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Dielectric Properties of Cottage Cheese and Surface Treatment Using Microwaves

A-G. Herve,[a] J. Tang,[a*] L. Luedecke[b] & H.Feng[a]

[a]Department of Biological Systems Engineering, Washington State University, Pullman, WA 99164-6120, USA
[b]Department of Food Science and Human Nutrition, Washington State University, Pullman, WA 99164-6120, USA

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ABSTRACT

This research determines the dielectric properties of cottage cheese and explores the application of microwave treatment to reduce surface spoilage microorganisms, extending the shelf-life of cottage cheese in sealed plastic containers. Dielectric properties of cottage cheese of 0, 2 and 4% fat content were measured at temperatures between 5 and 65°C. The penetration depths of microwaves of 2450 and 915 MHz were estimated to be between 1.2 and 3.2 cm. Microwaves were then used to treat the surface of the cheese in containers shielded on the sides and the bottom. Temperature distribution followed an exponential decay along the depth, as described by a model derived from Lambert's law. Microbiological, sensory and pH analyses of samples after treatment and 1–4 weeks after storage at 3°C showed that microwave surface treatment could contribute to extending the shelf-life of cottage cheese, but further studies are necessary to identify optimum conditions that would maintain appearance and texture.

*Author to whom correspondence should be addressed. Tel.: +1-509-335-2140; Fax: +1-509-335-2722; E-mail: jtang@mail.wsu.edu

INTRODUCTION

Cottage cheese is a popular nutritional dairy product with relatively low fat content (between 0 and 4%) and mild taste. In the US, the annual cottage cheese production was 538 million pounds in 1994 with a value of 513 million dollars. Cottage cheese is made commercially from fresh skim milk or reconstituted non-fat dry milk. The dairy ingredients are pasteurized usually at 72°C for 15–18 s, then cooled to 22–32°C. Two processes are commonly used for setting the milk: culturing or direct acidification. In culturing, a mixed culture is added to the cooled pasteurized milk. A small amount of rennet is usually added to strengthen the curd at the time of coagulation. After thorough agitation, the mix is held at 22°C for 16 h or at 32°C for 4 h while the curd sets. In direct acidification, the processes vary. In some procedures, pasteurized milk is cooled to 4°C or below and one or more acidic ingredients are added. Coagulating enzymes may also be added. The mix is heated to about 32°C and held without stirring for 30–90 min. When the curd is set, it is cut into cubes. The curd is then slowly cooked to 49–55°C to expel the whey. The curd is drained and washed two or three times to reduce the temperature and to remove the whey. A pre-pasteurized creaming mixture is blended with the curd. The cottage cheese is then packaged and stored, preferably at 0–5°C (Emmons and Tuckey, 1967).

Cottage cheese with no preservatives has a short shelf-life. Spoilage usually occurs within about 21 days in refrigerated conditions, mainly as a result of post-process contamination and growth of gram-negative psychrotrophic bacteria (Bigalke, 1985; Bishop and White, 1985; Chen and Zall, 1987). Defects in cottage cheese resulting from the growth of psychrotrophic bacteria include off-flavors such as stale, bitter, fruity, putrid, rancid and acid. Sorbate at a concentration of 0.25% can be used to extend the shelf-life of cottage cheese, but it imparts undesirable bitterness to the product. Dissolving CO_2 in cottage cheese prior to packaging in air-tight containers, such as glass jars, can effectively inhibit the growth of gram-negative bacteria and extend the shelf-life up to 60 days at 4°C (Chen and Hotchkiss, 1991). This method, however, may not be effective in ordinary plastic containers made from high density polyethylene or polystyrene, because those materials do not provide a good barrier to O_2 and CO_2. Moir *et al.* (1993) also reported that CO_2 concentration in the head space in polystyrene containers decreased with storage time. It is, therefore, very likely that the top surface of the cottage cheese in these plastic containers will spoil much faster than the bulk of the cheese with dissolved CO_2. One possible solution is to reduce the initial psychrotrophic counts at the top surface. Low initial microbial levels together with CO_2 flushing still greatly extend the shelf-life of cottage cheese in polystyrene containers (Moir *et al.*, 1993).

The objectives of this study were to determine the dielectric properties of cottage cheese and to explore the application of microwaves in reducing the surface psychrotrophic bacteria counts by thermally treating the surface of cottage cheese in containers. Microwaves were used as the heating source for the following reasons: (1) cheese can be treated in the package thereby avoiding recontamination; (2) the penetration depth of microwaves is relatively small in foods containing dissolved salt so that most of the cottage cheese is not affected by the treatments; and (3) a relatively high temperature can be reached in a short time.

MATERIALS AND METHODS

Measurement of dielectric properties

In this study, we intended to heat the surface of cottage cheese in the package without significantly raising the bulk temperature in order to maintain quality. It was, therefore, essential to know the penetration depth of microwaves in cottage cheese. The dielectric constant, ε', of a material reflects the ability to store electrical energy and the loss factor, ε'', indicates the ability to dissipate electrical energy as heat. Both properties of cottage cheese are required to estimate the penetration depth of microwaves and to predict the development of the temperature profile during microwave treatment. These two properties are, however, not reported in the literature. A HP 85070 dielectric probe kit (Hewlett Packard, Fullerton, CA) was used to measure the dielectric properties of small curd cottage cheese of three different fat contents (0, 2 and 4%) at four temperatures (5, 25, 45 and 65°C) and two microwave frequencies, 915 and 2450 MHz. These two frequencies are allocated by the US Federal Communication Commission for microwave heating (2450 MHz is used in home microwave ovens and both frequencies are used in industrial applications). The measurement system was calibrated using a standard short-air-distilled water procedure prior to each test run.

For each cheese, three samples were used and the dielectric property measurements were repeated three times for each sample. A water bath conditioned the samples at the desired temperature with an accuracy of ± 0.5°C. The temperature of the samples was measured with a digital thermometer (Barnant 115, Barnant Inc., Barrington, IL). Difficulty was experienced when measuring the properties of cottage cheese at 65°C. At this temperature, the cottage cheese was not homogeneous: curd was separated from whey and proteins started coagulating. The dielectric constant and loss factor measured by directly immersing the probe in the mixture were inconsistent because of the separated whey and curd. To resolve this problem, the cottage cheese was filtered at 65°C and the dielectric properties of curd and free fluid were measured separately. Then, the weighed averages between the dielectric properties of fluid and curd were determined.

Food dielectric properties are primarily determined by moisture and salt content. In general, the greater the moisture and salt content, the shallower the microwave penetration depth, and consequently the less uniform the heating rate throughout the product (Bengtsson and Risman, 1971; Roebuck *et al.*, 1972; Nelson, 1978; Nelson *et al.*, 1991; Calay *et al.*, 1995). To understand the contribution of some main constituents (salt and lactose) of cottage cheeses to the conversion of microwave energy into thermal energy, the dielectric properties of a 0.5% salt solution and of a 0.5% salt and 5% lactose solution were measured. The salt and lactose contents were selected based on the labeled composition of cottage cheese samples used in the study (Table 1).

