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Using whey protein gel as a model food to study dielectric heating properties of salmon (*Oncorhynchus gorbuscha*) fillets

Yu Wang [a], Juming Tang [a,*], Barbara Rasco [b], Shaojin Wang [a], Ali A. Alshami [a], Fanbin Kong [a]

[a] Biological Systems Engineering, Washington State University, PO Box 646120, Pullman, WA 99164-6120, USA
[b] Food Science and Human Nutrition, Washington State University, PO Box 646376, Pullman, WA 99164-6376, USA

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ABSTRACT

It is desirable to develop rapid commercial microwave and radio frequency sterilization processes to produce high quality shelf stable muscle foods, particularly aquatic foods. Whey protein gels containing D-ribose and salt were studied as a model food to determine heating patterns in salmon fillets during high temperature microwave sterilization processes. Dielectric constant (ε') and loss factor (ε'') of whey protein gels with D-ribose (0.5 g/100 g, 1 g/100 g, and 1.5 g/100 g) at different salt contents (0, 0.1 g/100 g, 0.2 g/100 g, 0.3 g/100 g, 0.4 g/100 g, and 0.5 g/100 g) and frozen and thawed pink salmon (*Oncorhynchus gorbuscha*) fillets were determined over the frequency range of 27–1800 MHz at temperatures ranging from 20 to 120 °C. The dielectric properties of whey protein gels containing 1 g/100 g D-ribose and 0.2 g/100 g or 0.3 g/100 g salt closely matched the dielectric behavior of salmon fillets in both radio frequency (RF, 27 MHz) and microwave (MW, 915–1800 MHz) ranges. Altering the salt content had a greater impact on dielectric constant and loss factors at lower frequencies. These results suggest that whey protein gel may be a good model food for microwave sterilization process development, particularly for determining the locations of cold and hot spots in complex muscle foods.

1. Introduction

Creating a microwave processed shelf-stable salmon product is a new concept and could provide important opportunities for the salmon industry. There is commercial demand for seafood entrées composed of whole fillets and sauces that are ready to heat and consume. Microwave (MW) and radio frequency (RF) sterilization processes may provide a rapid heating technology for processing heat labile muscle foods such as salmon fillets or steaks. Non-uniform heating with MW and RF processes can be a major problem, because of different sizes, shapes, and dielectric properties of salmon fillets (Berek & Wickersheim, 1988; Birla, Wang, & Tang, 2008). Since non-uniform heating leads to cold and hot spots within the food (Ryynänen & Ohlsson, 1996), it is critical to validate these processes for food safety (Rasco, 1997, 1999; Buzby, Frenzen, & Rasco, 2001). Determining the optimized process parameters relies on reliable product temperature measurement for the cold spot. Often initial studies are best conducted with the inexpensive model foods. Whey protein gels containing D-ribose and salt were studied as a model food to determine heating patterns in foods during high temperature microwave sterilization processes (Lau et al., 2003; Sakai, Mao, Koshima, & Watanabe, 2005; Tang et al., 2008). Monitoring dielectric heating by following the formation of Maillard browning products in whey protein gels can be used to predict hot and cold spots in dielectric heating systems (Kim, Taub, Choi, & Prakash, 1995; Wang, Tang, Cavalieri, & Davis, 2003a; Wang et al., 2003b; Wang, Wig, Tang, & Hallberg, 2003c; Pandit, Tang, Liu, & Pitts, 2005; Pandit, Tang, Liu, & Mikhaylenko, 2007). Lau et al. (2003) indicate that whey protein gels with 1 g/100 g D-ribose had suitable kinetic properties that allow for sufficient and quantifiable color development and permit effective visualization of heat distribution within gels during microwave heating. However, it is critical that the model food has similar thermal and dielectric properties to those of the real food. Developing a MW sterilization process for salmon fillets also requires an understanding of how this product would respond during dielectric heating. Impedance analyzers are widely used to determine the dielectric properties of dairy, fruits and other food materials (Herve, Tang, Luedecke, & Feng, 1998; Ikediala, Tang, Drake, & Neven, 2000; Feng, Tang, & Cavalieri, 2002; Nelson & Bartley 2002; Al-Holy, Wang, Tang & Rasco, 2005; Wang et al., 2003b, 2005). In this study, impedance analyzers were used to determine the dielectric properties of whey protein gels containing salt and D-ribose to develop a model food that

* Corresponding author. Tel.: +1 509 335 2140; fax: +1 509 335 2722.
E-mail address: jtang@wsu.edu (J. Tang).

