Dielectric Properties of Mashed Potatoes Relevant to Microwave and Radio-frequency Pasteurization and Sterilization Processes

D. GUAN, M. CHENG, Y. WANG, AND J. TANG

ABSTRACT: Dielectric properties of mashed potatoes relevant to microwave and radio-frequency (RF) pasteurization and sterilization processes were measured over 1 to 1800 MHz and 20 °C to 120 °C. Effects of moisture content (81.6% to 87.8%, wb) and salt content (0.8% to 2.8%, wb) were investigated. Dielectric loss factors and constants decreased with frequency. Dielectric loss factors increased with temperature and salt content, but dielectric constants were not significantly affected. Ionic conductivity played a dominant role at low frequencies. Power penetration depth increased with moisture content and decreased with temperature, frequency, and salt content. Regression equations were developed to relate the dielectric properties to temperature, moisture, and salt contents.

Keywords: dielectric properties, mashed potatoes, microwave, radio frequency, pasteurization, sterilization

Introduction

Experimental studies on microwave and radio-frequency (RF) heating, also called dielectric heating, started in the middle of the 20th century (Cathcart and others 1947; Kenyon and others 1971). Dielectric heating can be more uniform than conventional heating because of the direct interaction between food materials and electromagnetic waves (Datta and Hu 1992). However, many factors, such as variations in electric fields, food constituents, and the location of food packages in a microwave or RF applicator, can still lead to the nonuniform heating (Berek and Wickersheim 1988), which makes the survival of microorganisms possible at less-heated locations within the processed food products (Schiffmann 1990; Stanford 1990). Techniques to improve uniformity of dielectric heating include rotating and oscillating foods, providing an absorbing medium (water) to surround products (Stenström 1974; Guan and others 2002, 2003; Wang and others 2003a), cycling power (Morris 1991), and varying frequency and phase (Bows 1999; Bows and others 1999). In spite of the above techniques, there is a need for a knowledge of the dielectric properties (dielectric constant [ε'] and dielectric loss factor [ε'']) of food materials to develop effective dielectric heating processes (for example, 915 and 2450 MHz for microwave; 27 and 40 MHz for RF heating).

The dielectric properties of foods determine how they react to an external electric field (Kuang and Nelson 1998). ε' reflects the ability of a material to store electromagnetic energy, and ε'' measures the ability of a material to dissipate electric energy as heat. The frequency of the electromagnetic waves, temperature, water content, and salt content of food materials can affect the related dielectric properties and the resultant dielectric heating (Engelder and Buffler 1991; Galema 1997). Extensive experimentally obtained data for the dielectric properties of various foods have been reported in the literature; but reliable values of dielectric properties of foods above 100 °C for both microwave and RF ranges are scarce. Ohlsson and Bengtsson (1975) measured 16 industrially prepared foods from 40 °C to 140 °C but only at microwave frequencies of 450, 900, and 2800 MHz. They stated that dielectric-properties data could not be extrapolated from low temperature up to sterilization region. Sipahioglu and Barringer (2003) reported the dielectric properties of selected fruits and vegetables from 5 °C to 130 °C at 2450 MHz. Only Wang and others (2003b) recently reported the dielectric properties of macaroni and cheese entrees, macaroni noodles, and whey protein gel products at both microwave and radio frequencies (27 to 1800 MHz) and temperatures up to 121 °C.

Efforts have been made to relate dielectric properties to food composition, temperature, and frequency. Calay and others (1995) developed a series of polynomial equations to estimate dielectric properties of a wide range of food materials in 3 major groups (that is, grains, fruits and vegetables, and meat products). The predictive equations included the influence of food composition (that is, moisture, salt, and fat content) and temperature (mostly below 70 °C) at microwave frequencies between 900 and 3000 MHz for vegetables and meats and up to 10000 MHz for grains. But the equations for more than 50% of the food materials had relatively small coefficients of determination (r^2 between 0.70 to 0.82). Sun and others (1995) also compiled dielectric properties for fruits, vegetables, meats, and fish (all moisture contents greater than 60%, wb) recorded in the literature and performed regression analyses in the frequency range of 2400 to 2500 MHz and the temperature range between 5 °C and 65 °C. They proposed to use easily measurable but dielectrically important compositions (that is, moisture and salt contents) as the main factors in the predictive equations. After fitting to the reported data in the literature, they concluded that it was impossible to develop a generic composition-based equation for all food products. The equations need to be specific for 1 product or a group of products. Yagmaee and Durance (2002) developed polynomial equations for simple and mixed aqueous solutions of NaCl (0% to 6%, wt/wt), D-sorbitol (0% to 18%, wt/wt) and sucrose (0% to 60%, wt/wt)

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based on dielectric property data measured at 21 °C and 2450 MHz. For simple solutions containing 1 solute, the equations worked very well. But for mixed solutions, effects of different solutes were not additive. Sipahioglu and Barringer (2003) developed the predictive equations at 2450 MHz for 15 vegetables and fruits. The equations included effects of temperature, moisture, and ash contents. They have found that separating vegetables from fruits increased the correlation between dielectric properties and food composition and temperature. ε' was reported to be better predicted than the ε''. In summary, it is generally recognized in the literature that it is impossible to predict the dielectric properties of complex food products over broad temperature and frequency ranges. Direct dielectric properties measurement needs to be conducted over specific composition, temperature, and frequency range if accurate values of those properties for selected food materials are desired in dielectric heating studies.

At Washington State Univ. (WSU, Pullman, Wash., U.S.A.), a pilot-scale single-mode 915-MHz microwave-circulated water combination (MCWC) heating system and a pilot-scale 27 MHz RF heating system were developed for food pasteurization and sterilization research. Both systems can shorten the overall processing time and help retain natural texture and flavor of selected foods (Guan and others 2002; Wang and others 2003a). For further process development and validation of microwave and RF sterilization protocols, mashed potatoes were chosen as a model food. Mashed potatoes are relatively homogeneous and easy to formulate and, thus, can be used as a benchmark product reference. Although Regier and others (2001) measured the dielectric properties of mashed potatoes as a function of temperature (–17.7 °C to 80 °C) and preparation procedures at 2450 MHz, it was still necessary to obtain dielectric properties of mashed potatoes at other microwave and RF frequencies, particularly over the pasteurization and sterilization temperature range (80 °C to 120 °C).

The objectives of this study were to study the influences of frequency, moisture, and salt contents on the dielectric properties of mashed potatoes over a temperature range suited for pasteurization and sterilization processes based on dielectric heating. The obtained information can benefit the related computer simulation work on dielectric heating and the designs of industrial microwave and RF heating systems in the future.

