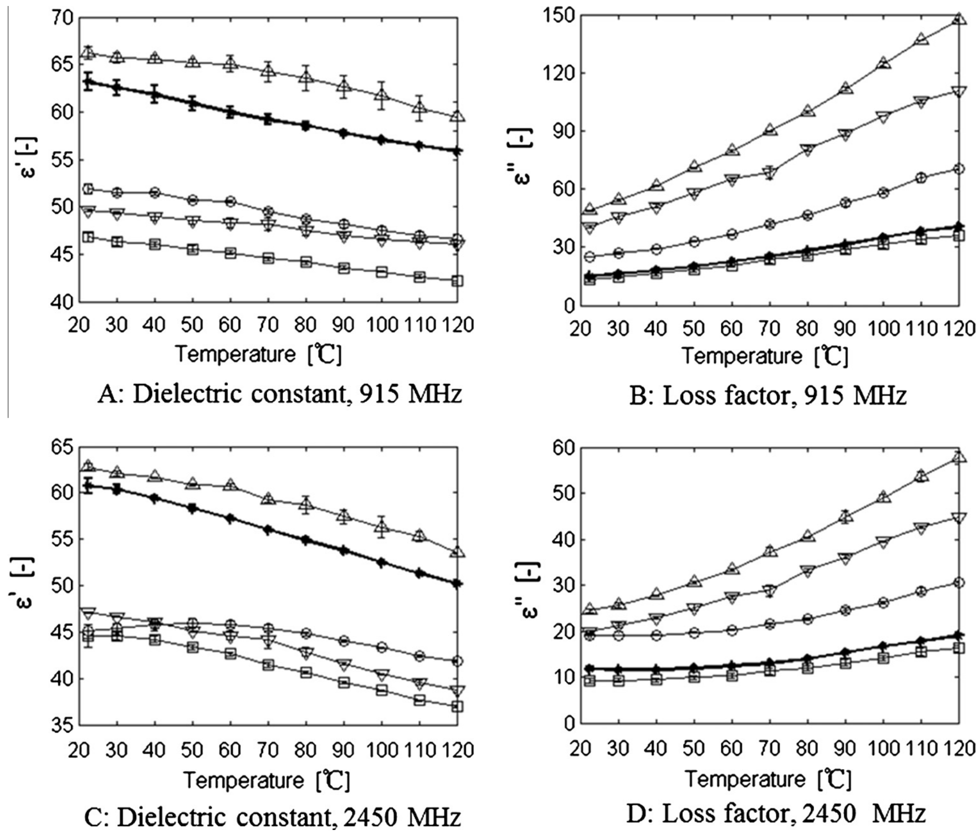

Fig. 8. Dielectric properties of 20% bentonite pastes with different additives (—✱— no additive, —△— 1.2% salt —□— 15% vegetable oil, —▽— 1.2% salt and 15% oil, —○— 1.2% salt and 30% sucrose) changing with temperature. A: dielectric constant at 915 MHz, B: loss factor at 915 MHz, C: dielectric constant at 2450 MHz, D: loss factor at 2450 MHz.

Table 1
Regression equations for dielectric properties of bentonite pastes varying with temperature and different ingredients[a].

Parameters: temperature (T) and bentonite concentration (B)		
915 MHz	$\varepsilon' = 73.96 - 18.25T - 17.15B + 13.16T*B + 1.312T^2 + 3.178B^2$	$r^2_{adj} = 0.9984$
	$\varepsilon'' = 9.020 + 2.982T + 9.743B + 20.66T*B + 8.222T^2 - 2.487B^2$	$r^2_{adj} = 0.9987$
2450 MHz	$\varepsilon' = 72.92 - 18.75T - 17.01B + 9.060T*B + 2.958B^2$	$r^2_{adj} = 0.9926$
	$\varepsilon'' = 10.53 - 9.161T + 3.292B + 10.93T*B + 8.470T^2 - 1.911B^2$	$r^2_{adj} = 0.9893$
Parameters: temperature (T) and salt concentration (S)		
915 MHz	$\varepsilon' = 62.44 - 7.218T + 4.657S$	$r^2_{adj} = 0.9530$
	$\varepsilon'' = 16.63 + 9.082T + 24.51S + 73.17T*S + 15.48T^2 + 6.294S^2$	$r^2_{adj} = 0.9986$
2450 MHz	$\varepsilon' = 61.18 - 9.205T + 3.068T*S - 2.732T^2 + 1.924S^2$	$r^2_{adj} = 0.9795$
	$\varepsilon'' = 12.23 - 3.618T + 6.215S + 26.00T*S + 10.51T^2 + 5.512S^2$	$r^2_{adj} = 0.9981$
Parameters: temperature (T) and vegetable oil concentration (V)		
915 MHz	$\varepsilon' = 63.07 - 7.643T - 21.13V + 3.618T*V + 4.624V^2$	$r^2_{adj} = 0.9965$
	$\varepsilon'' = 13.75 + 20.55T - 4.472T*V + 6.421T^2$	$r^2_{adj} = 0.9959$
2450 MHz	$\varepsilon' = 61.39 - 11.42T - 20.27V + 3.560T*V + 4.099V^2$	$r^2_{adj} = 0.9942$
	$\varepsilon'' = 11.53 - 5.395V + 7.413T^2 + 3.151V^2$	$r^2_{adj} = 0.9933$