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matches the dielectric properties at 27–1800 MHz, and hence heating performance, of salmon. This procedure may possibly be extended to develop model foods for other products.

2. Materials and methods

2.1. Whey protein gel preparation

Whey protein gel was made of 20 g/100 g Alacen 878 (powder) whey protein concentrate (New Zealand Milk Products, Santa Rosa, CA) containing 75.83 g/100 g protein on a wet basis, with additional D-ribose (Sigma–Aldrich, St. Louis, MO) and food grade non-iodized salt (Morton International, Chicago, IL) in distilled water. The suspension was mixed continuously in a beaker for 2 h at room temperature using a magnetic stirrer to achieve homogeneity; the whey protein suspension was then transferred into a stainless steel cylinder container (2.5 cm diameter and 10.2 cm length) and heated at 80 °C in a water bath for 40 min.

Previous studies have shown that the 20 g/100 g whey protein solution forms a firm gel after heating at 80 °C for 40 min (Lau et al., 2003; Wang et al., 2003c) without causing any detectable browning product formation. The prepared whey protein gels with suitable levels of D-ribose only change color at temperatures beyond 100 °C. D-Ribose could be efficiently converted to a furanone (Kim & Taub, 1993; Kim et al., 1995) and was added to whey protein solutions at levels without limiting the supply of substrates in color formation. But the concentration of D-ribose should be controlled to a level such that the formation of the furanone increases proportionately during a typical microwave sterilization process (2–8 min at 121 °C, Guan et al., 2003) without reaching a point of color saturation. The time necessary to reach a saturation point during heating varies with ribose concentration; a whey protein sample with 1 g/100 g D-ribose reached saturation within a reasonable time ($F_o = 18$ min at 121 °C) (Pandit et al., 2005).

The range of salt was based upon proximate composition for canned salmon and similar items (Lyng, Zhang, & Brunton, 2005). The eight formulations of whey protein gels are presented in Table 1.

2.2. Salmon fillet sample preparation

Frozen pink salmon fillets (*Oncornynchus gorbuscha*, female, deep skinless, boneless) were used for dielectric property measurements. The tested samples were fresh wild Alaska pink salmon from the same catch, harvested in August 2005 and provided by Ocean Beauty Seafood, Inc. Kodiak, Alaska. The average weight of whole salmon was 1.35 ± 0.1 kg per piece, with average length 370 ± 10 mm, and average width 120 ± 10 mm. The fish were filleted and deep skinned immediately after slaughter and then gutted, iced, frozen (−31 °C) and shipped overnight to Washington State University, Pullman, WA. During shipment, frozen fish fillets were layered in a Styrofoam shipping container with a plastic fold-over liner and kept frozen with gel ice. Upon arrival, fish were at −30 °C and were stored at this temperature. Fish were defrosted at 4 °C overnight before measurements were taken.

Table 1
Compositions of whey protein gel (20 g/100 g whey protein) at different concentrations of D-ribose and NaCl (on a wet weight basis).

Formulations	1	2	3	4	5	6	7	8
D-Ribose Content (g/100 g)	0.5	1	1	1	1	1	1	1.5
Salt content (NaCl) (g/100 g)	0.3	0	0.1	0.2	0.3	0.4	0.5	0.3
Distilled water (g/100 g)	79.2	79	78.9	78.8	78.7	78.6	78.5	78.2

2.3. Experimental set up and dielectric properties measurement

The dielectric properties of whey protein gels and pink salmon muscle were measured over a temperature range from 20 °C to 120 °C and a frequency range from 27 MHz to 1800 MHz. using an Agilent 4291B impedance analyzer (Agilent Technologies, Palo Alto, CA) and a custom built test cell as previously described (Pandit et al., 2005; Wang, Tang, Rasco, Kong, & Wang, 2008). Specimens were made by cutting the defrosted salmon fillet into cylinders of 2.5 cm diameter, 10 cm length, before loading into the temperature controlled test cell. All measurements were performed in triplicate.

2.4. Penetration depth

The penetration depth of electromagnetic waves in food is defined as the depth where the power is reduced to $1/e$ ($e = 2.718$) of the power entering the surface, which depends upon the food composition. It is generally used to predict whether MW or RF energy penetrates through a particular thickness of food so that a relatively uniform heating could be achieved during dielectric heating (Al-Holy et al., 2005). The following equation was used to determine the penetration depth (Buffler, 1993):

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

where d_p is the penetration depth (m); ε' is the dielectric constant and ε'' is the dielectric loss factor; c is the speed of light in free space (3.00×10^8 m/s) and f is the frequency of the MW or RF waves (Hz).

