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Dielectric properties of foods relevant to RF and microwave pasteurization and sterilization

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Abstract

A custom-built temperature-controlled test cell and an Agilent 4291B impedance analyzer were used to determine the dielectric properties of a whey protein gel, a liquid whey protein mixture, and a macaroni and cheese product and their constituents. Dielectric constants, loss factors, and penetration depths for each sample over a temperature range from 20 to 121.1 °C, at frequencies of 27, 40, 915, and 1800 MHz are reported. As temperature increased, dielectric constants of whey protein products increased at 27 and 40 MHz, but decreased at 915 and 1800 MHz. Dielectric loss factors of whey protein products increased sharply with increasing temperatures at 27 and 40 MHz, but increased mildly at 915 and 1800 MHz. Similar results were observed with macaroni and cheese. The penetration depths of electromagnetic energy at 27 and 40 MHz were about four times as great as those at the microwave frequencies 915 and 1800 MHz in all tested samples.

Keywords: Dielectric properties; Penetration depth; Radio frequency; Microwave; Pasteurization/sterilization

1. Introduction

When a low acid ($pH > 4.5$) food is retorted to achieve commercial sterility and shelf-stability, the degradation of color, flavor, texture, and nutrients is unavoidable (Lund, 1988, Chapter 12). In conventional thermal processes, slow heat conduction from the heating medium to the cold-spot often results in treatment of the material at the periphery of the container that is far more severe than that required to achieve commercial sterility (Meredith, 1998). Dielectric heating, which includes radio frequency (RF) and microwave heating, has potential to replace conventional retort processes. Retorting can be greatly improved upon by eliminating the excessive heating (as found in retort processing) with rapid and more uniform heating from a direct interaction between RF or microwave energy and the food. However, in order to properly design an effective dielectric heating system, it is desirable to determine the factors that affect the rate of heating throughout the product. The dielectric properties of foods are the principal parameters that determine the coupling and distribution of electromagnetic energy during dielectric heating (Mudgett, 1986, Chapter 7). Dielectric properties are normally described in terms of the complex relative permittivity, ε_r:

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \quad (1)$$

where $j = \sqrt{-1}$. The real part of the relative complex permittivity, ε_r', known as the dielectric constant, describes the ability of a material to store energy in response to an applied electric field. The imaginary part of the relative complex permittivity, ε_r'', known as the loss factor, describes the ability of a material to dissipate energy in response to an applied electric field, which typically results in heat generation (Lorrain, Corson, & Lorrain, 1988, Chapter 10; Mudgett, 1986, Chapter 7; Nyfors & Vainikainen, 1989, Chapter 2). The dielectric properties of foods are often temperature dependent (Nelson, 1991), and therefore, must be known over the full range of temperatures experienced by the product to allow prediction of dielectric heating behavior. Many studies of dielectric properties have been reported in the literature, but dielectric data in those studies were not

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obtained at temperatures above the boiling point of water (Mudgett, 1986, Chapter 7), except for one study reported by Ohlsson and Bengtsson (1975) for microwave heating. Moreover, individual studies typically focused on simple substances such as alcohols, or on raw food materials, such as potatoes or apples. Some studies have attempted to predict dielectric behavior from the dielectric properties of a material's constituents (Nelson, 1991), but this becomes very difficult for complex recipes, e.g. ready-to-eat entrees. The dielectric properties of a food depend upon its composition. It is beneficial to conduct dielectric properties measurements for each product that is to undergo a dielectric heating process.

Another important concept in dielectric heating, known as power penetration depth (Buffler, 1993, Chapter 5), defines the distance an incident electromagnetic wave can penetrate beneath the surface of a material as the power decreases to $1/e$ of its power at the surface. It is calculated by equation:

$$d_{\mathrm{p}} = \frac{c}{2\sqrt{2}\pi f\left\{\varepsilon_{\mathrm{r}}'\left[\sqrt{1+\left(\frac{\varepsilon_{\mathrm{r}}''}{\varepsilon_{\mathrm{r}}'}\right)^2}-1\right]\right\}^{1/2}} \tag{2}$$

where c is the speed of light in vacuum, 2.998×10^8 m/s, f is the temporal frequency. This property is generally used to select appropriate thickness of food package to ensure a relatively uniform heating along the depth of a food package.

The objective of this research was to study the dielectric constants, loss factors, and radiation penetration depths of whey protein gel, liquid whey protein mixture, macaroni noodles, cheese sauce, and macaroni and cheese over a temperature range from 20 to 121.1 °C at frequencies of 27, 40, 915, and 1800 MHz. The temperature ranges covers typical conditions used in commercial pasteurization and sterilization processes and 121.1 °C is commonly used as a reference temperature in thermal process calculations in food engineering (Teixeira, 1992, Chapter 11; Toledo, 1991, Chapter 9). Frequencies of 27, 40, and 915 MHz are allocated for use in Industrial, Scientific, and Medical (ISM) heating applications according to international agreement, and 1800 MHz is the upper limit of the impedance analyzer used to determine the dielectric properties in this study.

2. Materials and methods

2.1. Dielectric properties measurement system and test cell

A dielectric properties measurement system used in this study consisted of an Agilent (formerly Hewlett Packard) 4291B impedance analyzer with a calibration kit (Agilent Technologies, Palo Alto, CA), a custom-built test cell, a VWR Model 1157 programmable circulator (VWR Science Products, West Chester, PA), a high-temperature coaxial cable, and the dielectric probe included in the Hewlett Packard 85070B dielectric probe kit (Fig. 1). The 4291B impedance analyzer can make measurements over the frequency range 1 to 1800 MHz. The probe was rated for use in the temperature range −40 to +200 °C. The impedance analyzer was connected through an IEEE-488 (GPIB) bus to a desktop personal computer, which used with custom-designed software DMS 85070 (Innovative Measurement Solutions), controlled the impedance analyzer and logged measured data. This system was suitable for measurements at temperatures up to 130 °C.

Before the measurements, the impedance analyzer was warmed up for at least 30 min, following the manufacturer's recommendations. All electrical connections were checked and cleaned with pure ethanol to remove any residue. The system was calibrated before each set of measurement because of small variations in the cable position, connections, ambient temperature, and other factors can affect the performance of the system. A 4291B calibration kit, which included four calibration standards: an open, a short, a 50 Ω load, and a low-loss

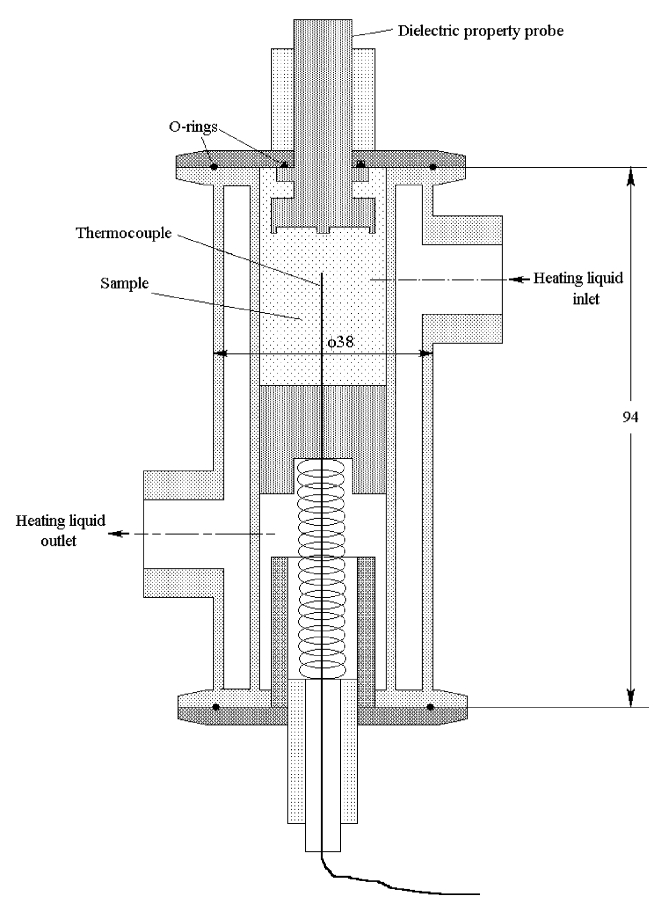

Fig. 1. Diagram of pressure-proof dielectric test cell (stainless steel), dimensions in mm.

