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Dielectric properties of salmon fillets as a function of temperature and composition

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Abstract

Dielectric properties for anterior, middle, tail, and belly portions of Alaska pink salmon (*Oncornynchus gorbuscha*) fillets were measured at frequencies between 27 and 1800 MHz from 20 to 120 °C to provide insights for improving the modeling of microwave (MW) and radio frequency (RF) commercial sterilization processes of salmon products. Compositional differences contributed to the observed slight differences in the dielectric properties for different parts of salmon fillet. For all portions of the fillet, similar trends in dielectric constant and loss factor measurements were observed as a function of temperature (20–120 °C). At RF frequencies of 27 and 40 MHz, the dielectric constant decreased with increasing temperature. But at microwave frequencies (e.g., 915, 1800 MHz), an opposite trend was observed. The dielectric loss factor increased with increasing temperature over the tested frequency range. Calculations from electrical conductivity of minced salmon fillets measured at different temperatures suggest that ionic conductivity was the major contributor to temperature dependent behaviors of dielectric properties at RF frequencies.

Keywords: Penetration depth; Electrical conductivity; Dielectric heating; Microwave; Radio frequency

1. Introduction

In radio frequency (RF) and microwave heating, temperature distribution within the food is strongly influenced by the complex relative permittivity of food. Complex relative permittivity is defined as $\varepsilon^* = \varepsilon' - j\varepsilon''$, where the real component is the dielectric constant (ε') and the imaginary component is the dielectric loss factor (ε''). The dielectric constant ε' reflects the ability of the material to store electrical energy, while the loss factor ε'' determines the ability of the food to dissipate electrical energy as heat (Mudgett, 1994). These two parameters, collectively referred to dielectric properties, are important for determining power absorption, penetration depth and temperature profile within a food as it heats in RF or microwave systems.

The dielectric properties for a wide range of foods have been documented; however, there are little data for aquatic products at commercial sterilization temperatures. Because the dielectric properties of foods are temperature dependent (Nelson, 1992; Wang et al., 2003a,b; Guan et al., 2004; Al-Holy et al., 2005), studies must be conducted over the wide range of temperatures experienced by the product during thermal processing if dielectric heating behavior is to be accurately predicted. In one study, Tran and Stuchly (1987) reported the dielectric properties of uncooked beef, beef liver, chicken and salmon at frequencies from 100 to 2500 MHz for temperatures between 1.2 and 65 °C. Sun et al. (1995) developed equations for a series of foods including meat as a function of temperature, moisture and ash content up to 70 °C. Wang et al. (2003b) conducted research on the dielectric properties of cooked macaroni noodles, cheese sauce, macaroni and cheese, and whey protein gel over a temperature range from 20 to 121.1 °C. Guan et al. (2004) studied the dielectric behavior

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of mashed potatoes at temperature from 20 to 120 °C within microwave and RF range. However, there have been few systematic studies on the dielectric behavior of fish muscle at commercial sterilization temperatures. In this study, the dielectric properties of pink salmon at a temperature range between 20 and 120 °C were investigated.

During thermal processing, the native structure of muscle foods undergoes several changes, including area shrinkage caused by heat-induced protein denaturation and shrinkage of the muscle fibers. Similar to other muscle foods, fish muscle tends to contract upon cooking, which releases intracellular water along with soluble constituents that include both polar and ionic compounds (Hamm and Deatherage, 1960; Bouton et al., 1976; Bowers et al., 1987; Barbera and Tassone, 2006; Kong et al., 2007).

The compositional or structural differences within a fish fillet may affect dielectric heating. Chemical composition and muscle structure vary along the length of a fish fillet and from anterior to the tail, so their dielectric properties may vary. Water is the major constituent of fish muscle tissue. Fish muscle has more water than terrestrial muscle foods (Weatherly and Gill, 1987). The live weight of the average fish consists of: 70–80% moisture, 20–30% proteins, (wb); and 2–12% fat (wb) (Love, 1980). But these values vary considerably within and between species and also with size, gender, sexual maturity and fecundity, feeding conditions, time of year, water temperature and salinity. Essentially, there is no carbohydrate in fish muscle, and variable amounts of fat (Weatherly and Gill, 1987; Shearer, 1994).

The compositional effect on the dielectric properties of food is complex and not well defined. Calay et al. (1995) reported that the dielectric constant appears to consistently increase with moisture content for foods. However, Guan et al. (2004) observed that dielectric constant of food changed little over a relatively narrow range of moisture content (81.6–87.8%). Feng et al. (2002) indicated that the dielectric constant of red delicious apples (*Malus domestica Borkh*) increased with increasing temperature at 915 and 1800 MHz when the moisture content of the apples was less than 70%, and then decreased when moisture content was more than 70%. The effect of changes in moisture content on the dielectric loss factor is less clear, however compositional factors play an important role, particular salt content (Guan et al., 2004).

The primary objective of this study was to measure the dielectric properties for different sections of pink salmon fillets at temperatures from 20 to 120 °C to determine how compositional changes could affect dielectric heating behavior. The effect of compositional changes (fat, ash content, and either moisture content and water activity) and the electrical conductivity was determined to provide an understanding of which compositional factors provide the greatest contribution to temperature dependent behaviors of salmon fillet during dielectric heating. Predictive equations were developed at different temperatures and frequencies.

2. Materials and methods

2.1. Salmon fillet sample preparation

Samples of deep frozen pink salmon fillets (*Oncornynchus gorbuscha*, female, deep-skinless, boneless) were used for dielectric properties measurement. The fish samples were fresh wild Alaska pink salmon from the same catch, harvested in August, 2005 and provided by Ocean Beauty Seafood, Inc., Kodiak, Alaska, with an average weight of 1.35 ± 0.1 kg and similar size (370 ± 10 mm in length and 120 ± 10 mm in width). The fish samples were filleted and deep skinned immediately after slaughter and then gutted, iced, frozen (−31 °C) and shipped overnight to Washington State University, Pullman, WA. To maintain the sample temperature, frozen fish fillets were layered in a styrofoam shipping container with a plastic fold-over liner. Gel ice was included inside the container to keep the product frozen during shipment. Upon arrival, the fish samples were stored at −30 °C. Fish samples were defrosted overnight before measurements were taken. Fillet were subdivided into four parts: 'anterior', 'middle', 'tail', and 'belly' as shown in Fig. 1.

