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Dielectric properties and model food application of tylose water pastes during microwave thawing and heating

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ABSTRACT

The dielectric properties of tylose water pastes during microwave thawing and heating were measured over 300–3000 MHz and −30 to +60 °C, and the feasibility of their use as a frozen model food instead of frozen lean tuna was evaluated. The effects of salt (NaCl) content (0.5–2.0%, wb) on the dielectric properties were investigated. Although salt is a good additive for increasing the dielectric loss factor, higher salt addition increased the thawing time and non-uniformity through decreased penetration depth. A similar response to increasing temperature between frozen lean tuna and tylose paste was observed during MW thawing and heating at 2450 MHz, due to similarities in penetration depth. This was possible by an appropriate adjustment of the dielectric properties of tylose by salt addition (0.5% NaCl). This study confirmed the potential of frozen tylose paste as a model food in evaluating performance of microwave thawing of real foods.

1. Introduction

Microwave ovens have come into wide use because of their ability to re-heat food quickly and conveniently, but the fact that they can cause non-uniform temperatures in food is a major problem (Li and Sun, 2002). This drawback is widely amplified in food thawing, mainly due to the large gap between the dielectric properties (DPs) of the solid and liquid phases of water (the major component of foods). Thus, the wide variation in the DPs of foods between the frozen and defrosted zones, inducing thermal runaway, constitutes a major challenge in thawing assisted by microwave (MW) systems (Akkari et al., 2005). According to Curet et al. (2014), the lack of information on this phenomenon is probably preventing further commercial development of this technology, despite considerable interest, and is also one of the reasons why less information has been published on thawing applications in the food industry, compared to other applications.

A popular approach to dealing with thermal runaway is the evaluation of the interactions between electromagnetic waves and frozen materials. Accurate DPs in frozen and partially frozen materials are critical for determining the rates and uniformity of heating in operations involving frozen foods, such as microwave thawing and tempering (Datta et al., 2014). DPs are electrical properties that govern the interactions between MW radiation and food. The DPs can be described by the dielectric constant (ε'), the ability of the product to store electromagnetic energy, and the dielectric loss factor (ε''), its ability to dissipate electromagnetic energy. While several works have been reported in the literature for temperatures above 0 °C, limited data are available on MW bands in the thawing temperature range.

Although the DPs of food materials have been reported to vary with ingredients, pre-heating conditions, and thermal treatments (Ryynänen, 1995; Sakai et al., 2005), it is difficult to use food materials for periodical test runs to verify the system stability in microwave processing development. Moreover, each batch of food samples can only be used once. This leads to a large amount of waste, especially for an industrial system with a high production capacity. To manage these problems, model foods – with consistent and predictable DPs – can be used as dummy loads. According to Luan et al. (2015), the material used for dummy loads should have the following features: low cost, thermal stability for reuse, homogeneous ingredients, easy to prepare, and comparable dielectric and thermal properties to different categories of foods.

In previous studies, bentonite water pastes (Liu and Sakai, 1999; Llave and Sakai, in press; Luan et al., 2015), agar gel (Padua, 1993a,b; Sakai et al., 2005), tylose or methyl cellulose (Zhang and Datta,

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2005), whey protein gel (Lau et al., 2003; Wang et al., 2009), and synthetic paste (Cheng et al., 1997; Sakai et al., 1996) have been used to create model foods used in microwave heating research. However, few works have reported the DPs of model foods at the thawing range temperature, in which a phase change occurs (Llave and Sakai, in press).

Some studies claimed that in the frozen zone, the DPs of tylose are similar to those of beef muscle (Basak and Ayappa, 1997; Taher and Farid, 2001). Thus, they are used as a substitute for frozen beef in MW related experiments. However, although tylose is the most widely used model food in MW thawing studies (Chamchong and Datta, 1999; Curet et al., 2008, 2014; Taoukis et al., 1987; Zeng and Faghri, 1994), there is a lack of data at temperatures below 0 °C, especially in the phase change region over a wide frequency range for industrial applications. For example, though Chamchong and Datta (1999) reported the DPs of tylose measured above freezing, for the partially frozen region they proposed two empirical equations for the prediction of ε' and ε'', assuming a linear relationship with the fraction of unfrozen water and matching experimental data at the two extremes only: (a) just starting to freeze (initial freezing point) and (b) completely frozen (around −25 °C). Curet et al. (2008) also reported the DPs of tylose, and developed empirical exponential equations based on temperature for the estimation of ε''. However, for ε'' they assumed a constant value. Therefore, the variation of DPs with temperature needs to be accurately characterized, especially during phase transition phenomena.