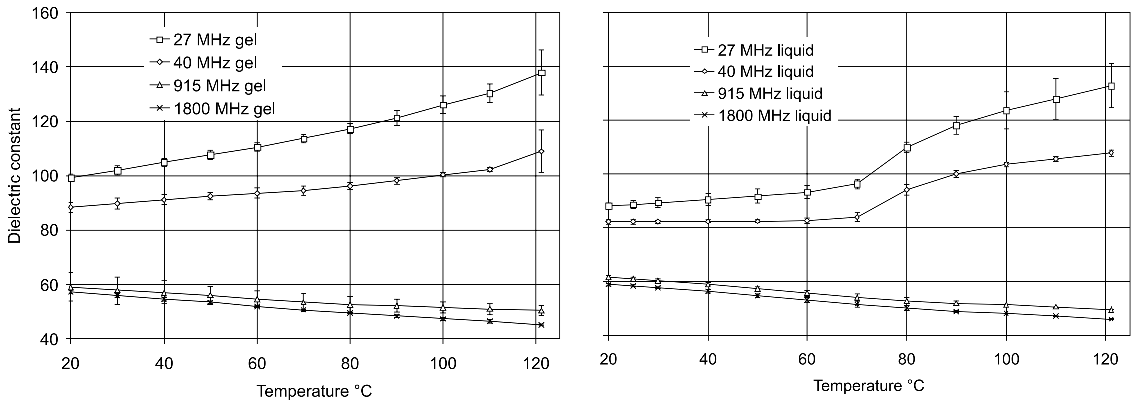

Fig. 2. Dielectric constants of whey protein gel and liquid whey protein mixture as a function of temperature at four frequencies.

capacitor, was used in this study to calibrate the impedance analyzer. Following this, an 85070B dielectric probe kit, which included a short circuit (a gold-plated precision shorting block), an open circuit (air), and a known load (pure water at 25 °C) was used to calibrate the testing probe.

Once the system was calibrated, a sample was placed into a custom-built temperature-controlled test cell (Fig. 1). The probe was then sealed into the loaded test cell and kept in contact with the sample during the measurement. The test cell was constructed of 2 coaxial sections of 1 in. and 1 and 1.5 in. OD 304 stainless steel sanitary tubing welded to a 1 in. sanitary ferrule at each end, to serve as sample holder and water jacket. The dielectric probe was installed through a solid sanitary end cap and sealed with an o-ring. The probe and end cap mated with the top end of the water-jacketed sample holder, sealed with a gasket and held in place using a sanitary clamp. A thermocouple port was mounted through the bottom sanitary end cap covering the other end of the sample holder. A stainless steel spring and a stainless steel piston provided constant pressure on the sample, maintaining close contact between the sample and the probe's tip through whole measurement. A thin 1.02 mm rigid stainless steel thermocouple probe passed through a pressure-tight gland in the thermocouple port, through the center of a spring and piston, and into the center of the sample to determine temperature of the sample. The programmable circulator was used to pump a temperature-controlled liquid (90% ethylene glycol and 10% water by volume) through the water jacket of the test cell, allowing the cylindrical sample inside to be heated or cooled. The circulator was capable of providing fluid at stable temperatures ranging from 10 to 130 °C during measurements.

2.2. Whey protein gel and liquid whey protein mixture

Dielectric property measurements were performed on two different materials: whey protein mixture/gel and macaroni and cheese. Macaroni and cheese was selected because it was used extensively as a heat sensitive food in a parallel dielectric heating sterilization research in our laboratory. Whey protein mixture/gel was selected because it was used as a model food to study the uniformity of dielectric heating using a chemical marker method (Kim, Taub, Choi, & Prakash, 1996, Chapter 6). The whey protein mixture/gel was made of 20% Alacen 882 whey protein concentrate (New Zealand Milk Products, Santa Rosa, CA) containing 80% protein on dry basis, 2% glucose (Fisher Scientific, Fair Lawn, NJ), 0.59% sodium chloride, with the remainder distilled water. The liquid whey protein mixture was prepared by mixing whey powder, glucose, sodium chloride and distilled water in a beaker. The mixture was then stirred for 1.5–2 h at room temperature on a magnetic stirring device. In preparing the gel, a 6 lb military group ration polymeric tray ($292 \times 229 \times 49$ mm) was filled with the liquid whey mixture and heat sealed with a lid. The sealed tray was immersed into a water bath at 80 °C for 40 min to form the gel. The gel was salt-doped to closely match the sodium content of the packaged macaroni and cheese since dielectric loss of foods depends, to a large extent, on the concentration of sodium chloride.

Measurements on whey protein gel and liquid whey protein mixture were conducted at every 10 °C increment from 20 to 121.1 °C. Intervals of 10 min were allowed to achieve each 10 °C increment in the sample before dielectric properties were measured. This period was adequate for the sample to reach a stable state of temperature. Additional measurements were also conducted on gel whose temperature was directly raised from room temperature to each of the four temperatures: 60 °C (10 min), 80 °C (15 min), 100 °C (22 min), and 121.1 °C (40 min) to check if the sample heating procedures (temperature being raised in 10 °C intervals or being raised directly to a set point) affected the results of the measurements.

Table 1
Compositions and ingredients of cooked macaroni noodles, cheese sauce, and macaroni and cheese

Product		CHO	Fat	Protein	Ash	H_2O	Total
Cooked macaroni noodles	Raw macaroni (g)	124.80	2.00	20.80	1.20	17.30	166.10
	H_2O (g)					174.00	174.00
	Total constitute (g)	124.80	2.00	20.80	1.20	191.30	340.10
	% mass basis (%)	36.70	0.59	6.12	0.35	56.25	100.00
Cheese sauce	Milk (g)	3.05	2.15	2.15	0.45	54.20	62.00
	Margarine (g)	0.10	25.00	0.20	0.90	10.60	36.80
	Cheese mix (g)	26.50	1.50	6.35	0.75	4.40	39.50
	H_2O (g)					71.00	71.00
	Total constitute (g)	29.65	28.65	8.70	2.10	140.20	209.30
	% mass basis (%)	14.17	13.69	4.16	1.00	66.99	100.00
Macaroni and cheese	Total constitute (g)	154.45	30.65	29.50	3.30	331.50	549.40
	% mass basis (%)	28.11	5.58	5.37	0.60	60.34	100.00

2.3. Macaroni noodles, cheese sauce, and macaroni and cheese

To prepare the sample of macaroni and cheese, 166 g of semolina noodles (IGA, Inc., Chicago, IL) were cooked for 6 min in boiling water to make 340 g of cooked noodles. A sauce was made of 62 g whole milk, 36.9 g margarine (Imperial, Lipton, Englewood, Cliffs, NJ), 39.5 g cheese powder (Kraft Foods Inc., Northfield, IL), and 71 g of water. The sauce was prepared by mixing melted margarine and cheese powder with milk and water at 80 °C using a stirring bar. The cheese sauce and drained noodles were combined to prepare the macaroni and cheese product. This precooking method was considered the most suitable for RF heating after many preliminary tests in term of heating uniformity and good texture. The ingredients of the macaroni (noodle), the sauce, and the macaroni and cheese product are shown in Table 1.