Theoretical calculations

Lambert's law as shown in eqn (1) describes microwave power reduction as a result of conversion of microwave energy into thermal energy in an infinitely large lossy material (von Hippel, 1954):

TABLE 1
Compositions of the Three Cottage Cheeses Tested in the Study as Shown in the Nutritional Label of the Product. The Data are From the Manufacturer of the Cottage Cheese

	Fat content		
Amount/serving (121 g)	*0%*	*2%*	*4%*
Total fat	0 g	2.5 g	5 g
Sodium	490 mg	500 mg	510 mg
Total carbohydrates	6 g	5 g	6 g
Proteins	14 g	13 g	14 g

$$P(z) = P_o e^{-z/dp} \tag{1}$$

where P_o is the incident power intensity and $P(z)$ is the power intensity at a distance z from the surface; dp is the penetration depth (cm) and it is related to dielectric properties as (Buffler, 1993):

$$dp = \frac{\lambda_o \sqrt{2}}{2\pi} \left\{ \varepsilon' \left[\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'} \right)^2} - 1 \right] \right\}^{-1/2} \tag{2}$$

where λ_o is the wavelength of microwaves in free space. λ_o is 32.8 cm for 915 MHz and 12.2 cm for 2450 MHz.

The conversion of microwave power into heat in a unit volume is:

$$p(z) = -\frac{\partial P(z)}{\partial z} = \frac{P_o}{dp} e^{-z/dp} \tag{3}$$

Assuming that heat conduction is negligible during the short microwave heating period, temperature increase $\Delta T(z)$ at a given depth z in a small volume ΔV in a given time interval Δt can be estimated by the following energy balance relation:

$$p(z)\Delta V = \Delta V \rho C \frac{\Delta T(z,t)}{\Delta t} \tag{4}$$

or

$$\Delta T(z,t) = \frac{p(z)}{\rho C} \Delta t \tag{5}$$

where ρ is the density and C is the specific heat.

Substituting eqn (2) into eqn (5) yields:

$$\Delta T(z,t) = \frac{P_o \Delta t}{dp\rho C} e^{-z/dp} \tag{6}$$

From eqn (1), the surface temperature increase is:

$$\Delta T(0,t) = \frac{P_o \Delta t}{dp\rho C} \tag{7}$$

From eqn (6) and (7):

$$\frac{\Delta T(z,t)}{\Delta T(0,t)} = e^{-z/dp} \tag{8}$$

Assuming constant properties and uniform initial temperature, the temperature profile can be obtained from:

$$\frac{T(z,t) - T_o}{T(0,t) - T_o} = e^{-z/dp} \tag{9}$$

where T_o is the initial temperature. eqn (9) is valid only when heat conduction is negligible. Dolande and Datta (1993) developed the following relation to evaluate the contribution of heat conduction to temperature increase versus that of microwave heating:

$$\frac{\frac{\partial T}{\partial t}|\text{heat conduction}}{\frac{\partial T}{\partial t}|\text{microwaveheating}} = \frac{\alpha t}{dp^2} \tag{10}$$

where the thermal diffusivity $\alpha = k/(\rho C)$, and k is the thermal conductivity.
For the experiments in this study, the ratio in eqn (10) was estimated to be less than 0.04 for the 915 MHz treatments, and less than 0.06 for the 2450 MHz treatments. Therefore, contribution of heat conduction to temperature changes was not considered in the analysis of this study.

Measurement of temperature distribution in containers after microwave treatment

Preliminary tests showed that it was desireable to obtain a uniform cheese surface temperature between 50 and 60°C to reduce the spoilage microorganisms. Higher temperatures would result in brown and soft curd and a separation of whey from the curd. Tochman *et al.* (1985) also reported that heating of cottage cheese above 71°C caused extreme product disintegration. In addition, high vapor pressure generated above 60°C (> 20 kPa) is likely to force the lid off the containers.

Temperature was measured at five different locations on the surface of microwave-treated cottage cheese in containers and at six depths along the center axis of the containers. The temperature probe was pre-calibrated to yield an accuracy of ±0.3°C.

Microwave treatments

Three microwave treatments were selected to treat the surface of 4% fat content cottage cheese which is the most popular cottage cheese in the US. Two microwave ovens were used: a 2450 MHz microwave oven with a nominal power output of 1000 W (Sharp Carousel 1000 W High Speed, Sharp Electronic Corporation, Mahwah, NJ) and a pilot-scale 915 MHz microwave system (Fig. 1) with a rotating platform and stirrer in the cavity and a variable power supply between 0 and 5 kW (Microdry, Inc., Crestwood, KY). Forty one cartons of small curd cottage cheese (with no preservatives) fresh from a Washington State cheese manufacturer were purchased through a local store. All units were from the same batch with labeled shelf-life of 2 weeks after the date they were acquired. Ten cartons were used as controls and 30 cartons were pasteurized, 10 for each treatment. Before microwave treatments, the bottom and sides of the 16 oz cottage cheese containers, molded from high density polyethylene with 54 mil (0.2 mm) thick walls, were covered with aluminum foil so that microwaves only penetrated and treated the top surface of the cottage cheese (Fig. 2).

Treatment A

A single carton of cottage cheese on a rotary platform was treated for 70 s at 1 kW with 2450 MHz microwaves. Every 10 s, the carton was manually rotated 45° clockwise in order to increase the uniformity of the cheese surface temperature. After 70 s of heating, the microwave oven was stopped for 50 s followed by four 7-s cycle microwave treatments with 50 s breaks between heat cycles to maintain the surface temperature between 50 and 60°C. The treated sample was then placed in a refrigerator at 3°C for storage.

Treatment B

This treatment is similar to treatment A, except that the initial heating time was 80 s instead of 70 s. The surface temperature of the cottage cheese was, therefore, maintained at a higher temperature.

Treatment C

The cottage cheese placed on the rotating platform in the 915 MHz microwave oven was treated for 2.5 min at 1 kW. The cheese was then heated for 1.5 min at 200 W to maintain the cheese surface temperature between 50 and 60°C. No manual rotation was made, because 915 MHz microwaves inherently result in more uniform heating due to the longer wavelength than 2450 MHz microwaves.

pH measurement

pH measurements were made with an Orion digital pH meter (Orion Research Inc., Cambridge, MA) equipped with a glass electrode. Measurements were taken with duplicate samples immediately and every week after the treatment throughout the storage period.

