Technical paper

Dielectric Properties of Frozen Surimi at 915 MHz and 2450 MHz

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Dielectric properties of two types of unsalted frozen surimi (SA grade made on shipboard and K grade made in onshore plants) at 2450 MHz and 915 MHz were measured from -30°C to 30°C by the open-ended coaxial probe method. The values of dielectric constant and loss factor varied with temperature, being very small at low temperatures, whereas above the freezing point the values increased rapidly. Penetration depths which were calculated from the dielectric constant and loss factor also varied with temperature. Moreover, there was no difference in the dielectric constant or loss factor of the two kinds of surimi below the freezing point; there was a difference in the dielectric constant above the freezing point, however, due to the difference in moisture content of the surimi.

Keywords: dielectric properties, frozen surimi, microwave thawing

Frozen surimi is the main component in kamaboko such as chikuwa and fish meat sausage. It is known that temperature and time of thawing severely affect the quality of kamaboko, and therefore the thawing of frozen surimi is an important step in kamaboko processing. Currently, modern surimi-based product plants generally thaw surimi in air-conditioned tempering rooms, or using contact-plate units (Okada, 1999). However, the conventional thawing method involves several disadvantages: long thawing time, large space requirement, growth of bacteria, surface oxidation, color change, and high fresh water consumption when thawed in a liquid (Ute & Werner, 1987). Use of a microwave may eliminate these disadvantages. Because microwaves are electromagnetic waves, the heat production is mainly due to dipole excitation and ion migration; consequently, rapid heating occurs effectively. However, one problem that has arisen is uneven or “runaway” heating (defined late), which occurs due to the temperature-dependent dielectric properties of foodstuffs. Therefore, controlling a uniform temperature is important, and accurate prediction of the temperature distribution during microwave thawing is necessary. Dielectric properties, especially the penetration depth (D_p) of materials, are important factors influencing microwave energy transfer and temperature distribution (Zeng & Faghri, 1994). Thus, the objective of this study was to determine the dielectric properties of frozen surimi at 915 MHz and 2450 MHz, which are the frequencies currently used for microwave thawing.

Materials and Methods

We chose two kinds of unsalted frozen surimi made from Alaska pollock: (1) made on shipboard (SA grade), USA, moisture content 74.0%, and (2) made in onshore plants (K grade), Japan, moisture content 78.8%.

The dielectric properties of the frozen surimi samples were measured from -30°C to 30°C at 10°C intervals, and were deter-

mined by dielectric constant measurement equipment. A schematic diagram of the equipment is shown in Fig. 1. This system consists of a dielectric probe (HP85070B, Hewlett Packard Corp., Santa Rosa, USA), a network analyzer (HP8719C, Hewlett Packard Corp.), a computer system, a probe cable and a constant temperature box. It can measure dielectric properties over a wide frequency range (200 MHz–13.5 GHz). Here, it was used at the frequencies of 2450 MHz and 915 MHz, currently used for microwave heating (Tanaka *et al.*, 1999; Mao *et al.*, 2003). Determination was repeated 3 times at each temperature, using fresh samples. The temperature of samples was measured with a thermocouple until it reached the desired temperature.

Statistical analysis Data were expressed as the mean values and were analyzed using the two-way layout of analysis of variance (ANOVA). *F* value was used to test the significance between the groups of data. Significance was accepted at $p < 0.05$.

Results and Discussion

The dielectric constant (ϵ') and loss factor (ϵ'') of the two kinds at both 915 MHz and 2450 MHz are shown in Fig. 2 and Fig. 3, respectively. In the freezing temperature range (below -10°C), the values of ϵ' and ϵ'' of the two kinds at 915 MHz (Fig. 2) and 2450 MHz (Fig. 3) were very small, and increased only slightly with increasing temperature. Liu and Sakai (1999) reported the similar tendency in tuna: when the temperature approached the thawing point (-2°C), ϵ' increased sharply from 2.75 at -30°C to 44.50 at -2°C , and ϵ'' increased rapidly from 0.06 at -30°C to 16.99 at 2450 MHz for SA grade.

The decisive factor for dielectric properties of non-salted food is water (Ryynanen, 1995). In the freezing range, the dipoles are “frozen in” and cannot rotate freely (Franks, 1972), therefore the values of ϵ' and ϵ'' become small. The dielectric properties of water (at 25°C , $\epsilon'=78$ and $\epsilon''=12.48$ at 2450 MHz) are higher than those of ice ($\epsilon'=3.2$ and $\epsilon''=0.009$ at 2450 MHz) (Schiffmann, 1986). In the thawing range, free rotation of the water molecules was induced by the phase change of the incorporated water.

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Fig. 1. Equipment for measuring dielectric constant. (1) Personal computer and HP85070B dielectric probe kit software, (2) HP8719C network analyzer, (3) dielectric probe, (4) constant temperature box, (5) sample, (6) laboratory jack.

For a wide variety of frozen food, however, unfrozen water has been observed in a frozen state: Mudgett *et al.* (1979) reported that at frequencies of 915 MHz and 2450 MHz and at temperatures of -20°C and -40°C , the values of ϵ' and ϵ'' of frozen beef, chicken breast, chicken thigh, pork and turkey roll were higher than those of food solids and ice. A similar phenomenon was found in this study, the values of ϵ' and ϵ'' (at -20°C , $\epsilon'=4.38$ and $\epsilon''=0.92$ for SA grade at 2450 MHz) of frozen surimi were significantly higher than those of ice, suggesting the presence of free water at freezing temperature.