Materials and Methods

Mashed potatoes preparation

Instant mashed-potato flakes were acquired from Oregon/Washington Potatoes Co. (Boardman, Oreg., U.S.A.). The mashed-potato flakes had 8.25 ± 0.04% (db) moisture, 5.64 ± 0.02% (db) ash, 11.64 ± 0.10% (db) total protein, and 68.6 ± 1.90% (db) starch. The moisture content was measured by AOAC method (925.10 1990), and ash content was measured by AACC method (30.25 1983). Protein content was determined by AACC Method (46.30 2000), using a LECO FP528 instrument (LECO Corp., St. Joseph, Mich., U.S.A.) equipped with a thermoconductivity detector. Total starch content was measured by AACC method (76.13 1983) using the Megazyme kits (Megazyme Intl. Ireland Ltd., Wicklow, Ireland).

The supplier of the potato flakes recommended a water/potato ratio of 5.5:1 (mass) to formulate mashed potatoes. In this study, mashed potatoes were prepared with 4 water/potato mass ratios (4:1, 5:1, 5.5:1, and 6.5:1), and the corresponding moisture contents were 81.6%, 84.7%, 85.9%, and 87.8% (wb), respectively. Mashed potatoes were either runny or too coarse beyond the above moisture range. Nonsalted samples (moisture content: 85.9%, wb) had a salt content of 0.8% (wb). Salt-enriched samples (salt content: 1.3%, 1.8%, and 2.8%, wb) having a moisture content of 85.9% (wb) were prepared by mixing mashed-potato flakes and salt solutions with predetermined concentrations. Conductivities of mashed potatoes were measured in 3 replicates using a conductivity meter (CON-500, Cole-Parmer Instrument Co., Vernon Hills, Ill., U.S.A.). Prepared mashed potatoes were stored at 4 °C for measurement within 48 h.

Dielectric properties measurement

Open-ended coaxial-line probe method was used to measure dielectric properties of mashed potatoes because it requires no particular sample shapes and offers broad-brand measurement. The measurement system (Figure 1) consisted of an RF impedance analyzer with a calibration kit (4291B, Agilent Technologies, Palo Alto, Calif., U.S.A.), a test cell custom-built at WSU (20-mm inner dia, 94-mm height, stainless steel), a high-temperature coaxial cable, a dielectric probe kit (85070B, Hewlett Packard Corp., Santa Clara, Calif., U.S.A.), and an oil bath equipped with a programmable circulator (Model 1157, VWR Science Products, West Chester, Pa., U.S.A.). The system can measure sample dielectric properties over a frequency range from 1 to 1800 MHz and a temperature range from 10 °C to 130 °C. During the

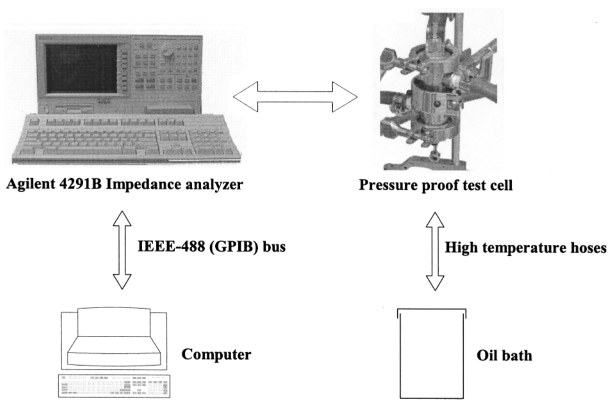


Figure 1—Dielectric measurement system at Washington State Univ.

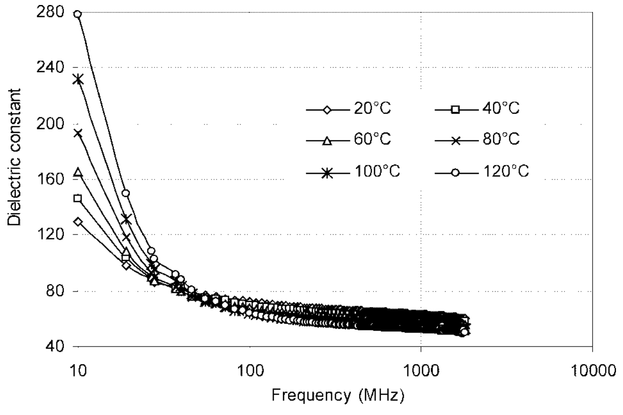


Figure 2—Change of dielectric constant of mashed potatoes (moisture content: 81.6%, wb; salt content: 0.8%, wb) with frequency at 6 temperatures

measurement, the mashed potato sample was placed into the test cell, where the dielectric probe was sealed and kept in close contact with samples through pressure from a stainless-steel spring and a stainless-steel piston. Detailed description of the calibration and measurement procedures is given by Wang and others (2003b).

After calibration, each sample of mashed potatoes was measured at 201 discrete frequencies between 1 and 1800 MHz at 20 °C, 40 °C, 60 °C, 80 °C, 100 °C, and 120 °C, respectively. Mean values and standard deviations were calculated from 3 replicates. The data at 27, 40, 433, and 915 MHz are reported because they are allocated for industrial, scientific, and medical application (European Radio Communications Committee and U.S. Federal Communication Commission). Dielectric data at 1800 MHz, the upper limit of the impedance analyzer, are also reported.

Table 1—Mean ± standard deviation (3 replicates) of dielectric properties for mashed potatoes (salt content: 0.8%, wb) with different moisture levels (%, wb)