2.2. Fat content, ash and moisture determinations

The flesh from each part of the salmon fillet was homogenized and analyzed separately in triplicate for moisture, fat, and ash contents. Ash content was determined by a dry ashing method at 550 °C in a muffle oven (Thermolyne, Dubuque, Iowa, USA) according to Part 942.05 in AOAC (1995). The moisture content was determined by drying in a vacuum oven (National Appliance Co., Skokie, Ill., USA) for 6 h at 75 °C and 65 mmHg according to Part 934.06 of AOAC (1995). Fat content was determined by Modified Folch Method (Folch et al., 1957). Mean values for fat, moisture, and ash were compared using *t*-tests (Microsoft Excel, 2003).

2.3. Experimental set up and dielectric properties measurement

The dielectric properties were measured with an Agilent 4291 B Impedance analyzer (Innovative Measurement Solutions, Inc., Santa Clara, CA). A custom built

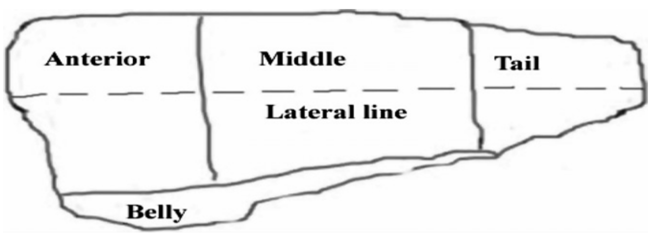

Fig. 1. Schematic showing parts of the pink salmon fillets used for analyses.

temperature test cell (Wang et al., 2003b; Wang et al., 2005) connected to an oil bath (PolyScience Products, Niles, Ill., USA) was used to control sample temperature during dielectric property measurement. The system was calibrated before each independent measurement to avoid possible variations in the connections, ambient temperature and other factors that might affect the system performance. The typical error of the system was about 5% following standard calibration procedures. Sample specimens were made by cutting partially defrosted salmon fillet (−2 °C) into cylinders of 2.5 cm in diameter, 10 cm in length, before loading into the temperature controlled test cell. The sample temperature in the central point of the test cell was measured with Type-T thermocouples.

The first dielectric measurements were taken when the temperature of the sample inside the measurement cell stabilized at 20 °C. Subsequent measurements were made in 10 °C increments up to 120 °C. It took about 8–10 min for the oil bath to increase in temperature of the sample for a 10 °C increase. An entire run took about 2–3 h. All measurements were made between 1 and 1800 MHz, in triplicate.

2.4. Electrical conductivity measurement

At RF and microwave frequencies, ionic conduction and dipole rotation in high moisture content foods are the dominant loss mechanisms. This can be mathematically expressed as (Ryynänen, 1995; Wang et al., 2005):

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

with

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

By taking a logarithm on both sides of Eq. (2), one obtains

$$\log \varepsilon''_\sigma = -\log f + \log \frac{\sigma}{2\pi\varepsilon_0} \tag{3}$$

where subscripts d and σ stand for contributions due to dipole rotation and ionic conduction, respectively; σ is the ionic conductivity (S m^{-1}) of a material, f is the frequency (Hz), and ε_0 is the permittivity of free space or vacuum (8.854×10^{-12} F m^{-1}).

To evaluate the influence of ionic conductivity on the loss factor of salmon fillets, electrical conductivity of minced pink salmon fillets in a temperature range between 20 and 50 °C was measured with an electrical conductivity meter (Cole-Parmer Con 500 series economy conductivity bench top meter, Chicago, IL). The minced samples made it possible for the electrode to be in close contact with the tissue material, allowing accurate measurement of the electric conductivity. Our preliminary tests showed no difference in the dielectric properties between minced fillets and the intact fillets that went through one freezing–thawing circle.

The conductivity meter was calibrated using a conductivity standard solution (1500 μmho/cm, 4500 μmho/cm) with a known value close to that of the measured samples. Calibration was conducted before each measurement according to the manufacturer's manual. The conductivity test cell was rinsed with de-ionized water before and between sample measurements in order to remove any impurities adhering to the probe body. Prior to measurement, 10 g of pink salmon fillet sample were minced in a grinder for about 2 min and put into a beaker, then heated in a water bath. During the electrical conductivity measurements, the probes were placed in close contact with minced samples. Electrical conductivity (mS cm^{-1}) of the fish samples was measured at 20, 30, 40 and 50 °C, in triplicate. The simple measurement of the electrical conductivity of the fish samples can be used as a means to estimate the dielectric loss factor, or vice versa in the RF range. The measured electrical conductivity in the selected temperature range was used to determine the influence of temperatures on the contribution of ionic conductivity to the loss factor.

3. Results and discussion

3.1. Dielectric constant

Table 1 lists the results of the dielectric properties of pink salmon fillet for four positions at RF (27 and 40 MHz) and microwave frequencies (433, 915 MHz) allocated by the US Federal Communications Commission (FCC) for industrial heating, as well as the highest frequency (1800 MHz) of the measurement system. The upper frequency is close to another FCC allocated frequency, 2450 MHz, used worldwide in domestic microwave ovens and industrial microwave systems.