Measurements were made on samples of cooked macaroni noodles, on cheese sauce, and on macaroni and cheese mixture, respectively. The samples were blended well before each measurement. Intervals of 10 min were allowed for each 10 °C increment of the sample before dielectric properties were measured. Measurements were also conducted on macaroni and cheese product whose temperature was raised directly from room temperature to 121.1 °C to check if the sample heating procedures (temperature being raised every 10 °C or being raised directly to a set point) affected the results of the measurements for the materials tested in the study.

3. Results and discussion

Measured values of dielectric constant and loss factor as functions of temperature and frequency are shown in Tables 2–6, and in Figs. 2–9. No significant difference in dielectric properties was found between the samples whose temperature was raised in 10 °C increments and the samples whose temperatures were raised directly from room temperature to a set point (Tables 2 and 6). This suggests that sample heating procedures (temperatures being raised every 10 °C versus being raised directly to a set point) did not affect the results of the dielectric property measurements for the materials tested in this study.

3.1. Dielectric constant

Dielectric constants of whey protein gels and liquid whey protein mixture increased in the RF range (27 and 40 MHz) as temperature increased, but decreased in the microwave range (915 and 1800 MHz) as temperature increased (Fig. 2). The same trend was observed with macaroni and cheese but the changes were not as sharp as found with whey products (Fig. 3). The dielectric constants of whey products at 27 and 40 MHz, and cheese sauce at 27 MHz were greater than 80 (Figs. 2 and 4). Stuchly, Athey, Samaras and Taylor (1982), and Sheen and Woodhead (1999) also reported that dielectric constants of biological tissues and agricultural products were greater than 80. Sheen and Woodhead, (1999) attributed this phenomenon to a poorly conditioned calibration at low frequencies. During calibration, low lossy reference—pure water gives a very similar reflection coefficient to that of air at low frequencies leading to a calibration with inaccurate coefficient. We speculated, during measurement, ions at the face of the probe could lead to erroneously high readings of the dielectric constant, and that this effect was particularly pronounced for materials having a high loss factor. The ion content (and, consequently, the equivalent loss factor and conductivity) for many of the food products used with the dielectric probe system was expected to be quite high, which would almost certainly affect the low frequency dielectric constant measurements. While

Table 2
Dielectric properties of whey protein gels

Product	T (°C)		27 MHz	40 MHz	915 MHz	1800 MHz
Whey protein gel	20	ε'	99.23 ± 1.27	88.27 ± 1.76	59.03 ± 5.26	57.17 ± 0.60
		ε''	835.97 ± 10.05	569.17 ± 7.59	34.80 ± 2.36	23.30 ± 1.25
	30	ε'	101.97 ± 1.55	89.77 ± 2.07	57.77 ± 5.06	55.87 ± 0.74
		ε''	981.77 ± 25.74	668.13 ± 18.58	39.17 ± 2.86	24.73 ± 1.33
	40	ε'	104.97 ± 1.50	91.23 ± 1.91	57.00 ± 4.27	54.67 ± 0.67
		ε''	1155.57 ± 25.84	785.47 ± 18.84	44.10 ± 2.55	26.67 ± 1.18
	50	ε'	107.73 ± 1.59	92.43 ± 1.38	56.03 ± 3.37	53.43 ± 0.55
		ε''	1337.03 ± 33.62	907.60 ± 23.86	49.50 ± 2.45	28.93 ± 1.10
	60	ε'	110.5 ± 1.57	93.57 ± 1.84	54.53 ± 3.09	51.83 ± 0.31
		ε''	1534.10 ± 37.73	1040.33 ± 27.02	54.63 ± 2.92	31.20 ± 1.31
	70	ε'	113.63 ± 1.69	94.60 ± 1.73	53.43 ± 3.15	50.60 ± 0.36
		ε''	1739.77 ± 41.65	1178.67 ± 30.02	60.93 ± 3.09	34.17 ± 1.42
	80	ε'	117.23 ± 1.84	96.17 ± 1.52	52.57 ± 3.00	49.43 ± 0.45
		ε''	1956.17 ± 40.37	1323.93 ± 29.41	67.50 ± 2.88	37.43 ± 1.46
	90	ε'	121.33 ± 2.72	98.13 ± 1.18	52.10 ± 2.36	48.33 ± 0.55
		ε''	2172.27 ± 48.17	1473.57 ± 35.16	73.97 ± 2.42	40.67 ± 1.27
	100	ε'	126.07 ± 3.25	100.37 ± 0.96	51.63 ± 2.05	47.30 ± 0.66
		ε''	2392.70 ± 49.36	1622.67 ± 35.99	80.57 ± 2.04	44.03 ± 1.14
	110	ε'	130.40 ± 3.32	102.30 ± 0.70	50.97 ± 2.00	46.37 ± 0.70
		ε''	2626.60 ± 42.66	1781.23 ± 31.71	87.80 ± 1.77	47.80 ± 0.98
	121.1	ε'	137.97 ± 8.19	108.90 ± 7.81	50.33 ± 1.90	44.97 ± 0.38
		ε''	2854.87 ± 40.27	1935.13 ± 25.58	95.27 ± 0.50	51.77 ± 0.40
Temperature was raised from 20 °C directly to a set point	20	ε'	95.52 ± 1.38	86.77 ± 1.53	59.58 ± 0.78	55.60 ± 0.88
		ε''	802.73 ± 11.69	545.45 ± 8.38	29.41 ± 2.15	21.56 ± 1.75
	60	ε'	109.70 ± 1.58	95.54 ± 1.78	55.50 ± 2.79	50.73 ± 0.79
		ε''	1410.08 ± 22.48	955.72 ± 19.38	48.37 ± 2.99	28.93 ± 1.56
	80	ε'	116.37 ± 1.76	98.61 ± 1.55	53.86 ± 1.01	48.23 ± 1.86
		ε''	1777.81 ± 28.65	1206.79 ± 30.13	59.83 ± 2.77	34.45 ± 1.34
	100	ε'	120.35 ± 1.89	98.61 ± 1.44	51.65 ± 1.90	45.59 ± 0.73
		ε''	2198.94 ± 31.33	1486.79 ± 33.67	72.28 ± 3.02	40.74 ± 0.98
	121.1	ε'	126.35 ± 2.08	100.76 ± 5.36	51.11 ± 1.11	44.30 ± 0.55
		ε''	2755.64 ± 29.56	1860.01 ± 31.58	88.54 ± 0.87	48.90 ± 0.76

accurate wideband dielectric constant measurements would have been useful, this was not seen as a significant drawback in the applications considered in this work. The dielectric constant of pure water, for example, 78.2 at 25 °C and 55.4 at 100 °C is understood to be constant between direct current and 100 MHz (Hasted, 1972, Chapter 7). While food materials typically have a high water content (e.g., $\geqslant 80\%$), their other constituents also play a role in determining the dielectric constant, and may not be constant below 100 MHz. Even so, it was believed that the dielectric constant could be regarded as constant at low frequencies for many materials. Although certain precautions need to be taken in using the value of dielectric constants obtained at low frequencies in this study, the observed trends of dielectric behavior are useful in providing insights into the dielectric characteristics of the tested material during a heating process.