Sample	T(°C)		27 MHz	40 MHz	433 MHz	915 MHz	1800 MHz
81.6%	20	ϵ'	87.5 ± 1.0	80.4 ± 2.4	60.7 ± 5.3	56.4 ± 7.6	58.4 ± 2.8
		ϵ''	328.2 ± 11.5	224.4 ± 7.3	33.1 ± 4.5	22.3 ± 3.6	15.8 ± 0.5
	40	ϵ'	89.1 ± 1.2	78.3 ± 1.3	59.7 ± 2.7	56.8 ± 3.4	57.3 ± 1.0
		ϵ''	459.0 ± 16.1	312.8 ± 11.2	38.6 ± 3.9	23.7 ± 3.4	15.6 ± 0.8
	60	ϵ'	90.7 ± 2.1	79.2 ± 0.6	57.8 ± 2.4	55.3 ± 2.5	55.5 ± 0.6
		ϵ''	605.0 ± 19.2	410.4 ± 12.4	46.2 ± 4.2	26.1 ± 3.7	16.1 ± 1.0
	80	ϵ'	94.0 ± 3.1	79.3 ± 0.7	56.2 ± 1.5	53.6 ± 2.0	53.0 ± 1.0
		ϵ''	783.4 ± 15.4	530.3 ± 9.6	56.1 ± 2.7	30.7 ± 3.2	17.8 ± 0.9
	100	ϵ'	100.7 ± 4.3	82.5 ± 1.9	55.0 ± 1.3	52.8 ± 1.7	51.5 ± 0.9
		ϵ''	1001.8 ± 18.4	678.1 ± 11.0	68.6 ± 1.4	35.9 ± 2.1	20.2 ± 0.6
	120	ϵ'	113.2 ± 7.1	88.6 ± 4.1	54.6 ± 1.5	52.5 ± 1.0	50.4 ± 1.3
		ϵ''	1340.0 ± 60.3	906.3 ± 42.4	88.5 ± 2.9	44.4 ± 1.2	24.4 ± 0.6
84.7%	20	ϵ'	88.6 ± 3.7	82.4 ± 1.4	68.7 ± 0.5	66.3 ± 0.3	63.7 ± 0.1
		ϵ''	297.5 ± 11.9	203.6 ± 7.0	26.6 ± 3.3	18.9 ± 3.8	15.7 ± 2.1
	40	ϵ'	89.1 ± 5.7	81.2 ± 2.7	65.5 ± 0.3	63.4 ± 0.0	61.4 ± 0.1
		ϵ''	409.8 ± 22.3	279.6 ± 13.6	32.9 ± 3.4	20.6 ± 3.6	14.8 ± 2.0
	60	ϵ'	89.9 ± 7.3	79.5 ± 3.6	62.3 ± 0.2	60.4 ± 0.4	58.6 ± 0.2
		ϵ''	541.0 ± 31.9	367.9 ± 19.5	40.1 ± 3.2	22.8 ± 3.0	14.9 ± 1.7
	80	ϵ'	91.3 ± 9.2	78.4 ± 4.3	58.9 ± 0.4	57.0 ± 0.6	55.4 ± 0.4
		ϵ''	689.7 ± 47.5	468.4 ± 29.2	48.9 ± 3.8	26.4 ± 3.1	16.0 ± 1.8
	100	ϵ'	96.1 ± 10.6	79.5 ± 7.7	56.1 ± 1.7	53.7 ± 2.1	53.0 ± 1.1
		ϵ''	895.9 ± 43.5	607.5 ± 25.8	62.7 ± 5.5	33.8 ± 5.7	18.9 ± 2.5
	120	ϵ'	102.8 ± 12.1	81.6 ± 10.1	53.6 ± 2.6	51.1 ± 3.1	50.9 ± 1.4
		ϵ''	1153.8 ± 49.2	782.4 ± 29.1	78.8 ± 5.8	41.5 ± 6.0	22.5 ± 2.6
85.9%	20	ϵ'	89.2 ± 7.2	82.2 ± 4.9	68.1 ± 2.1	64.2 ± 1.4	65.8 ± 1.9
		ϵ''	276.6 ± 29.9	188.8 ± 20.8	32.1 ± 3.2	27.1 ± 3.0	16.3 ± 0.7
	40	ϵ'	89.8 ± 8.1	81.0 ± 5.0	67.0 ± 1.6	65.7 ± 0.7	63.7 ± 0.6
		ϵ''	382.9 ± 42.4	260.3 ± 29.5	32.6 ± 5.0	22.8 ± 4.5	14.4 ± 1.5
	60	ϵ'	90.5 ± 8.0	79.4 ± 4.2	63.7 ± 1.5	62.5 ± 0.8	60.7 ± 0.6
		ϵ''	513.6 ± 42.0	348.2 ± 28.7	39.9 ± 4.7	25.2 ± 4.2	14.7 ± 1.3
	80	ϵ'	92.5 ± 9.7	78.5 ± 4.4	60.8 ± 2.0	59.9 ± 1.5	58.0 ± 1.0
		ϵ''	660.1 ± 63.9	446.9 ± 43.3	47.7 ± 5.3	27.6 ± 4.0	15.4 ± 1.5
	100	ϵ'	96.8 ± 9.9	79.0 ± 3.6	58.2 ± 1.0	57.3 ± 0.7	55.5 ± 0.5
		ϵ''	839.9 ± 61.8	567.9 ± 42.0	58.3 ± 5.5	32.0 ± 4.4	17.5 ± 1.6
	120	ϵ'	102.1 ± 10.5	80.0 ± 3.2	55.4 ± 0.4	54.5 ± 0.4	52.8 ± 0.1
		ϵ''	1060.1 ± 60.6	716.6 ± 41.1	71.7 ± 4.8	38.1 ± 3.8	20.1 ± 1.3
87.8%	20	ϵ'	88.2 ± 5.5	81.3 ± 4.4	68.7 ± 6.6	66.0 ± 8.6	65.6 ± 4.9
		ϵ''	277.4 ± 23.2	189.3 ± 14.3	27.1 ± 5.8	20.3 ± 8.1	14.8 ± 1.4
	40	ϵ'	89.0 ± 4.9	79.8 ± 3.2	66.7 ± 4.3	65.5 ± 6.0	63.7 ± 4.5
		ϵ''	380.9 ± 31.4	259.2 ± 19.9	29.5 ± 0.9	18.6 ± 3.1	12.9 ± 0.4
	60	ϵ'	89.3 ± 5.7	77.7 ± 3.4	62.7 ± 4.2	61.6 ± 5.7	60.5 ± 3.8
		ϵ''	497.7 ± 44.4	337.9 ± 28.2	36.6 ± 0.6	21.2 ± 2.8	13.0 ± 0.3
	80	ϵ'	91.9 ± 5.3	77.3 ± 2.3	60.3 ± 2.3	59.6 ± 3.0	57.7 ± 2.5
		ϵ''	638.4 ± 61.7	432.7 ± 39.8	43.3 ± 2.9	22.6 ± 0.9	13.5 ± 0.7
	100	ϵ'	98.8 ± 7.9	79.4 ± 3.0	58.5 ± 2.0	57.7 ± 2.7	55.8 ± 2.1
		ϵ''	846.3 ± 77.8	573.1 ± 70.4	55.9 ± 5.9	28.2 ± 2.6	15.9 ± 1.4
	120	ϵ'	104.9 ± 8.0	80.9 ± 2.7	56.1 ± 1.7	55.3 ± 2.3	53.6 ± 1.8
		ϵ''	1066.0 ± 105.0	721.8 ± 68.2	69.8 ± 5.5	34.9 ± 2.3	19.0 ± 1.2

Regression equations

The regression considered the effects of temperature, moisture, and salt contents. Polynomial relationships, mostly used in the literature for complex food systems, were chosen to develop the regression equations at 27, 40, 433, and 915 MHz. Response variables (ε' and ε'') were fit through regression analysis (Minitab, Minitab Inc., State College, Pa., U.S.A.), using the least square technique. The regression equations and all the predictors in the equations had a significance of $P < 0.001$. The goodness of fit was assessed from the adjusted coefficient of determination (r^2_{adj}) of the equation.