Between 20 and 120 °C, dielectric constant (ε') of pink salmon fillet (overall average) steadily increased with temperatures at low frequencies (27 MHz and 40 MHz), but moderately decreased at high frequencies (433 MHz, 915 MHz and 1800 MHz) (Fig. 2). At 27 MHz, for example, the dielectric constant ε' for overall average of pink salmon increased from 97.8 at 20 °C to 149.6 at 120 °C, respectively. The difference in dielectric constant between the two temperatures was about 52. It was also observed that the difference in the dielectric constant at 40 MHz between 20 and 120 °C was about 36. While at 915 MHz, ε' was reduced from 56.5 at 20 °C to 48.6 at 120 °C. The reduction in the observed dielectric constants at microwave frequencies may have been caused by interruption to the ordered water molecule arrangement because of increased intermolecular vibrations at elevated temperatures. Similar trends have been reported for other food products with high moisture contents (Herve et al., 1998; Tang, 2005). The reason for increases in dielectric properties with increasing temperature at RF frequencies are less understood, though this trend has been reported for a wide range of high moisture products, including whey protein gels, macaroni and cheese, and mashed potato (Wang et al., 2003b; Guan et al., 2004).

Table 1
Mean ± standard deviation of dielectric properties[a] for pink salmon[b] at four positions

Sample	T (°C)		27 MHz	40 MHz	433 MHz	915 MHz	1800 MHz
Anterior	20	ε'	97.9 ± 9.3	87.6 ± 8.8	59.4 ± 7.6	55.1 ± 6.7	51.7 ± 6.3
		ε''	430.6 ± 80.0	296.3 ± 53.9	36.4 ± 5.9	22.6 ± 4.1	17.4 ± 2.7
	40	ε'	105.4 ± 8.9	92.6 ± 8.3	58.6 ± 6.5	54.2 ± 5.8	50.5 ± 5.2
		ε''	603.6 ± 110.4	413.9 ± 74.3	48.3 ± 7.8	27.6 ± 4.6	19.0 ± 2.7
	60	ε'	117.1 ± 12.1	100.8 ± 10.9	56.6 ± 7.2	51.4 ± 6.5	47.5 ± 5.8
		ε''	766.1 ± 157.9	525.5 ± 106.3	60.8 ± 11.0	33.0 ± 5.9	21.0 ± 3.5
	80	ε'	128.4 ± 17.4	109.1 ± 15.3	55.2 ± 8.4	48.9 ± 7.3	44.8 ± 6.3
		ε''	877.8 ± 227.9	603.0 ± 154.3	70.4 ± 16.0	37.7 ± 8.1	23.1 ± 4.7
	100	ε'	133.8 ± 19.1	112.8 ± 16.6	54.4 ± 9.1	47.5 ± 7.1	43.4 ± 5.7
		ε''	1048.0 ± 309.8	717.9 ± 209.3	82.6 ± 21.1	44.0 ± 9.7	25.7 ± 6.0
	120	ε'	139.6 ± 20.1	116.8 ± 17.3	55.1 ± 10.0	47.1 ± 7.4	42.3 ± 5.8
		ε''	1305.3 ± 435.0	890.8 ± 292.9	100.1 ± 29.0	52.9 ± 13.4	30.3 ± 8.0
Middle	20	ε'	94.7 ± 1.2	85.3 ± 0.9	60.8 ± 0.4	57.0 ± 0.6	53.8 ± 0.8
		ε''	458.3 ± 28.3	313.9 ± 18.4	37.4 ± 1.2	22.8 ± 1.2	17.8 ± 0.6
	40	ε'	101.2 ± 3.1	89.3 ± 1.9	59.5 ± 1.1	55.6 ± 1.0	52.4 ± 1.3
		ε''	650.0 ± 85.4	443.8 ± 56.6	50.0 ± 4.4	28.1 ± 2.7	19.4 ± 1.3
	60	ε'	115.5 ± 5.2	99.1 ± 2.8	58.4 ± 1.5	53.7 ± 1.7	50.2 ± 2.1
		ε''	850.8 ± 155.8	581.4 ± 104.0	64.7 ± 8.3	34.8 ± 4.2	22.3 ± 2.0
	80	ε'	129.5 ± 3.2	109.0 ± 3.0	57.1 ± 0.7	51.5 ± 1.1	47.9 ± 1.7
		ε''	1001.7 ± 185.9	685.4 ± 123.6	76.8 ± 9.3	40.7 ± 4.2	24.6 ± 2.1
	100	ε'	137.8 ± 5.5	114.4 ± 2.3	56.7 ± 1.7	50.8 ± 1.9	47.0 ± 2.6
		ε''	1241.4 ± 314.0	847.6 ± 209.1	93.5 ± 16.7	49.0 ± 7.4	28.1 ± 4.4
	120	ε'	147.4 ± 13.2	119.7 ± 2.3	57.9 ± 2.8	50.7 ± 2.9	46.6 ± 3.7
		ε''	1594.1 ± 482.1	1085.2 ± 23.5	116.8 ± 26.6	60.4 ± 11.8	34.1 ± 6.9
Tail	20	ε'	101.4 ± 2.5	90.9 ± 3.2	63.7 ± 3.6	59.5 ± 3.3	56.2 ± 3.5
		ε''	479.4 ± 36.3	328.6 ± 23.4	39.3 ± 1.3	24.4 ± 1.2	18.9 ± 1.2
	40	ε'	108.7 ± 3.3	95.5 ± 3.8	62.1 ± 3.9	57.7 ± 3.8	54.4 ± 4.0
		ε''	646.9 ± 71.9	442.6 ± 47.1	50.8 ± 3.5	29.0 ± 2.0	20.3 ± 1.7
	60	ε'	123.0 ± 3.8	105.5 ± 3.8	60.8 ± 4.1	55.7 ± 4.2	52.1 ± 4.4
		ε''	840.9 ± 119.7	575.7 ± 78.8	65.3 ± 5.6	35.4 ± 2.5	23.0 ± 2.0
	80	ε'	137.9 ± 3.9	116.3 ± 4.4	59.1 ± 3.6	52.6 ± 3.6	48.7 ± 3.9
		ε''	955.9 ± 130.6	655.9 ± 86.8	75.8 ± 6.9	40.4 ± 3.4	25.2 ± 2.4
	100	ε'	145.6 ± 3.8	121.9 ± 4.3	58.0 ± 2.8	50.7 ± 2.9	46.6 ± 3.6
		ε''	1104.6 ± 103.4	757.1 ± 69.4	87.2 ± 5.8	46.4 ± 3.2	27.7 ± 2.4
	120	ε'	152.8 ± 3.1	126.9 ± 3.5	58.3 ± 1.8	49.5 ± 2.4	45.2 ± 3.3
		ε''	1334.5 ± 82.5	912.0 ± 56.0	103.0 ± 4.5	54.7 ± 3.0	31.9 ± 3.0
Belly	20	ε'	97.0 ± 6.9	85.2 ± 4.3	57.8 ± 2.0	54.4 ± 2.1	50.9 ± 1.4
		ε''	378.4 ± 11.8	260.7 ± 6.9	32.7 ± 0.5	20.2 ± 0.2	16.1 ± 0.2
	40	ε'	107.6 ± 9.0	91.8 ± 5.9	56.3 ± 1.4	52.6 ± 1.0	49.3 ± 0.4
		ε''	523.5 ± 32.1	360.0 ± 20.8	43.1 ± 1.0	24.7 ± 0.3	17.3 ± 0.5
	60	ε'	122.7 ± 8.7	102.4 ± 5.1	55.5 ± 0.7	50.9 ± 1.0	47.4 ± 0.9
		ε''	677.4 ± 58.8	466.0 ± 38.4	55.2 ± 2.4	30.2 ± 1.0	19.5 ± 0.7
	80	ε'	138.3 ± 6.3	113.8 ± 2.9	55.0 ± 1.2	49.0 ± 1.8	45.1 ± 2.0
		ε''	790.8 ± 110.8	544.9 ± 73.4	65.5 ± 5.9	35.4 ± 2.8	22.0 ± 1.4
	100	ε'	148.3 ± 7.0	120.6 ± 3.1	55.0 ± 0.9	47.7 ± 1.9	43.5 ± 2.3
		ε''	956.7 ± 139.5	657.5 ± 93.1	77.7 ± 7.5	41.6 ± 3.5	25.3 ± 1.6
	120	ε'	158.7 ± 9.0	127.6 ± 3.8	55.4 ± 0.2	46.8 ± 1.7	43.6 ± 4.0
		ε''	1178.3 ± 199.2	807.1 ± 133.3	92.9 ± 11.5	50.8 ± 7.0	30.6 ± 3.5