At 27 and 40 MHz, dielectric constants of liquid whey protein mixture were about 10% lower than that of whey protein gel at temperature from 20 to 70 °C (Fig. 2). There was a sudden increase of dielectric constant at temperatures from 70 to 90 °C, then the curves for liquids at 27 and 40 MHz almost overlapped with that of gel at temperature over 90 °C (Fig. 2). This might have been attributed to a denaturation of main component of whey protein gel, β-lactoglobulin, at about 80 °C (Bernal & Jelen, 1985). Also, we observed a phase change from liquid mixture to solid gel at about 80 °C.

Dielectric constant of cooked macaroni noodles in the RF range (27, 40 MHz) increased with temperature (Table 4 and Fig. 5), much like that of whey protein

Table 3
Dielectric properties of liquid whey protein mixture

Product	T (°C)		27 MHz	40 MHz	915 MHz	1800 MHz
Liquid whey protein mixture	20	ε'	88.10 ± 1.13	82.20 ± 0.71	61.65 ± 0.78	58.90 ± 0.57
		ε''	885.80 ± 5.66	596.85 ± 3.75	33.55 ± 0.07	23.10 ± 0.14
	25	ε'	88.65 ± 1.48	82.20 ± 0.71	61.10 ± 0.71	58.45 ± 0.49
		ε''	961.85 ± 7.85	648.40 ± 5.23	35.65 ± 0.07	23.75 ± 0.21
	30	ε'	89.30 ± 1.70	82.25 ± 0.49	60.40 ± 0.57	57.80 ± 0.42
		ε''	1061.45 ± 13.65	715.15 ± 9.55	38.25 ± 0.21	24.65 ± 0.21
	40	ε'	90.55 ± 2.33	82.40 ± 0.57	59.00 ± 0.57	56.45 ± 0.49
		ε''	1255.60 ± 11.88	845.25 ± 8.13	43.60 ± 0.14	26.75 ± 0.21
	50	ε'	91.65 ± 2.62	82.45 ± 0.64	57.40 ± 0.85	54.85 ± 0.78
		ε''	1469.90 ± 21.64	988.75 ± 14.64	49.55 ± 0.49	29.35 ± 0.35
	60	ε'	93.20 ± 2.55	82.70 ± 0.99	55.70 ± 1.13	53.20 ± 0.99
		ε''	1683.35 ± 35.57	1131.95 ± 24.11	55.55 ± 0.92	32.00 ± 0.71
	70	ε'	96.30 ± 1.84	83.95 ± 1.63	54.20 ± 1.41	51.70 ± 1.27
		ε''	1879.15 ± 54.52	1263.20 ± 36.77	61.30 ± 1.56	34.75 ± 0.92
	80	ε'	109.80 ± 1.98	94.05 ± 1.91	52.95 ± 1.20	50.15 ± 0.92
		ε''	2088.95 ± 35.43	1405.55 ± 24.40	68.85 ± 1.20	38.40 ± 0.85
	90	ε'	118.05 ± 3.32	100.00 ± 1.27	52.05 ± 0.78	49.00 ± 0.42
		ε''	2294.60 ± 23.62	1549.05 ± 16.33	75.90 ± 0.71	41.90 ± 0.57
	100	ε'	123.60 ± 6.93	103.50 ± 0.85	51.60 ± 0.00	48.30 ± 0.14
		ε''	2567.55 ± 38.82	1733.10 ± 25.88	84.25 ± 1.20	46.10 ± 0.28
	110	ε'	127.85 ± 7.57	105.55 ± 0.92	50.70 ± 0.00	47.20 ± 0.14
		ε''	2800.25 ± 37.55	1890.30 ± 25.03	91.30 ± 1.13	49.70 ± 0.28
	121.1	ε'	132.70 ± 8.20	107.80 ± 1.13	49.70 ± 0.00	46.15 ± 0.07
		ε''	3084.25 ± 30.90	2082.05 ± 20.29	99.75 ± 1.06	53.90 ± 0.57

products. Dielectric constant of cooked macaroni noodles in the microwave range (915 and 1800 MHz) also increased with increasing temperature (Fig. 5) in contrast to the trend observed with whey products. This might be due to the relatively lower water content (56%) of the cooked macaroni noodles. This is in agreement with the trend reported by Feng, Tang, and Cavalieri (2002). They indicated that dielectric constants of red delicious apples (*Malus domestica* Borkh) increased with increase of temperature in the microwave range (915 and 1800 MHz) when moisture content of apples was less than 70%, and decreased when moisture content was more than 70%.

3.2. Dielectric loss factor

Dielectric loss factors of whey protein gels and liquid whey protein mixture increased sharply at 27 and 40 MHz with increasing temperature, but relatively little change was observed at 915 and 1800 MHz (Fig. 6). The same trend was observed with macaroni and cheese but not as steeply sloped as the curves for whey gel (Fig. 7).

Electric conduction and various polarization mechanisms, including dipole, electronic, atomic and Maxwell–Wanger all contribute to the dielectric loss factor (Kuang & Nelson, 1998; Metaxas & Meredith, 1993). The loss factor of a material possessing ionic solution can be expressed as:

$$\varepsilon'' = \varepsilon''_{\mathrm{d}} + \varepsilon''_{\sigma} \tag{3}$$

where $\varepsilon''_{\mathrm{d}}$ is relative dipole loss, and ε''_{σ} is relative ionic loss. Loss factor contributed by ionic conductivity increases with the increase of temperature while loss factor contributed by dipole rotation of free water decreases with the increase of temperature at the two fixed microwave frequencies (915 MHz and 2450 MHz) (Fig. 8). Moreover, ionic conductivity plays a major role at lower frequencies (below 200 MHz, for example), while both ionic conductivity and dipole rotation of free water play a combination role at microwave frequencies (e.g. 915 and 1800 MHz). Therefore, loss factors of whey protein products, and macaroni and cheese increased sharply at 27 and 40 MHz with the increase of temperature. Meanwhile, loss factors increased mildly or barely changed at 915 and 1800 MHz due to the opposing effects of ionic conductivity and dipole rotation of free water. The results indicated that run away heating (synergy of temperature and loss factor) is very likely to