Power penetration depth

Power penetration depth, 1 of the essential dielectric processing parameters, is defined as the distance that the incident power decreases to 1/e (e = 2.718) of its value at the surface. The power penetration depth can be calculated by the following equation (Buffler 1993):

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

where c is the speed for light in free space (3×10^8 m/s), and f is the frequency (Hz).

Results and Discussion

ε''s and ε'''s of mashed potatoes at 27, 40, 433, 915, and 1800 MHz are given in Table 1 and Table 2 for 4 moisture levels (81.6%, 84.7%, 85.9%, and 87.8%, wb; salt content: 0.8%, wb) and 4 salt levels (0.8%, 1.3%, 1.8%, and 2.8%, wb; moisture content: 85.9%, wb), respectively.

Effect of frequency

Both ε' and ε'' decreased with frequency (Figure 2 and 3). This agrees with the observations reported by Pace and others (1968), who measured dielectric properties of raw potatoes (moisture content: 79.5% to 83.3%, wb) at 300, 1000, and 3000 MHz, respectively. It is interesting to observe that ε' increased with increasing temperature below a certain frequency (around 55.97 MHz in this study); above this "threshold" frequency, ε' decreased with increasing temperature (Figure 2). A similar phenomenon was observed for whey protein gel products with a moisture content of 74% (wb) (Nelson and Bartley 2002).

Table 2—Mean ± standard deviation (3 replicates) of dielectric properties for mashed potatoes (moisture content: 85.9%, wb) with different salt levels (%, wb)

Sample	T(°C)		27 MHz	40 MHz	433 MHz	915 MHz	1800 MHz
0.8%	20	ϵ'	89.2 ± 7.2	82.2 ± 4.9	68.1 ± 2.1	64.2 ± 1.4	65.8 ± 1.9
		ϵ''	276.6 ± 29.9	188.8 ± 20.8	32.1 ± 3.2	27.1 ± 3.0	16.3 ± 0.7
	40	ϵ'	89.8 ± 8.1	81.0 ± 5.0	67.0 ± 1.6	65.7 ± 0.7	63.7 ± 0.6
		ϵ''	382.9 ± 42.4	260.3 ± 29.5	32.6 ± 5.0	22.8 ± 4.5	14.4 ± 1.5
	60	ϵ'	90.5 ± 8.0	79.4 ± 4.2	63.7 ± 1.5	62.5 ± 0.7	60.7 ± 0.6
		ϵ''	513.6 ± 42.0	348.2 ± 28.7	39.9 ± 4.7	25.2 ± 4.2	14.7 ± 1.3
	80	ϵ'	92.5 ± 9.7	78.5 ± 4.4	60.8 ± 2.0	59.9 ± 1.5	58.0 ± 1.1
		ϵ''	660.1 ± 63.9	446.9 ± 43.3	47.7 ± 5.3	27.6 ± 4.0	15.4 ± 1.8
	100	ϵ'	96.8 ± 9.9	79.0 ± 3.6	58.2 ± 1.0	57.3 ± 0.7	55.5 ± 0.5
		ϵ''	839.9 ± 61.8	567.9 ± 42.0	58.3 ± 5.5	32.0 ± 4.4	17.4 ± 1.6
	120	ϵ'	102.1 ± 10.5	78.0 ± 3.2	55.4 ± 0.4	54.5 ± 0.4	52.8 ± 0.1
		ϵ''	1060.1 ± 60.6	716.6 ± 41.1	71.7 ± 4.8	38.1 ± 3.8	20.1 ± 1.3
1.3%	20	ϵ'	88.2 ± 1.7	81.9 ± 2.6	68.4 ± 2.6	66.0 ± 2.5	64.3 ± 3.5
		ϵ''	583.0 ± 38.2	393.4 ± 25.4	41.2 ± 2.7	24.0 ± 1.9	17.5 ± 0.1
	40	ϵ'	88.5 ± 1.2	79.9 ± 2.2	64.7 ± 3.0	62.5 ± 2.9	61.1 ± 4.2
		ϵ''	817.1 ± 59.4	550.3 ± 39.3	54.8 ± 4.0	29.4 ± 2.4	18.4 ± 0.8
	60	ϵ'	90.1 ± 0.2	79.1 ± 1.2	61.8 ± 2.5	59.6 ± 2.5	58.6 ± 3.5
		ϵ''	1097.1 ± 64.3	738.5 ± 42.6	71.5 ± 4.2	36.7 ± 2.5	21.4 ± 0.6
	80	ϵ'	92.2 ± 0.5	78.4 ± 0.8	58.9 ± 2.2	56.6 ± 2.4	55.6 ± 4.0
		ϵ''	1416.9 ± 80.4	952.9 ± 53.1	90.7 ± 5.0	45.3 ± 2.8	25.4 ± 0.9
	100	ϵ'	95.4 ± 1.6	78.7 ± 1.9	56.5 ± 2.2	54.3 ± 2.2	52.9 ± 3.2
		ϵ''	1782.5 ± 92.9	1197.8 ± 61.7	112.8 ± 5.8	55.5 ± 3.1	30.4 ± 1.7
	120	ϵ'	102.8 ± 1.1	81.5 ± 1.0	54.6 ± 0.5	52.3 ± 0.8	53.0 ± 0.9
		ϵ''	2238.3 ± 42.5	1507.3 ± 28.5	140.8 ± 2.8	68.5 ± 1.7	36.0 ± 2.1
1.8%	20	ϵ'	78.2 ± 6.1	71.4 ± 5.4	56.9 ± 5.0	55.1 ± 4.3	53.5 ± 5.0
		ϵ''	713.3 ± 112.7	480.5 ± 75.3	49.4 ± 6.8	28.4 ± 3.0	19.4 ± 1.4
	40	ϵ'	79.4 ± 5.0	70.4 ± 4.1	54.7 ± 3.4	52.8 ± 2.8	51.7 ± 3.5
		ϵ''	999.6 ± 118.9	672.3 ± 79.8	66.3 ± 7.2	35.6 ± 3.1	21.5 ± 1.2
	60	ϵ'	79.9 ± 3.0	68.6 ± 2.6	51.5 ± 2.2	49.4 ± 1.8	48.3 ± 2.9
		ϵ''	1306.7 ± 93.8	878.2 ± 62.7	84.4 ± 5.7	43.4 ± 2.5	24.7 ± 1.1
	80	ϵ'	81.6 ± 0.4	67.5 ± 0.3	48.0 ± 0.1	46.1 ± 0.4	45.2 ± 1.0
		ϵ''	1614.4 ± 27.1	1084.5 ± 20.0	102.8 ± 0.3	51.7 ± 0.5	28.7 ± 0.4
	100	ϵ'	94.1 ± 2.7	74.3 ± 1.6	48.6 ± 0.6	46.7 ± 0.2	46.3 ± 1.7
		ϵ''	2225.4 ± 48.9	1498.1 ± 32.7	140.5 ± 2.8	69.3 ± 0.9	37.5 ± 0.5
	120	ϵ'	112.2 ± 5.8	84.3 ± 3.9	50.8 ± 1.3	48.7 ± 1.0	48.8 ± 2.9
		ϵ''	3125.2 ± 74.6	2104.4 ± 50.5	195.6 ± 4.6	95.2 ± 1.8	50.7 ± 1.2
2.8%[a]	20	ϵ'	100.6 ± 0.8	87.9 ± 0.3	65.2 ± 0.3	62.4 ± 0.4	59.4 ± 0.4
		ϵ''	1405.3 ± 22.9	945.5 ± 15.6	95.7 ± 2.7	52.4 ± 2.2	32.4 ± 1.5
	40	ϵ'	104.5 ± 0.4	87.9 ± 0.4	62.4 ± 1.2	59.7 ± 0.9	57.9 ± 0.9
		ϵ''	1905.7 ± 73.3	1280.0 ± 49.1	125.0 ± 5.8	65.0 ± 3.7	37.1 ± 1.4
	60	ϵ'	109.4 ± 1.0	88.0 ± 1.6	59.0 ± 2.4	56.0 ± 2.0	55.8 ± 0.2
		ϵ''	2524.4 ± 56.0	1699.3 ± 37.7	162.2 ± 4.9	82.2 ± 3.4	45.1 ± 1.5
	80	ϵ'	120.2 ± 0.0	91.7 ± 1.1	56.7 ± 2.7	55.1 ± 1.8	54.8 ± 0.5
		ϵ''	3352.1 ± 124.2	2257.1 ± 83.8	212.2 ± 9.3	105.3 ± 5.7	56.1 ± 2.6
	100	ϵ'	133.5 ± 0.9	97.2 ± 1.6	54.5 ± 3.0	53.0 ± 1.8	53.6 ± 2.5
		ϵ''	4197.4 ± 54.3	2822. ± 36.6	263.8 ± 5.2	129.0 ± 4.1	69.9 ± 4.2