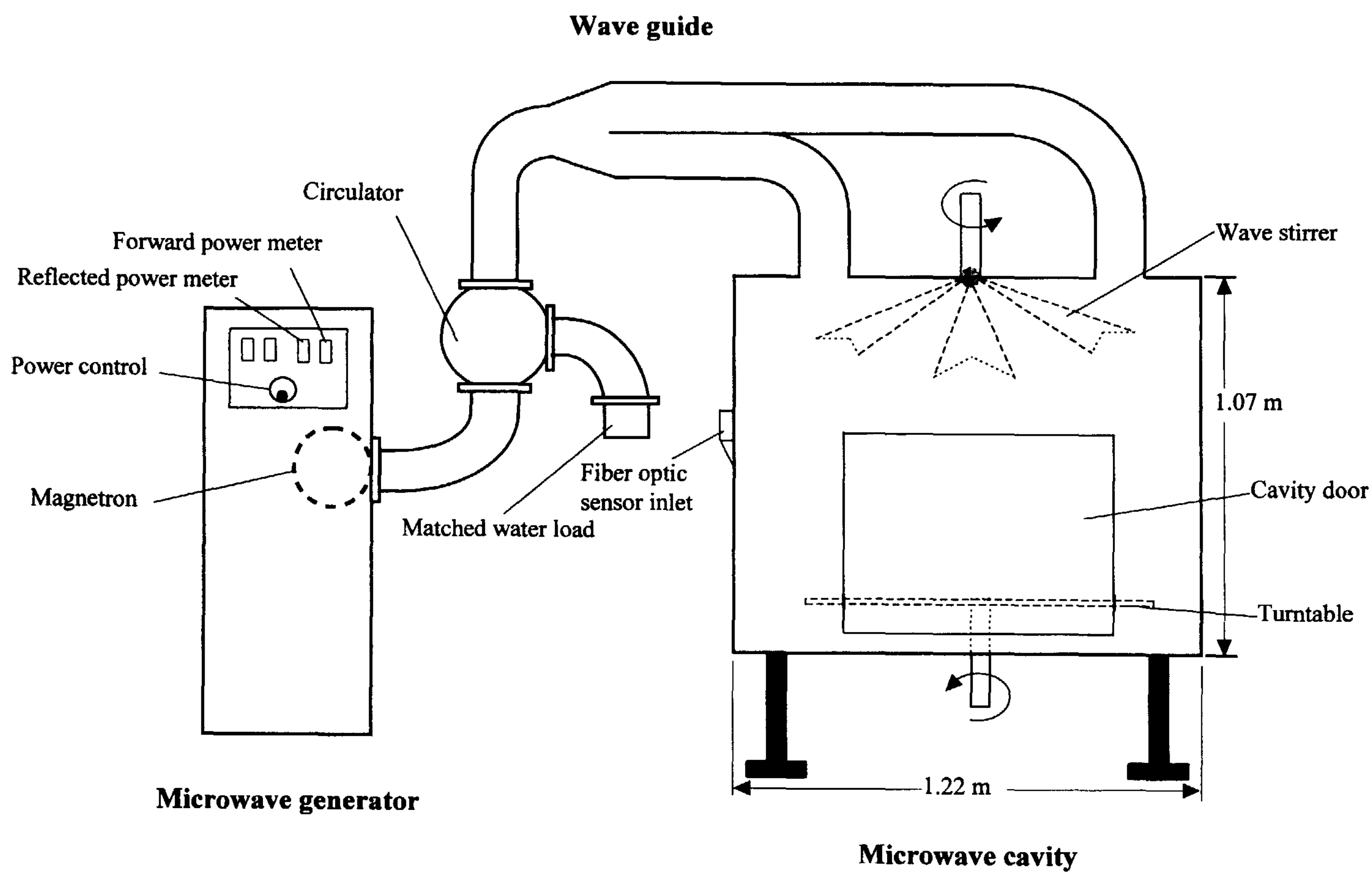


Fig. 1. Schematic diagram of 915 MHz pilot-scale microwave system (0–5 kW).

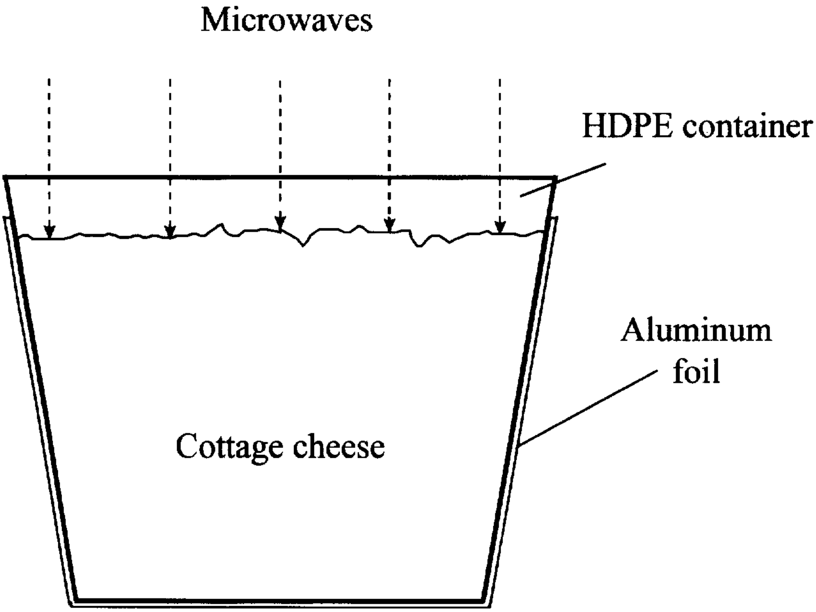


Fig. 2. Microwave surface treatment of cottage cheese in 16 oz high density polyethylene containers shielded on the sides and bottom with aluminum foil.

Microbiological analysis

Psychrotrophic bacteria counts were measured according to the Crystal Violet Tetrazolium (CVT) procedure described by Marshall (1992). Yeasts and molds were not determined, as they were not detected in previous microbial tests.

The above analyses were performed before the treatment, 1 day after the treatments and every week afterwards. Two cottage cheeses per treatment were analyzed each week and two petri-dishes were used for each dilution for each cottage cheese.

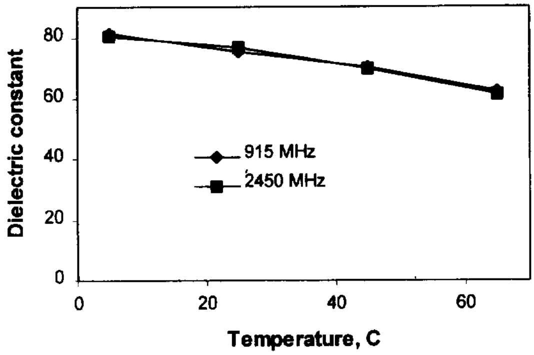
Sensory analysis

A panel of three trained and semi-trained judges tested the cottage cheese every week. They evaluated flavor, texture and appearance.

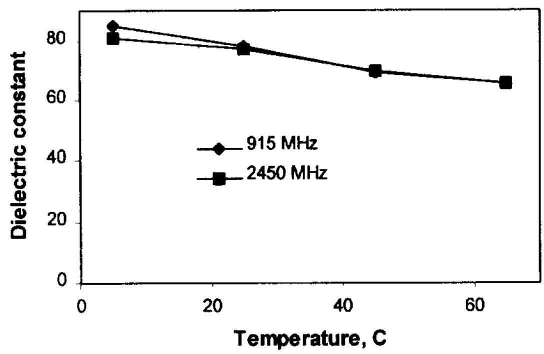
RESULTS AND DISCUSSION

Dielectric properties

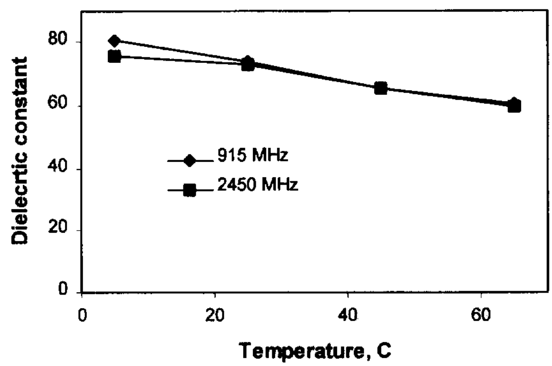
The dielectric constants, ε', of distilled and de-ionized water, a 0.5% salt solution, and a solution of 0.5% salt and 5% lactose, are shown in Fig. 3. ε' values were close among the solutions at a given temperature. Thus, salt and lactose at the tested concentrations did not influence ε'. The dielectric constant decreased with increasing temperature. ε' was not affected by the two microwave frequencies.



Distilled deionized water



0.5% NaCl solution



0.5% NaCl and 5% lactose solution

Fig. 3. Dielectric constants of three solutions at 2450 and 915 MHz. The data are means of five replicated measurements. Standard deviations were 0.2–1.6.

The loss factor ε'' values of the 0.5% salt solution and of the 0.5% salt and 5% lactose solution were similar at all levels of measured temperature (Fig. 4), but significantly larger than those of distilled de-ionized water, especially above room temperatures. Five percent lactose did not have much effect on the loss factor of the 0.5% salt solution. The trend of dielectric properties changes of the 0.5% salt solution as affected by temperature was similar to that of cottage cheeses (Fig. 6). Dissolved salt, therefore, played an important role in controlling the dielectric properties of cottage cheeses.