Table 4
Dielectric properties of cooked macaroni noodles

Product	T (°C)		27 MHz	40 MHz	915 MHz	1800 MHz
Cooked macaroni noodles	20	ε'	35.10 ± 0.14	34.55 ± 0.78	29.15 ± 0.35	27.60 ± 1.27
		ε''	15.80 ± 0.71	11.65 ± 0.07	4.20 ± 1.41	6.05 ± 0.49
	30	ε'	36.30 ± 3.11	35.65 ± 3.46	30.05 ± 2.47	29.15 ± 3.18
		ε''	16.80 ± 2.83	12.65 ± 2.05	4.15 ± 1.06	5.30 ± 0.42
	40	ε'	38.20 ± 2.97	37.45 ± 3.32	31.85 ± 2.76	30.90 ± 2.69
		ε''	21.35 ± 3.75	15.70 ± 2.83	4.70 ± 0.14	5.05 ± 0.49
	50	ε'	39.50 ± 2.55	38.80 ± 2.83	33.25 ± 2.47	32.35 ± 2.33
		ε''	27.00 ± 3.54	19.70 ± 2.55	4.65 ± 0.21	4.75 ± 0.35
	60	ε'	40.80 ± 1.84	39.95 ± 2.33	34.30 ± 1.98	33.60 ± 1.84
		ε''	34.20 ± 2.97	24.45 ± 2.33	4.60 ± 0.14	4.40 ± 0.28
	70	ε'	42.70 ± 2.26	41.95 ± 2.62	36.30 ± 2.55	35.50 ± 2.12
		ε''	43.85 ± 4.03	31.00 ± 2.97	4.80 ± 0.42	4.30 ± 0.42
	80	ε'	44.55 ± 2.33	43.70 ± 2.69	38.0 ± 2.40	37.30 ± 1.84
		ε''	55.70 ± 5.66	39.15 ± 4.03	5.10 ± 0.57	4.25 ± 0.35
	90	ε'	46.50 ± 1.13	45.40 ± 1.41	39.40 ± 1.41	38.75 ± 0.92
		ε''	70.80 ± 3.25	49.25 ± 2.33	5.40 ± 0.42	4.20 ± 0.28
	100	ε'	48.10 ± 0.85	46.85 ± 1.20	40.70 ± 1.41	39.90 ± 0.71
		ε''	87.05 ± 3.32	60.30 ± 2.12	5.85 ± 0.64	4.30 ± 0.28
	110	ε'	47.80 ± 1.27	46.55 ± 1.63	40.45 ± 1.91	39.75 ± 1.20
		ε''	97.80 ± 4.53	67.55 ± 2.90	6.00 ± 0.71	4.20 ± 0.28
	121.1	ε'	48.80 ± 1.56	47.40 ± 1.84	40.90 ± 1.84	40.15 ± 1.34
		ε''	113.60 ± 5.09	78.40 ± 3.25	6.55 ± 0.64	4.40 ± 0.28

Table 5
Dielectric properties of cheese sauce

Product	T (°C)		27 MHz	40 MHz	915 MHz	1800 MHz
Cheese sauce	20	ε'	69.37 ± 4.3	59.57 ± 3.51	42.90 ± 1.91	39.37 ± 3.37
		ε''	1309.97 ± 117.60	885.57 ± 80.46	46.17 ± 4.84	27.90 ± 2.79
	30	ε'	71.57 ± 5.36	59.77 ± 4.45	41.00 ± 2.43	38.97 ± 3.65
		ε''	1557.90 ± 140.65	1052.7 ± 96.11	52.70 ± 4.44	30.47 ± 2.78
	40	ε'	75.03 ± 5.59	60.67 ± 4.14	40.13 ± 2.04	38.27 ± 3.39
		ε''	1845.70 ± 151.45	1246.43 ± 103.55	60.77 ± 4.75	34.03 ± 2.87
	50	ε'	78.33 ± 5.78	61.70 ± 4.49	39.10 ± 1.68	37.40 ± 3.06
		ε''	2134.13 ± 154.65	1443.50 ± 108.45	69.03 ± 4.98	37.80 ± 2.91
	60	ε'	82.43 ± 6.81	63.00 ± 4.93	37.87 ± 1.33	36.37 ± 2.70
		ε''	2462.23 ± 181.96	1666.63 ± 125.20	78.43 ± 6.19	42.27 ± 3.51
	70	ε'	86.77 ± 6.52	64.63 ± 4.82	36.87 ± 1.06	35.40 ± 2.35
		ε''	2771.67 ± 166.60	1876.23 ± 115.22	87.47 ± 5.61	46.47 ± 3.05
	80	ε'	91.23 ± 7.38	66.37 ± 5.42	35.83 ± 0.84	34.43 ± 2.14
		ε''	3096.90 ± 162.62	2096.90 ± 112.63	97.00 ± 5.55	51.07 ± 3.22
	90	ε'	96.63 ± 7.31	68.60 ± 5.28	34.87 ± 0.74	33.37 ± 1.99
		ε''	3414.13 ± 121.85	2312.1 ± 85.20	106.43 ± 4.19	55.60 ± 2.72
	100	ε'	101.50 ± 7.40	70.93 ± 5.42	34.07 ± 0.76	32.57 ± 1.74
		ε''	3696.90 ± 127.35	2504.2 ± 89.31	114.97 ± 4.40	59.67 ± 2.78
	110	ε'	106.57 ± 8.18	73.03 ± 5.61	33.20 ± 0.96	31.70 ± 1.51
		ε''	4005.90 ± 111.88	2709.2 ± 78.96	124.17 ± 4.05	64.20 ± 2.70
	121.1	ε'	111.70 ± 5.94	75.15 ± 4.35	31.70 ± 0.49	31.60 ± 0.21
		ε''	4410.9 ± 17.29	2985.5 ± 11.00	136.80 ± 0.14	70.20 ± 1.70

Table 6
Dielectric properties of macaroni and cheese

Product	T (°C)		27 MHz	40 MHz	915 MHz	1800 MHz
Macaroni and cheese	20	ε'	70.90 ± 8.96	65.27 ± 8.29	40.23 ± 3.71	38.77 ± 5.41
		ε''	400.03 ± 55.18	273.47 ± 37.76	21.33 ± 3.81	17.40 ± 3.39
	30	ε'	72.40 ± 9.09	66.53 ± 8.52	40.87 ± 3.18	39.07 ± 5.35
		ε''	486.57 ± 66.47	331.40 ± 45.06	23.47 ± 4.26	17.90 ± 3.46
	40	ε'	72.87 ± 8.22	66.63 ± 7.65	40.90 ± 2.88	39.30 ± 5.10
		ε''	593.50 ± 63.65	403.13 ± 43.11	27.30 ± 5.51	19.03 ± 3.21
	50	ε'	72.67 ± 8.87	66.27 ± 8.20	40.53 ± 3.07	38.90 ± 5.16
		ε''	688.70 ± 67.08	466.53 ± 45.38	29.77 ± 5.55	19.70 ± 3.03
	60	ε'	73.07 ± 8.55	66.13 ± 7.91	40.03 ± 3.00	38.53 ± 5.08
		ε''	800.30 ± 57.46	541.43 ± 38.88	32.87 ± 5.21	20.93 ± 2.71
	70	ε'	74.03 ± 8.03	66.67 ± 7.51	40.07 ± 2.70	38.17 ± 4.89
		ε''	921.37 ± 62.49	622.73 ± 42.61	36.23 ± 4.76	22.23 ± 2.49
	80	ε'	73.83 ± 8.13	65.67 ± 7.43	39.53 ± 2.39	37.57 ± 4.92
		ε''	1060.27 ± 55.75	716.17 ± 37.55	39.70 ± 4.75	23.67 ± 2.44
	90	ε'	76.67 ± 8.37	67.17 ± 7.34	40.67 ± 4.88	37.17 ± 4.60
		ε''	1208.60 ± 67.57	815.70 ± 45.29	43.23 ± 3.30	25.23 ± 1.40
	100	ε'	80.93 ± 5.59	69.90 ± 4.75	40.67 ± 4.38	37.13 ± 4.52
		ε''	1382.23 ± 117.32	932.73 ± 78.84	48.17 ± 2.55	27.57 ± 0.84
	110	ε'	83.23 ± 4.91	71.13 ± 3.60	40.37 ± 4.48	36.77 ± 4.67
		ε''	1536.13 ± 164.25	1035.87 ± 110.15	52.37 ± 3.04	29.57 ± 1.36
	121.1	ε'	84.33 ± 5.26	71.07 ± 4.17	38.93 ± 4.82	35.57 ± 4.84
		ε''	1712.80 ± 172.76	1154.57 ± 115.96	57.40 ± 3.64	31.87 ± 1.75
Temperature was raised directly from 20 to 121.1	20	ε'	70.30 ± 1.84	65.50 ± 1.70	38.15 ± 0.21	40.20 ± 0.71
		ε''	406.05 ± 4.88	278.80 ± 3.11	20.15 ± 0.21	16.60 ± 0.71
	121.1	ε'	78.05 ± 0.64	69.65 ± 0.35	36.10 ± 0.28	39.55 ± 0.35
		ε''	1563.25 ± 22.98	1057.05 ± 15.77	52.75 ± 0.07	30.00 ± 0.00