[a] At 120 °C, the dielectric data for the mashed potatoes sample were beyond the measurement range.

Effect of temperature

At the frequency of 27 MHz, ε' of mashed potatoes without added salt gently increased with temperature from 20 °C to 120 °C; at the frequency of 40 MHz, ε' was about 80 and did not change much; ε' decreased with temperature at 433, 915, and 1800 MHz (Figure 4). Similar trends were reported by Wang and others (2003b) for whey protein gels, liquid whey protein mixture, cooked macaroni noodles, and cheese sauce at 27 MHz, 915 MHz, and 1800 MHz, respectively. ε' values reported by Regier and others (2001) for mashed potatoes at 2450 MHz also decreased with temperature. ε' values for red delicious apples (*Malus domestica* Borkh) with moisture content greater than 70% were also reported to decrease with temperature at 915 and 1800 MHz (Feng and others 2002). ε' values at 27 MHz and 40 MHz can be greater than 80 (Figure 4), which agreed with observations reported by Stuchly and Stuchly (1980) for certain biological tissues and agricultural products over a frequency range from 1 to 200 MHz. Sheen and Woodhead (1999) attributed this phenomenon to a poorly conditioned calibration at low frequencies.

ε''s of mashed potatoes increased sharply with temperature (20 °C to 120 °C) at 27 and 40 MHz (Figure 5). This sharp increase was not observed at 433, 915, and 1800 MHz. For instance, the ε'' values of mashed potatoes increased from 276.6 to 1060.1 (relative increase: 280%) at 27 MHz, and the corresponding change was from 27.1 to 38.1 (relative increase: 40%) at 915 MHz and from 16.3 to 20.1 (relative increase: 23.3%) at 1800 MHz. Regier and others (2001) reported that the ε'' of mashed potatoes with 86.6% moisture (wb) and 0.39% ash content decreased with temperature at 2450 MHz.

Based on Figure 5, mashed potatoes are likely to experience more thermal runaway heating at 27 MHz than at 915 MHz and 2450 MHz. It is thus extremely critical to provide a uniform electric field for 27 MHz RF pasteurization and sterilization applicators to minimize the thermal runaway heating and ensure the system stability (Wang and others 2003a).

Effect of moisture

ε' generally changed little within the tested moisture range in this study (Table 1). But increasing moisture content reduced ε'' at all measuring conditions (Figure 6). This agrees with the observation reported by Nelson (1978). Moisture contents in the tested range affected ε'' less at 433, 915, and 1800 MHz than at 27 and 40 MHz. The effect of moisture content on the dielectric properties of hygroscopic materials strongly depends upon the form of water in the materials. For food materials with moisture contents of 35% to 40% or above, the majority of water of foods is in the state of free form and is supposed to be the dominant component governing the overall dielectric behavior of foods (Sun and others 1995). In a high moisture range (above 35% to 40%), ε″ shows little dependence on moisture content (Mudgett and others 1980), which was observed in this study.

Effect of salt

The changes of dielectric properties with respect to temperature and frequency are similar for both salt-enriched and nonsalted samples. Added salt did not significantly influence ε′; however, addition of salt sharply increased ε″ (Table 2). Both the absolute increase and the relative increase were larger at 27 MHz than at 915 MHz. At the frequency of 27 MHz, the absolute in-

Table 3—Regression equations for the dielectric properties of mashed potatoes[a]