In the freezing range temperature, ϵ' and ϵ'' showed almost no difference between the two types of surimi ($p>0.05$), while in the melting zone, since the influence of moisture content on ϵ' is significant, the higher the moisture content of surimi, the higher the value of ϵ' ; the values of ϵ' of K grade surimi were higher than those of SA grade. Similar phenomena have been reported in many food materials (Tanaka *et al.*, 1999; Liu & Sakai, 1999). Moreover, ϵ'' at both frequencies showed no significant difference ($p>0.05$) between the SA and K grade surimi.

Above the thawing point, ϵ' and ϵ'' of surimi varied with temperature and frequency: with decreasing frequency, ϵ' increased whereas ϵ'' decreased for the two types of frozen surimi. The frequency dependence of ϵ' and ϵ'' was also in agreement with that of other foods such as shrimp, beef, turkey and pork and fish (Tanaka *et al.*, 1999; Ohlsson & Bengtsson, 1975).

The great difference in dielectric properties of surimi between the frozen and thawed range can pose problems in uniform thawing. This effect is known as runaway heating, which refer to the process in which a material absorbs increasing amounts of energy as its temperature rises, leading to a very rapid increase in temperature (Ashim & Datta, 2001). For thawing of frozen surimi, the thawed part would be rapidly heated while there would be still some ice left in the rest of the surimi, since the thawed part has a higher ϵ'' and thus lower characteristic impedance than the frozen parts with a low ϵ'' .

Using data of the dielectric properties of surimi, the heating effect can be calculated, because microwave energy is determined by an attenuation factor (α) that relates to the material's dielectric properties,

$$\alpha = \frac{2\pi}{\lambda_0} \sqrt{\frac{\epsilon' [1 + ((\epsilon''/\epsilon')^2)^{1/2}] - 1}{2}}, \quad (1)$$

Fig. 2. Dielectric constant (ϵ') and loss factor (ϵ'') of unsalted frozen surimi related to temperature and type: (○) K grade, (□) S grade at 915 MHz.

Fig. 3. Dielectric constant (ϵ') and loss factor (ϵ'') of unsalted frozen surimi related to temperature and type: (○) K grade, (□) S grade at 2450 MHz.

where λ_0 is the free-space microwave wavelength, which is 32.76 cm for 915 MHz and 12.24 cm for 2450 MHz, respectively. The attenuation factor determines the absorption of energy as a function of depth from the surface, as described by Lambert's law:

$$I_x = I_0 \exp(-\alpha x), \quad (2)$$

where I_0 is the power flux at the surface, and I_x is the power flux at a depth of x cm in the direction of propagation (Kirk & Holmes, 1975).

The attenuation factor is also the reciprocal of a material's penetration depths (D_p), which were calculated with Eq. (3) (Ashim & Datta, 2001), and are shown in Fig. 4.

$$D_p = \frac{1}{\alpha}. \quad (3)$$

D_p is defined as the depth at which the microwave power is

Fig. 4. Penetration depth of frozen surimi related to temperature type: (○) K grade, (□) S grade at 915 MHz at (—) 915 MHz and (.....) 2450 MHz.

reduced to $1/e$ ($=1/2.7183 \approx 37\%$) of its surface value (Ashim & Datta, 2001).

D_p decreased with increased temperature below the thawing point, from 2.08 cm (-30°C) to 0.4 cm (-2°C) at 2450 MHz for SA grade, whereas it showed almost no change with increasing temperature above the thawing point. D_p showed a large difference relative to phase change. The microwave energy was able to permeate more deeply inside a sample in the frozen state, and surface heating became stronger after thawing. D_p also changed with frequency: D_p at 915 MHz was greater than that at 2450 MHz, showing there is a greater tendency for surface thawing to occur at 2450 MHz. The two-way layout of ANOVA revealed no significant difference ($p > 0.05$) in penetration depths between the two types of surimi, proving that the type of production plant does not influence the ability of surimi to absorb microwave energy.

From the data of Fig. 4, the changes in D_p for the two types of surimi with temperature were fitted with a polynomial model as:

2450 MHz

$$D_p = -0.0002T^3 - 0.00103T^2 - 0.189T + 0.1426 \quad (R^2 = 0.9797) \quad -30^\circ\text{C} \leq T \leq -2^\circ\text{C}$$

$$D_p = -4 \times 10^{-6}T^3 + 0.0001T^2 - 0.0003T + 0.3783 \quad (R^2 = 0.918) \quad 0^\circ\text{C} \leq T \leq 30^\circ\text{C}$$

915 MHz

$$D_p = -0.0004T^3 - 0.0213T^2 - 0.413T + 0.4948 \quad (R^2 = 0.9786) \quad -30^\circ\text{C} \leq T \leq -2^\circ\text{C}$$

$$D_p = -2 \times 10^{-6}T^3 + 0.0001T^2 + 0.0007T + 0.9714 \quad (R^2 = 0.9798) \quad -2^\circ\text{C} \leq T \leq 30^\circ\text{C}$$

The equations can be used in the models which describe the temperature distribution in surimi during microwave thawing.

Microwave thawing has been theoretically studied by a large number of investigators based on Maxwell's or Lambert's equation using the dielectric properties. Zeng and Faghri (1994) studied the experimental and numerical study of microwave thawing of an analogous food material, a two-dimensional mathematical model was developed to deal with the complicated thawing process, which includes the frozen mushy and thawed phases. Lee and Marchant (1999) reported a study on microwave thawing of a semi-infinite one-dimensional slab. They developed an approximate analytical model using the Galerkin method and the calculated results were close to the experiment data. Taher and Farid (2001) reported the experimental and theoretical investigation of microwave thawing of frozen minced beef. Therefore, data on the dielectric properties of frozen surimi materials are indispensable to simulate the process of microwave thawing for frozen surimi.

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