occur in the RF range while it is not as likely in the microwave frequency range. This suggests the importance of appropriate design of RF applicator to provide initial uniform electric magnetic field in a thermal process based on RF energy.

The values of dielectric properties of macaroni and cheese were found to be between those of its constituents, lower than those of cheese sauce but higher than those of cooked macaroni noodles (Figs. 9 and 10). This was due to the fact that both the water content and ion

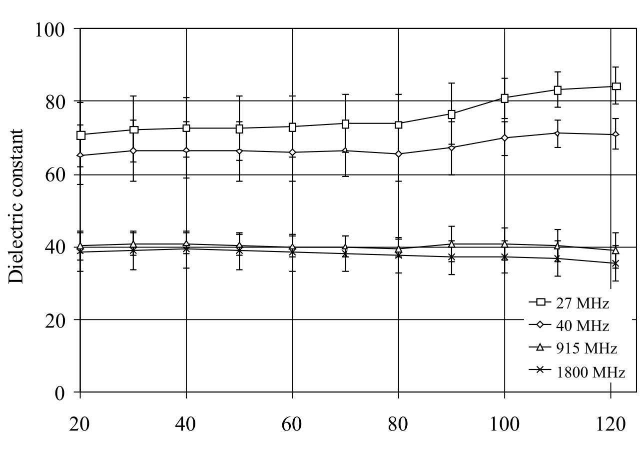

Fig. 3. Dielectric constants of macaroni and cheese as a function of temperature at four frequencies.

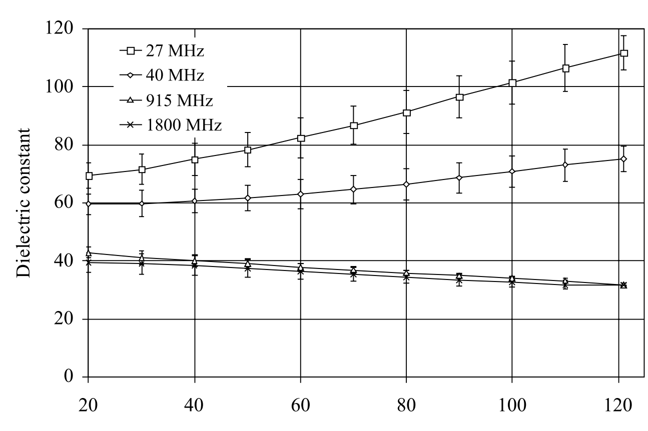

Fig. 4. Dielectric constants of cheese sauce as a function of temperature at four frequencies.

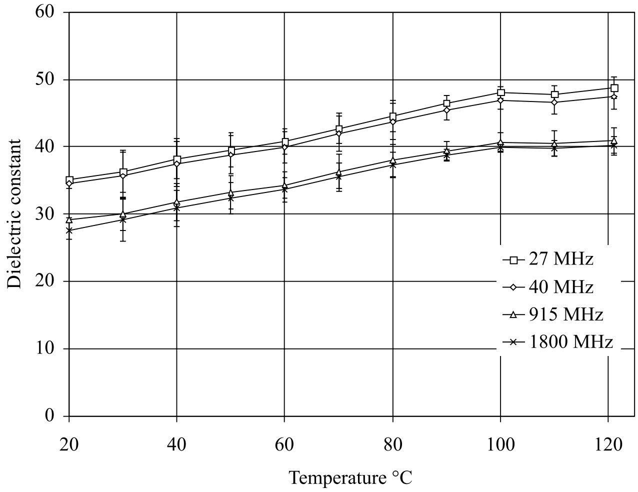

Fig. 5. Dielectric constant of cooked macaroni noodles as a function of temperature at four frequencies.

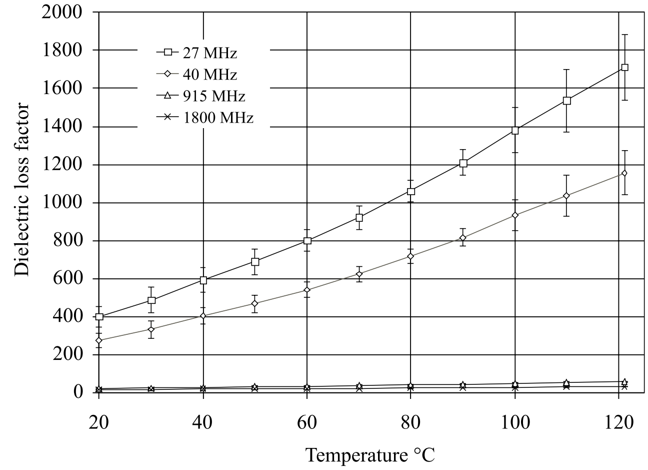

Fig. 7. Dielectric factors of macaroni and cheese as a function of temperature at four frequencies.

content of macaroni and cheese were between those of its constituents.