Dielectric constant (ϵ′)		
27 MHz	$\epsilon' = 54.0 + 98.5\ S - 81.2\ S^2 + 0.000019\ T^3 + 0.00121\ T^2 \times S - 0.000026\ T^2 \times M + 18.6\ S^3$	($r^2_{adj} = 0.95$)
40 MHz	$\epsilon' = 37.5 + 114\ S - 86.4\ S^2 + 0.000020\ T^3 + 0.000683\ T^2 \times S - 0.000035\ T^2 \times M + 18.6\ S^3$	($r^2_{adj} = 0.91$)
433 MHz	$\epsilon' = -59.2 + 0.940\ M + 115\ S - 0.00138\ T \times M - 82.4\ S^2 + 16.8\ S^3$	($r^2_{adj} = 0.92$)
915 MHz	$\epsilon' = -85.5 + 1.26\ M + 105\ S - 76.3\ S^2 + 0.000012\ T^3 - 0.000025\ T^2 \times M + 15.7\ S^3$	($r^2_{adj} = 0.91$)
Dielectric loss factor (ϵ″)		
27 MHz	$\epsilon'' = -285 + (636 + 0.0893\ T^2)\ S$	($r^2_{adj} = 0.98$)
40 MHz	$\epsilon'' = -187 + (426 + 0.0601\ T^2)\ S$	($r^2_{adj} = 0.98$)
433 MHz	$\epsilon'' = -9.51 + (39.1 + 0.0053\ T^2)\ S$	($r^2_{adj} = 0.97$)
915 MHz	$\epsilon'' = 0.12 + (19.3 + 0.00234\ T^2)\ S$	($r^2_{adj} = 0.96$)

[a] T = temperature (°C), M = moisture content (%, wb), S = salt content (%, wb).

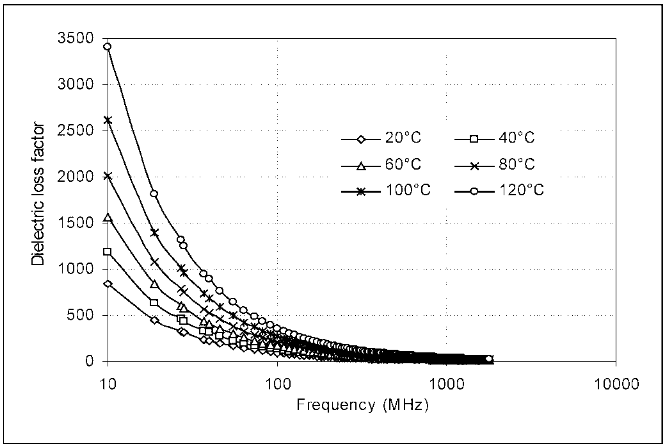


Figure 3—Change of dielectric loss factor of mashed potatoes (moisture content: 81.6%, wb; salt content: 0.8%, wb) with frequency at 6 temperatures

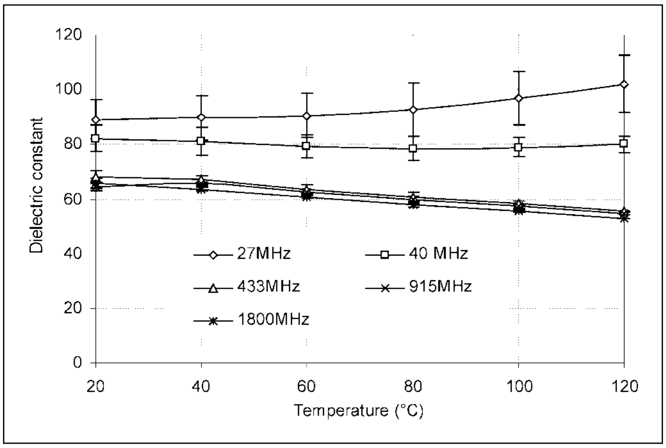


Figure 4—Change of dielectric constant of mashed potatoes (moisture content: 85.9%, wb; salt content: 0.8%, wb) with temperature at 5 frequencies

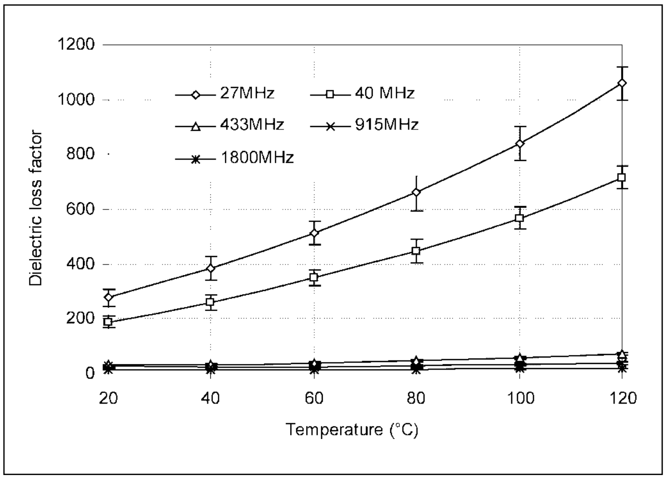


Figure 5—Change of dielectric loss factor of mashed potatoes (moisture content: 85.9%, wb; salt content: 0.8%, wb) with temperature at 5 frequencies

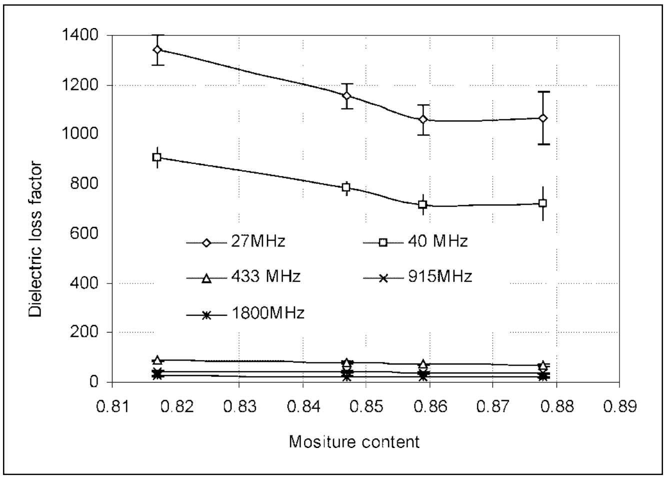


Figure 6—Loss factor of mashed potatoes (salt content: 0.8%, wb) as affected by moisture content (120 °C)

crease of ε'' between 1.8% (wb) salted mashed potatoes and nonsalted samples (salt content: 0.8%, wb) is 436.7 at 20 °C, representing a relative increase of 157.9%; the absolute increase is 2065.1 at 120 °C, representing a relative increase of 194.8% (Table 2; Figure 7). At the frequency of 915 MHz, the absolute and relative increases are 6.7% and 30.9% at 20 °C; the corresponding values are 57.1% and 149.6% at 120 °C (Table 2; Figure 8).

The influence of salts is directly related to the nuclear charge effect and depends on the size and charge of the dissolved ions (Bircan and Barringer 1998). Salts or dissolved ions reduce polarization of water and the overall ε' by binding water; salts also increase the ε'' above that of pure water because of electrophoretic migration (Mudgett 1986). As observed in this study, the presence of an electrolyte (NaCl) did not seem to influence ε' greatly, but it did have a marked effect on the ε''.