[a] ε' is the dielectric constant and ε'' is the dielectric loss factor.
[b] Results of each position of pink salmon fillet are the mean values over three independent trials.

3.2. Dielectric loss factor

The salmon samples used in this study had moisture contents between 74.97% and 76.14%, fat contents between 1.67% and 2.17% (wet basis), and ash contents between 4.78% and 5.34% (Table 2). The temperature dependent behavior of the dielectric loss factor of salmon fillet should be determined by the free water and the dissolved ions (Ohlsson et al., 1974; Nelson and Bartley, 2002). In high moisture foods, dielectric loss factor (ε'') in the tested frequency range are mainly influenced by two components: dipole and ionic losses. Dipole loss results from water dipoles rotation, and its value decreases with temperature at microwave frequencies, while ionic loss results from migration of ions and increases with temperature over both microwave and RF frequencies (Tang et al., 2002; Wang et al., 2003a,b).

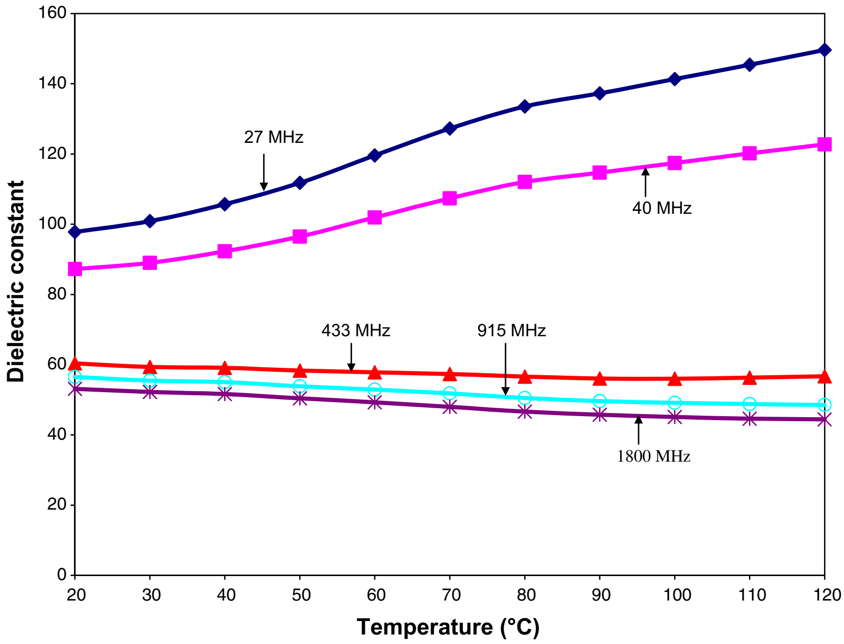

Fig. 2. Change of dielectric constant of pink salmon (overall average) with temperature at five frequencies.

Table 2
Fat, moisture and ash content of pink salmon samples (on a wet weight basis) ($n = 3$)

Sample position	% Fat	% Moisture	% Ash
Anterior	$1.67 \pm 0.01^{a*}$	75.25 ± 0.18^{a}	5.34 ± 0.06^{a}
Middle	1.66 ± 0.01^{a}	74.97 ± 0.52^{a}	5.28 ± 0.04^{a}
Tail	1.67 ± 0.02^{a}	76.14 ± 0.25^{a}	4.98 ± 0.03^{a}
Belly	2.17 ± 0.01^{b}	75.69 ± 0.09^{a}	4.78 ± 0.08^{b}

[*] Different letters within a column indicate that means are significantly different ($P < 0.05$).