[a] All the parameters are normalized values within 0 and 1. The equivalent original ranges are: *T*, 20–120 °C; *B*, 7.5%–25%; *S*, 0–1.2%; *V*, 0–15%.

Eq. (6) demonstrates that the changing rate (slope) of the dielectric constant in response to temperature was affected by bentonite concentration with a coefficient of 13.16 and temperature with a coefficient of 2.624. This coefficient implies the influence of the parameter (i.e. bentonite concentration or temperature) on the slope. However, due to the existence of constant term in Eq. (6) the coefficient could not directly reflect the influence of each parameter on the slope. A influence factor was used to describe the proportion of each component in Eq. (6). The influence factor of the parameter (bentonite) was defined as following:

$$\text{Influence factor} = \frac{13.16}{-18.25 + 2.624T} \tag{7}$$

The influence factor of a variable indicated its maximum ability to adjust the changing rate of the response value against temperature. The influence factor of different ingredients for dielectric constant and loss factor are summarized in Table 2. These results were helpful in selecting parameters to adjust the dielectric properties range of bentonite pastes and their responses to temperature. It was observed that the slope value of dielectric constant varying with

Table 2
Influence factor of ingredients on the slope of dielectric properties against temperature.

	915 MHz (ε')		915 MHz (ε'')		2450 MHz (ε')		2450 MHz (ε'')	
	$T = 0$	$T = 1$	$T = 0$	$T = 1$	$T = 0$	$T = 1$	$T = 0$	$T = 1$
Bentonite (7.5–25%)	−0.721	−0.842	6.928	1.064	−0.483	−0.483	−1.193	1.404
Salt (0–1.2%)	0	0	8.057	1.827	−0.333	−0.209	−7.186	1.494
Vegetable oil (0–15%)	−0.473	−0.473	−0.218	−0.134	−0.312	−0.312	0	0

temperature was more sensitive to bentonite concentration than to vegetable oil. However, the slope of loss factor was affected more by salt than by bentonite. The salt had a significant influence on the slope of loss factor and a very limited influence on the slope of dielectric constant. On the contrary, vegetable oil had a big influence on the slope of dielectric constant and a small influence on the loss factor.

To simulate a food material with given dielectric properties, the changing rate of dielectric constant against temperature should be calculated first to determine a suitable bentonite concentration. Then vegetable oil could be used to adjust the value of dielectric constant. Once the dielectric constant over the required temperature range was matched, loss factor could be modified by adjusting salt concentration.

4. Conclusion

The Dielectric properties of bentonite pastes decreased with frequency within the range 300–3000 MHz which was similar to those of food materials. At 915 MHz, dielectric constant decreased and loss factor increased, respectively, with increasing temperature and bentonite concentration. At 2450 MHz, similar trend was observed. However, at low bentonite concentration, loss factor decreased first with increasing temperature and then increased. The decrease of overall loss factor at low temperature range (<50 °C) was due to the decrease of dipole loss. However, the ionic loss increased with increasing temperature. At high temperature range (>50 °C), the ionic loss became the major contributor to the overall loss factor and an increasing trend was observed.

The addition of salt could greatly increase the dielectric loss factor of bentonite pastes by increasing the ionic loss. The dielectric constant was not affected much by the addition of salt. The dielectric constant of bentonite pastes was greatly reduced by the addition of vegetable oil. However, vegetable oil had slightly influence on loss factor. Compared with sucrose, vegetable oil could reduce the dielectric constant to the same level with only half of the sucrose concentration and had less effect on the loss factor. Salt and vegetable oil were good additives to adjust the loss factor and dielectric constant, respectively. However, due to the interaction effects between the salt and vegetable oil, the effects of salt on the loss factor and oil on the dielectric constant were weakened a little.

Good fitted regression equations were developed to reveal the influence of ingredients and temperature on dielectric properties of bentonite pastes. Derived from these equations, bentonite had higher impact factor than vegetable oil on the changing rate of dielectric constant against to temperature. However, for loss factor changing with temperature, salt had a higher impact factor than bentonite. By selecting suitable additives, bentonite pastes could be developed to match dielectric properties of various foods and be used as dummy load for evaluating performance of industrial microwave assisted thermal processing systems.

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