To evaluate the influence of added salt (NaCl), the ε'' of a food material can be expressed as:

$$\varepsilon'' = \varepsilon''_d + \varepsilon''_\sigma \tag{2}$$

where ε''_d is the relative dipole loss (due to polarized molecules), and ε''_σ is the relative ionic loss. ε''_σ is related to the electrical conductivity of a food material (σ) with the relationship (Metaxas and Meredith 1993):

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

where ε_0 is the permitivity of free space (8.854×10^{-12} *Farad/m*) and f is the frequency of the electromagnetic waves. The following equation was obtained by taking the log value on both sides of Eq. 3:

$$\log \varepsilon''_\sigma = \log \sigma - \log 2\pi f \varepsilon_0 \tag{4}$$

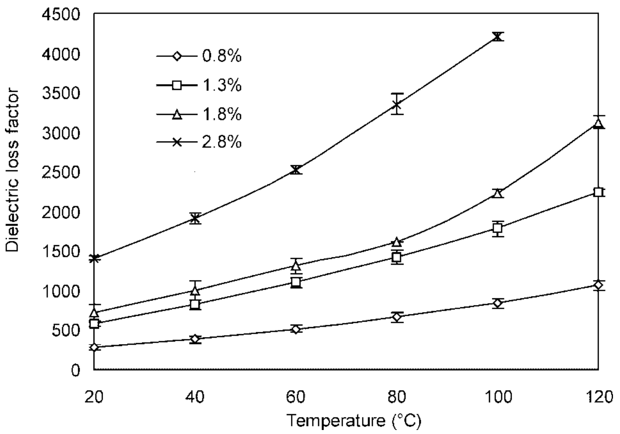
or

$$\log \varepsilon''_\sigma = -\log f + C \tag{5}$$

where C is a constant:

$$C = \log \sigma - \log 2\pi \varepsilon_0 \tag{6}$$

According to Eq. 2 and 5, the dielectric loss factor and the frequency would have a linear relationship in a log-log graph if the relative ionic loss (ε''_σ) were the main contributor to the overall dielectric loss (ε''). The mashed potatoes with 0.8%, 1.3%, 1.8%, and 2.8% salt levels used in this study had conductivities of 3.51 ± 0.05, 8.56 ± 0.12, 12.80 ± 0.10, and 21.65 ± 0.59 (unit: mS/cm; temperature: 20 °C to 22.5 °C), respectively. The values of ε''_σ were calculated from measured electric conductivities using Eq. 3 and were compared with the measured overall ε'' at 20 °C at the same frequencies in a log-log format (Figure 9). Linear relationships were observed in ε'' over a frequency range covering 27 and 900 MHz for mashed potato with 2.8% salt content, but over a much smaller frequency range between 27 and 40 MHz for potato with 0.8% salt. In the linear range in the log-log plot (Figure 9), the log values of the calculated ε''_σ were very close to the measured ε'' values. This suggests that the ionic conductivity in tested mashed potatoes played a major role for the overall dielectric characteristics of the material at low frequencies. The predominant role of ionic conductivity in the overall loss factor values of the mashed potato in low frequencies (for example, 27 and 40



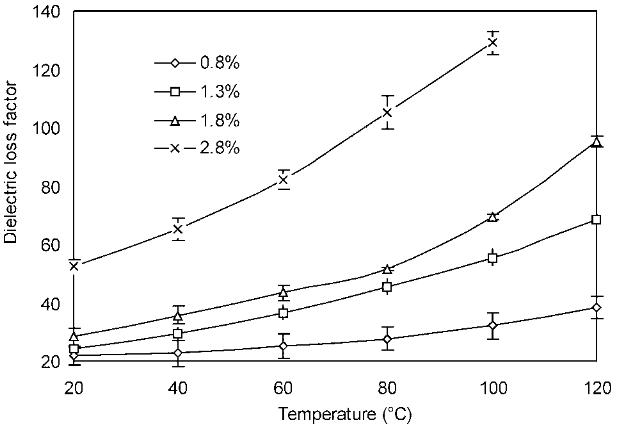


Figure 7 (above)—Effect of added salt on the dielectric loss factor of mashed potatoes (moisture content: 85.9%, wb) at 27 MHz

Figure 8 (above right)—Effect of added salt on the dielectric loss factor of mashed potatoes (moisture content: 85.9%, wb) at 915 MHz

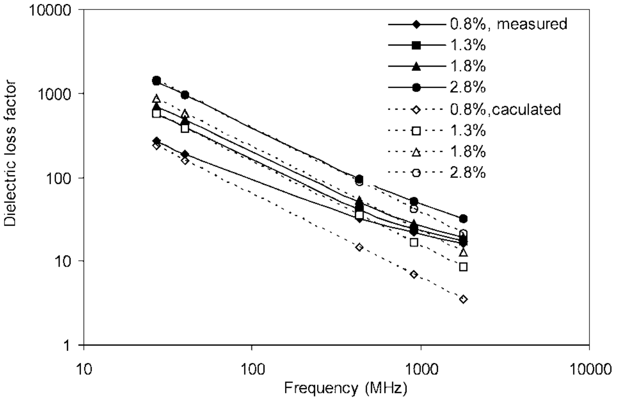


Figure 9 (right)—Measured and calculated dielectric loss factors for mashed potatoes (moisture content: 85.9%, wb; 20 °C) with different salt levels

MHz) explains the positive temperature dependencies observed in Figure 5 as illustrated by Tang and others (2002). At high frequencies (433, 900, and 1800 MHz), the values of ε''_σ were much smaller than that of ε'' for mashed potato with 0.8 to 1.3% salt, suggesting the increasing importance of the contribution of dipole molecules, such as free water, to the overall ε''.

Regression equations

The regression equations for the dielectric properties of mashed potatoes as affected by temperature, moisture, and total salt contents are shown in Table 3 at 4 frequencies (27, 40, 433, and 915 MHz). The regression equations for the ε'' were formulated on the basis of the 2 major components of mashed potatoes (that is, moisture and salt contents). A similar composition-based equation form was used in Sun and others (1995). However, this form of equation did not apply to ε's because of the low r^2_{adj} (0.25 to 0.65) obtained. All the regression equations have r^2_{adj} values equal to or above 0.91. The calculated data for ε' differed from measured values by less than 10%, and the calculated data for ε'' differed from measured values by 1% to 25%, except that the discrepancies were up to 40% at 20 °C.