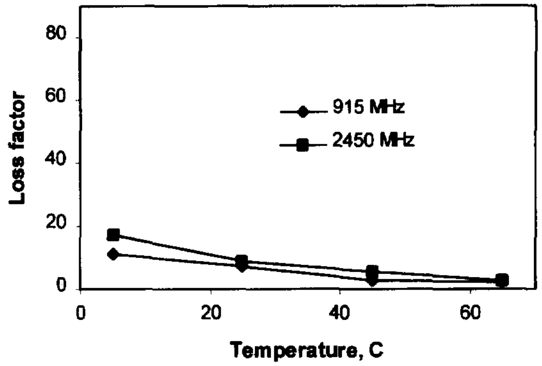
In general, the loss factor ε'' of 0.5% salt solution is higher at 915 MHz than at 2450 MHz, due to more intensive ionic polarization at the lower microwave frequency. Higher ε'' values at 915 MHz at elevated temperatures may be the result of reduced solution viscosity, which leads to increased mobility of ions and, thus, higher electric conductivity. The loss factor of salt solutions, however, decreases with increasing temperature at 2450 MHz. This is because at 2450 MHz dispersion resulting from the dipole rotation of water molecules is predominant, and at elevated temperature fewer hydrogen bonds are formed and reformed causing a decrease in the ε'' value with increased temperature (Ohlsson, 1989). For pure water, ε'' decreased with an increase in temperature at both frequencies again because of the predominant dipole rotation of water molecules as the loss mechanism.

The mean dielectric constants of three different cheeses are shown in Fig. 5 and listed in Table 2. The three curves have the same trend for the three kinds of cottage cheese. Slightly lower ε' values were obtained with 4% fat cottage cheese at all temperature levels. The difference in the ε' values between different cottage cheeses was caused by different fat contents. The lower the fat content, the higher the ε', as more moisture in the lower fat cottage cheese contributed to higher ε' values. Values of ε' of cottage cheeses decreased slightly when the temperature increased and ε' seemed also to be affected slightly by frequency.

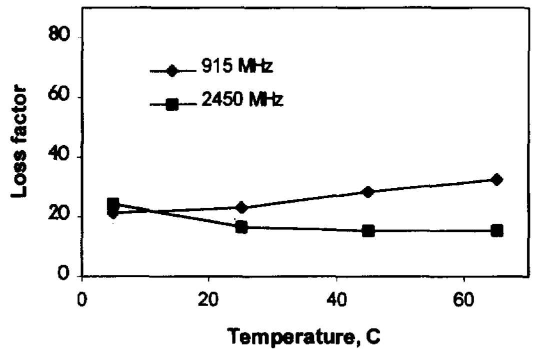
The loss factors of the three cottage cheeses at four different temperatures are presented in Fig. 6 and Table 2. ε'' values for 2 and 4% fat cottage cheeses were close at all the measured temperatures, but they were in general slightly smaller than that of the 0% fat cottage cheese. The bulky fat molecules have low dielectric properties (Ryynänen, 1994), and fat tends to suppress both dielectric constant and loss factor in mixtures (Bengtsson and Risman, 1971). Similar to that of the 0.5% salt solution, ε'' of cottage cheeses was less at the higher frequency and decreased with decreasing temperature.

Penetration depth of microwaves

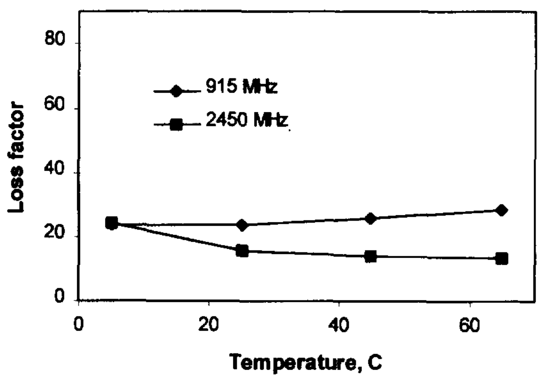
The penetration depths of microwaves in cottage cheeses were calculated from eqn (2). The penetration depth was similar among the three fat cottage cheeses at each frequency and temperature level, except that 915 MHz microwaves had smaller penetration depth in 0% fat cottage cheese than in 2 and 4% fat cottage cheeses at 5 and 25°C (Fig. 7). The penetration depth of 2450 MHz microwaves in cottage cheeses was influenced little by temperature, and that of 915 MHz decreased with increasing temperature. Penetration depth of 915 MHz microwaves in cottage cheese was greater than that of 2450 MHz microwaves, especially at lower termperatures.



Distilled deionized water



0.5% NaCl solution



0.5% NaCl and 5% lactose solution

Fig. 4. Loss factors of three solutions at 2450 and 915 MHz. The data are means of five replicated measurements. Standard deviations were 0.2–0.5.

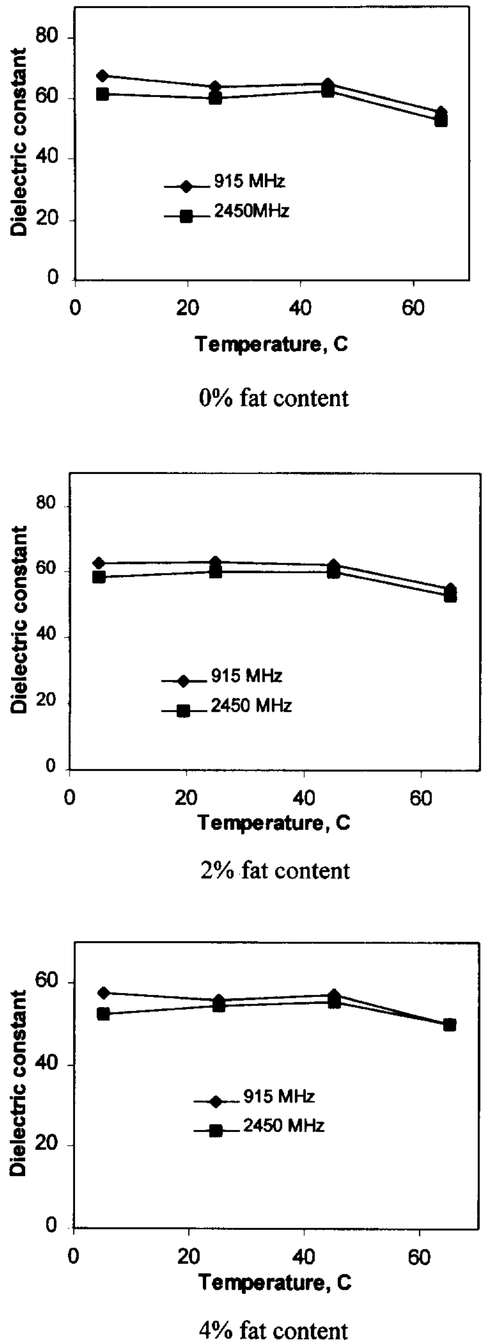


Fig. 5. Dielectric constants of three different cottage cheeses at 2450 and 915 MHz. The data are means of nine measurements.