3. Results and discussion

3.1. Effect of frequency on dielectric properties of whey protein gel model food

The measured dielectric constant and loss factor of whey protein gel with 1 g/100 g D-ribose and 0.3 g/100 g NaCl are presented in Fig. 1 as a function of frequency from 27 MHz to 1800 MHz and temperature from 20 °C to 120 °C. The dielectric constant decreased with frequency but the rate of decrease changed around 300 MHz. The loss factor decreased linearly with the frequency on a log–log plot, which was similar to that of the salmon fillet (Wang et al., 2008). The dielectric constant increased with increasing temperature at the RF frequencies (27 and 40 MHz) but decreased with increasing temperature at MW frequencies (433, 915 and 1800 MHz). The loss factors generally increased with increasing temperature over the measured frequency range but more at the RF frequencies than at the MW frequencies.

3.2. Effect of D-ribose concentration

Fig. 2 shows that changing D-ribose content (0.5 g/100 g, 1 g/100 g, and 1.5 g/100 g) had little effect on ε' and ε'' of whey protein gels at 915 MHz ($P > 0.05$). The minor influence of sugars in the selected D-ribose content range on dielectric properties was also reported by Sakai et al. (2005) and Alshami (2007). Whey protein gel with 1 g/100 g D-ribose was selected for further studies at different salt contents.

For comparison, dielectric properties of salmon fillets were also included in Fig. 2. The difference in loss factors between whey protein gels and salmon fillets was discussed in Section 3.3.

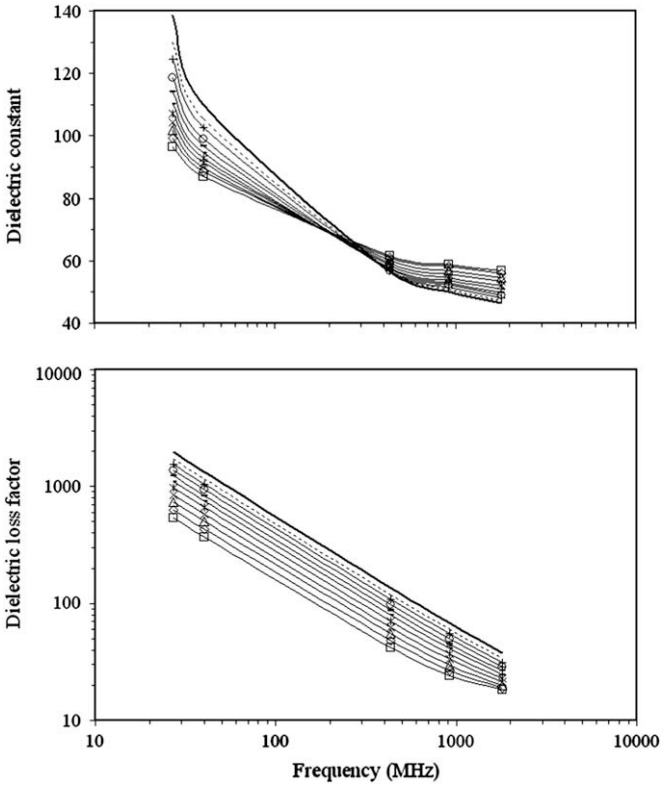

Fig. 1. Frequency dependent dielectric constant and loss factor of whey protein gel with 1 g/100 g D-ribose and 0.3 g/100 g NaCl at temperatures of 20 (□), 30 (◇), 40 (△), 50 (×), 60 (∗), 70 (-), 80 (–), 90 (○), 100 (+), 110 (——) and 120 °C (——).

3.3. Effect of salt concentration

Fig. 3 shows the changes in dielectric loss factor of whey protein gels with D-ribose (1 g/100 g) and five salt concentrations (0, 0.1 g/100 g, 0.2 g/100 g, 0.3 g/100 g, 0.4 g/100 g, and 0.5 g/100 g) at 915 MHz. Increasing salt in whey protein gels sharply increased their loss factor, caused mainly by increases in ionic conductivity (Guan, Cheng, Wang, & Tang, 2004; Wang et al., 2008). Overall, at any given salt level, loss factor of whey protein gels increased with temperatures but more sharply at high temperatures. The loss factor of salmon fillet, on the other hand,