At 27 and 40 MHz, the measured ε'' for salmon fillet indeed increased sharply with increasing temperature from 20 to 120 °C (Fig. 3). This has been the result of increased ionic conductivity with increasing temperature (see Table 3). The ε'' increased moderately (Fig. 4) at three microwave frequencies (433 MHz, 915 MHz and 1800 MHz), suggesting a reduced role of ionic conductivity at higher frequencies.

The loss factor values in Table 1 were similar to those reported in Tran and Stuchly (1987) for uncooked salmon meat at frequencies between 100 MHz and 2500 MHz. They reported dielectric properties of salmon (moisture content 71%, wet basis) with $\varepsilon' = 53.7$; $\varepsilon'' = 24.3$ at 20 °C at 900 MHz and $\varepsilon' = 57.7$; $\varepsilon'' = 39.0$ at 64 °C at 2000 MHz, while experimental results in this study indicated the dielectric properties of pink salmon (female, moisture content 75%, wet basis) with $\varepsilon' = 56.5$; $\varepsilon'' = 22.5$ at 20 °C and 915 MHz, $\varepsilon' = 49.3$ and $\varepsilon'' = 21.5$ at 60 °C and 1800 MHz over 4 positions in Table 1. Thus, the results of the dielectric measurements presented in this research agreed reasonably well with those in the published literature.

In general, four sections of pink salmon fillet (anterior, middle, tail, and belly) exhibited a similar trend for dielectric loss factor as a function of temperature at 27 and 915 MHz with a temperature range from 20 to 120 °C (Figs. 5 and 6). But the belly part of the salmon had lower dielectric loss factors (Figs. 5 and 6) than other parts of salmon fillets. These results were anticipated, as the proximate compositions of the four different positions (moisture content, fat content and ash content) were also similar; but with only small differences in fat content for terminal female pink salmon, particularly in the belly. The belly has a higher fat content as well as lower ash content compared to other sections (Tables 2 and 4). The salmon belly flap area was also found to be of high lipid content by Aursand et al. (1994), Zhou et al. (1996), and Katikou et al. (2001). But Herve et al. (1998) reported that the influence of fat on dielectric loss factor was very small at a total fat content of less than 4%.

3.3. Effect of ionic conductivity on loss factor

Measured values of electrical conductivities in minced salmon fish fillets are summarized in Table 3. Loss factors due to ionic conductivity (ε''_{σ}) at four temperatures were calculated from the values of ionic conductivity at four temperatures as function of frequency using Eq. (2). Fig. 7 compared the calculated loss factor due to ionic conductivity and measured total loss factors in a log–log plot. It is clear that at low frequencies, major contribution to the loss factor for the salmon fillet was ionic conduction. Increases in electric conductivity with increasing in temperature caused the overall loss factor to increase at those frequencies. As frequency increased beyond about 400 MHz, the overall loss factor value increasingly deviated from the curves drawn for loss factor due to reduced ionic

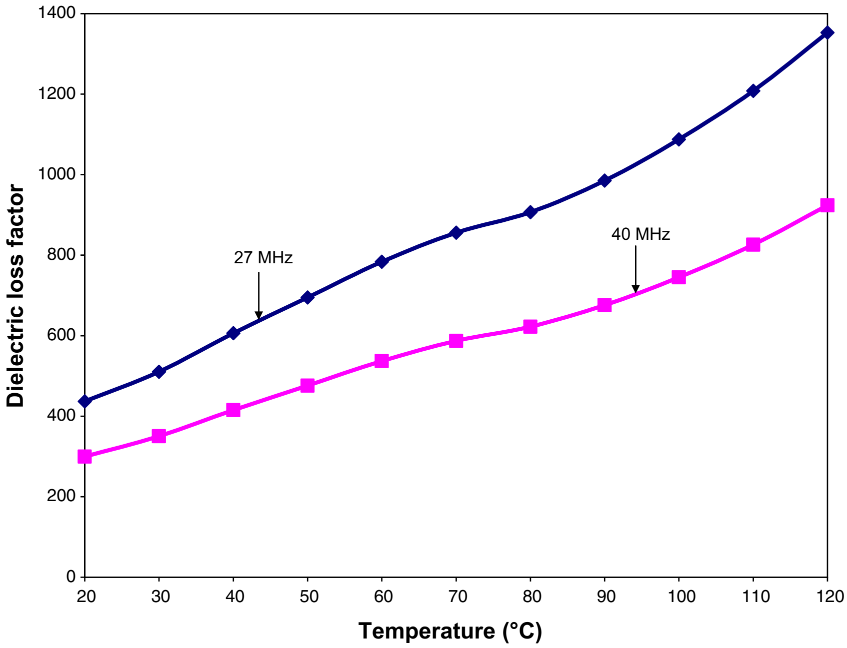

Fig. 3. Changes of dielectric loss factor of pink salmon (overall average) with temperature at 27 and 40 MHz.

Table 3
Comparison of dielectric loss factors at 27 MHz estimated from the electrical conductivity (EC: mean ± SD, mS cm^{-1}) and obtained from direct measurement with the impedance analyzer ($n = 3$)

T (°C)	Sample	Measured EC (mS cm^{-1})	Calculated $\varepsilon''\sigma$ from EC at 27 MHz	Measured ε'' at 27 MHz
20	Anterior	5.87 ± 0.17	391.33	430.57
	Middle	5.70 ± 0.16	380.22	458.32
	Tail	6.23 ± 0.83	415.56	479.39
	Belly	5.25 ± 0.06	350.22	378.41
30	Anterior	7.38 ± 0.17	492.22	502.01
	Middle	7.65 ± 0.13	510.00	543.45
	Tail	7.49 ± 0.36	499.11	555.68
	Belly	6.39 ± 0.21	426.00	440.21
40	Anterior	9.00 ± 0.33	599.78	603.63
	Middle	9.26 ± 0.16	617.33	650.04
	Tail	9.11 ± 0.26	607.33	646.88
	Belly	7.46 ± 0.27	497.33	523.45
50	Anterior	10.16 ± 0.21	677.33	683.67
	Middle	10.57 ± 0.31	704.89	744.25
	Tail	10.48 ± 0.28	698.44	749.33
	Belly	8.543 ± 0.08	569.56	602.29

conductivity (Fig. 7), suggesting the increasingly important role of dipole water molecules. This is in general agreement with observations made by Guan et al. (2004) for mashed potato containing 1.3% or more salt and by Wang et al. (2005) for subtropical and tropical fruits.