TABLE 2
Dielectric Properties of Cottage Cheese at 915 and 2450 MHz. The Data are Means of Nine Measurements

Frequency (MHz)	*Temp. (°C)*	*0% fat*		*2% fat*		*4% fat*	
		ε'	ε''	ε'	ε''	ε'	ε''
915	5	67.4±2.1	32.9±1.1	62.6±1.6	26.8±1.3	57.7±3.3	26.2±1.3
	25	63.5±2.1	36.7±3.4	62.8±0.7	31.9±0.8	55.9±1.8	30.1±1.0
	45	64.5±1.0	43.5±0.4	61.9±0.1	38.6±0.3	57.2±1.4	38.6±2.0
	65	55.2±8.3	51.2±5.6	54.9±4.5	58.2±5.8	50.4±3.3	55.1±4.9
2450	5	61.3±2.3	26.0±0.4	58.1±0.9	22.7±0.7	52.7±3.3	21.0±1.4
	25	59.9±5.3	22.4±2.0	59.8±1.1	20.6±0.2	54.6±2.3	19.5±0.4
	45	62.5±1.3	24.2±0.5	60.0±0.2	21.2±0.2	55.8±1.2	20.9±0.5
	65	52.4±3.5	23.1±5.6	52.6±6.2	24.8±4.6	50.2±4.0	24.2±3.5

Since the penetration depths of microwaves in all cottage cheeses were between 1 and 3 cm, it was possible to heat only the surface of a packaged cottage cheese, while maintaining a low bulk temperature and, thus, quality of the cheese.

Temperature distribution on the top surface

Temperature distribution on the top surface and along the depth of the cottage cheese heated by various microwave treatments before the holding period was determined by direct temperature measurements. The range of measured surface temperature among three replicates is shown in Fig. 8. The temperature on the surface of the cottage cheese after heating for 70 s at 1000 W with 2450 MHz microwaves was slightly below 51°C, and higher temperatures were recorded when heated for 80 s at 1000 W with 2450 MHz microwaves and for 150 s at 1 kW with 915 MHz microwaves. Even with manual rotation together with the use of the microwave carousel, the surface temperatures of samples treated with 2450 MHz were not uniform and not consistent. The surface temperatures of 915 MHz microwave treated samples were slightly more uniform and much more predictable.

Temperature distribution along the depth

Temperature measurements after microwave heating along the central axis indicate an exponential decrease in temperature along the depth of the cottage cheese (Fig. 8). The amount of this decrease was dictated by the penetration depth of the microwaves in the cottage cheese. In general, the temperature rise in the bulk cottage cheese treated with 915 MHz microwaves was larger than in that treated with 2450 MHz microwaves, as a result of the deeper penetration depth of 915 MHz microwaves. Since more energy was used to heat the bulk with 915 MHz microwaves, about twice as much time was required to raise the surface temperature to the same level with 915 MHz microwaves as compared to 2450 MHz microwaves at the same power level.

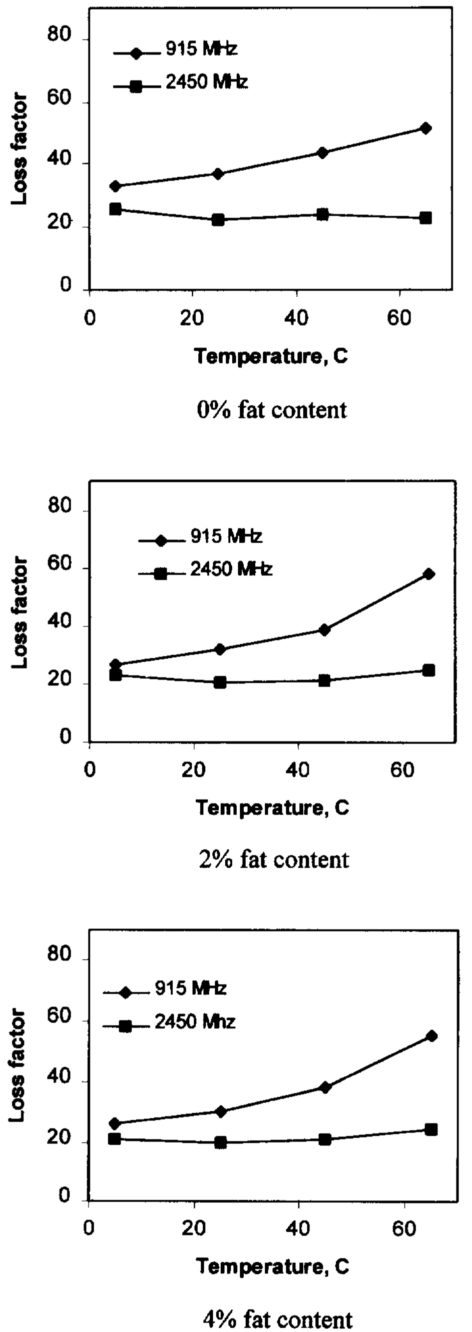


Fig. 6. Loss factors of three different cottage cheeses at 2450 and 915 MHz. The data are means of nine measurements.

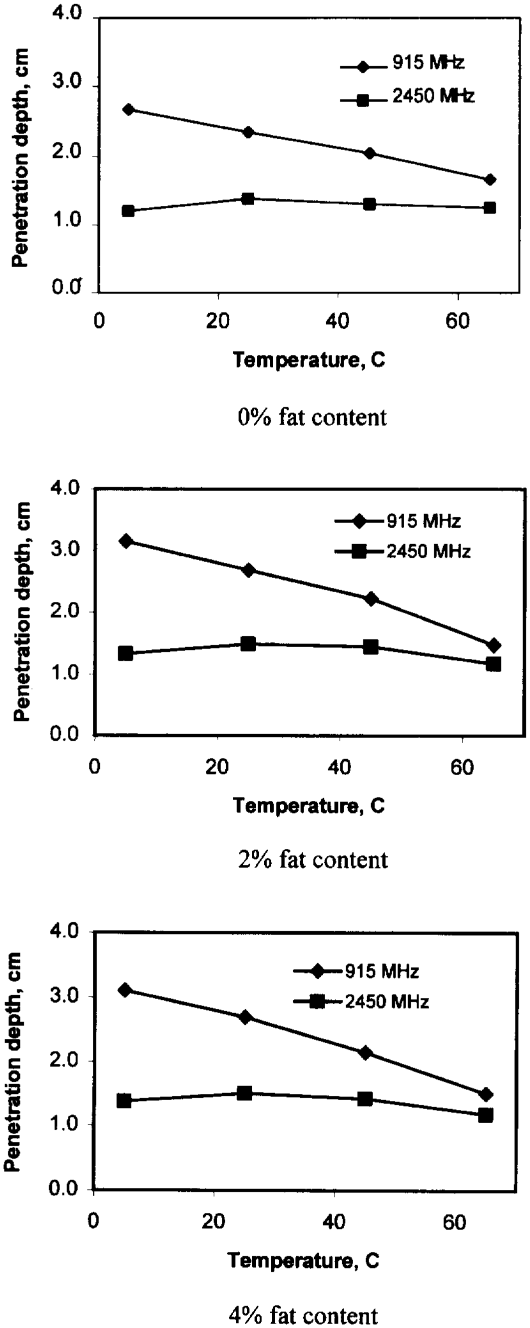
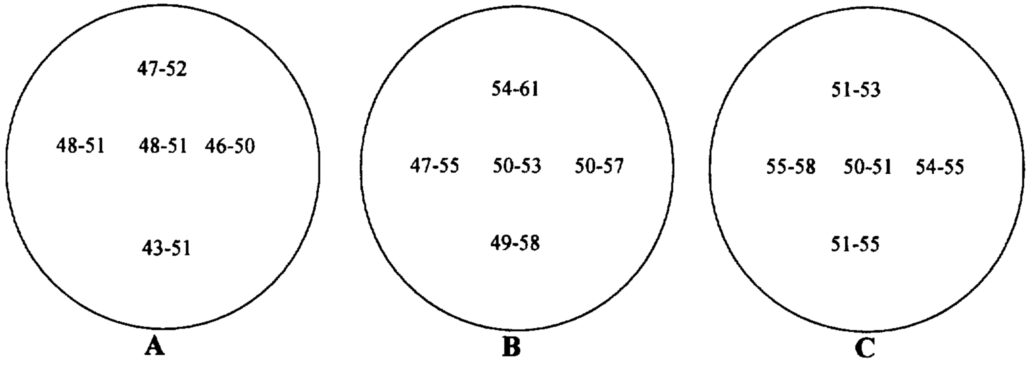
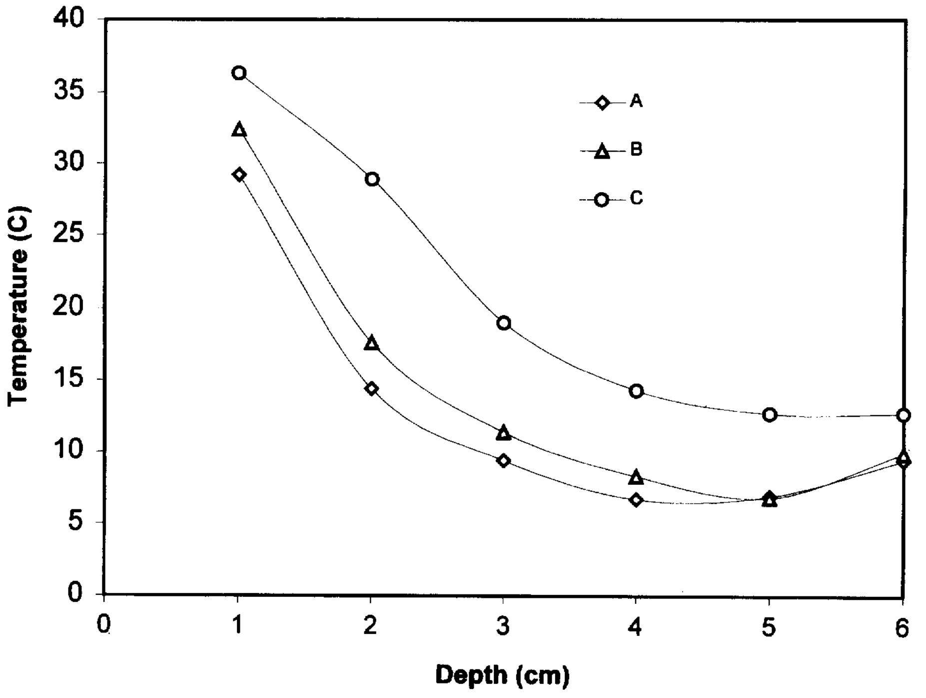