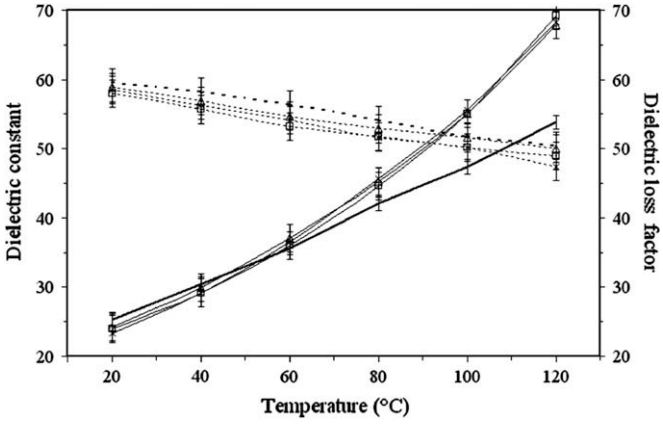

Fig. 2. Dielectric constant (dot) and loss factor (line) of pink salmon (bold) and whey protein gel (0.3 g/100 g NaCl) at D-ribose levels of 0.5 g/100 g (□), 1 g/100 g (△), and 1.5 g/100 g (×) at 915 MHz.

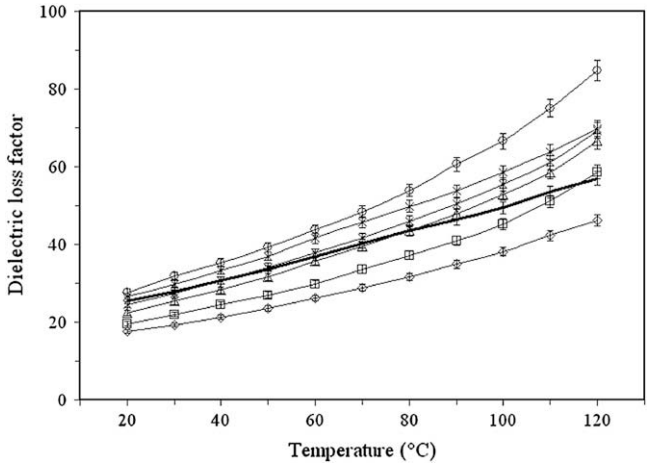

Fig. 3. Dielectric loss factor of pink salmon (——) and whey protein gel with D-ribose at 1 g/100 g and salt levels of 0 (◇), 0.1 g/100 g (□), 0.2 g/100 g (△), 0.3 g/100 g (×), 0.4 g/100 g (∗) and 0.5 g/100 g (○) at 915 MHz.

increased lineally over the whole tested temperature range (Fig. 3). In particular, the loss factor of whey protein gels with 0.2% and 0.3% salt contents was close to that of salmon fillets between 20 and 70 °C. Above 70 °C, those gels had increasingly higher loss factors than salmon fillets with increasing temperature (Fig. 3). It has been reported that for salt solutions loss factors increase sharply with temperature at frequencies far below the relaxation frequencies for free water (between 10,000 MHz and 30,000 MHz), because of increased ionic conductivity at elevated temperatures (Tang, 2005). In high moisture whey protein gels, the continuous matrix resembles a salt solution in terms of dielectric behavior. It is likely that the pink salmon muscle tissues and structures impede the migration of ions at elevated temperatures as compared to whey protein gels, resulting in a lower loss factor at the same salt level and temperature.

3.4. Comparison of dielectric properties of whey protein gel and pink salmon muscle

A gel with 1 g/100 g D-ribose and 0.2 g/100 g or 0.3 g/100 g NaCl had dielectric constants similar to those of pink salmon fillets both at 915 and 1800 MHz (Fig. 4). At lower temperatures (below 70 °C), the dielectric loss factors of the whey protein gel

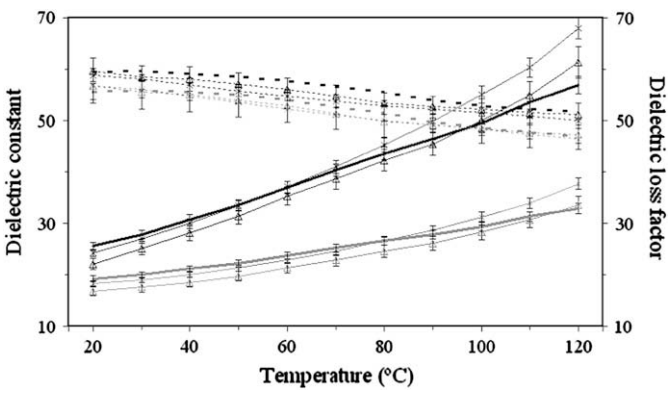

Fig. 4. Dielectric constant (dot) and loss factor (line) of pink salmon (bold) and whey protein gel (WPG, 1 g/100 g D-ribose) with 0.2 (△) and 0.3 g/100 g NaCl (×) at 915 MHz (black) and 1800 MHz (grey).