It is interesting to note that at RF frequencies, direct measurement of electrical conductivity of pink salmon fillet should lead to a very good estimation of overall loss factor of salmon fillet as illustrated in Table 3 for 27 MHz. Measuring electrical conductivities using conductivity probes is much simpler and less expensive compared to measurement of dielectric properties using network or impedance analyzers.

3.4. Penetration depth

Microwave power penetration depth is generally used to select appropriate thickness of food inside packages to ensure a relatively uniform heating along the depth of a food during dielectric heating processes (Wang et al., 2003b). The equation used to determine microwave power penetration depth is defined as:

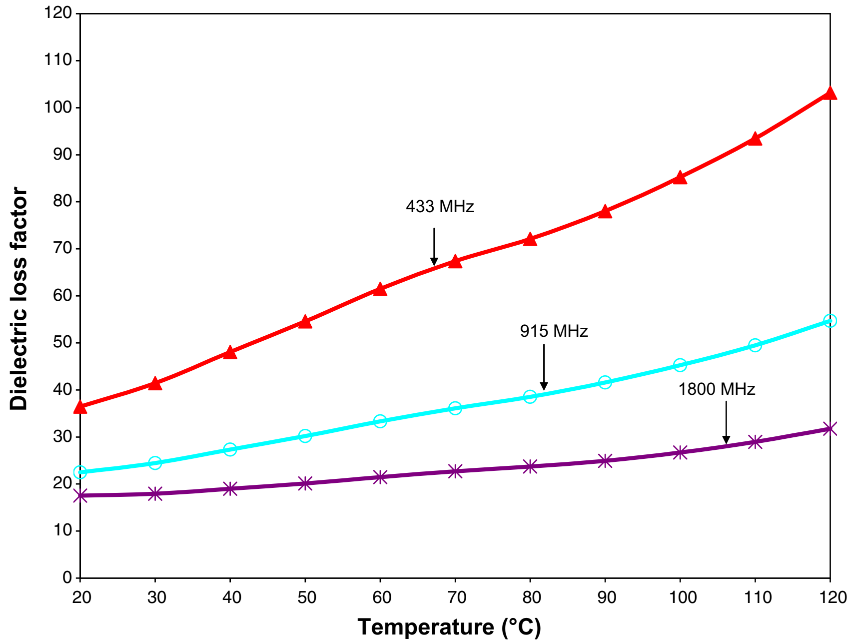

Fig. 4. Changes of dielectric loss factor of pink salmon (overall average) with temperature at 433, 915 and 1800 MHz.

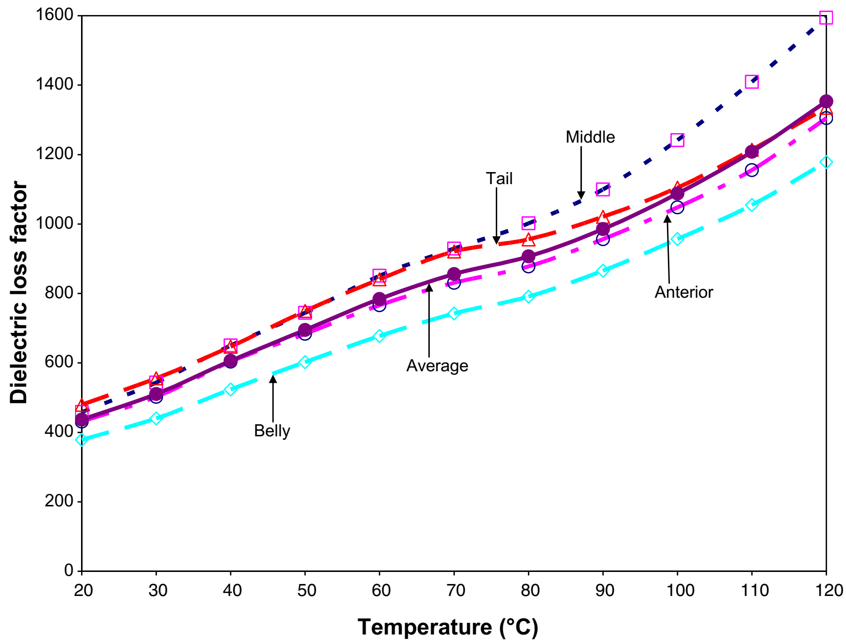

Fig. 5. Dielectric loss factor of pink salmon at four positions as a function of temperature at 27 MHz.

$$d_p = \frac{c}{2\pi f\sqrt{2\varepsilon'\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right]}} \tag{4}$$

where d_p is the power penetration depth (m) and c is the speed of light in free space (3×10^8 m/s).

Microwave power penetration depths for salmon were on an average about 66 mm at 27 MHz and 18 mm at 915 MHz at 20 °C, respectively. Penetration depths were reduced to 36 mm at 27 MHz and 7.5 mm at 915 MHz at 120 °C (Table 5). Penetration depth at 915 MHz was greater than that of 1800 MHz (Fig. 8 and Table 5). A higher penetration depth at 915 MHz than 2450 MHz was also reported by other researchers (Decareau, 1985; Tanaka et al., 1999; Gunasekaran et al., 2005). In general, penetration depths were reduced by about one-half when the temperature was increased from 20 to 120 °C at frequencies from 27 to 1800 MHz (Table 5). Results from other researchers also indicated that for most foods, the