Fig. 7. Penetration depth of 2450 and 915 MHz microwaves in cottage cheese of three different fat contents.



Surface Temperatures (°C) of cottage cheese in containers after three different microwave treatments.



Temperature of cottage cheese at various depths in containers after microwave treatments. Standard deviations were between 0.4°C for locations in the lower part of containers and 2.6°C for locations close to the surface.

Fig. 8. Temperature distribution along the depth of cottage cheese and at the top surface after three different treatments. A: Heating for 70 s at 2450 MHz; B: heating for 80 s at 2450 MHz; C: heating for 150 s at 915 MHz. Microwave power levels were all at a nominal 1 kW. Scattered data are means of three replicates.

The dimensionless temperature profile was approximated by eqn (11), which was derived from eqn (9) by considering a complete reflection of microwaves at the bottom surface of the container (the metal shielding surface):

$$\frac{T(z,t)-T_o}{T(0,t)-T_o} = e^{-z/dp} + e^{-[(d-z)+d]/dp} \tag{11}$$

where the depth of the cottage cheese is $d = 6$ cm and the initial temperature is $T_0 = 4°C$.

Using averaged values for penetration depth dp as calculated by the dielectric properties of cottage cheese, eqn (11) predicted well the trend in temperature distribution in the cottage cheese at both frequencies (Fig. 9). The relatively high measured temperatures at the bottom of the cottage cheese treated with 2450 MHz might have been caused by heat conduction from a warm bottom surface during handling prior to and during microwave treatment.

As illustrated in Fig. 9, the dimensionless temperature profile was significantly affected by microwave frequency. Surface temperature raised at much higher rates than that of the interior, and peak temperature (temperature ratio > 0.9) was confined to a thin top layer (< 0.3 cm).

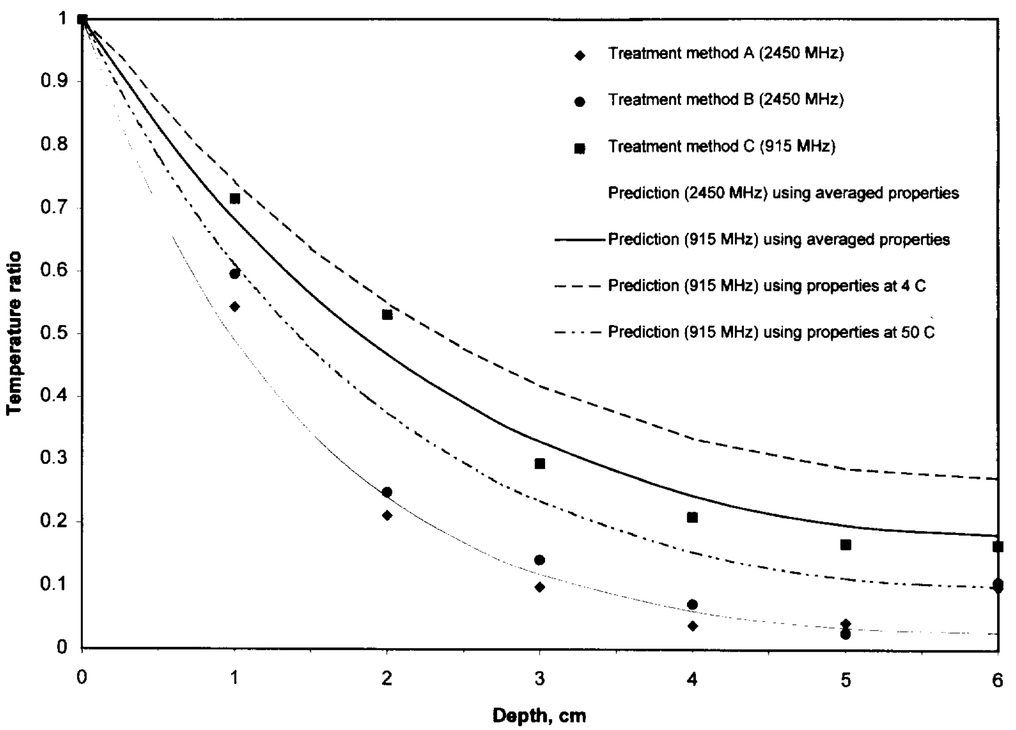


Fig. 9. Predicted and measured dimensionless temperature profile $[T(z,t)-T_o]/[T(0,t)-T_o]$ (eqn (11)) after three different microwave treatments.

As shown in Fig. 7, the penetration depth of 2450 MHz microwaves in cottage cheese is not significantly influenced by material temperature in the test range, while the depth of penetration of 915 MHz microwaves decreased with increasing temperature, primarily due to the interaction between dissolved salt and the 915 MHz microwaves. The effect of material properties on the dimensionless temperature profile corresponding to 915 MHz is demonstrated by the two dashed curves in Fig. 9. The differential temperature rise at high material temperatures was much greater than at lower temperatures. This reduces heating in the interior of the cottage cheese as the surface temperature rises during the microwave treatment.