Table 2
Average penetration depth (mm) for whey protein gel and pink salmon fillets ($N = 3$).

Sample	T (°C)	27 MHz	40 MHz	433 MHz	915 MHz	1800 MHz
Pink salmon fillet	20	67.1 ± 4.23	56.46 ± 3.54	24.52 ± 1.40	17.83 ± 1.08	11.18 ± 0.53
	40	55.59 ± 3.45	46.41 ± 2.84	18.92 ± 1.00	14.59 ± 0.74	10.21 ± 0.50
	60	48.36 ± 3.05	40.16 ± 2.50	15.16 ± 0.83	11.92 ± 0.60	8.88 ± 0.46
	80	44.85 ± 2.76	37.13 ± 2.26	13.19 ± 0.69	10.25 ± 0.48	7.88 ± 0.34
	100	40.61 ± 2.54	33.57 ± 2.09	11.53 ± 0.65	8.80 ± 0.44	6.94 ± 0.21
	120	36.10 ± 2.53	29.82 ± 2.09	10.02 ± 0.65	7.46 ± 0.36	5.88 ± 0.19
Whey protein gel + 0.5 g/100 g D-ribose + 0.3 g/100 g NaCl	20	58.46 ± 0.92	49.15 ± 0.77	21.99 ± 0.40	16.93 ± 0.15	11.48 ± 0.18
	40	49.20 ± 1.30	41.13 ± 1.10	17.16 ± 0.30	13.76 ± 0.16	10.42 ± 0.18
	60	42.19 ± 1.00	35.12 ± 0.85	13.73 ± 0.23	11.09 ± 0.24	8.76 ± 0.08
	80	36.96 ± 0.79	30.68 ± 0.67	11.38 ± 0.20	9.07 ± 0.16	7.49 ± 0.17
	100	32.63 ± 0.77	27.03 ± 0.65	9.66 ± 0.27	7.48 ± 0.18	6.07 ± 0.03
	120	28.30 ± 0.65	23.40 ± 0.57	8.07 ± 0.16	6.19 ± 0.55	4.93 ± 0.18
Whey protein gel + 1 g/100 g D-ribose + 0.3 g/100 g NaCl	20	58.54 ± 1.73	49.13 ± 1.36	21.73 ± 0.48	16.83 ± 0.43	11.06 ± 0.08
	40	49.25 ± 1.55	41.09 ± 1.22	16.87 ± 0.47	13.57 ± 0.49	9.92 ± 0.21
	60	42.39 ± 1.04	35.22 ± 0.80	13.55 ± 0.24	10.94 ± 0.26	8.58 ± 0.16
	80	37.25 ± 0.86	30.86 ± 0.65	11.28 ± 0.20	9.01 ± 0.23	7.29 ± 0.16
	100	33.13 ± 0.39	27.39 ± 0.27	9.64 ± 0.09	7.55 ± 0.04	6.17 ± 0.07
	120	29.22 ± 0.99	24.12 ± 0.80	8.22 ± 0.18	6.29 ± 0.20	5.13 ± 0.17
Whey protein gel + 1.5 g/100 g D-ribose + 0.3 g/100 g NaCl	20	59.93 ± 1.19	50.46 ± 1.02	22.56 ± 0.63	17.47 ± 0.78	11.26 ± 0.32
	40	49.58 ± 1.16	41.47 ± 0.98	17.24 ± 0.52	13.84 ± 0.77	10.31 ± 0.17
	60	42.18 ± 0.82	35.12 ± 0.69	13.63 ± 0.35	11.05 ± 0.51	8.80 ± 0.14
	80	36.88 ± 0.60	30.62 ± 0.50	11.33 ± 0.40	8.90 ± 0.55	7.34 ± 0.20
	100	32.78 ± 0.18	27.16 ± 0.15	9.64 ± 0.08	7.43 ± 0.34	6.27 ± 0.15
	120	29.21 ± 0.68	24.17 ± 0.58	8.33 ± 0.09	6.18 ± 0.23	5.27 ± 0.38
Whey protein gel + 1 g/100 g D-ribose + 0.1 g/100 g NaCl	20	68.18 ± 3.13	57.61 ± 2.69	27.10 ± 1.71	20.42 ± 0.97	12.74 ± 0.32
	40	56.50 ± 2.15	47.37 ± 1.81	20.82 ± 1.19	16.68 ± 0.99	11.70 ± 0.48
	60	47.85 ± 1.61	39.91 ± 1.35	16.39 ± 0.82	13.45 ± 0.78	10.10 ± 0.39
	80	41.26 ± 1.31	34.29 ± 1.11	13.34 ± 0.74	10.86 ± 0.60	8.41 ± 0.12
	100	36.18 ± 1.27	29.98 ± 1.06	11.10 ± 0.56	8.99 ± 0.40	7.09 ± 0.08
	120	30.61 ± 1.04	25.30 ± 0.84	8.88 ± 0.27	7.00 ± 0.19	6.01 ± 0.10
Whey protein gel + 1 g/100 g D-ribose + 0.2 g/100 g NaCl=	20	63.42 ± 0.80	53.33 ± 0.61	23.78 ± 0.60	18.53 ± 0.07	12.00 ± 0.19
	40	52.17 ± 1.03	43.55 ± 0.90	17.92 ± 0.73	14.56 ± 0.32	10.77 ± 0.11
	60	44.11 ± 0.36	36.65 ± 0.30	14.09 ± 0.45	11.55 ± 0.23	9.18 ± 0.15
	80	39.25 ± 0.88	32.50 ± 0.50	11.86 ± 0.19	9.62 ± 0.050	7.83 ± 0.09
	100	35.49 ± 1.74	29.33 ± 1.33	10.31 ± 0.22	8.22 ± 0.25	6.78 ± 0.22
	120	31.26 ± 2.76	25.79 ± 2.18	8.80 ± 0.58	6.91 ± 0.51	5.75 ± 0.40