The r^2_{adj} of each regression equation is generally comparable with those from the literature. For example, according to Calay and others (1995), the r^2_{adj} value for the predictive equation of the ε' of fruits and vegetables (moisture content: 50% to 90%, wb; temperature range: 0 °C to 70 °C; and frequency range: 0.9 to 3 GHz) is 0.82; the corresponding r^2_{adj} for the ε'' is 0.76. The r^2_{adj} to the predictive equations of the ε'' for potatoes (moisture content: 75.2%, wb; ash: 0.85%, wb) obtained by Sipahioglu and Barringer (2003) is 0.89. Furthermore, the equation was only a function of temperature and believed to be more accurate than the equation combining temperature, moisture, and ash content.

The regression equations in this study (Table 3) indicate that both temperature and salt content played an important role in the dielectric characteristics of the mashed potatoes within the tested moisture range (81.6% to 87.8%, wb).

Power penetration depth

Table 4 and 5 list calculated power penetration depths of electromagnetic energy at 5 frequencies in mashed potatoes with 4 moisture levels (salt content: 0.8%, wb) and 4 salt (added) levels (moisture content: 85.9%, wb). The power penetration depth generally decreased with increasing temperature and frequency. Changes in mois-

Table 4—Power penetration depth (mm) for mashed potatoes (salt content: 0.8%, wb) at different moisture levels (%, wb)

Moisture content (81.7%)	27 MHz	40 MHz	433 MHz	915 MHz	1800 MHz
20 °C	78.7	67.2	26.8	17.9	12.9
40 °C	64.3	54.0	23.1	16.9	13.0
60 °C	54.8	45.9	19.4	15.3	12.4
80 °C	47.4	39.5	16.2	12.9	11.0
100 °C	41.5	34.4	13.6	11.1	9.6
120 °C	35.6	29.4	11.1	9.2	7.9

Moisture content (84.7%)	27 MHz	40 MHz	433 MHz	915 MHz	1800 MHz
20 °C	84.0	72.1	35.0	22.7	13.6
40 °C	68.8	58.3	27.9	20.4	14.2
60 °C	58.4	49.0	22.7	18.1	13.7
80 °C	50.9	42.4	18.6	15.3	12.5
100 °C	44.1	36.6	14.7	11.8	10.4
120 °C	38.5	31.8	12.1	9.6	8.6

Moisture content (85.9%)	27 MHz	40 MHz	433 MHz	915 MHz	1800 MHz
20 °C	88.1	75.9	29.1	18.8	13.3
40 °C	71.8	61.0	28.4	18.8	14.8
60 °C	60.2	50.6	23.0	16.7	14.1
80 °C	52.2	43.6	19.2	15.0	13.2
100 °C	45.7	38.0	15.9	12.8	11.5
120 °C	40.3	33.3	13.1	10.6	9.8

Moisture content (87.8%)	27 MHz	40 MHz	433 MHz	915 MHz	1800 MHz
20 °C	87.8	75.6	34.4	21.1	14.6
40 °C	71.9	61.0	31.3	23.0	16.5
60 °C	61.3	51.5	24.8	19.6	15.9
80 °C	53.2	44.3	20.9	18.2	15.0
100 °C	45.6	37.8	16.5	14.4	12.6
120 °C	40.2	33.2	13.5	11.6	10.4

Table 5—Power penetration depth (mm) for mashed potatoes (moisture content: 85.9%, wb) at different salt levels (%, wb)

0.8% (wb)	27 MHz	40 MHz	433 MHz	915 MHz	1800 MHz
20 °C	88.1	75.9	29.1	18.8	13.3
40 °C	71.8	61.0	28.4	18.8	14.8
60 °C	60.2	50.6	23.0	16.7	14.1
80 °C	52.2	43.6	19.2	15.0	13.2
100 °C	45.7	38.0	15.9	12.8	11.5
120 °C	40.3	33.3	13.1	10.6	9.8

1.3% (wb)	27 MHz	40 MHz	433 MHz	915 MHz	1800 MHz
20 °C	55.8	47.2	23.1	17.9	12.3
40 °C	46.2	38.7	17.4	14.4	11.4
60 °C	39.3	32.8	13.6	11.4	9.6
80 °C	34.3	28.5	11.1	9.3	8.0
100 °C	30.4	25.2	9.3	7.6	6.6
120 °C	27.0	22.3	7.9	6.3	5.6

1.8% (wb)	27 MHz	40 MHz	433 MHz	915 MHz	1800 MHz
20 °C	49.5	41.5	18.1	14.1	10.2
40 °C	41.1	34.3	13.9	11.2	9.0
60 °C	35.7	29.6	11.3	9.1	7.7
80 °C	31.9	26.4	9.6	7.7	6.5
100 °C	27.1	22.4	7.8	6.1	5.1
120 °C	22.8	18.8	6.3	4.8	4.0

2.8% (wb)	27 MHz	40 MHz	433 MHz	915 MHz	1800 MHz
20 °C	34.6	28.8	11.0	8.4	6.5
40 °C	29.4	24.4	8.9	6.9	5.7
60 °C	25.4	21.0	7.3	5.6	4.7
80 °C	22.0	18.1	6.1	4.6	3.9
100 °C	19.6	16.2	5.3	4.0	3.2

ture content in the tested range did not significantly influence the penetration depth (Table 4). Increasing salt concentration sharply reduced the power penetration depth (Table 5). Addition of salt greatly changed the dielectric properties of mashed potatoes and the resultant power penetration depths at 27 and 915 MHz, which indicates that salt content instead of moisture content should be carefully monitored when preparing mashed potatoes for microwave and RF sterilization processes. Knowledge of penetration depths also helps in selecting a correct sample thickness to guide the microwave and RF heating processes. This study shows that microwave heating of mashed potatoes is advisable for packages with relatively smaller thickness (for example, 1 to 2 cm for 2-sided heating), and RF heating can be applied for packages and trays with large institutional sizes (for example, 4- to 8-cm depth).

Conclusions

ε' and ε'' for mashed potatoes decreased with increasing frequency. ε' gently increased with temperature at 27 MHz, was relatively stable at 40 MHz, and decreased with temperature at 433, 915, and 1800 MHz. The ε'' increased with temperature at all tested frequencies. Moisture contents in the tested range did not significantly affect the dielectric properties of mashed potatoes. Addition of salt in mashed potatoes increased the ε'', especially in the RF range. The penetration depth of electromagnetic energy in mashed potatoes decreased with the temperature and frequencies; it was less dependent on moisture content (81.6% to 87.8%) than added salt content (0.8% to 2.8%). This study shows that salt content should be carefully monitored during the preparation of mashed potato samples for sterilization using RF or microwave energy. Microwave heating of mashed potatoes is advisable for packages with relatively smaller thickness (for example, 1 to 2 cm), and RF heating can be applied for packages and trays with large institutional sizes (for example, 4- to 8-cm depth).

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