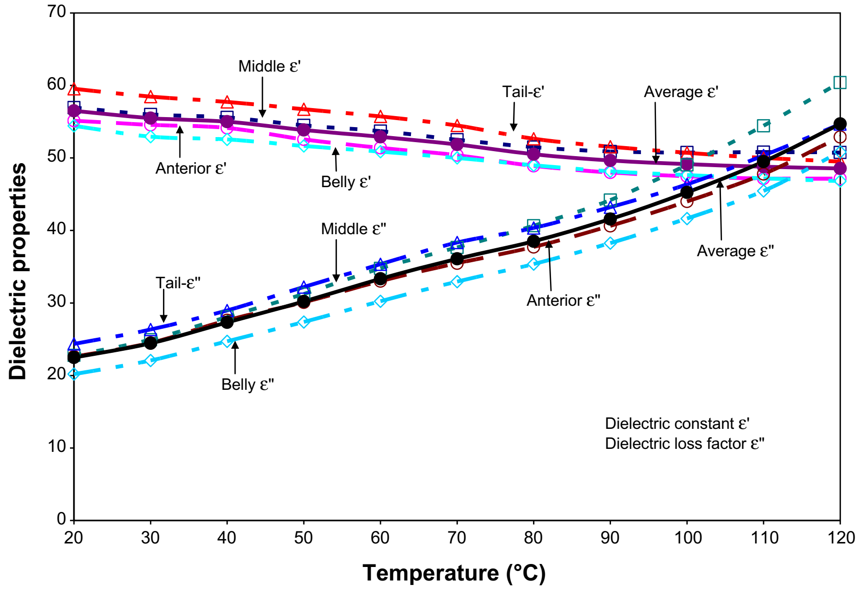

Fig. 6. Temperature dependence of dielectric properties of pink salmon at four positions at 915 MHz.

Table 4
Comparison of the fat content of raw pink salmon fillet (Modified Folch Method) with literature data (on a wet weight basis)

Salmon fillet position	% Fat content	
	Measured	Literature values
Anterior	1.67 ± 0.01	1.5 ± 0.1 (Head)*
Middle	1.66 ± 0.01	0.6–2.1 (Smolt)**
Tail	1.67 ± 0.02	2.2–5.4 (Adult)**
Belly	2.17 ± 0.01	Not available

* From Sathivel et al. (2006).
** From Iverson et al. (2001).

power penetration depths decrease as temperature increases. The change of frequency from RF range (27 MHz and 40 MHz) to microwave range (915 MHz and 2450 MHz) impacted penetration depth much more than change of temperature from 20 to 120 °C.

3.5. Regression analysis

Polynomial equations were developed for dielectric properties at 27 MHz and 915 MHz by using regression calculations. Similar equations for other frequencies (40 MHz, 433 MHz and 1800 MHz) can also be achieved by using this method.

The regression equations and all the predictors in the equations had a significance of $P < 0.001$, and the adjusted

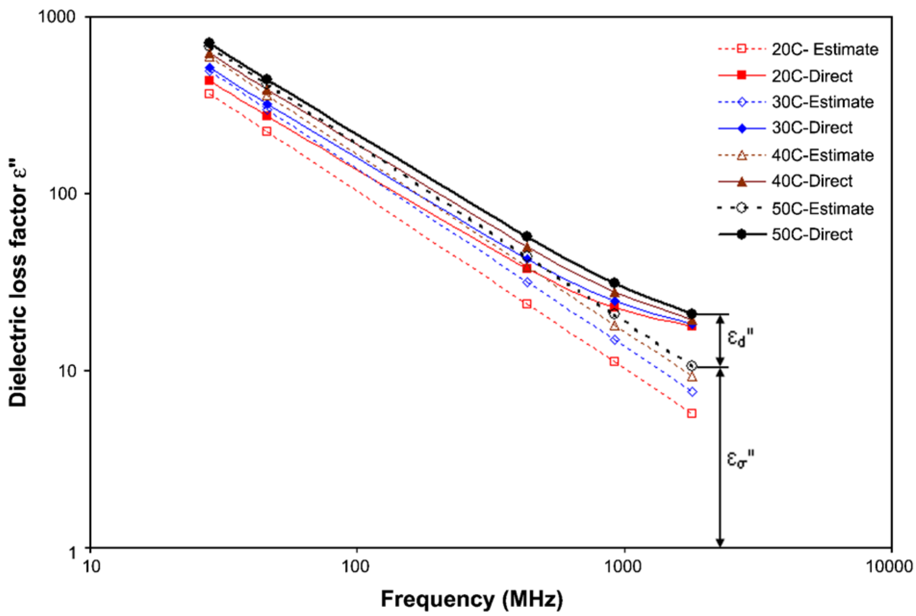

Fig. 7. Measured ε'' and estimated ε''_σ of salmon fillet as a function of frequency at 20–50 °C.

Table 5
Radiation penetration depth[a] (mm) for pink salmon fillet at four positions

Sample	T (°C)	27 MHz	40 MHz	433 MHz	915 MHz	1800 MHz
Anterior	20	67.41	56.69	24.29	17.48	11.09
	40	55.48	46.32	18.70	14.32	10.10
	60	48.72	40.47	15.16	11.85	8.88
	80	45.37	37.58	13.31	10.28	7.92
	100	41.14	34.04	11.68	8.88	7.05
	120	36.48	30.17	10.13	7.57	6.00
Middle	20	64.68	54.45	23.93	17.61	11.06
	40	52.96	44.24	18.27	14.26	10.04
	60	45.84	38.08	14.54	11.51	8.61
	80	42.11	34.87	12.54	9.82	7.68
	100	37.49	30.99	10.74	8.28	6.73
	120	32.78	27.05	9.15	6.95	5.61
Tail	20	63.39	53.34	23.32	16.85	10.65
	40	53.42	44.62	18.30	14.09	9.77
	60	46.35	38.51	14.61	11.51	8.51
	80	43.43	35.97	12.81	9.97	7.57
	100	40.15	33.21	11.40	8.69	6.79
	120	36.22	29.94	10.06	7.49	5.88
Belly	20	72.92	61.34	26.54	19.37	11.92
	40	60.49	50.44	20.39	15.70	10.93
	60	52.54	43.57	16.33	12.79	9.53
	80	48.47	40.08	14.11	10.91	8.33
	100	43.64	36.04	12.30	9.33	7.17
	120	38.93	32.12	10.73	7.81	6.02

[a] Results are the mean values over three independent trials.