with 0.3 g/100 g salt and 1 g/100 g D-ribose were closer to those of salmon fillets; while at higher temperatures (above 70 °C), the gel with 0.2 g/100 g salt and 1 g/100 g D-ribose content was a better match. The whey protein gel had lower protein content (15 g/100 g wet weight basis) than that of pink salmon fillets (~26 g/100 g) (Sidwell, 1981; Nettleton, 1983; Exler, 1987; HNIS, 1987; Pennington, Young, & Wilson, 1989). But the moisture contents of the two materials were similar (78.2–79.2 g/100 g for whey protein gels vs. 75–80 g/100 g for salmon fillets). In moist and non-porous foods, moisture content is the most important composition that influences their thermal characteristics, namely thermal conductivity and specific heat.

3.5. Penetration depth

Penetration depths for pink salmon fillets were 67.1 ± 4.23 mm at 27 MHz and 17.83 ± 1.08 mm at 915 MHz at 20 °C, respectively. The penetration depth was reduced to 36.10 ± 2.53 mm at 27 MHz and 7.46 ± 0.36 mm at 915 MHz when product temperature increased to 120 °C (Table 2). Penetration depths for whey protein gels with 1 g/100 g D-ribose and 0.3 g/100 g NaCl were 58.54 ± 1.73 mm at 27 MHz and 16.83 ± 0.43 mm at 915 MHz for 20 °C, respectively. The penetration depth was reduced to 29.22 ± 0.99 mm at 27 MHz and 6.29 ± 0.20 mm at 915 MHz at 120 °C (Table 2). The results indicate that penetration depths for whey protein gels with 1 g/100 g D-ribose and 0.2 g/100 g NaCl were close to the penetration depths of pink salmon fillets in both MW and RF frequencies ranges suggesting that it could be used as a model food in these heating applications.

4. Conclusion

The dielectric properties of pink salmon (*O. gorbuscha*) fillet can be modeled using a whey protein gel with D-ribose (1 g/100 g) and 0.2 g/100 g or 0.3 g/100 g NaCl at 1–1800–MHz and 20–120 °C. The dielectric constant for pink salmon fillet and whey protein gel both sharply increased with temperature at 27 MHz and 40 MHz and moderately decreased at 433 MHz, 915 MHz and 1800 MHz. The dielectric loss factor increased with increasing temperature at 915 MHz. The higher the salt content the larger the dielectric loss factor was. Adding salt to whey protein gels can be used to adjust its dielectric properties, thus providing flexibility as a model food for microwave sterilization processes.

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