Additives have been used to adjust the DPs of model foods to broaden their application range for different categories of foods. The most used additive for adjusting the ε'' of model foods is salt (NaCl). According to Datta et al. (2014), salt affects dielectric behavior through freezing point depression, leaving more water unfrozen at any temperature. Salt also increases the ionic content, and therefore the interactions with microwaves. Salt addition has been reported for bentonite pastes (Luan et al., 2015), tylose gels (Chamchong and Datta, 1999; Zhang and Datta, 2005), agar gel (Sakai et al., 2005), and whey protein gel (Wang et al., 2009). Sucrose has been used to reduce the ε' of agar gel (Padua, 1993a,b; Sakai et al., 2005), bentonite pastes (Luan et al., 2015), and egg whites (Zhang et al., 2013). Additionally, vegetable oil was used to reduce ε'' in bentonite pastes (Luan et al., 2015).

Although the DPs of frozen tylose pastes have been reported in the literature as mentioned above, there are very few data points in the partially frozen range, where the properties can be strongly influenced by composition, particularly the total water and salt content. Therefore, the objective of this study was to measure the DPs of tylose pastes with different salt contents from frozen temperatures (−30 °C) to a target temperature commonly used as the final point in reheating procedures (≤60 °C), in the range 300–3000 MHz. The dielectric behavior of tylose pastes with added salt during MW thawing and heating was used to explain the response to increasing temperature, at several positions. In addition, the feasibility of using tylose pastes as frozen food model with stable dummy loads for potential industrial MW tests in microwaveable food development was studied, comparing the performance of tylose with a real frozen food, lean tuna (*Thunnus maccoyii*), during MW thawing and heating at 2450 MHz.

2. Materials and methods

2.1. Preparation of tylose water pastes

Tylose paste was used in the experiments; a mixture of water (77% wb) and methyl cellulose (MC, MCE-1500, Shin-Etsu Chemical Co., Japan). Tylose is widely used as an experimental material in food-related research, partly because it has properties similar to meat, and also due to its ability to form into various shapes. Another advantage of using tylose is the easy manipulation of its DPs by adding different amounts of salt (Zhang and Datta, 2005).

Tylose water pastes were prepared by mixing tylose powder and distilled water in a beaker placed over a hot plate, and stirred at a constant temperature of 90 °C. Pastes with 23% (wb) tylose concentration were used in this study. The concentration of water was reduced with the addition of additives to keep the tylose concentration constant. This differs from the method followed by Chamchong and Datta (1999), in which the water concentration was kept stable, and the tylose and salt concentrations were changed. However, a similar approach as reported here was employed by Luan et al. (2015) for the bentonite pastes. Therefore, four salt solutions (NaCl) which were added to tylose paste were prepared: 0%, 0.5%, 1%, and 2% (wb). The salt was firstly dissolved in distilled water by stirring, and then uniformly mixed with tylose powder. After mixing, each tylose paste containing a predetermined concentration of salt was inlaid in a flattened cylindrical acrylic vessel (64 mm in diameter and 31 mm thick) for the MW heating experiments. For the measurement of DPs, cylindrical samples [32 mm in diameter and 34 mm thick] were obtained.

2.2. Fish sample preparation for validation

Flesh block sections (skinned and boned) of the cephalic dorsal parts of lean tuna (*T. maccoyii*) were purchased at Tsukiji fish market (Tokyo, Japan). Bodies still in the state of *rigor mortis* were deep frozen (KQF-5AL, Air Operation Technologies, Inc., Japan) and stored at −40 °C. The sample size was adjusted using a meat bandsaw cutting machine (LUXO S-II, LUXO Co., Ltd., Nagoya, Japan). Samples of the same size, as reported for tylose paste, were prepared for tuna muscle for the measurement of DPs and MW heating experiments. The moisture and crude fat contents of the samples (in wb) were 74.2 ± 1.3% and 1.2 ± 0.3%, respectively. For details of these measurements, please refer to Llave et al. (2014).

2.3. Temperature measurements

2.3.1. Measurement of internal temperature

For temperature control during MW processing, three fiber-optic temperature sensors ($\phi = 1.6$ mm) attached to a temperature measuring system (FTC-DIN-ST-TH, Photon Control, BC, Canada) were inserted at the center and a position near the upper and lower surface (6 × 6 mm from the outside) of the samples, as shown in Fig. 1. A drill was used to make a hole on the sample prior to inserting the fiber optic probe. These positions were held by fixing the sensor cables to a stationary position at the gate of the hole used to introduce the cables into the MW oven. A single fiber-optic sensor was also inserted to record the temperature during the measurement of DPs at the center position. Since there was no significant difference ($p > 0.05$) between the measurements of DPs with and without the fiber-optic sensor, it was decided that the sensor could be inserted for accurate recording of the temperature during the experiments.

2.3.2. Temperature distribution measurement

The surface temperature distributions at the top and bottom of the sample were determined immediately after thawing and heating at several time intervals, using an infrared (IR) camera (TH7102WV, NEC San-ei Instruments, Ltd., Tokyo, Japan) with an accuracy of ±2 °C. Moreover, to evaluate the interior thawing performance, samples were immediately bisected vertically and a thermal image was recorded with an IR camera for one of the cut surfaces within 10 s to avoid an increase in the surface temperature.