It is likely that the reflection of microwaves at the bottom surface of the container would result in standing waves near the lower part of the containers. This might have caused regional hot spots and cold spots at every quarter wavelength ($\lambda_m/4$) along the depth, where λ_m is estimated to be about 1.6 cm for 2450 MHz and 4.2 cm for 915 MHz in cottage cheese according to:

$$\lambda_m = \lambda_o \left\{ \frac{\varepsilon'}{2} \left[\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'} \right)^2} + 1 \right] \right\}^{1/2} \tag{12}$$

Since the microwaves were greatly attenuated in the cottage cheese, the effect of standing waves in the lower portion of the container should not be significant to affect the general pattern of surface heating during microwave treatment in this study. Similarly, due to large attenuation, the standing waves within the cottage cheese in horizontal directions, as caused by the reflections between the sides of shielded containers, might also be not significant.

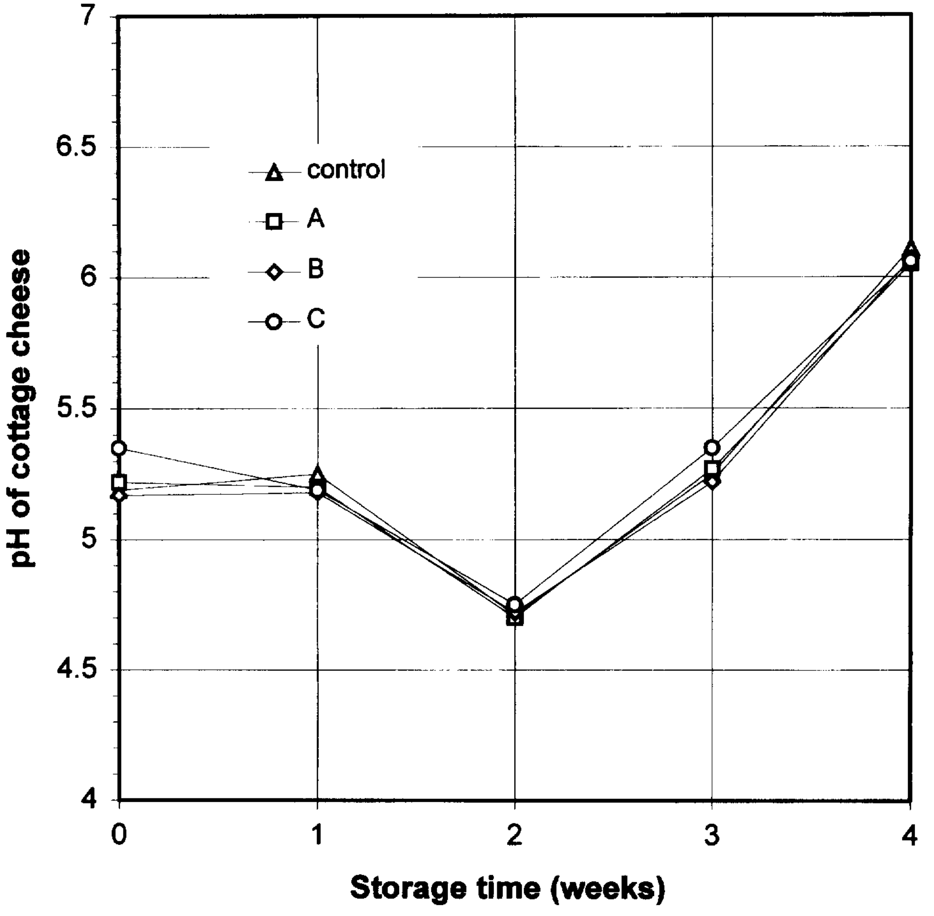
Because of the similarity among the predicted microwave penetration depths in three different cottage cheeses (Fig. 7), it is reasonable to expect that the temperature profiles in 0 and 2% fat content cheeses will be very similar to that in 4% fat content cheese when subjected to the same microwave treatments.

Effect of microwave treatment and storage time on pH

Figure 10 shows the pH of the control and treated cheeses immediately after the treatment and 1, 2, 3 and 4 weeks after treatment and holding at 3°C. Microwave treatments did not affect sample pH. The pH did not change immediately after treatment or after 1 week of storage. Between the first and second week, the pH decreased to 4.7 and then rapidly increased during the third and fourth weeks. The decrease in pH during the first 2 weeks was likely due to residual fermentation by lactics in the added cultured dressing. Both Kim *et al.* (1993) and Kneifel *et al.* (1993) reported that residual fermentation decreased the pH of yogurt held at 4°C. The increase in pH during the third and fourth weeks was probably due to proteolytic activity of psychrotrophs and also possibly utilization of acid by yeast and mold contaminants.

Effect of microwave treatment on psychrotroph counts

All microwave treatments reduced the psychrotroph counts in cottage cheese (Fig. 11). The psychrotroph counts in samples receiving treatment B (2450 MHz microwave heating for 80 s and holding for 4 min) were substantially lower than those receiving treatments A (2450 MHz microwave treatment for 70 s and holding for 4 min) or C (heating with 915 MHz microwaves for 150 s and holding for 1.5 min). Both the control cheese and the treated cheeses had an increase in psychrotroph count in the first week after treatment. The increase was dependent upon the



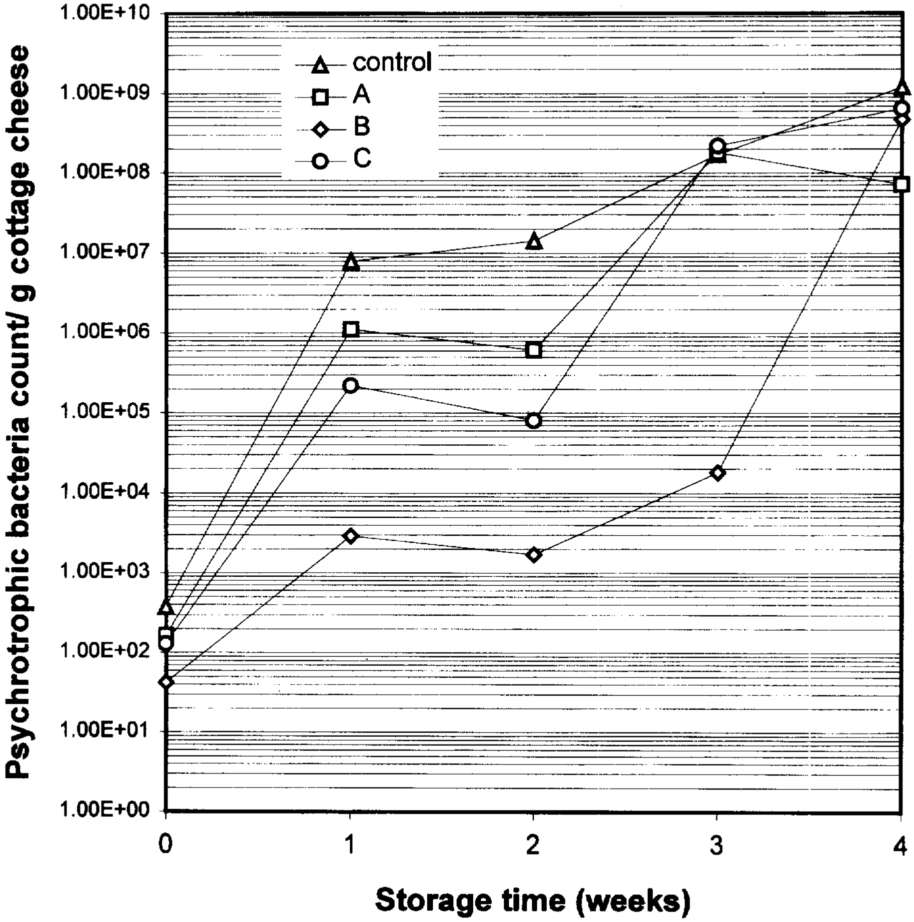
A - treated with 2450 MHz microwaves at 1 kW for 70 s, holding for 4 min.