3.3. Penetration depth

The power penetration depths for whey protein products (liquid mixture and gel) were about 45 mm at 27 MHz and 12 mm at 915 MHz at 20 °C. The penetration depths reduced to 24 mm at 27 MHz and 5 mm at 915 MHz when temperature reached 121.1 °C (Table 7). The penetration depths for macaroni and cheese were 68.3 mm at 27 MHz and 16.0 mm at 915 MHz at 20 °C. The penetration depths reduced to 31.0 mm at 27 MHz and 6.7 mm at 915 MHz when temperature reached 121.1 °C (Table 8). In summary, the penetration depths reduced by about half when temperature rose from 20 to 121.1 °C at four frequencies. The penetration depths in RF range (27 and 40 MHz) were about 5 times as much as that in microwave frequencies (915 and 2450 MHz) at each corresponding temperature. The results indicated that for most food, the power penetration depths de-

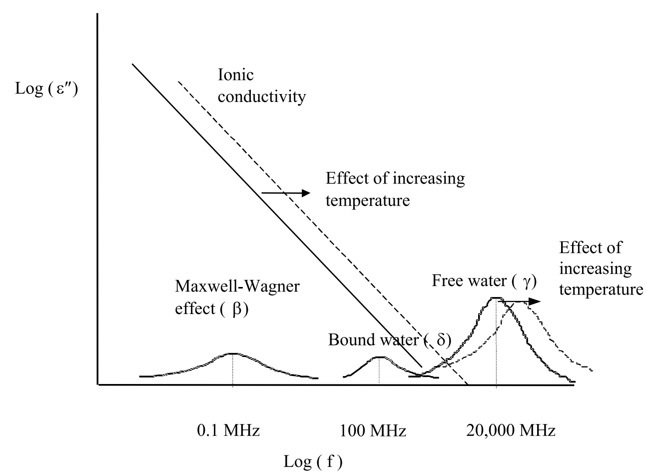

Fig. 8. Contribution of various mechanisms to the loss factor of high moisture materials as functions of frequency and temperature (Tang, Feng, & Lau, 2002, Chapter 1, based on Harvey & Hoekstra, 1972; Kuang & Nelson, 1998; Metaxas & Meredith, 1993; Roebuck & Goldblith, 1972).

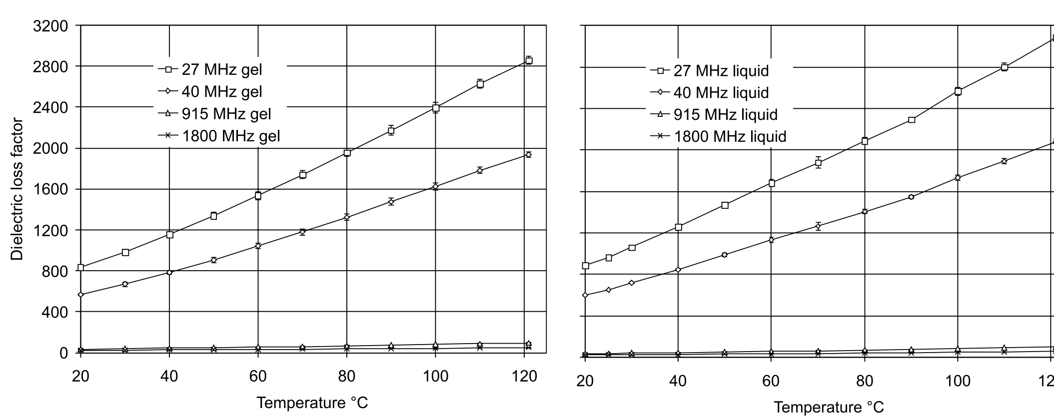

Fig. 6. Dielectric loss factors of whey protein gel and liquid whey protein mixture as a function of temperature at four frequencies.

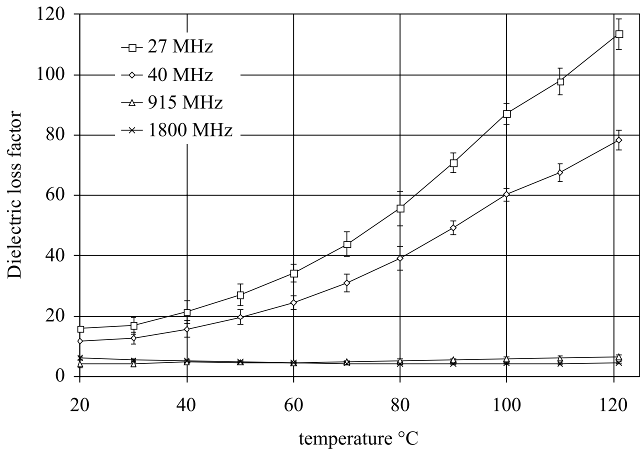

Fig. 9. Dielectric loss factors of cooked macaroni noodles as a function of temperature at four frequencies.

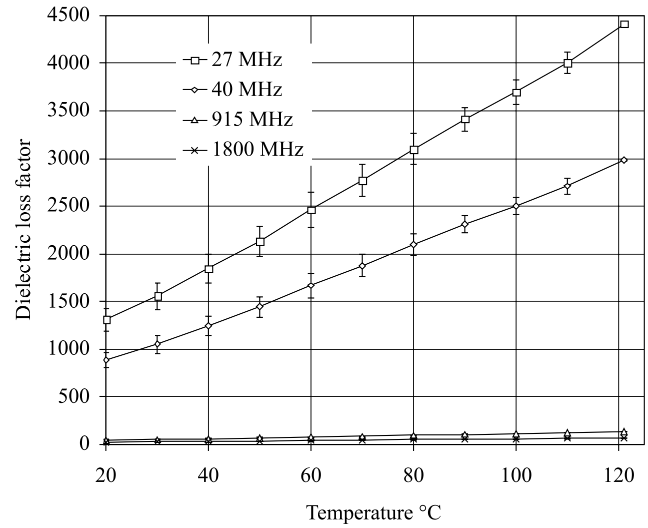

Fig. 10. Dielectric loss factors of cheese sauce as a function of temperature at four frequencies.

Table 7
Power penetration depths of electromagnetic waves in whey protein gels and liquid whey protein mixture

Product	*T* (°C)	Power penetration depth (mm)				
		27 MHz	40 MHz	915 MHz	1800 MHz	2450 MHz[a]
Whey protein gel	20	45.9	38.2	12.0	8.8	6.5
	30	42.0	34.9	10.6	8.2	6.0
	40	38.5	31.9	9.5	7.6	5.6
	50	35.6	29.5	8.5	6.9	5.1
	60	33.1	27.4	7.8	6.4	4.7
	70	31.0	25.6	7.0	5.8	4.3
	80	29.1	24.1	6.4	5.3	3.9
	90	27.6	22.7	6.0	5.0	3.6
	100	26.2	21.6	5.6	4.5	3.3
	110	25.0	20.6	5.2	4.2	3.1
	121.1	24.0	19.7	4.9	3.9	2.8
Liquid whey protein mixture	20	44.2	37.0	12.6	9.0	6.6
	25	42.2	35.3	11.9	8.7	6.4
	30	40.0	33.4	11.1	8.4	6.1
	40	36.6	30.5	9.7	7.7	5.6
	50	33.7	28.0	8.6	6.9	5.1
	60	31.3	26.0	7.7	6.3	4.6
	70	29.6	24.6	7.0	5.8	4.2
	80	28.1	23.3	6.3	5.2	3.8
	90	26.8	22.2	5.8	4.8	3.5
	100	25.3	20.9	5.4	4.4	3.2
	110	24.2	20.0	5.0	4.1	3.0
	121.1	23.0	19.0	4.7	3.8	2.8

[a] Calculated from extrapolated dielectric property data at each temperature.

crease as temperature increases; the power penetration depths decrease as frequency increases. The change of frequency from RF range (27 and 40 MHz) to microwave range (915 and 2450 MHz) impact penetration depths much more than change of temperature from 20 to 121.1 °C. In term of dielectric heating, RF power is suitable to deep food trays while microwave can be used in shallow food trays.

