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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