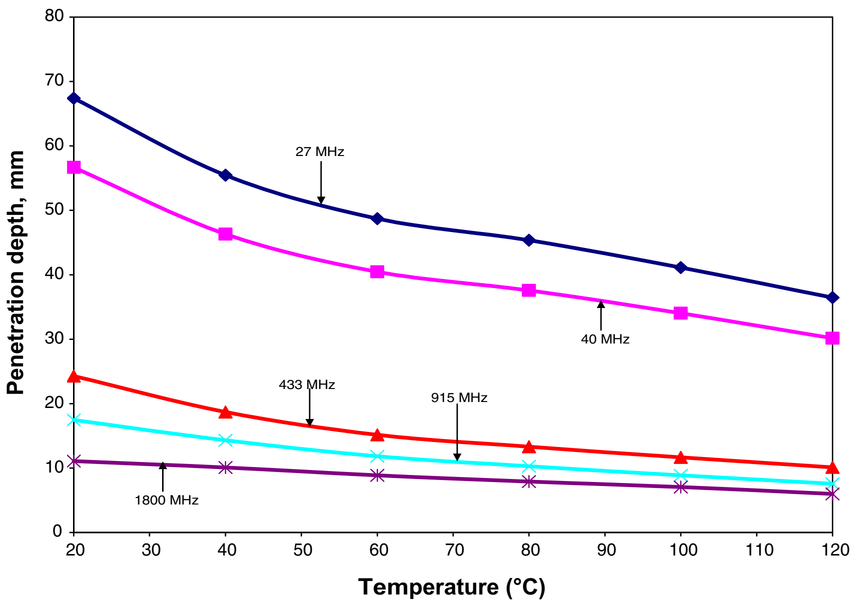

Fig. 8. Penetration depth of pink salmon anterior parts at temperatures from 20 to 120 °C (Triplicate measurements).

coefficients of determination of the equation, R^2 values, were greater than 0.95 (Table 6). Significant polynomial relationships were found for all combinations and can be used to predict the raw dielectric properties data for pink salmon fillet and incorporated into computer simulation models needed to study the coupled dielectric heating and heat transfer processes. Within the same frequency range, for example, at 915 MHz, the coefficients of the equations for both dielectric constant and loss factor at different positions of pink salmon fillet had small variations (±0.05). But at the same position of pink salmon fillet, for instance, the coefficients of the equation for salmon anterior at 27 MHz were greater than those at 915 MHz, which were in a good agreement with the experimental results that both dielectric constant and dielectric loss factor increased sharply with the increasing temperature at

Table 6
Predictive equations for the dielectric properties (y) of pink salmon as a function of temperature (T) at 27 MHz and 915 MHz

	Salmon fillet position	Regression equations $y = a\,T^2 + b\,T + c$			R^2
27 MHz	Dielectric constant ε'	$a \times 10^3$ (°C^{-2})	b (°C^{-1})	c (–)	
	Anterior	−1.750	0.6930	82.211	0.989
	Middle	−0.643	0.6556	78.736	0.990
	Tail	−1.315	0.7409	84.245	0.988
	Belly	−1.093	0.7980	79.255	0.996
	Average	−1.200	0.7219	81.112	0.991
	Dielectric loss factor ε''				
	Anterior	16.188	5.8935	324.572	0.991
	Middle	41.830	4.8515	370.135	0.993
	Tail	0.871	8.0040	327.514	0.991
	Belly	16.297	5.3514	275.575	0.995
	Average	18.797	6.0251	324.449	0.993
915 MHz	Dielectric constant ε'				
	Anterior	0.384	−0.1459	58.570	0.978
	Middle	0.530	−0.1431	59.974	0.977
	Tail	0.096	−0.1211	62.193	0.989
	Belly	0.250	−0.1119	56.473	0.994
	Average	0.315	−0.1305	59.302	0.987
	Dielectric loss factor ε''				
	Anterior	0.916	0.1623	19.259	0.996
	Middle	1.619	0.1379	19.719	0.997
	Tail	0.620	0.2104	19.834	0.997
	Belly	1.053	0.1475	17.009	0.997
	Average	1.052	0.1645	18.955	0.997

lower frequencies (*e.g.*, <200 MHz). From those regression constants, it is clear that the four sections of the pink salmon fillet (anterior, middle, tail, and belly) exhibited a similar trend for dielectric constant and loss factor as a function of temperature between 20 and 120 °C at 27 MHz and 915 MHz. These equations could be used to obtain the temperature dependent dielectric properties of salmon within a temperature range from 20 to 120 °C, if the compositions of samples were close to those in this study.

4. Conclusions

The dielectric properties of Alaska pink salmon fillet at four positions were studied at frequencies from 27 MHz to 1800 MHz and temperatures from 20 to 120 °C. The influence of temperature, frequency and fish composition on the dielectric properties was examined and quantified. The following conclusions can be derived:

- Dielectric constant increased at 27 MHz and 40 MHz, but decreased at 433 MHz, 915 MHz and 1800 MHz while the dielectric loss factor increased sharply at 27 MHz and 40 MHz with the increasing temperature, but increased slightly at 915 MHz and 1800 MHz.
- Calculated loss factors due to ionic conductivity at different temperatures clearly indicated the importance of ionic conduction as the main mechanism in dielectric dispersion in RF frequencies and provided explanation for the observed increase in overall loss factor with increasing temperature.
- Dielectric constant and dielectric loss factor of pink salmon belly were lower than other parts of salmon fillet due to a higher fat content in the fish belly.
- The penetration depths at RF range (27 MHz and 40 MHz) were about five times deeper than microwave frequencies range (915 MHz and 1800 MHz) at each measured temperature.
- Regression equations for predicting dielectric constant and dielectric loss factor at various temperatures and different positions of fish fillet were developed. The predictions of dielectric properties by these equations compared well with experimental values.

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