4. Conclusions

The procedure for heating the samples (temperature being raised every 10 °C versus being raised directly to a set point) did not affect the results of the dielectric property measurements for the materials tested in this study. Dielectric constants of whey protein products, and macaroni and cheese increased at 27 and 40 MHz,

Table 8
Power penetration depths of electromagnetic waves in cooked macaroni noodles, cheese sauce, and macaroni and cheese

Product	T (°C)	Power penetration depth (mm)				
		27 MHz	40 MHz	915 MHz	1800 MHz	2450 MHz[a]
Cooked macaroni noodles	20	678.9	610.5	67.3	23.2	17.0
	30	650.2	571.9	69.1	27.1	19.9
	40	530.2	475.0	62.8	29.3	21.5
	50	432.8	388.7	64.9	31.9	23.4
	60	354.6	321.6	66.6	35.0	25.7
	70	290.7	264.1	65.6	36.8	27.1
	80	241.7	218.1	63.2	38.2	28.1
	90	202.3	181.7	60.8	39.4	28.9
	100	174.5	155.4	57.1	39.0	28.7
	110	160.0	141.7	55.5	39.9	29.3
	121.1	144.5	126.9	51.1	38.3	28.1
Cheese sauce	20	35.5	29.3	8.2	6.3	4.6
	30	32.4	26.8	7.3	5.8	4.3
	40	29.7	24.5	6.5	5.2	3.8
	50	27.6	22.7	5.8	4.7	3.5
	60	25.6	21.1	5.3	4.3	3.1
	70	24.1	19.8	4.8	3.9	2.9
	80	22.8	18.7	4.5	3.6	2.6
	90	21.7	17.8	4.2	3.3	2.5
	100	20.9	17.1	4.0	3.2	2.3
	110	20.0	16.4	3.8	3.0	2.2
	121.1	19.1	15.6	3.5	2.8	2.1
Macaroni and cheese	20	68.3	57.5	16.0	9.7	7.1
	30	61.1	51.2	14.8	9.5	7.0
	40	54.6	45.6	12.8	9.0	6.6
	50	50.2	41.9	11.8	8.6	6.4
	60	46.3	38.6	10.8	8.1	6.0
	70	42.9	35.7	9.9	7.7	5.6
	80	39.8	33.0	9.1	7.2	5.3
	90	37.1	30.8	8.5	6.7	5.0
	100	34.6	28.7	7.8	6.2	4.6
	110	32.8	27.1	7.3	5.8	4.3
	121.1	31.0	25.6	6.7	5.4	4.0

[a] Calculated from extrapolated dielectric property data at each temperature.

but decreased at 915 and 1800 MHz as temperature increased from 20 to 121.1 °C. Dielectric loss factors of whey protein products, and macaroni and cheese increased sharply at 27 and 40 MHz with increasing temperature, but only increased slightly at 915 and 1800 MHz. This indicated that run away heating is very likely to occur at RF range while it is not as likely at microwave frequency range. The penetration depths at RF range (27 and 40 MHz) were about four times as deep as for microwave frequencies (915 and 2450 MHz) at each corresponding temperature. This feature allows RF energy to penetrate dielectric material more deeply with more uniform heating along the depth of a food package than microwave energy. It indicates that RF heating may be particularly useful when applied to institutional size packaged food products.

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References

Bernal, V., & Jelen, P. (1985). Thermal stability of whey proteins—a calorimetric study. *Journal of Dairy Science, 68*(11), 2847–2852.

Buffler, C. R. (Ed.) (1993). Microwave cooking and processing, *Microwave cooking and processing* (pp. 47–68). New York: Van Nostrand Reinhold.

Feng, H., Tang, J., & Cavalieri, R. P. (2002). Dielectric properties of dehydrated apples as affected by moisture and temperature. *Transaction of ASAE, 45*(1), 129–135.

Harvey, S. C., & Hoekstra, P. (1972). Dielectric relaxation spectra of water adsorbed on lysozyme. *Journal of Physical Chemistry, 76*(21), 2987–2994.

Hasted, J. B. (1972). Dielectric properties. In F. Franks (Ed.), *Water a comprehensive treatise* (pp. 255–309). New York: Plenum Press.

Kim, H., Taub, I. A., Choi, Y., & Prakash, A. (1996). Principle and applications of chemical markers of sterility in high-temperature-short-time processing of particulate foods. In T. Lee & H. Kim (Eds.), *Chemical markers for processed and stored foods* (pp. 54–69). Washington, DC: American Chemical Society.

Kuang, W., & Nelson, S. O. (1998). Low-frequency dielectric properties of biological tissues: a review with some new insights. *Transactions of ASAE, 41*(1), 173–184.

Lorrain, P., Corson, D. R., & Lorrain, F. (Eds.). (1988). *Electromagnetic fields and waves* (3rd ed., pp. 192–210). New York, NY: W.H. Freeman and Company.

Lund, D. B. (1988). Effects of heat processing on nutrients. In E. Karmas & R. S. Harris (Eds.), *Nutritional evaluation of food processing* (3rd ed., pp. 319–354). New York, NY: Van Nostrand Reinhold Co.

Meredith, R. (1998). *Engineers' handbook of industrial microwave heating*. London, UK: The Institution of Electrical Engineers.

Metaxas, A. C., & Meredith, R. J. (Eds.) (1993). Industrial microwave heating. *IEE power engineering series 4*, Peter Peregrinus Ltd., London.

Mudgett, R. E. (1986). Electrical properties of foods. In M. A. Rao & S. S. H. Rizvi (Eds.), *Engineering properties of foods* (pp. 329–390). New York, NY: Marcel Dekker, Inc.

Nelson, S. O. (1991). Dielectric properties of agricultural products. *IEEE Transaction on Electrical Insulation, 26*(5), 845–869.

Nyfors, E., & Vainikainen, P. (Eds.). (1989). *Industrial microwave sensors*. Norwood: Artech House.

Ohlsson, Th., & Bengtsson, N. E. (1975). Dielectric food data for microwave sterilization processing. *Journal of Microwave Power, 10*(1), 93–108.

Roebuck, B. D., & Goldblith, S. A. (1972). Dielectric properties of carbohydrate–water mixtures at microwave frequencies. *Journal of Food Science, 37*, 199–204.

Sheen, N. I., & Woodhead, I. M. (1999). An open-ended coaxial probe for broad-band permittivity measurement of agricultural products. *Journal of Agricultural Engineering Research, 74*, 193–202.

Stuchly, M. A., Athey, T. W., Samaras, G. M., & Taylor, G. E. (1982). Measurement of radio frequency permittivity of biological tissues with an open ended coaxial line: part II—experimental results. *IEEE Transactions on Microwave Theory and Techniques, 30*(1), 87–92.

Tang, J., Feng, H., & Lau, M. (2002). Microwave heating in food processing. In X. Young & J. Tang (Eds.), *Advances in bioprocessing engineering* (pp. 1–43). New Jersey: Scientific Press.

Teixeira, A. (1992). Thermal process calculations. In D. R. Heldman & D. B. Lund (Eds.), *Handbook of food engineering* (pp. 563–619). New York, NY: Marcel Dekker, Inc.

Toledo, R. T. (Ed.) (1991). Thermal process calculations, *Fundaments of food process engineering* (pp. 315–397). New York, NY: Chapman & Hall.