B - treated with 2450 MHz microwaves at 1 kW for 80 s, holding for 4 min.

C - treated with 915 MHz microwaves at 1 kW for 150 s, holding for 1.5 min.

Fig. 10. Change of pH in cottage cheese during storage after microwave treatments. A: Heating for 70 s at 2450 MHz and holding for 4 min; B: heating for 80 s at 2450 MHz and holding for 4 min; C: heating for 150 s at 915 MHz and holding for 1.5 min. Microwave power levels were all at 1 kW. The scattered data are means of two duplicated measurements.

severity of the microwave treatment. Between weeks one and two the control showed a small increase in count and the treated samples all showed a slight decrease in count. This decrease in count was likely due to the decrease in pH. The growth of most psychrotrophs decreases as the pH goes below 5.0. From week two to week four the psychrotroph count increased rapidly and was likely due to improved growth conditions as the pH moved above 5.0. The end of the second week of the study corresponded to the date the cottage cheese was scheduled for



A - treated with 2450 MHz microwaves at 1 kW for 70 s, holding for 4 min.

B - treated with 2450 MHz microwaves at 1 kW for 80 s, holding for 4 min.

C - treated with 915 MHz microwaves at 1 kW for 150 s, holding for 1.5 min.

Fig. 11. Change of psychrotropic bacteria count per gram of cottage cheese during storage after microwave treatments. The data are means of four counts from delicate samples.

removal from store shelves. The counts from the treated cheese suggested that the microwave treatment reduced the number of psychrotrophs and would increase the shelf-life of the cheese.

Results of sensory analysis

Compared to the control samples, microwave-treated samples appeared dry on the surface and had a pasty texture. The appearance improved during the first week, but the pasty texture persisted throughout the 28-day test. Immediately after treatment the cottage cheese samples had a slight acid flavor compared to the non-treated control. The control samples were bitter after 14 days and the microwave-treated samples were described as having an increased acid flavor. Twenty-one days after the treatment, the samples had a stale flavor. Twenty-eight days after treatment, the appearance of all samples was not acceptable and they were not tasted.

Since psychrotrophic bacteria grow well throughout the bulk of packaged cottage cheese (Moir *et al.*, 1993), surface treatment by microwaves cannot be used alone to extend the shelf-life of cottage cheese. It may be best used together with the dissolved CO_2 method for cottage cheese packaged in normal plastic containers. While the dissolved CO_2 inhibits microbial growth in the bulk, microwave surface treatment and the residual CO_2 in the head space delay the growth of psychrotrophs as well as yeast and mold on the top surface.

CONCLUSION

Measurements of dielectric properties indicated that the penetration depth of 915 and 2450 MHz microwaves in cottage cheese was between 1.2 and 3.2 cm. Salt and fat content played an important role in controlling the penetration depth. Top surface microwave treatment was possible when cottage cheese containers were shielded on the sides and the bottom. A model based on Lambert's law adequately predicted temperature distribution along the depth. The preliminary results of microbial and sensory studies suggest that microwave treatment of fresh cottage cheese could contribute to extending shelf-life by reducing surface psychrotrophs. Additional study is needed to determine how to avoid the pasty texture.

REFERENCES

Bengtsson, N. E. & Risman, P. O. (1971). Dielectric properties of food at 3 GHz as determined by a cavity perturbation technique. II. Measurements on food materials. *Journal of Microwave Power*, **6**, 107–123.

Bigalke, D. (1985). Dairy quality, production of quality cottage cheese, finished product standards, and distribution control. *Dairy & Food Sanitation*, **5**, 59–60.

Bishop, J. R. & White, C. H. (1985). Estimation of potential shelf-life of cottage cheese utilizing bacterial numbers and metabolites. *Journal of Food Protection*, **48**, 1054–1057 and 1061.

Buffler, C. R. (1993). *Microwave Cooking and Processing*. Van Nostrand Reinhold, New York.

Calay, R. K., Newborough, M., Probert, D. & Calay, P. S. (1995). Predictive equations for the dielectric properties of foods. *International Journal of Food Science and Technology*, **29**, 699–715.

Chen, J. H. & Hotchkiss, J. H. (1991). Effect of dissolved carbon dioxode on the growth of psychrotrophic organisms in cottage cheese. *Journal of Dairy Science*, **74**, 2941–2945.
Chen, J. H. & Zall, R. R. (1987). Packaged milk, cream, and cottage cheese can be monitored for freshness using polymer indicator labels. *Dairy & Food Sanitation*, **7**, 402–404.
Dolande, J. & Datta, A. (1993). Temperature profiles in microwave heating of solids: a systematic study. *Journal of Microwave Power and Electromagnetic Energy*, **28**, 58–67.
Emmons, D. B. & Tuckey, E. (1967). Cottage cheese and other cultured milk products. *Pfizer Cheese Monographs* Vol. 3. Chas. Pfizer & Co., Inc., New York.
Kim, E. R., Lee, K. W., Park, Y. H. & Kwak, H. S. (1993). The study of lactic acid bacteria in yoghurt during delivery and storage. *Korean Journal of Dairy Science*, **14**, 260–263.
Kneifel, W., Jaros, D. & Erhard, F. (1993). Microflora and acidification properties of yoghurt related products fermented with commercially available starter cultures. *International Journal of Food Microbiology*, **18**, 179–189.
Marshall, R. T. (1992). *Standard Methods for the Examination of Dairy Products*, 16th edn. American Public Health Association, Washington, DC **87–88**, 213–272.
Moir, C. J., Eyles, M. J. & Davey, J. A. (1993). Inhibition of pseudomonads in cottage cheese by packaging in atmospheres containing carbon dioxide. *Food Microbiology*, **10**, 345–351.
Nelson, S. O. (1978). Frequency and moisture dependence of the dielectric properties of high moisture corn. *Journal of Microwave Power*, **13**, 213–218.
Nelson, S. O., Prakash, A. & Lawrence, K. (1991). Moisture and temperature dependence of the permittivities of some hydrocolloids at 2.45 GHz. *Journal of Microwave Power and Electromagnetic Energy*, **26**, 178–185.
Ohlsson, T. (1989). Dielectric properties and microwave processing. In *Food Properties and Computer-aided Engineering of Food Processing Systems*, ed. R. P. Singh and A. G. Medina. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 73–92.
Roebuck, B. D., Goldblith, S. A. & Westphal, W. B. (1972). Dielectric properties of carbohydrate–water mixtures at microwave frequencies. *Journal of Food Science*, **37**, 199–204.
Ryynänen, S. (1994). The electromagnetic properties of food materials: a review of the basic principles. *Journal of Food Engineering*, **29**, 409–429.
Tochman, L. M., Charles, M. S. & Harte, B. R. (1985). Thermal treatment of cottage cheese 'in package' by microwave heating. *Journal of Food Protection*, **48**, 932–938.
von Hippel, A. R. (1954). *Dielectrics and Waves*. John Wiley, New York.